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On recent interannual variability of the Arctic winter mesosphere: Implications for tracer descent

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[1] Observations from the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) experiment on the NASA/Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite show an unusual vertical displacement of the winter Arctic stratopause in 2006 with zonal mean temperatures at 0.01 hPa ($\sim$78 km) exceeding 250 K. By contrast, at the conventional stratopause location near 0.7 hPa ($\sim$50 km), temperatures were unusually cold. Simulations with the NOGAPS-ALPHA model suggest that these are coupled to an unusually warm and disturbed lower stratosphere that filtered out many of the gravity waves that normally break at and above 50 km. The model also shows that downward transport in the 2006 Arctic vortex was enhanced relative to 2005. These results might explain observations of enhanced upper atmospheric NO descending to the upper stratosphere in 2006 and highlights the importance of gravity waves in modulating the coupling of the upper atmosphere with the stratosphere. **Citation:** Siskind, D. E., S. D. Eckermann, L. Coy, J. P. McCormack, and C. E. Randall (2007), On recent interannual variability of the Arctic winter mesosphere: Implications for tracer descent, *Geophys. Res. Lett.*, *34*, L09806, doi:10.1029/2007GL029293.

1. Introduction

[2] In early 2004 and early 2006, satellite observations have shown unusual intrusions of mesospheric air, enriched in odd nitrogen ($NO_x = NO + NO_2$) and carbon monoxide (CO), into the upper stratosphere [*Randall et al.*, 2005, 2006]. NO is involved in catalytic destruction of ozone, and in 2004 significantly reduced upper stratospheric ozone was observed. The intrusions in 2004 were tentatively linked to the occurrence of strong solar storms in the Oct–Dec, 2003 period [*Randall et al.*, 2005]. Solar storms and associated increased geomagnetic activity will produce enhanced energetic particle precipitation (EPP), especially in the 90–110 km altitude region. These EPP events will dissociate N_2 and produce large amounts of NO_x. One of the more intriguing questions in aeronomy is under what circumstances this NO can be transported down through the mesosphere to the stratosphere where it can react with stratospheric ozone. One key element is to isolate the NO in polar night to prevent its dissociation by solar UV. Wintertime planetary wave activity, for example, can transport polar NO to lower latitudes, increasing its exposure to dissociating sunlight and reducing the net flux of NO into the stratosphere [*Siskind et al.*, 2000].

[3] The 2006 NO intrusions are particularly intriguing because they were observed at the end of a winter season characterized by low levels of geomagnetic activity. This suggests mesospheric meteorological variability was important in facilitating the rapid downward transport with minimal chemical loss. *Randall et al.* [2006] argued that an unusually strong upper-level vortex led to greater confinement of NO_x in the polar night.

[4] Previous work [*Randall et al.*, 2006; *Manney et al.*, 2005] relied on meteorological analyses that were capped at 1 hPa. Here we analyze data from the TIMED/SABER instrument that extend into the lower thermosphere to reveal unusual middle atmospheric temperatures at the time when enhanced NO was observed. We compare three-dimensional general circulation model (GCM) simulations of this 2006 period to simulations of the same period in 2005. These results demonstrate that isolated descent in the mesosphere was enhanced during 2006 and we suggest reasons for this. Finally, we suggest how understanding the variable meteorology of the mesospheric winter could help resolve the longstanding controversy about EPP and its effect on stratospheric NO_x and O_3.

2. SABER Observations

[5] SABER is a 10-channel broadband, limb-viewing, infrared radiometer which has been measuring stratospheric and mesospheric temperatures since the launch of the TIMED satellite in December 2001. Temperature is retrieved from the 15 μm CO_2 emission, which is in local thermodynamic equilibrium (LTE) in the stratosphere and lower mesosphere and in non-LTE in the middle to upper mesosphere and lower thermosphere (MLT). Initial temperatures from a non-LTE retrieval have been presented by *Mertens et al.* [2004]. *Siskind et al.* [2005] show they agreed well with ground-based OH* airglow temperatures. Here we use retrievals with the non-LTE effects included (Version 1.06 in the SABER database).

