National Aeronautics and Space Administration

Exploration of Stratopause and Tropopause Evolution in Polar Winter In Satellite Data and Meteorological Analyses

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1 Introduction

Until the past several years, daily global or hemispheric temperature datasets extending through the mesosphere were largely unavailable. With the launch of the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) instrument in 2002 and the Aura Microwave Limb Sounder (MLS) in 2004, we now have a wealth of such data. In addition, the Atmospheric Chemistry Experiment-Fourier Transform Spectrometer (ACE-FTS) has been recording daily temperature profiles at high latitudes in the polar winter of both hemispheres since 2004. Some data centers, particularly the European Center for Medium-Range Weather Forecasting (ECMWF) and NASA's Global Modeling and Assimilation Office (GMAO) are now providing assimilated meteorological analyses that extend into the mesosphere; however, above the upper stratosphere, there are no direct data constraints, so the fields depend strongly on the dynamics and parameterizations in the underlying general circulation models, and there have heretofore been few data with which to compare them. We use MLS, SABER, ACE-FTS and ground-based data to detail the evolution of temperatures from the upper troposphere/lower stratosphere into the mesosphere during recent polar winters, focusing on the stratopause region and the ability of the of the analyses to capture the observed stratopause evolution. We contrast conditions in extreme cold and extremely warm and disturbed recent Arctic winters: 2003-2004 and 2005-2006 had strong, prolonged major stratospheric sudden warmings (SSWs) in January, with an unusually strong upper stratospheric vortex reforming afterward and a late final warming; 2004-2005 was the coldest Arctic winter on record, but had an early final warming in mid-March.

2 The 2005-2006 Stratopause in Satellite Data and Meteorological Analyses

2.1 Time Evolution

- 70°N zonal mean temperatures from MLS and SABER (Figure 1, top two panels) show the stratopause (temperature maximum, or static stability $\approx 4\times10^{-4}\ \mathrm{s}^{-2}$ – black contour on MLS and SABER panels) dropping by 20–30 km during the 2006 SSW.
- Overlaid wind contours (black, -60, -30, 0 ms^{-1}, white, 30, 60, 90 ms^{-1}) on analysis (bottom three) panels show progression of SSW.
- When the vortex breaks down in late January (easterlies throughout stratosphere), there is a complete disappearance of the warm stratopause layer, with nearly isothermal conditions from ∼50 to 0.03 hPa.
- After the SSW, the stratopause reforms at very high altitude (∼0.03 hPa, 75 km at 70°N), then warms and drops to near typical altitude by late March.
- The GEOS-4, GEOS-5 and ECMWF analyses represent the stratopause fairly well before and during the SSW, but cannot capture the reformation at high altitude (near their model tops).
- Figure 2 shows the time evolution of the latitudinal structure of stratopause altitude and temperature, with strong altitude and temperature gradients demarking the previously-reported "separated" polar stratopause.
- The high-altitude stratopause reformation occurs along the poleward side of the redeveloping upper stratospheric jet (1 hPa zonal mean wind contours, values as in Figure 1, on lower panels of Figure 2).
- Figures 1 and 2 show good agreement between MLS and SABER stratopause evolution and temperature.
- GEOS-4 and GEOS-5 stratopause temperatures are too high, especially during the stratopause reformation when their stratopause altitude is too low; ECMWF temperatures are too low during the stratopause reformation.
- More modest, but still significant, biases in the analyses' stratopause characteristics are seen at mid-latitudes, where the stratopause is low enough to be in a region where some data are ingested into the analyses.

