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Aura Microwave Limb Sounder Observations of Dynamics and Transport During the Record-breaking 2009 Arctic Stratospheric Major Warming

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Abstract. A major stratospheric sudden warming (SSW) in January 2009 was the strongest and most prolonged on record. Aura Microwave Limb Sounder (MLS) observations are used to provide an overview of dynamics and transport during the 2009 SSW, and to compare with the intense, long-lasting SSW in January 2006. The Arctic polar vortex split during the 2009 SSW, whereas the 2006 SSW was a vortex displacement event. Winds reversed to easterly more rapidly and reverted to westerly more slowly in 2009 than in 2006. More mixing of trace gases out of the vortex during the decay of the vortex fragments, and less before the fulfillment of major SSW criteria, was seen in 2009 than in 2006; persistent well-defined fragments of vortex and anticyclone air were more prevalent in 2009. The 2009 SSW had a more profound impact on the lower stratosphere than any previously observed SSW, with no significant recovery of the vortex in that region. The stratopause breakdown and subsequent reformation at very high altitude, accompanied by enhanced descent into a rapidly strengthening upper stratospheric vortex, were similar in 2009 and 2006. Many differences between 2006 and 2009 appear to be related to the different character of the SSWs in the two years.

1. Introduction

Major stratospheric sudden warmings (SSW) dramatically disrupt the typical wintertime circulation of the stratosphere and mesosphere. They are triggered by anomalous wave activity propagating from the upper troposphere and may, in turn, affect tropospheric weather patterns [e.g., *Baldwin and Dunkerton*, 2001]. Climate-change induced alterations in SSW frequency and characteristics are expected due to changes in the Brewer-Dobson circulation, and such changes will in turn impact stratospheric ozone (O_3) loss and recovery and tropospheric climate [e.g., *Charlton-Perez et al.*, 2008; *WMO*, 2007]. Only in the past few years have sufficient data been available to thoroughly study dynamics and transport during SSWs throughout the upper troposphere through the mesosphere. An unusually strong, prolonged SSW in January 2006 was the first to be characterized in detail using recent datasets: Upward propagating waves generated above a ridge in mid-January 2006 led to a breakdown of the stratospheric vortex [*Coy et al.*, 2009], with criteria for a major SSW (10 hPa zonal mean winds and temperature gradient reversal poleward of 60°N) fulfilled on 21 January [e.g., *Manney et al.*, 2008b, hereinafter M08]. The stratopause broke down during the SSW, then reformed at very high altitude (near 75 km) [*Siskind et al.*, 2007, M08]. Trace gas observations indicate enhanced descent into a strong reformed upper stratospheric/lower mesospheric (USLM) vortex [e.g., *Randall et al.*, 2006; *Manney et al.*, 2008a, 2009]. *Manney et al.* [2009, hereinafter M09] used Aura Microwave Limb Sounder (MLS) and Atmospheric Chemistry Experiment-Fourier Transform Spectrometer data, with chemistry transport model simulations

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and meteorological analyses from a data assimilation system (DAS), to study transport during the 2006 SSW throughout the upper troposphere and middle atmosphere.

SSWs can be classified as vortex displacement or vortex split events [e.g., *Charlton and Polvani*, 2007, hereinafter CP07]. The 2006 SSW was a vortex displacement event [M08]. In January 2009, another very strong prolonged major SSW occurred, this time a vortex split event; major SSW criteria were fulfilled on 24 January. Differences are expected in dynamics and transport between vortex split and vortex displacement events. We use temperature, geopotential height and trace gas data from Aura MLS, with meteorological fields from the Goddard Earth Observing System-Version 5.2.0 (GEOS-5) DAS, to survey dynamics and transport during the 2009 SSW and to present initial comparisons with the 2006 SSW. The MLS and DAS fields and analysis methods are described by M08 and M09.

2. Dynamical Overview

Figure 1 gives an overview of dynamics during the 2009 SSW using MLS temperature and geopotential height (Z) data [*Schwartz et al.*, 2008]; winds and static stability are calculated as described by M08. Starting on ∼9 January, unusually high values of maximum 45–55°N 147 hPa Z (Figure 1g) appeared; a sharp peak in mid-January to highly anomalous values was accompanied by strong wave-2 amplification in the midstratosphere (Figure 1f), and a subsequent rapid drop in 60°N zonal mean wind (Figure 1d). Similar to the evolution in 2006 [M08], the stratopause warmed and dropped as the SSW developed (Figure 1a, c), then broke down, leading to a nearly isothermal middle atmosphere at the end of January. The stratopause identification algorithm does not search for temperature maxima below 30 km; arguably, the stratopause – the primary temperature maximum – might be identified as being near 15 km in late January 2009; in 2006, the primary temperature maximum dropped to ∼30 km. In early February, the polar stratopause reformed at very high altitude, near 80 km at 80°N, in both 2006 and 2009 (Figure 1c). As in 2006, the GEOS-5 (and other) DAS failed to capture the behavior of the stratopause after the 2009 SSW, placing the altitude of reformation too low (Figure 1a, c).