[6] Figure 1 shows zonal-mean SABER temperatures on 13 February for 2005 and 2006, dates chosen using the work of *Randall et al.* [2006, Figure 4] as a guide. In 2005, the temperature structure is similar to standard climatologies [*Randel et al.*, 2004]. However, in 2006 an unusual vertical displacement of the polar stratopause to $\sim$0.01 hPa ($\sim$80 km) is seen: additionally, the 0.2–5 hPa region is unusually cold and the lower stratosphere at 20–100 hPa is anomalously warm, associated with a major stratospheric

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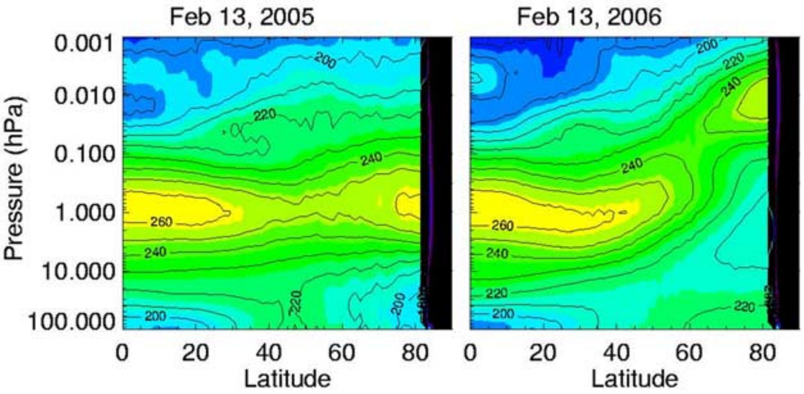

Figure 1. Zonal mean daily averaged SABER temperatures (K).

warming (available at http://www.wmo.ch/web/arep/gaw/arctic_bull/arctic-bulletin-2005–2006.pdf) [also *Manney et al.*, 2005]. SABER temperatures during the prior two weeks show a gradual development of this displaced polar stratopause structure, with zonal mean temperatures at 1 hPa decreasing from about 250 K to <210 K and temperatures at 0.01 hPa increasing from <210 K to >250 K.

3. NOGAPS-ALPHA Modeling

[7] To understand what might be responsible for the unusual temperature structure of the middle atmosphere in 2004 and 2006, and to link that structure with descent of mesospheric air, we have performed simulations with the NOGAPS-ALPHA GCM (Navy Operational Global Atmospheric Prediction System- Advanced Level Physics High Altitude). This model has previously been used to study a stratospheric warming/mesospheric cooling observed by SABER in August 2002 [*Coy et al.*, 2005] and the unusual break-up of the Antarctic ozone hole in September 2002 [*Allen et al.*, 2006].

[8] For the present work, NOGAPS-ALPHA has been extended in several ways. First, the model top was lifted to 10^{-4} hPa with 74 model levels. Our stratospheric long-wave cooling scheme now transitions to the non-LTE cooling parameterization of *Fomichev et al.* [1998] above 75 km. The model heating is still as described by *Eckermann et al.* [2004], but we have improved the ozone climatology by accounting for diurnal variations in the mesosphere and extended it up to 10^{-3} hPa based on guidance from HRDI and SABER data (D. Marsh, personal communication, 2006). All runs used a triangular truncation of T79 ($\sim$1.5° horizontal resolution).

[9] Our NOGAPS-ALPHA “hindcast” runs use an initialization procedure described by *Eckermann et al.* [2006]. Briefly, archived global analyses for a given date and time are read in on reference pressures from 1000-0.4 hPa, with 0.4 hPa fields extrapolated upwards and progressively blended with zonal mean wind and temperature climatologies to crudely initialize altitudes where analysis fields are absent. This global state is interpolated to the NOGAPS-ALPHA grid, then balanced internally using nonlinear normal mode initialization and hydrostatic adjustment procedures prior to commencing model integrations.

[10] Six 14-day hindcasts were performed. Three were initialized on 31 January, 2005 and three were initialized on 31 January, 2006, all at 0 UTC. For each year, one run used a Rayleigh friction (RF) profile as a simple invariant proxy for mesospheric gravity wave drag (GWD) [see *Coy et al.*, 2005], one run used the subgrid-scale orographic GWD (OGWD) parameterization of *Palmer et al.* [1986], and one run was a control without RF or parameterized OGWD. *Palmer et al.*’s [1986] scheme is an improvement over the simple RF profile because it gives a realistic depiction of the geographic location of mountain wave sources and also accounts for filtering of mountain waves by the background winds.

[11] Figure 2 shows zonal mean temperatures from the six runs on the last day of the simulation (0 UTC, 13 February). In 2005, the best agreement with the data in Figure 1 is from runs using the parameterized OGWD and, to a lesser degree, with RF. In 2006, the displaced stratopause and the cold region near 1 hPa are best represented by the OGWD and no-drag runs. Further, imposing RF in the 2006 case yields poor agreement with the data. Thus only the OGWD runs capture the essential morphology of the stratospheric temperatures in both 2005 and 2006. The similarity of the 2006 OGWD simulation to the 2006 no-drag simulation and, correspondingly, of the 2005 OGWD simulation to the 2005 RF simulation points strongly to reduced mesospheric GWD as the source of the anomalously elevated Arctic winter stratopause seen by SABER in 2006, relative to 2005.