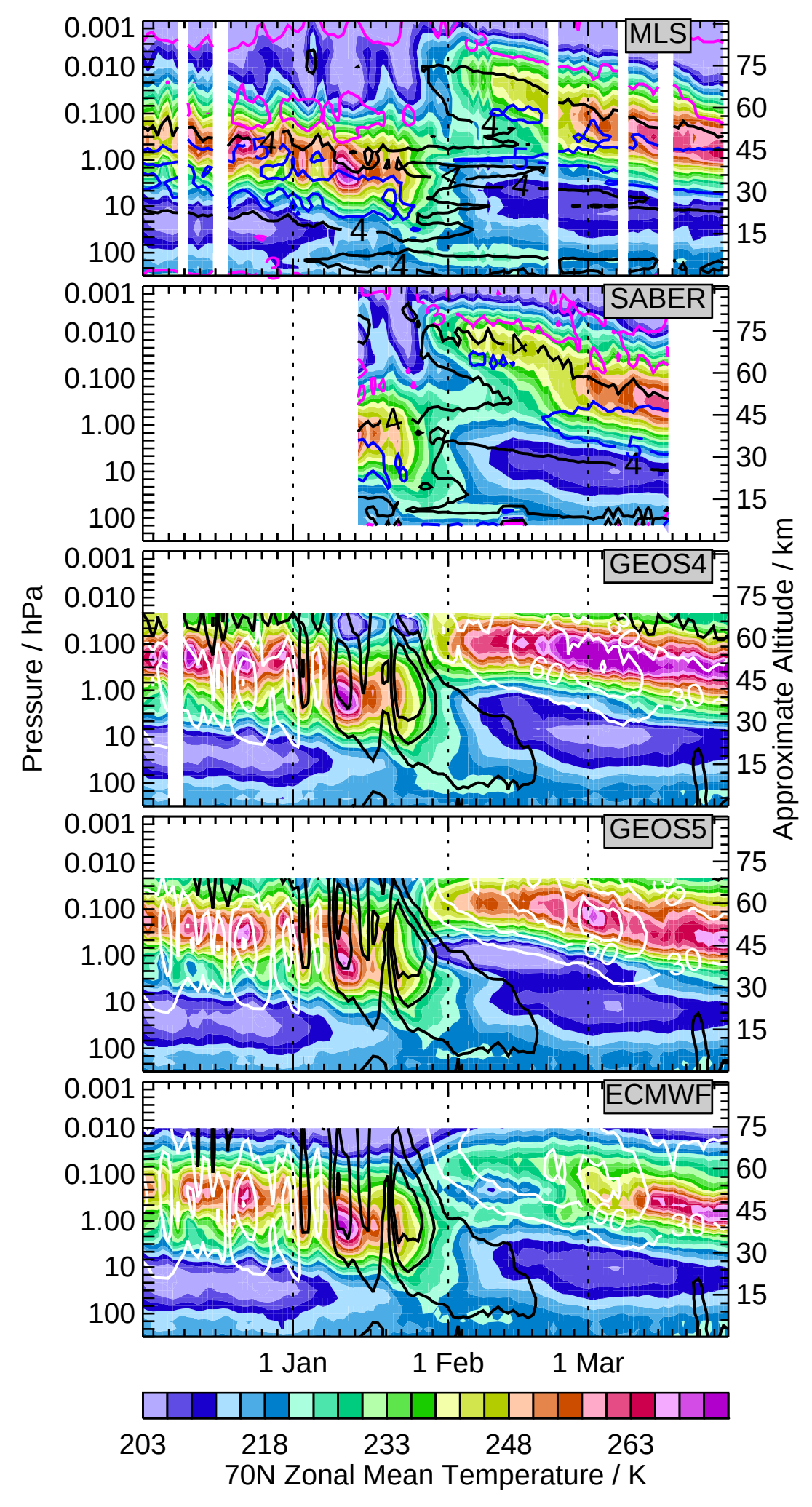

Figure 1

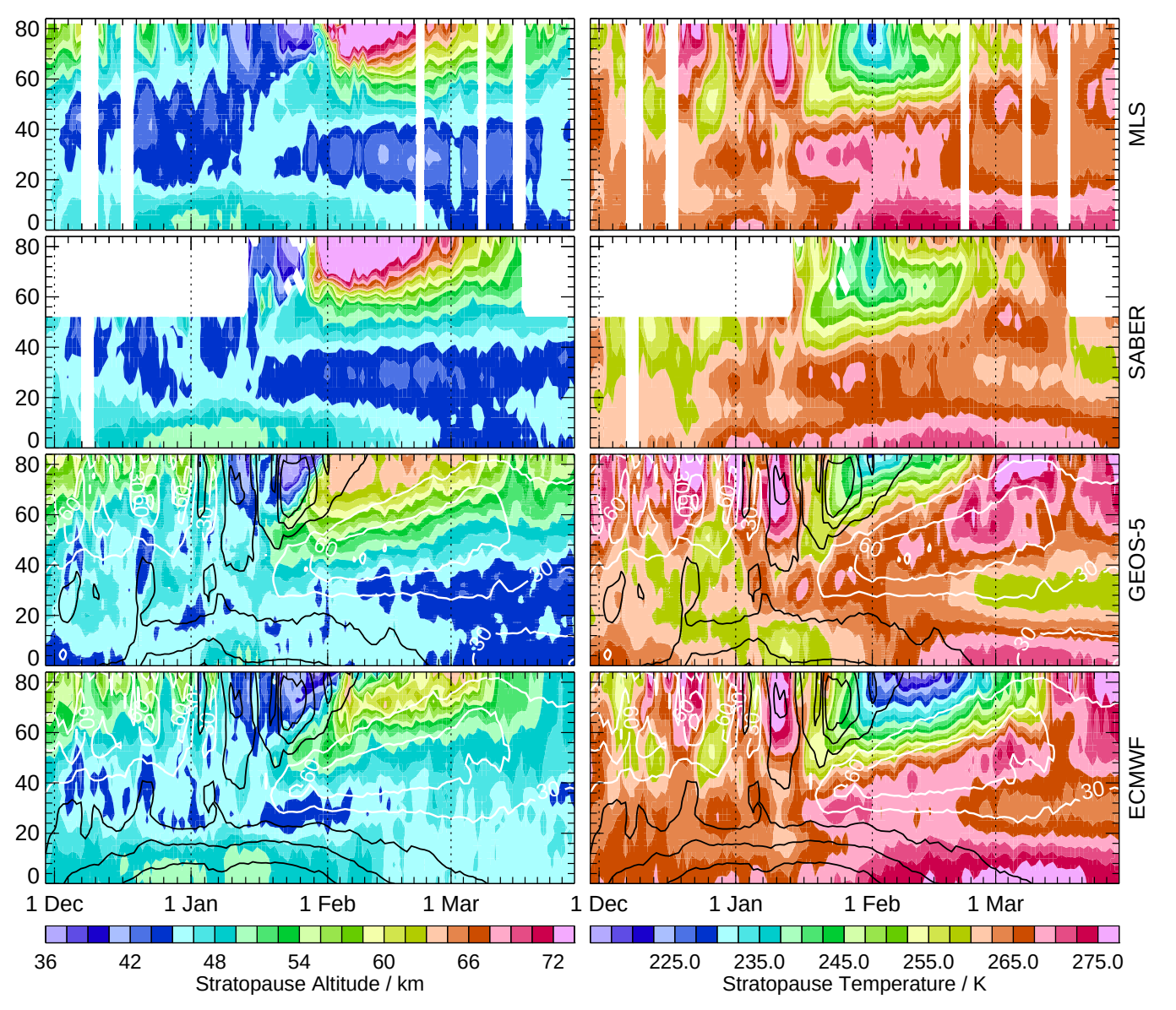

Figure 2

2.2 Synoptic Structure

- 70°N longitude/pressure temperature sections (Figure 3) show synoptic structure of stratopause.
- Before and at the start of the SSW (16 January), the stratopause is separated in latitude as well as longitude, with lowest temperatures near 270°E between minimum and maximum stratopause altitudes.
- A secondary temperature maximum (a common feature in winter) extends from the higher branch of the stratopause over the lower branch.
- The GEOS and ECMWF analyses cannot capture the secondary temperature maximum, but represent the stratopause well before the SSW.
- On 30 January, the high-latitude stratosphere is nearly isothermal (Figure 3, contours show static stability as in Figure 1) and a large cold pool covers the polar regions north of ∼60°N (not shown).
- After its reformation (25 February), the stratopause is continuous around 70°N, but shows large altitude variations, with lower temperatures in transition regions.
- Though the GEOS and ECMWF analyses capture this structure qualitatively, the altitude range is compressed and large biases are seen in temperature.