In the mesosphere, several brief wind reversals preceded the one associated with the major SSW; mesospheric easterlies related to the SSW occurred 8–10 days before the middle stratospheric wind reversal (Figure 1b). The mesospheric wind reversal was gradual compared to the rapid transition from strong westerlies to strong easterlies in the middle and upper stratosphere. The wind reversal was later (typical of SSWs) and more prolonged at lower altitudes. As in 2006, the vortex reformed strongly and quickly in the USLM and weakly in the middle stratosphere. Consistent with the failings in temperatures, GEOS-5 USLM winds accelerate too slowly after the SSW. The 2009 SSW had a deeper influence than that in 2006, with wind reversals extending below 300 hPa during the SSW and near zero winds persisting through March below ∼20 km (in 2006, easterlies extended only down to ∼100 hPa, and westerlies reappeared at all levels by ∼20 February [M08]).

Contrasts and similarities emerge between the dynamics of the 2006 and 2009 SSWs (blue lines in Figures 1c through 1g show behavior in 2005–2006). The breakdown and reappearance of the stratopause and reformation of the USLM vortex were very similar (e.g., Figure 1c), consistent with CP07's finding of similar temperature evolution during vortex split and vortex displacement SSWs. Very large wave-1 (wave-2) during the SSW in 2006 (2009) (Figure 1e, f) is consistent with vortex displacement (split) events. December wave-1 amplitudes were large in both years; wave-1 minor SSWs preceding a major SSW are also often associated with "pre-conditioning", i.e., changes in the zonal flow that focus upward propagating waves poleward and decelerate winds in the middle to upper stratosphere, triggering a SSW [e.g., *Labitzke*, 1981; *Andrews et al.*, 1987]. Wave-1 amplitudes were larger prior to the 2009 SSW, suggesting a larger role of preconditioning. Deceleration of the 60°N winds in 2009 was more rapid than that in 2006 (Figure 1d), and they recovered more slowly afterward. These differences in dynamics are consistent with differing characteristics of vortex split and vortex displacement events described by CP07.

147 hPa MLS midlatitude Z maxima (Figure 1g) showed several significant peaks in January 2006, with the maximum near mid-January associated with an eastward-propagating ridge forcing changes that focused propagating waves poleward [*Coy et al.*, 2009]. In 2009, high Z maxima starting before mid-January indicate a ridge comparable in strength to, but more persistent than, that in 2006; just after mid-January, this ridge intensified further, leading to wave propagation that triggered the stratospheric vortex breakdown.

The 2006 SSW, along with a similar event in 2004, was the strongest and longest-lasting on record [*Manney et al.*, 2005, M08]. The diagnostics in Figure 1 show that the 2009 SSW surpassed that in 2006 and had a more profound and lasting effect on the lower stratosphere.

3. Trace Gas Transport Observed by MLS

Vortex-averaged CO (Figure 2, top) indicates strong descent into the USLM vortex starting in fall, as is typical [e.g., M09]. Comparison with 2005–2006 [M09] shows that confined descent in December 2008 was weaker and less mono-

