

# The evolution of the stratopause during the 2006 major warming: Satellite Data and Assimilated Meteorological Analyses

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**Abstract.** Microwave Limb Sounder and Sounding of the Atmosphere with Broadband Emission Radiometry data show the polar stratopause, usually higher than and separated from that at midlatitudes, dropping from  $\sim 55$ – $60$  to near  $30$  km during the development of a major stratospheric sudden warming (SSW) in January 2006; the stratopause and mesosphere then cool dramatically after the peak of the SSW. After a period when the stratosphere is nearly isothermal, a cool stratopause reforms near  $75$  km in early February, then drops to  $\sim 55$  km and warms. The stratopause is separated in longitude as well as latitude, with lowest temperatures in the transition regions between higher and lower stratopauses. Operational assimilated meteorological analyses, which are not constrained by data at stratopause altitude, do not capture a secondary temperature maximum that overlies the stratopause or the very high stratopause that reforms after the SSW; they underestimate the stratopause altitude variation during the SSW. High-quality daily satellite temperature measurements are invaluable in improving our understanding of stratopause evolution and its representation in models and assimilation systems.

## 1. Introduction

The stratopause region has not been extensively studied, largely because of the sparsity and poor resolution of data covering the upper stratosphere/lower mesosphere (USLM). *Labitzke* [1972] used rocket and early satellite data to show a drop of  $\sim 20$  km in stratopause altitude during a stratospheric sudden warming (SSW), accompanied by a mesospheric cooling. *Hitchman et al.* [1989] showed that the elevated “separated” polar winter stratopause was consistent

with formation via gravity wave (GW) processes. Until the past few years, global daily temperature measurements covering the USLM were available for only a few short periods and most had very poor ( $\sim 15$  km or greater) vertical resolution. Since the launch of Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) in January 2002, such profiles have been available with good quality and resolution [ $\sim 2$  km, e.g., *Remsberg et al.*, 2003] and  $\sim 3^\circ$  along-orbit spacing, but with an  $\sim 60$ -day “yaw” cycle whereby the instrument only observes high latitudes in one hemisphere at a time. Since August 2004, the Microwave Limb Sounder (MLS) on NASA’s Earth Observing System Aura satellite has provided daily near-global ( $\pm 82^\circ$ ) temperature profiles from 315 to 0.001 hPa with vertical resolution of  $\sim 6$ – $9$  km in the USLM and  $\sim 1.6^\circ$  along-orbit spacing [e.g., *Livesey et al.*, 2005; *Waters et al.*, 2006].

Operational assimilated meteorological analyses, including ones that extend through the USLM from NASA’s Global Modeling and Assimilation Office (GMAO) and the Euro-

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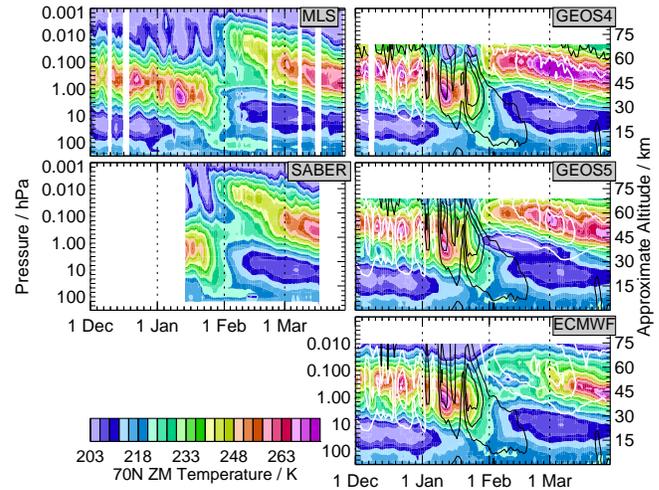
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pean Center for Medium-Range Weather Forecasts (ECMWF), are often used for studies of middle atmosphere temperature. Currently, the highest altitude temperature inputs to these are in the upper stratosphere from nadir sounding satellites with very poor vertical resolution. USLM temperatures are thus very weakly constrained by data and rely primarily on the underlying general circulation models (GCMs), which have differing treatments of the mesosphere, model top effects, and GW parameterizations. Since data for comparisons have been sparse, the quality of the analyses in the USLM is largely unknown.

The evolution of the stratopause during the prolonged SSW that began in January 2006 is detailed here using MLS (v1.5) and SABER (v1.06) data, and compared with that in GMAO's Goddard Earth Observing System v4.03 and v5.01 (GEOS-4 and GEOS-5) analyses [Bloom *et al.*, 2005; Reinecker *et al.*, 2007] and the T799/91-level ECMWF analyses that became operational in February 2006 [Untch *et al.*, 2006]. Both use GCMs with a model top at 0.01 hPa. The GEOS analyses use a simple non-orographic GW parameterization [Garcia and Boville, 1994] to represent waves with non-zero phase speed that are important in the USLM; ECMWF uses Rayleigh friction at altitudes above 5 hPa to slow down the otherwise too strong polar night jet.