[12] To investigate the possibility of interannual variability in mesospheric GWD, Figure 3 shows 14-day averages from the OGWD runs of zonal-mean zonal winds, mean-flow accelerations due to parameterized OGWD, and wave 1 geopotential height amplitudes. Figures 3a and 3b show that the zonal wind field was dramatically different for the two years. While 2005 winds are close to climatology, the 2006 winds were unusually weak in the stratosphere poleward of 50°N, but unusually strong in the mesosphere. Our calculated strong upper-level cold vortex in 2006 is consistent with the observations of *Randall et al.* [2006].

[13] The interannual variation in the zonal winds has important consequences for the calculated OGWD. Thus Figure 3c reveals strong OGWD in 2005 at $\sim$0.1–1 hPa and near 70°N, as seen in climate GCMs with parameterized OGWD [e.g., *McLandress*, 1998, Figure 12]. In 2006,

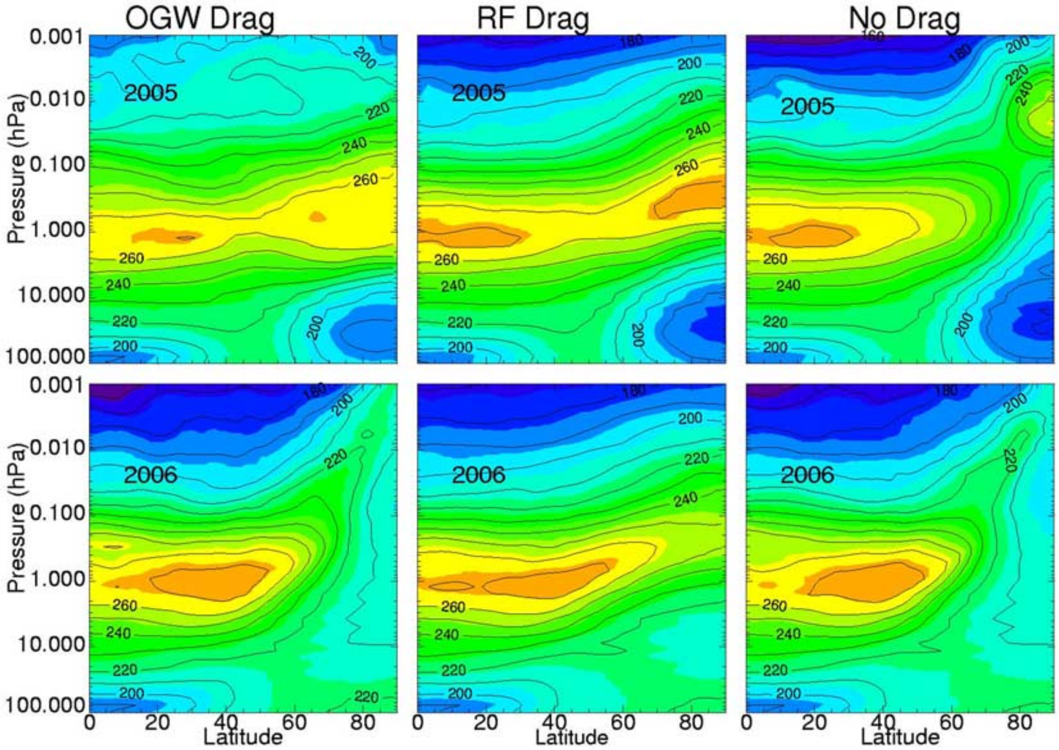

Figure 2. Zonal mean model temperatures, all for 0 UTC for either (top) Feb 13, 2005 or (bottom) Feb 13, 2006, for runs using OGWD, RF, and no drag.

however, OGWD is almost entirely absent poleward of 60°N because the weak lower stratospheric zonal winds (Figure 3b) filter out most mountain waves. The reduced mesospheric OGWD due to this weakened warm stratospheric vortex yields an anomalously strong cold vortex in the upper stratosphere and mesosphere (Figure 3b) [*Randall et al.*, 2006]. These findings are consistent with our general understanding that the separated polar winter stratopause is