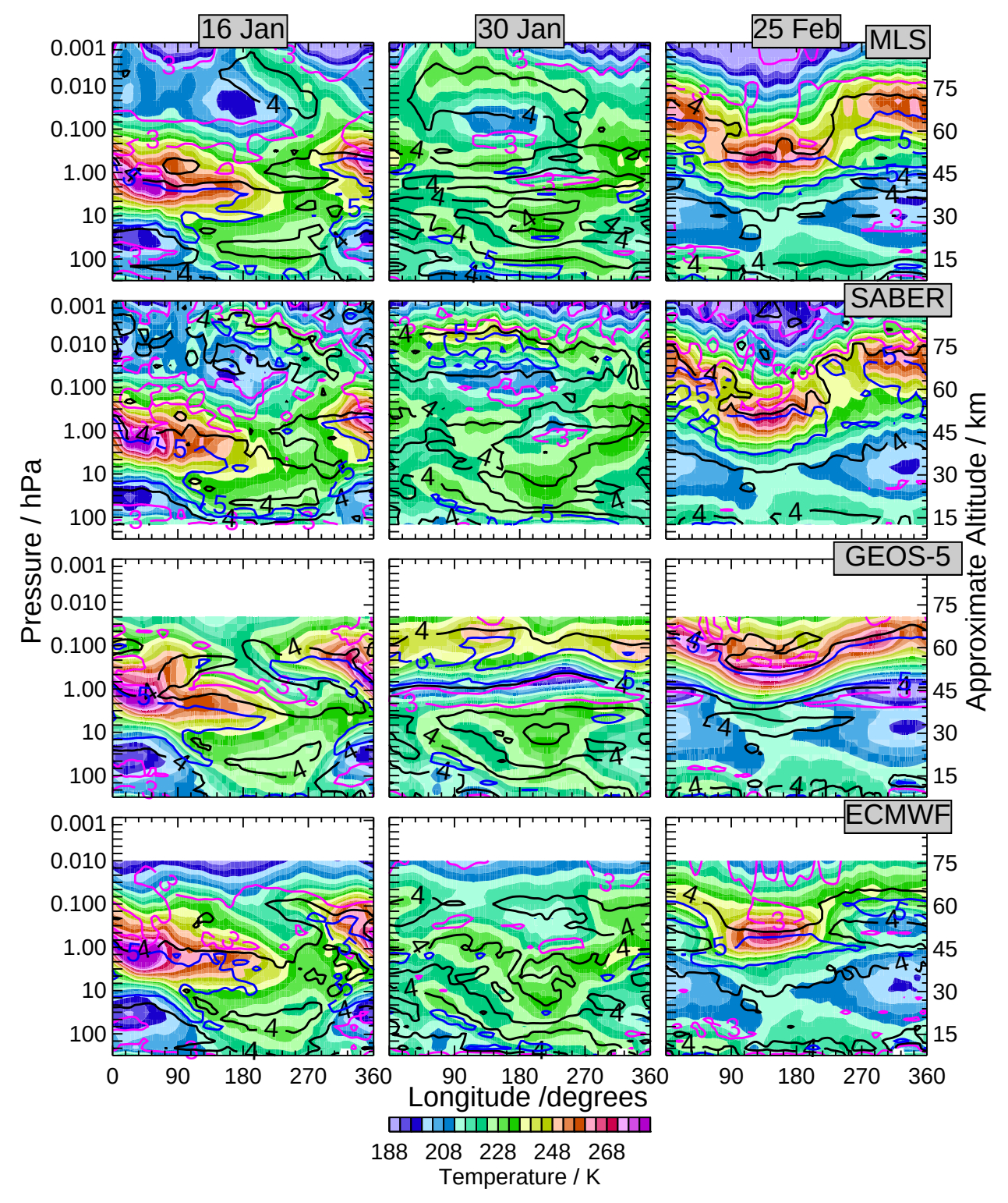

Figure 3

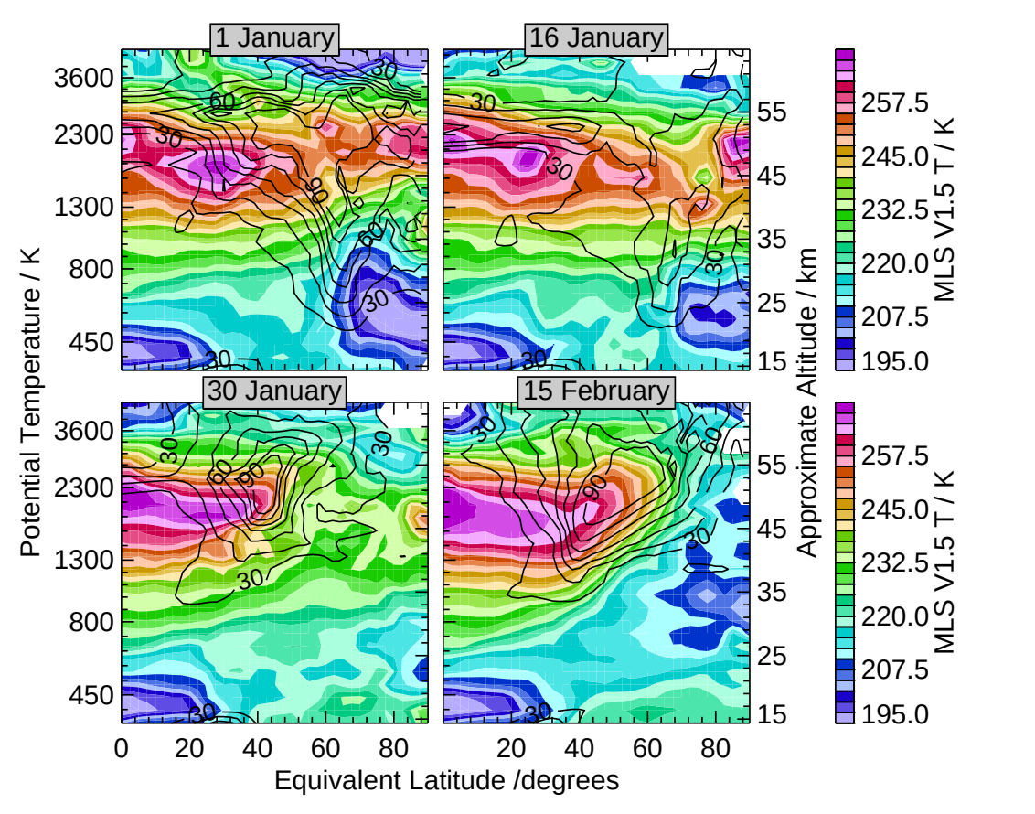

Figure 4

2.3 Vortex and Stratopause Structure

- Figure 4 shows temperature evolution in relation to the stratospheric vortex in equivalent latitude/potential temperature sections before the SSW (1 January), near its beginning (16 January), during its peak (30 January), and during recovery (15 February).
- Polar and mid-latitude stratopauses remain separated throughout the period, across the axis of the polar night jet.
- During the vortex breakdown (30 January), the polar stratopause is lower and cooler than at mid-latitudes, as opposed to higher and warmer before and after the SSW (and in less disturbed winters, Section 3).
- Before the SSW, the secondary temperature maximum seen in Figure 3 extends equatorward across the lower latitude branch of the double jet at the stratopause.