## 2. Evolution of the Stratopause

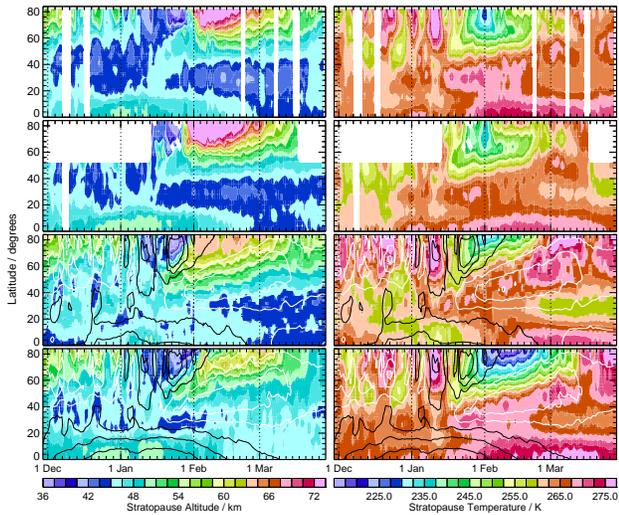
Figure 1 shows zonal mean 70°N temperatures and zonal winds during the 2005–2006 Arctic winter; Figure 2 shows the latitude dependence of stratopause altitude and temperature. Until early January, the polar stratopause altitude was fairly constant near 55–60 km (Figures 1 and 2; the higher stratopause north of ~60°N until late December (Figure 2) shows the climatological pattern noted by Hitchman *et al.* [1989]). Zonal mean easterlies appeared in the USLM in early January, and the conditions for a major SSW were fulfilled by 21 January (easterlies north of 60°N at 10 hPa, not shown). Concurrently with the onset of easterlies in the USLM, the stratopause began dropping and warming rapidly. Stratopause cooling began in mid- to late-January, when easterlies were at a maximum in the USLM and extended through the middle stratosphere; the cooling started just poleward of the reforming westerly jet core. By late January, the stratopause was very low and ill-defined, with a cool, nearly isothermal region from ~30 to 0.1 hPa. The stratopause reappeared as a well-defined structure in early February near 0.01 hPa (~75 km) with much lower temperatures than before the SSW. The strong latitudinal gradients in stratopause altitude poleward of the jet core after its reformation show the separation of the polar stratopause from that at midlatitudes. GCM simulations [Siskind *et al.*, 2007] sug-



**Figure 1.** Pressure-time sections at 70°N of zonal mean temperature from (top to bottom) MLS, SABER, GEOS-4, GEOS-5, and ECMWF, from 1 December 2005 through 31 March 2006. Overlaid contours on GEOS and ECMWF plots are 70°N zonal mean winds from  $-60$  to  $90 \text{ ms}^{-1}$  by  $30 \text{ ms}^{-1}$ , with easterlies and zero values in black, westerlies in white.

gest that the high stratopause in mid-February 2006 resulted from filtering during the SSW of GWs that usually break at and above 50 km; the GW parameterization used was critical to how well the model captured the very high stratopause after the SSW. After mid-February, the stratopause dropped and warmed, reaching an altitude and temperature similar to those in early winter by mid-March.

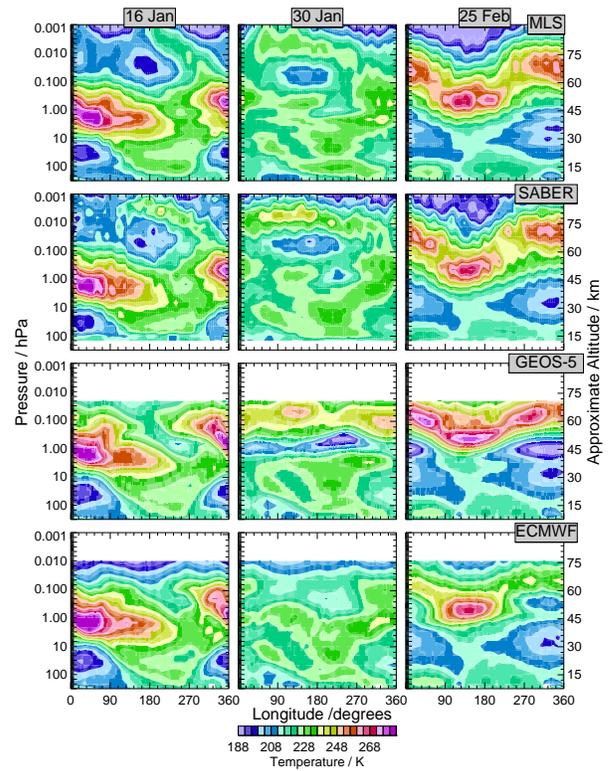
Stratopause evolution agrees well between SABER and MLS data; it is warmer and typically slightly lower in MLS v1.5 than in SABER data, consistent with a known high bias in MLS v1.5 USLM temperatures [e.g., Froidevaux *et al.*, 2006]. Stratopause evolution also agrees well qualitatively with the analyses until late January when the stratopause was ill-defined, and after early March when the stratopause had dropped/warmed. However, as expected given the proximity to the model tops and the lack of data constraints, the analyses do not capture the reformation of the stratopause at high altitude; in fact, the level where it reforms is near or above the top analysis level. GEOS-4 and GEOS-5 show the stratopause reforming near 0.08 hPa with much higher temperatures than observed; the ECMWF stratopause remains cool and ill-defined until early March, and warms later than that in the satellite data. GEOS-4 and GEOS-5 show qualitatively similar evolution (Figure 1), but the polar stratopause in GEOS-4 is much too warm throughout the winter. When