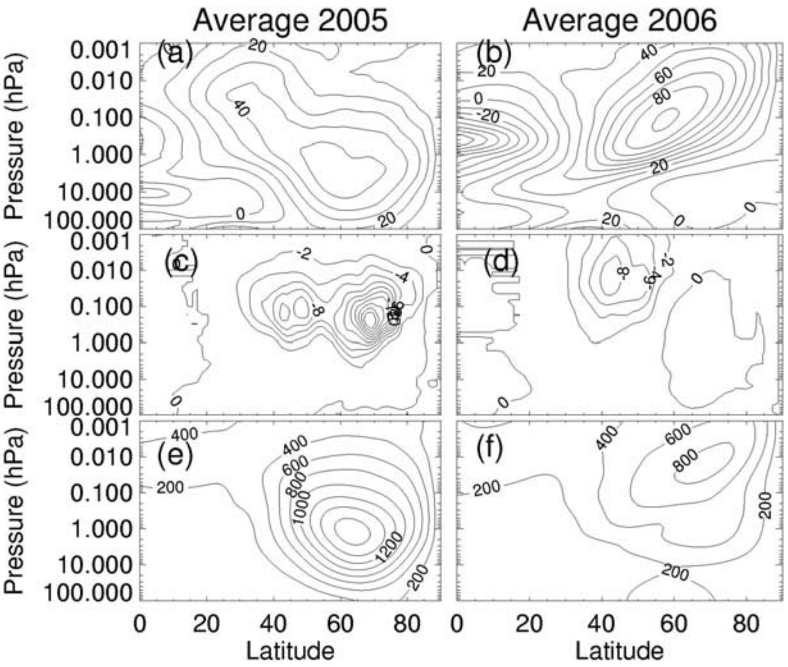

Figure 3. (a) Zonal mean wind from the 2005 GCM simulation. Units are m s^{-1}. (b) Same as Figure 3a but for 2006. (c) Mean OGWD for the 2005 simulation. Units are m s^{-1} day^{-1}. (d) Same as Figure 3c but for 2006. (e) Mean amplitude of perturbation wave 1 geopotential height (m) for the period of the 2005 NOGAPS simulation. The wave 1 amplitude was obtained by linear regression to the perturbation geopotential at each latitude circle. (f) Same as Figure 3e but for 2006.

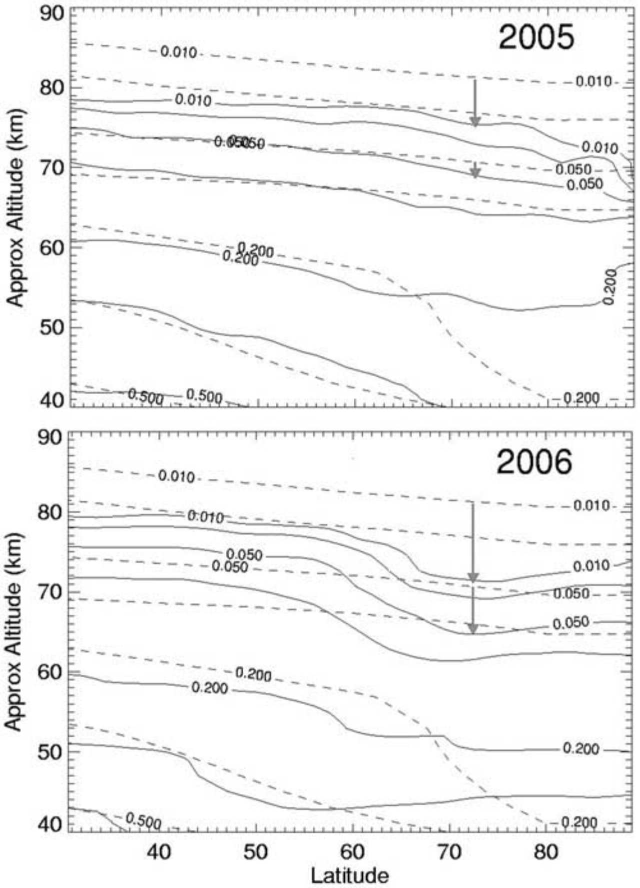

Figure 4. Contours of "pseudo-CH_4" (ppmv, see text for a description) after day 14 of the OGWD runs. Initial pseudo-CH_4 (dashed lines) and the final pseudo-CH_4 (solid lines) are shown. (top) The 2005 simulation and (bottom) the 2006 simulation. The vertical arrows are visual guides to the change in the altitude of the 0.01 ppmv contour (upper arrow) and the 0.05 ppmv contour (lower arrow) at 72°N. Note the greater change in 2006.

gravity wave-driven [*Hitchman et al.*, 1989], since here suppressed OGWD eliminates it. Finally, Figure 3f shows a high altitude planetary wave near 0.01 hPa (compare with Figure 3e for 2005). The dissipation of this wave above this altitude should lead to net poleward and downward motion via downward control [*Garcia and Boville*, 1994]. This, in turn should contribute to at least a portion of the observed temperature increase.