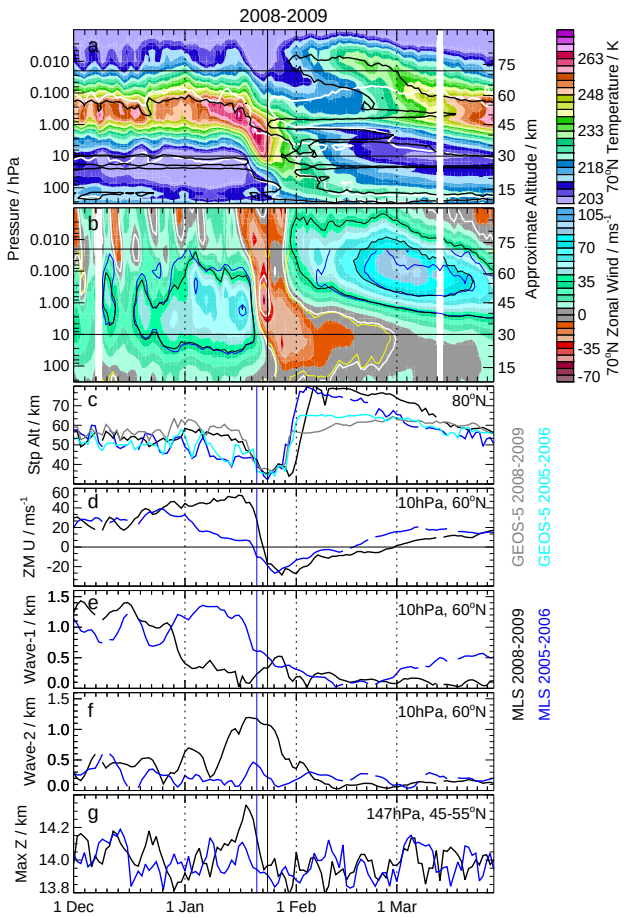

Figure 1. 70°N pressure-time sections of (a) MLS zonal mean temperature (overlays: MLS (black) and GEOS-5 (white) 4×10^{-4} s^{-2} static stability) and (b) MLS-derived zonal mean wind (overlays: MLS (white/black) and GEOS-5 (yellow/blue) -35, 0, 35, 70 ms^{-1} winds. Thin horizontal lines in (a) and (b) are at 0.02 (highest level with GEOS-5 data) and 10 hPa (where major SSW criteria are defined). (c) 80°N MLS (2009 black/2006 blue) and GEOS-5 (2009 grey/2006 cyan) stratopause altitudes. (d) 10-hPa, 60°N MLS-derived zonal mean winds. (e) wave 1 and (f) wave 2 10-hPa, 60°N MLS geopotential height (Z) amplitudes. (g) Maximum MLS 147 hPa Z between 45 and 55°N. (d) through (g) show 2008–2009 in black, 2005–2006 in blue; black/blue vertical lines show date when major SSW criteria were first met in 2009/2006.

tonic than that in December 2005, suggesting greater vortex variability in the upper stratosphere. In both years, CO decreased suddenly during the SSW as vortex air mixed with extra-vortex air. The 2009 CO reduction was both more abrupt and less complete than that in 2006: CO began decreasing rapidly before mid-January 2006 at ∼40 to 50 km, then dropped suddenly at lower altitudes at the time of the vortex breakup; in 2009, the pattern of strong (albeit non-monotonic) descent was apparent through the time of the vortex split, after which it decreased suddenly at all levels above ∼35 km. CO values of ∼135–225 ppbv lingered at 40–45 km until mid-February after the 2009 SSW; CO in that region just after the 2006 SSW were <90 ppbv [M09].

In the middle stratosphere, the signature of confined descent is seen in the downward progression of the N_2O contours before the SSW (Figure 2, bottom). This descent was slightly stronger in 2009 than in 2006 below ∼600 K (compare 90 ppbv contours) in December, suggesting a more quiescent lower stratospheric vortex at that time. A slight upward progression of the N_2O contours began in early January 2006 [also see M09], indicating less complete confinement of vortex air; in contrast, in 2009, the downward progression of contours from confined descent continued until after the vortex split, when N_2O dramatically increased between ∼500 and 1000 K, starting first at higher levels. The largest increases occurred several days after the vortex split, and were more sudden and of much greater magnitude than those in 2006.

The vortex split on ∼20 January in the upper stratosphere (1700 K, Figure 3), ∼24 January in the midstratosphere (850 K, Figure 4), and ∼30 January in the lower stratosphere (520 K, Figure 4), consistent with the typical top-down development of SSWs. The MLS trace gas fields clearly show material being drawn off the vortices as they decay at all levels (e.g., 28 January at 1700 K, 1 February at 850 K, 15 February at 520 K). Largest decreases (increases) in high-EqL CO, H_2O (N_2O) are associated, not with the vortex split, but with the subsequent decay and further fragmenting of the vortex remnants, ∼28 January/1 February/15 February at 1700/850/520 K. This is in contrast to the vortex displacement event in 2006, during which tracer changes were more gradual and began before major SSW criteria were fulfilled.

Descent of high mesospheric CO into the strong reformed vortex began almost immediately after the SSW (Figure 2); high CO reached the vortex core at 1700 K by ∼10 March (e.g., 18 March map). This behavior is quite similar to that in 2006, except for the lingering slightly elevated CO values in the vortex core throughout the SSW.