Above material from Manney et al., "The evolution of the stratopause during the 2006 major warming: Satellite Data and Assimilated Meteorological Analyses", submitted to JGR (available at http://mls.jpl.nasa.gov).

3 Stratopause and Tropopause Variability in the High Arctic, 2003-2004 Through 2005-2006

3.1 Overview

Validation campaigns for the ACE mission have been conducted in the late Arctic winters of 2004, 2005, 2006 and 2007 at Eureka (80°N, 86°W). The material in this section, from Manney et al., "The high Arctic in extreme winters: Vortex, temperature, and MLS and ACE-FTS trace gas evolution" (ACPD, 7, 10,235–10,285, 2007), examines variability in recent extremely cold (2004-2005) and extremely warm/disturbed (2003-2004 and 2005-2006) Arctic winters in the context of conditions at Eureka.

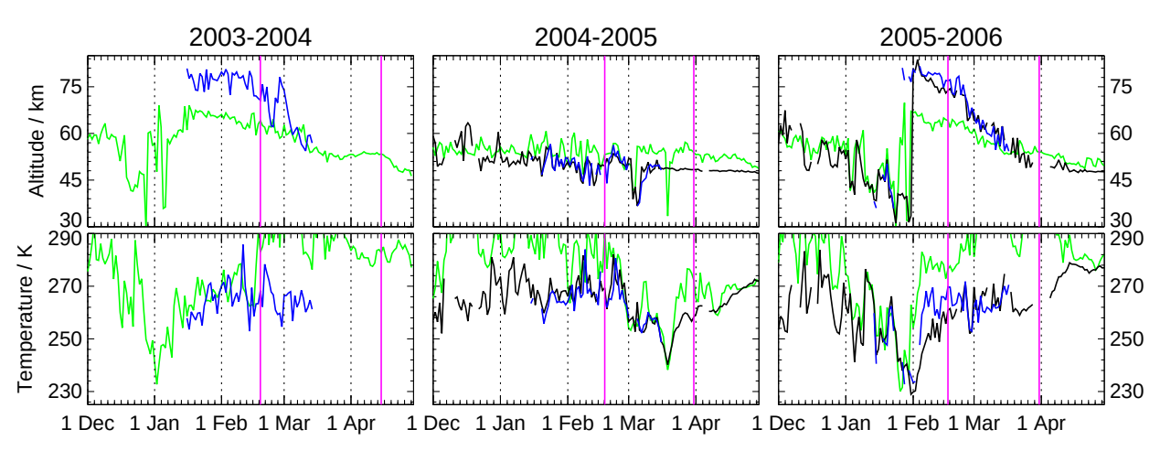

Figure 5

- Figure 5 shows stratopause altitude and temperature at Eureka from SABER (blue) and MLS (black) measurements and GEOS-4 analyses (green) during the three winters.
- During the cold 2004-2005 winter, stratopause altitude and temperature were nearly constant (near 55 km, 250-270 K) until the major final warming in March.
- SABER and GEOS-4 stratopause structure in 2003-2004 suggest very similar behavior during that major SSW to that detailed above (Section 2) during the 2006 SSW.

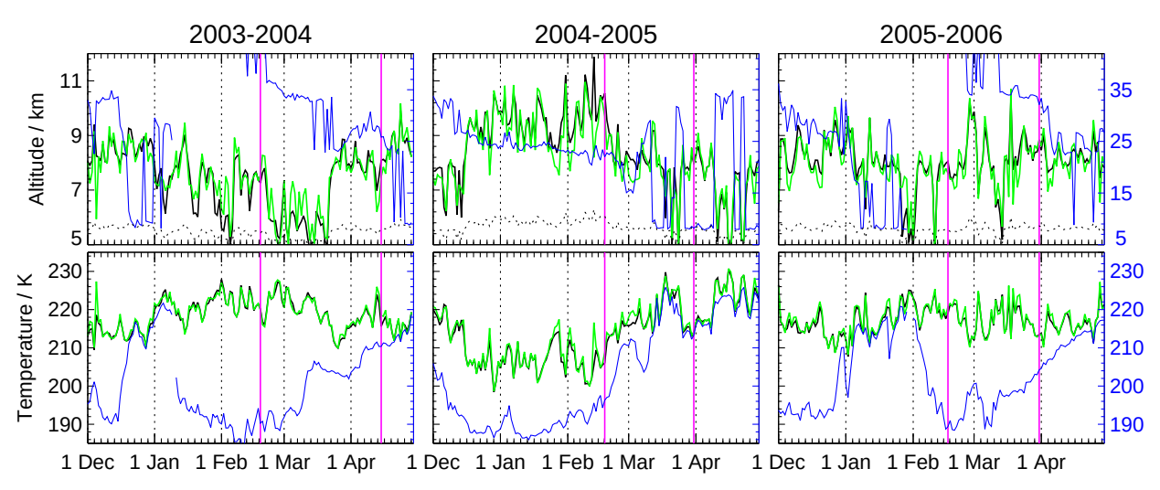

Figure 6

- Tropopause (WMO, black, and dynamical, green) and coldpoint (blue, temperature minimum below 1 hPa) altitude and temperature at Eureka from GEOS-4 (Figure 6) also show contrasting behavior in cold and disturbed winters
- In 2004-2005, the coldpoint is near 15–20 km, whereas in 2003-2004 and 2005-2006, it rises to ∼40 km during the recovery from the SSWs.
- Tropopause temperature hovered around 220 K during the disturbed winters, while dropping to near 205 K during most of the 2004-2005 winter.

3.2 Lidar Comparisons

- Lidar profiles from the Eureka campaigns in 2004, 2005 and 2006 are compared with SABER (red), ACE-FTS (orange), and MLS (blue) measurements, and GEOS-4 (purple), GEOS-5 (dark green), and ECMWF (light green) analyses.
- Agreement between lidar and satellite data is good through ∼0.1 hPa.
- Above ∼0.1 hPa, the lidar often shows a cold bias in 2004 and 2006 (when the mesosphere was unusually warm) and a smaller warm bias in 2005 (when the mesosphere was cooler than typical). This is related to the constant seed value (220 K) used in the lidar temperature retrievals to initialize at 70 km.