**Figure 2.** Latitude-time sections of (left) stratopause altitude (km, calculated as the “warm point”) and (right) stratopause temperature (K) from (top to bottom) MLS, SABER, GEOS-5 and ECMWF, from 1 December 2005 through 31 March 2006. Overlaid contours are as in Figure 1, but at 1 hPa.

the stratopause is cold in late January and February, GEOS-5 temperatures are higher than in the satellite data and the cold region is confined nearer the pole; ECMWF shows lower temperatures for a longer time during this period. The qualitative differences between the analyses highlight the dependence on the underlying models and parameterizations.

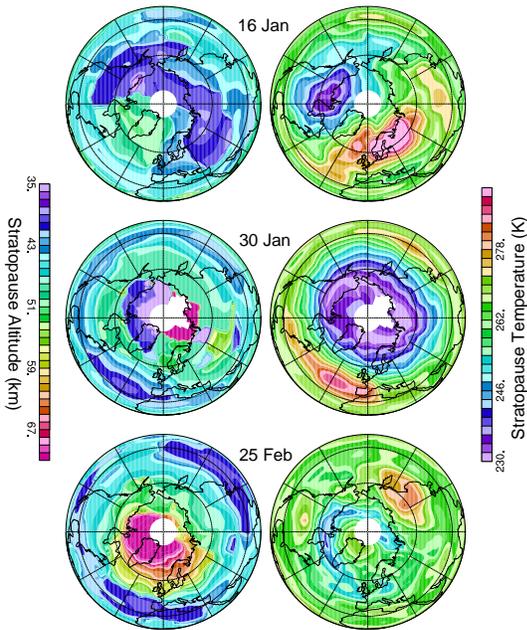
Longitude-height sections at 70°N (Figure 3), and maps of MLS stratopause altitude and temperature (Figure 4) detail the synoptic evolution of the stratopause. The analyses capture the structure of the stratopause before the peak of the SSW (Figure 3, 16 January). The stratopause is separated in longitude as well as latitude, with minimum altitude near 240°E, maximum altitude near 280°E, and lowest temperatures in the region between. 16 January satellite data show a secondary temperature maximum extending up from the high altitude side, overlying the stratopause from ~120 to 270°E; this is a common feature in polar winter. MLS/SABER differences in this feature are likely related to the poorer vertical resolution of MLS in the mesosphere. This feature is too high to be captured by the analyses; both show a lower, much less extended secondary maximum. The 30 January plots emphasize how nearly isothermal the polar stratosphere is after the SSW. Both MLS and SABER show weak local temperature maxima near 0.1 and 0.03 hPa. The GEOS-5 analysis shows a vertically-compressed version of the same pattern, whereas the ECMWF analysis shows a better representation of the lower part of the pattern,



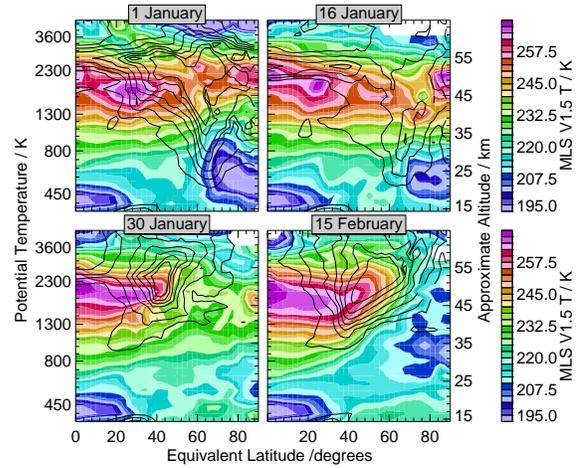
**Figure 3.** Longitude-pressure sections at 70°N of temperature (K) from (top to bottom) MLS, SABER, GEOS-5 and ECMWF, on (left to right) 16 and 30 January and 25 February 2006.

but no overlying second maximum. Cold, nearly isothermal conditions cover the entire polar region (Figure 4). On 25 February, when the stratopause has dropped and warmed towards typical values, the satellite data show the altitude varying smoothly around the latitude circle from about 0.01 to 0.68 hPa (Figures 3 and 4), with lowest temperatures in the transition regions between low and high stratopauses; the analyses capture the lower portion of this, but show the higher maxima at lower altitude, resulting in a much smaller range of stratopause altitudes.