At 850 K, the vortex was elongated after mid-January, but not noticeably constricted into two lobes until ∼23 Jan-

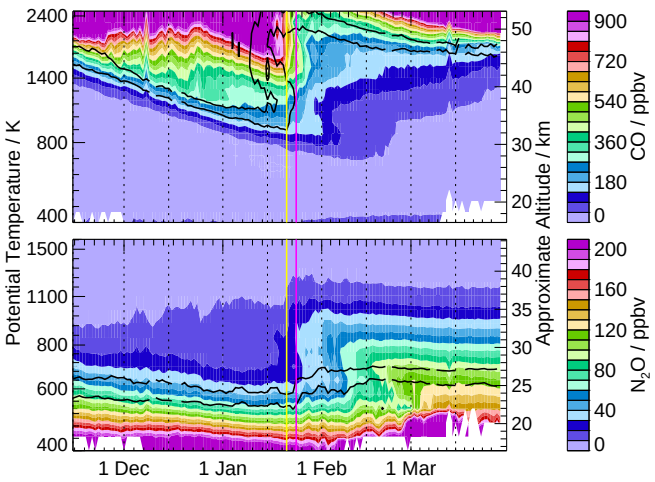

Figure 2. Vortex-averaged MLS CO (top, 400–2500 K) and N_2O (bottom, 400–1600 K) during the 2008–2009 winter. Overlaid contours are CO values of 270 and 540 ppbv and N_2O values of 60 and 90 ppbv in 2005–2006. Yellow/magenta lines show date major SSW criteria were fulfilled in 2006/2009.

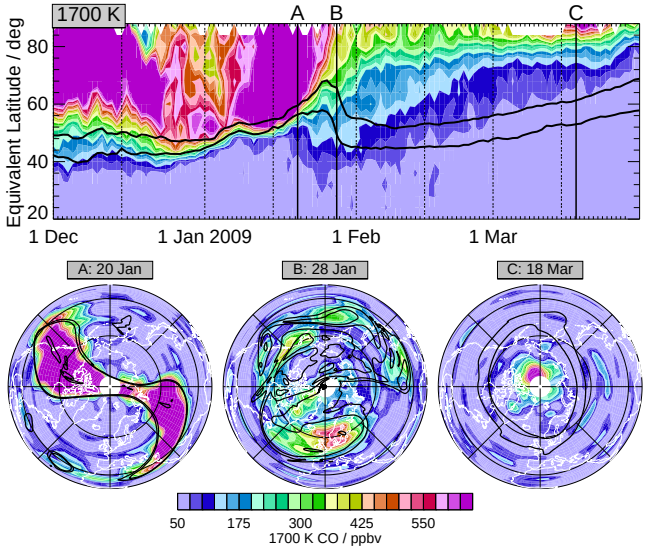

Figure 3. 1700 K MLS CO equivalent latitude (EqL)/time series (top) and maps on marked days (bottom). Black overlays are PV contours near the vortex edge. The maps show 0–90°N, with 0°E at bottom, 90°E at right.

uary (see http://mls.jpl.nasa.gov for daily maps), after which it rapidly split (Figure 4, 24 January map). The middle-stratospheric N_2O decrease near 40°EqL after ∼15 January is associated with tongues drawn off the vortex (e.g., 24 January map). Numerous small, well-defined, vortex and anticyclone remnants lingered for over a month after the SSW (1, 15 February maps). PV and N_2O gradients tightened near 40–50°EqL starting in late February, indicating reestablishment of a (weak) vortex transport barrier. While the overall recovery was similar to that in 2006, the persistence of small, confined vortex and anticyclone remnants (with corresponding well-defined regions of low and high N_2O, respectively) was not apparent long after the SSW in 2006.

At 520 K, from ∼20 January through ∼13 February, tongues of tropical air were drawn up to very high latitudes (see maps), noticeably decreasing 40–60°EqL H_2O. After mid-February, the 520 K vortex was virtually non-existent, though a small core of high H_2O values lingered through early March. No significant recovery of the lower stratospheric vortex occurred after the SSW. Compared to the 2006 SSW, during which less complete vortex disappearance and slight recovery were seen, the impact of the 2009 SSW on the lower stratosphere was even more profound and prolonged. Before the SSW, temperatures were well below the threshold for polar stratospheric cloud (PSC) formation (blue contours in Figure 4 at 520 K) from mid-December through ∼24 January. MLS ClO, HCl and O_3 (not shown; daily maps available at http://mls.jpl.nasa.gov) indicate extensive chlorine activation and suggest chemical O_3 loss during this period, enabled/enhanced by the vortex distortion bringing much of the PSC-processed air into sunlit regions.