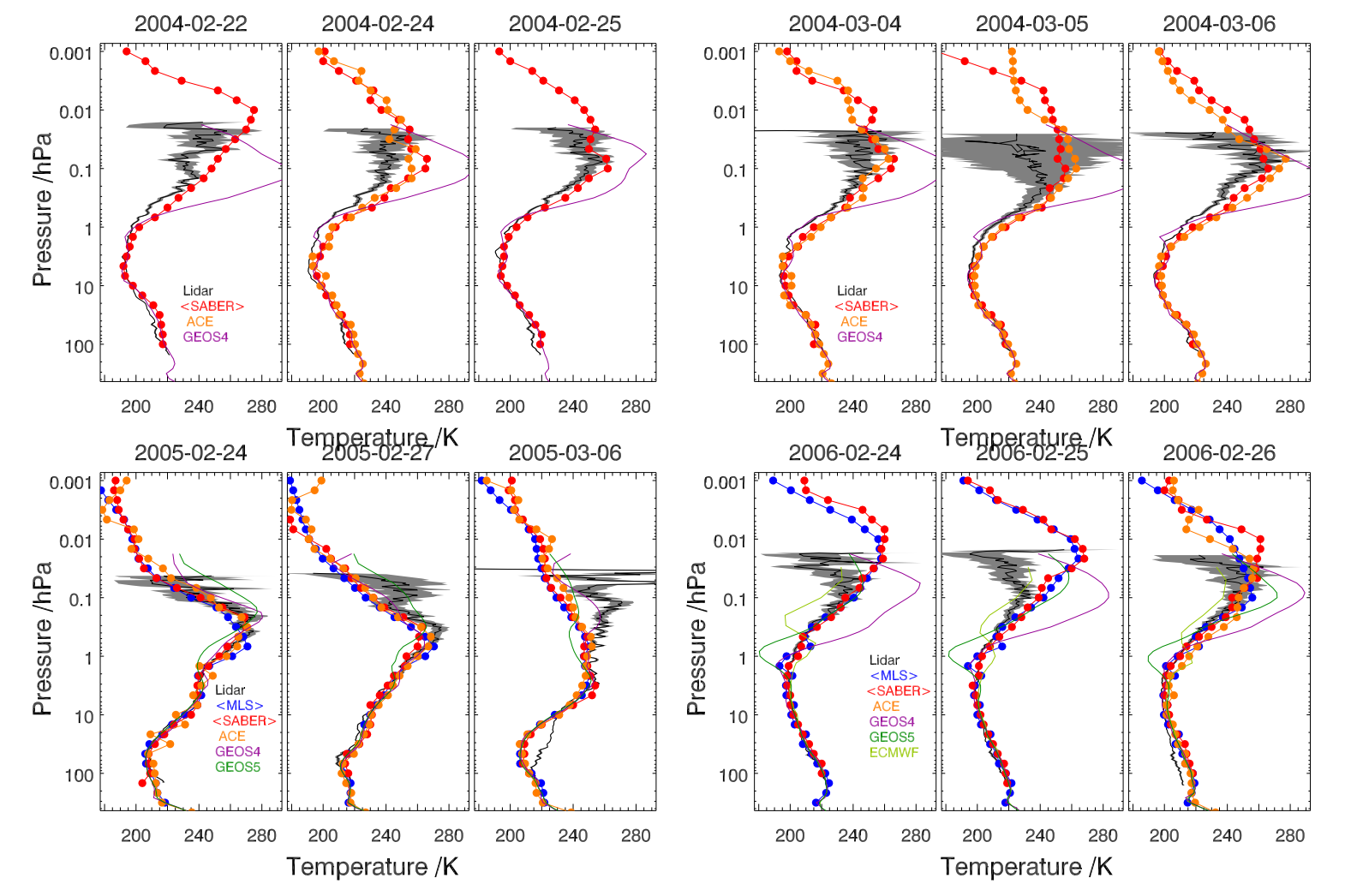

Figure 8

- The GEOS and ECMWF analyses show fairly good agreement with lidar and satellite data across the stratopause in 2005, while mis-representing both temperature and altitude in 2004 and 2006, consistent with the analysis in Section 2.
- Comparing February profiles in the three years shows the contrast between "typical" winter temperature structure (coldpoint near 50 hPa, stratopause near 0.5 hPa) in 2005 and the anomalous structure following the prolonged SSWs in 2004 and 2006 (coldpoint near 3 hPa, stratopause near 0.03 hPa).