Figure 5 shows the structure of the stratopause in relation to the USLM jet as a function of equivalent-latitude (EqL, the latitude that would enclose the same area as a given potential vorticity (PV) contour). The EqL/potential temperature sections of MLS temperature extend only as high as the GEOS-4 PV used for mapping is available, but avoid the smearing of values from different air masses inherent in zonal means. On 1 January, before the SSW (note strong jet) the stratopause showed the characteristic sepa-



**Figure 4.** Maps of MLS stratopause altitude (km, left) and stratopause temperature (K, right) on 16 and 30 January and 25 February 2006. Projection is orthographic, with 0° longitude at the bottom and 90°E to the right; domain is 0 to 90°N.



**Figure 5.** EQL/potential temperature sections of MLS temperature (K) on 1, 16, and 30 January and 15 February 2006. GEOS-4 EQL is used to map MLS data. Overlaid contours are GEOS-4 windspeeds from 30 to 90 m/s by 10 m/s.

ration [Hitchman *et al.*, 1989] across the upper part of the stratospheric polar vortex, and was slightly cooler than the mid-EqL stratopause. By 16 January, the vortex had broken down in the USLM (weak winds) and was rapidly weakening in the midstratosphere; the separated stratopause had dropped to near the altitude of the weak jet, and warmed at highest EqLs. By 30 January, the polar stratopause was well below and much cooler than the mid-EqL stratopause; the polar vortex started to reform in the USLM, but with a lower latitude jet (larger vortex area). By 15 February, the vortex was very strong in the USLM, but only beginning to reform in the middle stratosphere (see also Figure 1). The stratopause was tilted upward along the jet axis, transitioning to being high and cold at highest EqLs.

### 3. Discussion and Summary

The evolution of the stratopause during the major SSW in January/February 2006 has been detailed using MLS and SABER satellite data. The polar stratopause, initially higher than and separated from that in midlatitudes, dropped by 20–30 km during the SSW to near 30 km, warming during and cooling after the peak of the SSW. After a period when the stratosphere was nearly isothermal, a cool polar stratopause reformed near 75 km, then rapidly warmed and dropped to near 55 km. The stratopause altitude during the SSW varied by over 40 km. The stratopause is separated in longitude as well as latitude, with lowest temperatures in the transition regions between higher and lower stratopauses.

Before and well after the SSW, GEOS and ECMWF assimilated analyses represent the structure and evolution well despite the lack of data constraint. They do not, however, capture a secondary temperature maximum that overlies the stratopause. The analyses also cannot capture the very high stratopause after the SSW (which is near or above their top levels), the details of the nearly-isothermal region extending through the USLM, or the extent of altitude variations with longitude. They underestimate the extent of altitude changes during the SSW by 10–15 km. The inability of current analyses to capture the correct structure of the stratopause requires further investigation: Issues such as the double stratopause and the failure of the analyses to capture the high stratopause after the warming cast doubt on the adequacy of the GW drag codes for this task, either because of limitations in the codes themselves, the low upper boundaries of the underlying GCMs, or the remote impact of data insertion at lower levels. Results from a free-running GCM with a high top [Siskind *et al.*, 2007] suggest that more sophisticated GW parameterizations can improve representation of these features. MLS and SABER provide the kind of high-quality, daily temperature observations covering the USLM that are needed to understand the USLM and to improve its representation in models and assimilation systems.

After the 2006 SSW, the vortex reformed quickly and strongly in the upper stratosphere, but remained weak in the middle and lower stratosphere. A SSW in the 2003–2004 winter showed very similar evolution [Manney *et al.*, 2005]. SABER and GEOS-4 temperatures during the 2003–2004 SSW show a very similar pattern of stratopause evolution to that in 2006. In contrast, a brief major SSW in late February 2007, without a strong upper stratospheric recovery, produced only a very modest drop of the stratopause, with an immediate return to pre-SSW altitudes. Further study of stratopause evolution, both in existing and future satellite data and in the historical record using these comparisons as guidance for the types of behavior captured accurately by the analyses, can help understand and model the mechanisms underlying the observed behavior, and allow exploration of possible implications for the lower atmosphere and detection of climate effects.

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