4. Variation in Descent Rates

[14] Figure 4 plots zonal averages of a CH_4-like constituent, which was advected and photochemically updated in our OGWD runs [see *Eckermann et al.*, 2004]. We refer to it here as "pseudo-CH_4" because it was initialized from a monthly zonal mean climatology that is based upon our 2D model results [*McCormack and Siskind*, 2002], rather than analysis, and so cannot be compared with observations. We use it here to diagnose the relative difference in net descent rates between 2005 and 2006, since it is initialized identically in each run.

[15] Pseudo-CH_4 isopleths in Figure 4 show a pronounced dip at 65–80 km in 2006 that is not present in 2005, indicating greater net downward flux descent in 2006 compared with 2005. The arrows in Figure 4 illustrate the change in altitude for the 10 and 50 ppbv contours at 72°N. Over the 2 week period, the net descent of the 10 ppbv contour is ~10 km in 2006 and ~6 km in 2005. The 50 ppbv contour descends ~6 km in 2006 and only ~2 km in 2005. This enhanced descent in 2006 would allow NO_x to more easily reach the lower mesosphere where the chemical lifetime is longer and where it would remain confined in the strong polar vortex (Figure 3b) and thus be shielded from photodissociative loss. We thus conclude that an important factor in the enhanced downward NO_x (and CO) fluxes reported by *Randall et al.* [2006] is greater net descent in the altitude region above 60 km in early February 2006.

5. Historical Context

[16] Here, we speculate whether enhanced downward transport of NO_x also occurred in previous years. *Callis et al.* [1998] argued that NO_2 observations in 1985 could be explained only if they included elevated EPP in their 2D model simulations. Contrary to this, while a link between southern stratospheric NO_x and EPP has been established [*Randall et al.*, 1998, 2007; *Siskind et al.*, 2000], *Hood and Soukharev* [2006] suggest that such a link in the north is insignificant.

[17] Our results here specifically show how persistent, weak zonal winds in the stratosphere can create the conditions for enhanced mesospheric NO_x descent. Interestingly, the winter of 1984–1985 was meteorologically similar to 2003–2004 [*Manney et al.*, 2005]. Although not shown here, SABER temperatures in early 2004 are very similar to 2006, consistent with the enhanced descent reported by *Randall et al.* [2006]. It is therefore likely that 1984–85 was also a year of a displaced stratopause, and enhanced descent, and, possibly, enhanced stratospheric NO_2 as reported by *Callis et al.* [1998]. Because we do not at present expect these unusual dynamical conditions to follow a predictable 11 year cycle, we do not expect the NO_x flux into the Arctic stratosphere to follow an 11 year cycle. Contrary to many historical model simulations [e.g., *Huang and Brasseur*, 1993], we instead expect the NO_x flux to respond to unusual weather in the middle atmosphere, which often is forced from the troposphere [e.g., *Allen et al.*, 2006].

6. Conclusion

[18] Our GCM simulations capture important elements of the unusual meteorology associated with the enhanced descent of NO_x into the upper stratosphere in January/February 2006 (and by implication for the same period in 2004). Specifically, these include the unusually warm lowermost stratosphere, the unusually cold upper stratosphere, the strong polar vortex which extends well up into the mesosphere and the displacement of the temperature peak associated with the stratopause up to near 80 km. Our results suggest that the highly disturbed lowermost stratosphere in 2006 blocked the propagation of gravity waves

which normally break in the stratopause/lower mesosphere region. Since this dynamical forcing normally would warm the 50 km region, in 2006, this region cooled radiatively leading to a strong upper-level vortex. At the same time, a planetary wave 1 propagated into the upper mesosphere. The breaking of this wave may have provided a momentum source which drove enhanced descent in 2006. This enhanced descent facilitated the transport of thermospheric NO_x into the lower mesosphere where it remained isolated in the strong polar vortex.

[19] Our work is incomplete in that there are still a number of deficiencies in our simulation of the polar winter temperatures. We fall considerably short of the 250K peak zonal mean temperature at.01 hPa in 2006. Also, even in a more typical year, 2005, our lower stratosphere is too cold and our upper stratosphere/lower mesosphere is too warm. These deficiencies may be related to our neglect of non-orographic gravity wave drag [*McLandress*, 1998]. Our model does not include chemical heating from oxygen recombination [*Mlynczak and Solomon*, 1993] in the upper mesosphere; undoubtedly this would act to warm our upper mesosphere and improve the agreement with SABER. Future work will seek to redress these deficiencies.

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