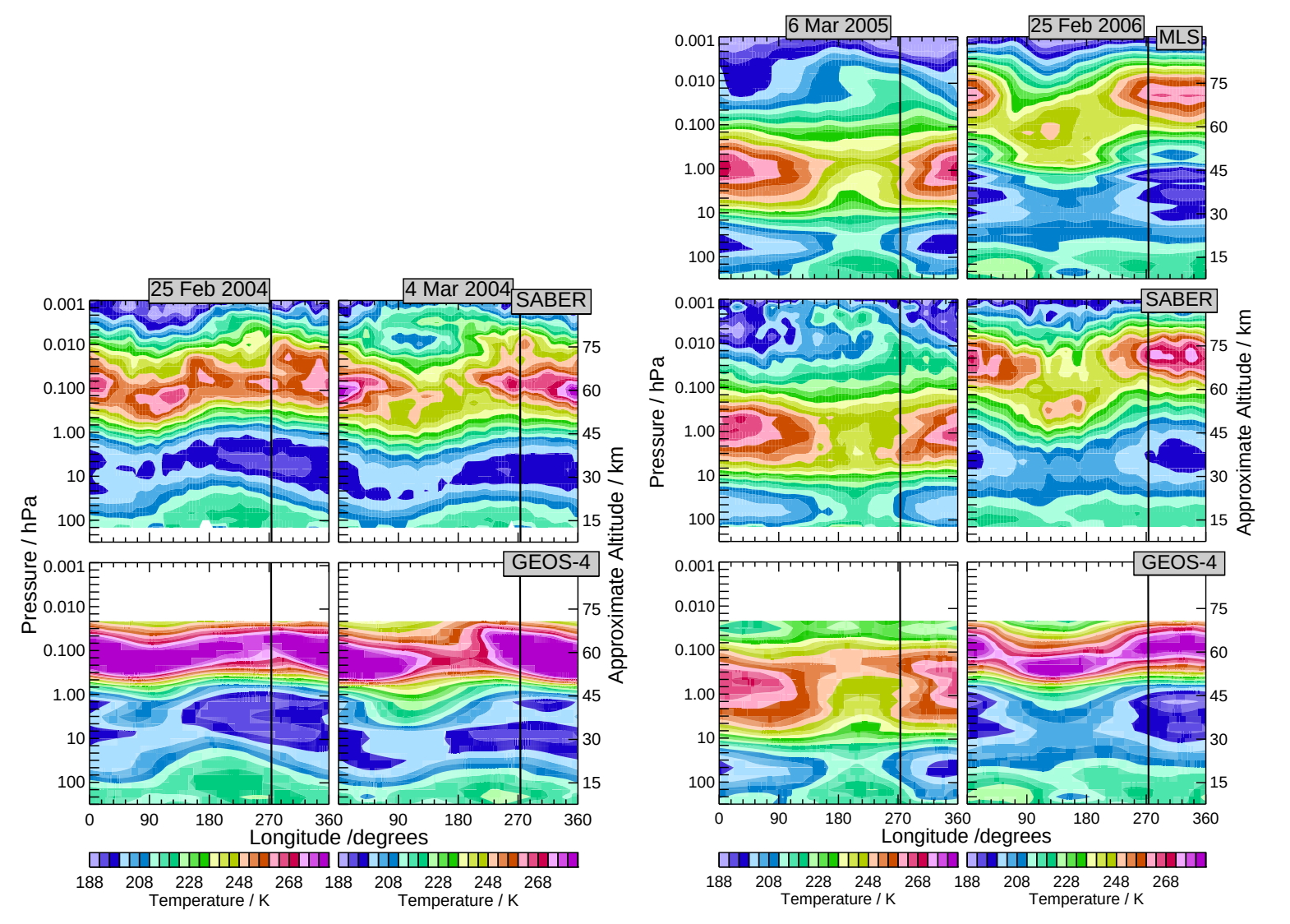

Figure 9

- Longitude/pressure sections of 80°N temperature with Eureka's longitude marked (Figure 9) suggest atmospheric origins for differences in small-scale structure in lidar and satellite profiles (Figure 8) on 25 February 2004, 4 March 2004, and 6 March 2005.
- The large low bias in the lidar profile on 25 February 2006 (Figure 8) does not appear to correspond to any atmospheric variations (Figure 9, far right), supporting the interpretation that it arises from initialization with a seed temperature that is much lower (∼40 K on this date) than the actual temperature.

3.3 Radiosonde Comparisons

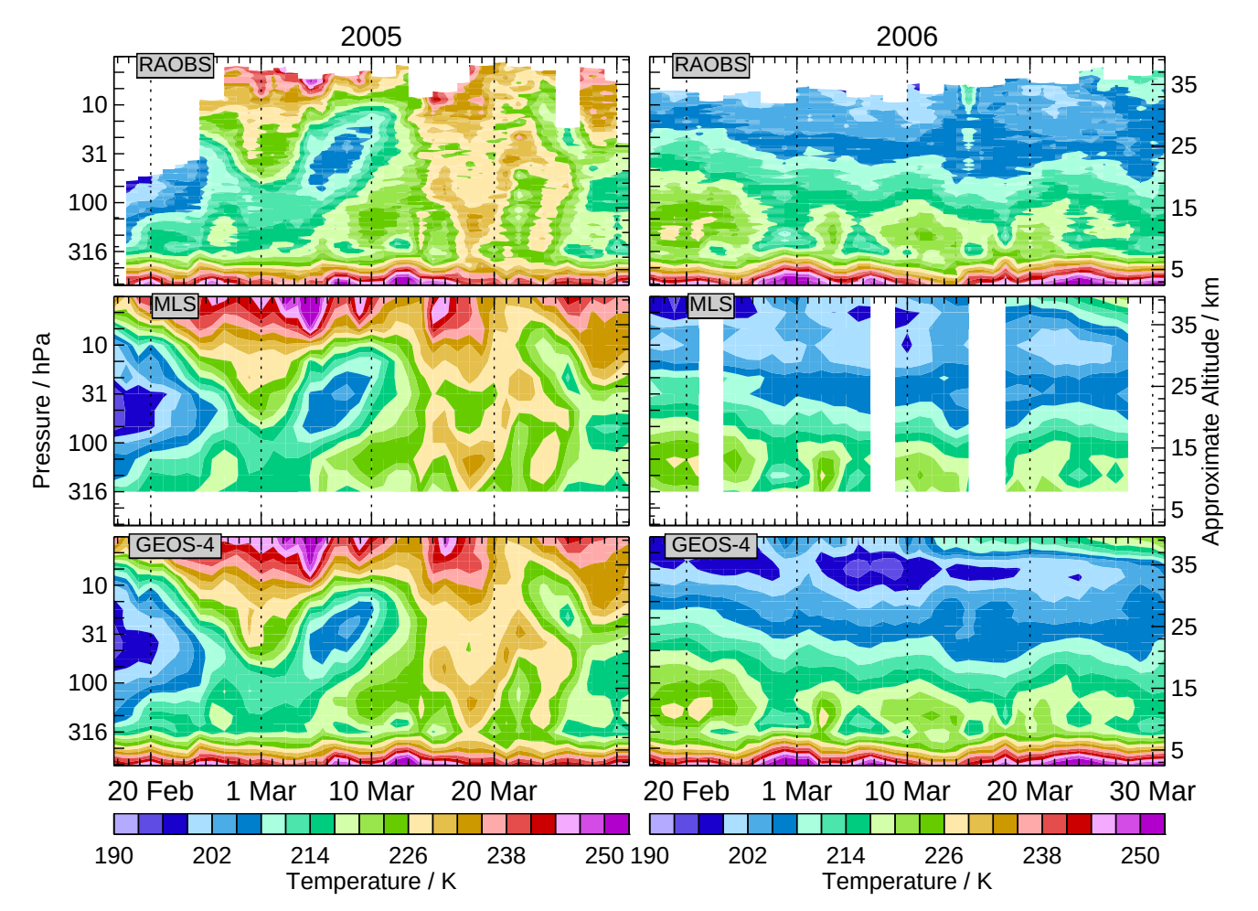

Figure 10

- Figure 10 shows timeseries during the 2005 and 2006 Eureka campaigns of temperatures at Eureka from radiosondes, MLS and GEOS-4.
- The 2005 campaign was during the early final warming, whereas the 2006 campaign was in the recovery from the January SSW, when a strong, cold vortex had reformed in the upper stratosphere; consistent with this, upper stratospheric temperatures in 2006 were much lower than in 2005, while lower stratosphere/tropopause temperatures were higher.
- Radiosonde, MLS and GEOS-4 tropopause level and lower stratospheric temperatures agree quite well; fine structure in radiosonde data is related to their very high resolution (∼50 m).
- GEOS-4 mid to upper stratospheric temperatures are slightly lower than MLS and radiosondes, and the coldpoint is at slightly lower altitude than MLS in 2006; in 2005, all datasets agree well.