4. Summary

Aura MLS observations of temperature, geopotential height and trace gases make possible a comprehensive overview of dynamics and transport during the most prolonged and strongest major SSW on record, in January 2009. Previously observed intense SSWs in January were vortex displacement events, whereas the 2009 SSW split the vortex. Some features of the 2009 SSW were similar to those of the long-lasting SSW in January 2006: The stratopause dropped dramatically and broke down, then reformed at very high (∼75–80 km) altitude; DAS analyses failed to capture the stratopause evolution. Enhanced descent brought high CO down into an unusually strong reestablished USLM vortex. The middle stratospheric vortex reformed weakly. Other features of the 2009 SSW contrast with the behavior in 2006: There was a stronger geopotential height maximum in the lowermost stratosphere associated with forcing the 2009 SSW; winds reversed to easterly more rapidly, reverted

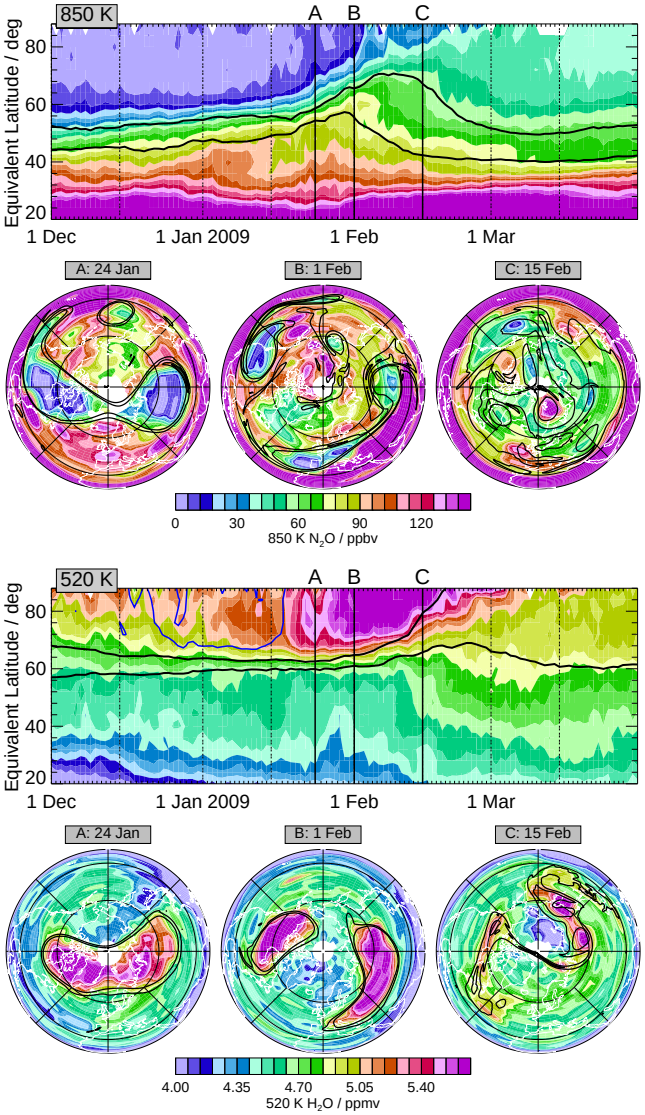

Figure 4. As in Figure 3, but for 850 K N_2O (top) and 520 K H_2O (bottom). Blue contours at 520 K are 190 and 195 K temperatures.

to westerlies more slowly, and the reversal extended farther down into the upper troposphere/lower stratosphere. Trace gases were mixed out of the vortex rapidly, primarily during the decay of vortex fragments, after the 2009 SSW, as opposed to more gradually (beginning before the SSW) and less completely in 2006. More persistent well-defined fragments of vortex and anticyclone air were observed in 2009 than in 2006. The 2009 lower stratospheric vortex dissipated more completely than that in 2006 and showed no sign of recovery. More rapid wind reversal has previously been shown to be associated with vortex split than with vortex displacement events [CP07], and the synoptic evolution of the two large vortex fragments in 2009, with vortex air remaining largely well confined in each until after the split, suggests that differences in transport are also related to the differing character of the 2009 and 2006 SSWs. Extensive satellite observations of the 2006 and 2009 SSWs covering the upper troposphere through the mesosphere allow us to characterize these events in unprecedented detail. Further studies of these extreme events, including implications for stratospheric ozone loss and stratosphere-troposphere exchange, are in progress. Also under investigation are coupled circulation anomalies from the mesosphere through the troposphere [*J. N. Lee, et al., "Aura Microwave Limb Sounder Observations of the Northern Annular Mode", in preparation*], effects of stratosphere-troposphere coupling on tropospheric weather, and the nature of the forcing.

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