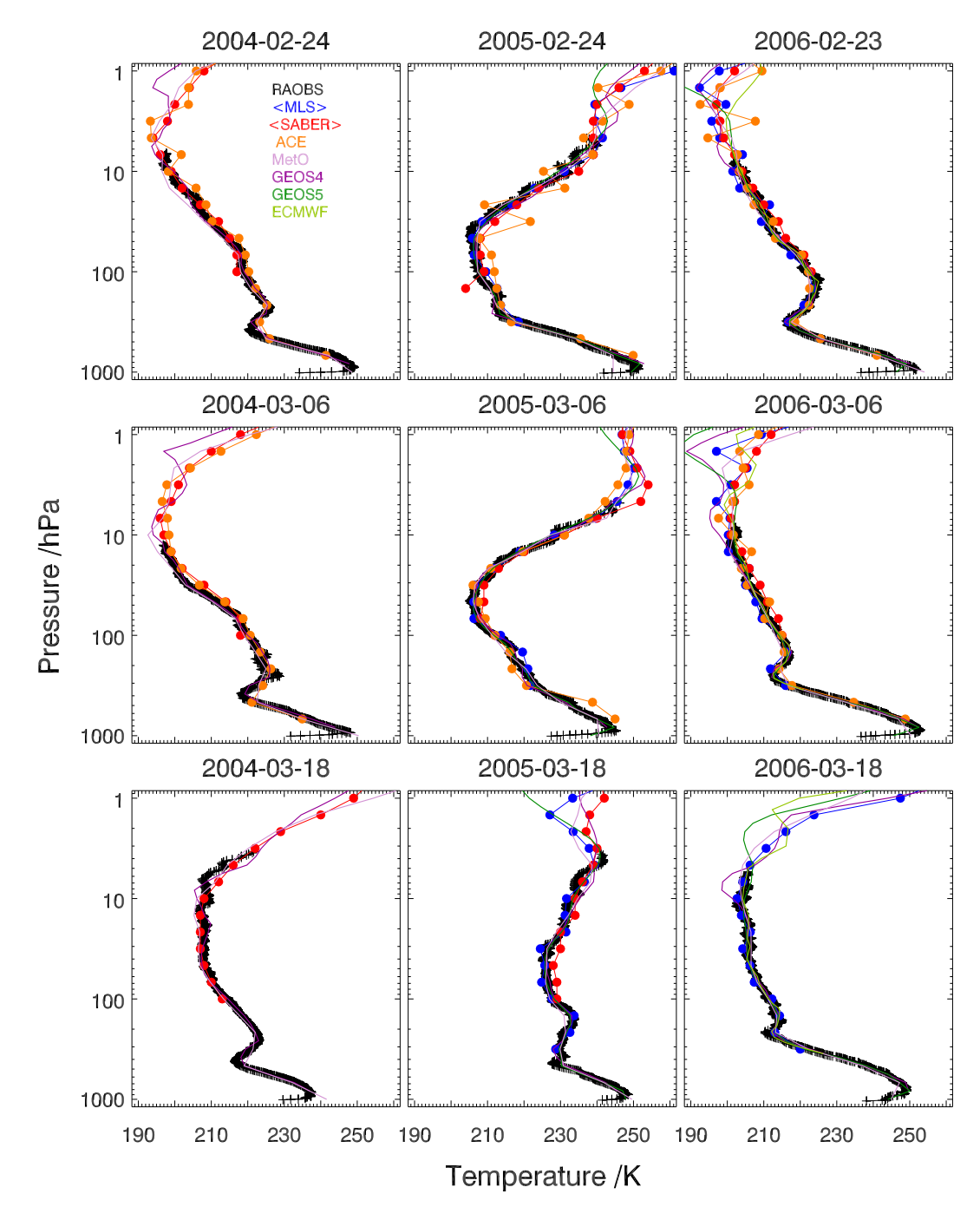

Figure 11

- Radiosonde/satellite data/analyses profile comparisons in each year (Figure 11) show quite good agreement, except for unrealistic structure in GEOS-4 near the top of some radiosonde profiles (e.g., near 10 hPa on 18 March 2006).

3.4 Transport Implications

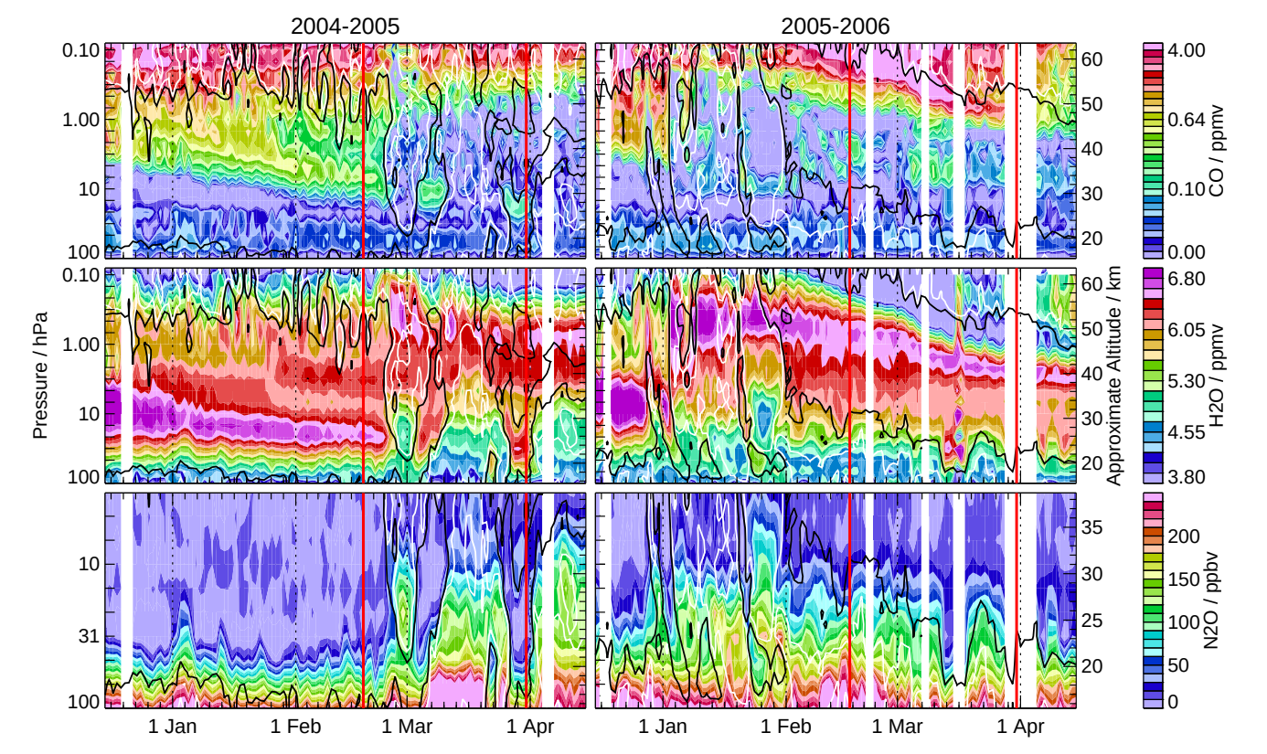

Figure 12

- Very different patterns of transport are seen in cold and disturbed winters, due to different horizontal wind conditions producing variations in vortex/ extra-vortex mixing, and to different temperature structures producing changes in diabatic descent.
- Figure 12 shows MLS CO, H_2O and N_2O values over Eureka during January–March 2005 and 2006, highlighting some of these differences.
- A signature of strong descent appears in CO and H_2O in 2006 after early February when the upper stratospheric vortex reformed to become very strong and cold – both greater diabatic cooling associated with vortex reformation, and more complete confinement in the strong reformed vortex contribute to this much stronger descent signature in late winter 2006 than at the same time in 2005.
- Differences in the middle and lower stratosphere primarily reflect variations in vortex location/conditions: The vortex was over Eureka in 2006, with low (high) N_2O (N_2O), but away from Eureka and breaking up in 2005, with high (low) N_2O (H_2O).
- Brief periods when the vortex moved over Eureka in March 2005 are seen in abrupt increases (decrease) in N_2O (H_2O and CO).

4 Future Work

Work in progress using MLS, SABER, ACE-FTS and other satellite data to explore stratopause and tropopause evolution includes:

- Further analyses to develop a climatology of seasonal, interannual and inter-hemispheric variability in stratopause conditions.
- Examination of tropopause evolution in relation to MLS trace gas measurements and extra-tropical stratosphere-troposphere exchange.
- Using satellite data to help assess and improve assimilated fields in and above the upper stratosphere.

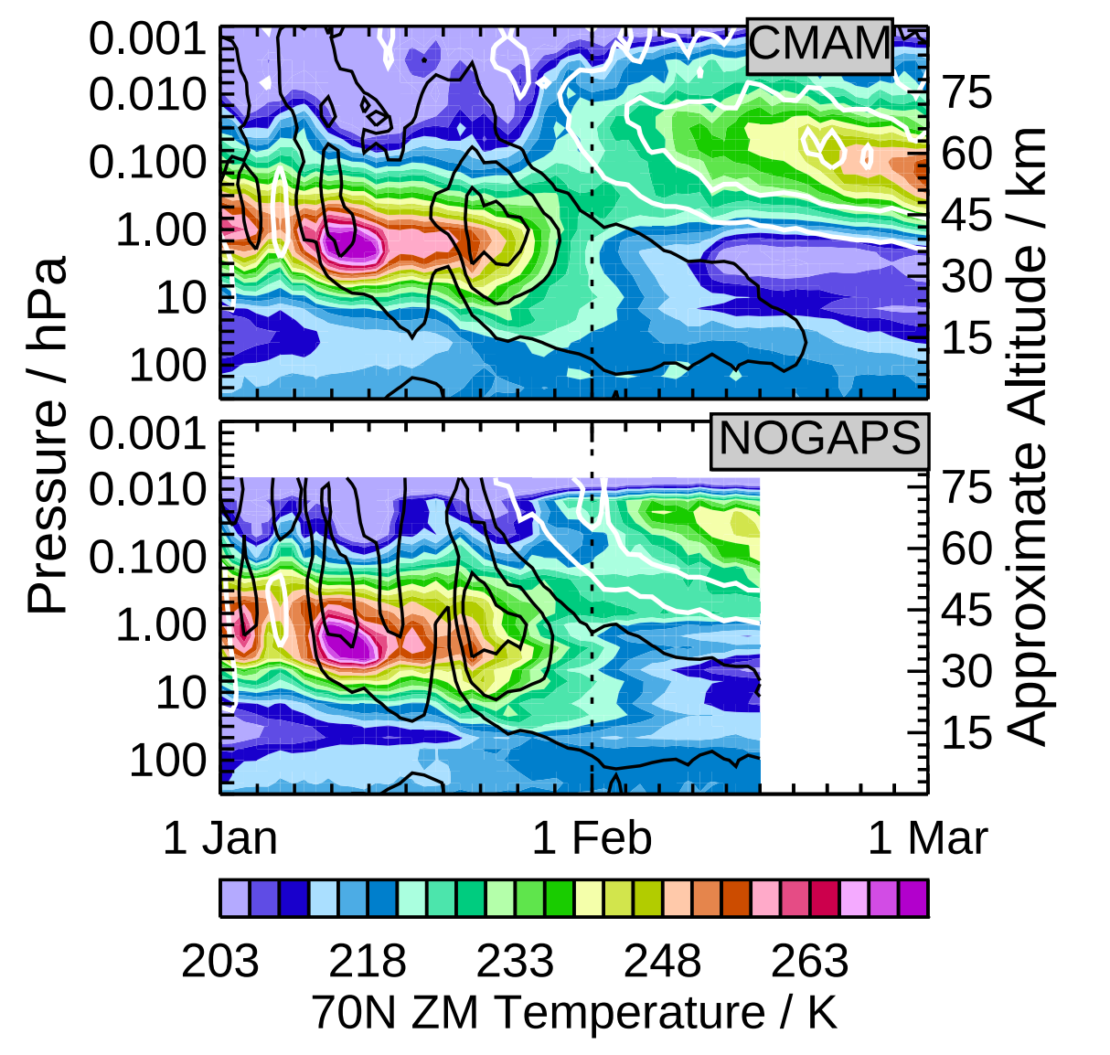

Figure 13

- Figure 13 shows 70°N zonal mean temperatures in 2006 from two research assimilation systems:
  - CMAM has a high (above 0.001 hPa) model top and a more sophisticated gravity wave drag scheme.
  - The NOGAPS-ALPHA run assimilates MLS and SABER temperature and O_3.
- Both show evidence of improvements in representation of the reformation of the stratopause at high altitudes over the analyses shown in Figure 1.

The availability of the high-quality temperature and trace gas data from MLS, ACE-FTS and SABER will allow much more detailed study of the upper stratosphere and mesosphere than previously possible, and facilitate improvements in assimilated fields in that region.