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Descent from the polar mesosphere and anomalously high stratopause observed in 8 years of water vapor and temperature satellite observations by the Odin Sub-Millimeter Radiometer

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[1] Using newly analyzed mesospheric water vapor and temperature observations from the Sub-Millimeter Radiometer instrument aboard the Odin research satellite over the period 2001–2009, we present evidence for an anomalously strong descent of dry mesospheric air from the lower mesosphere into the upper stratosphere in the winters of 2004, 2006, and 2009. In the three cases, the descent follows the recovery of the upper stratospheric polar vortex from a major midwinter stratospheric sudden warming. It is also accompanied by the rapid formation of an anomalously warm polar mesospheric layer, i.e., an elevated polar stratopause, near 75 km, and its slower descent to prewarming level (near 1 hPa) over 1.5–2 months. These three winters stand out in the current record of Odin/Sub-Millimeter Radiometer observations started in July 2001.

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1. Introduction

[2] Downward transport of minor constituents from the polar mesosphere can significantly alter the stratospheric chemical composition. In particular, the downward transport of nitrogen oxides (NO_x) produced by background low-energy auroral electrons and energetic particle precipitation in the mesosphere and thermosphere, provides a significant source for NO_x in the stratosphere. In the winter polar stratosphere, NO_x are long-lived, and they drive an important catalytic cycle of ozone destruction when sunlight returns [*Randall et al.*, 2006, and references therein]. In late winter and spring 2004, very large NO_2 abundances were observed in the northern hemisphere (NH) polar upper stratosphere by satellite instruments, such as the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE/FTS, hereafter ACE), the Global Ozone Monitoring by Observations of Stars (GOMOS), the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), the Polar Ozone and Aerosol Measurement, and the Halogen Occultation Experiment [*Natarajan et al.*, 2004; *López-Puertas et al.*, 2005; *Orsolini et al.*, 2005; *Renard et al.*, 2009]. The observed elevated NO_2 abundances caused a large ozone depletion of up to 60% in the upper stratosphere [*Randall et al.*, 2005]. Large NO_2 enhancements were also detected by GOMOS in late winter and spring 2006 [*Seppälä et al.*, 2007] and by ACE in late winter and spring 2006 and 2009 [*Randall et al.*, 2009], but not in the corresponding 2005, 2007, or 2008 periods. Hence, these satellite observations reveal large interannual variability in NO_x flux. This wintertime descent from the mesosphere is also important for the stratospheric nitric acid budget (e.g., *Orsolini et al.*, 2009, and references therein).

[3] Long-lived species like carbon monoxide (CO) or methane (CH_4) are useful as tracers for mesospheric descent into the stratosphere. Descent of mesospheric CO into the winter polar stratosphere was investigated by *Solomon et al.* [1985] in a 2-D model. Air masses with CO or CH_4 abundances indicative of mesospheric origin can be found even in the lower stratosphere, following a prolonged descent within the winter polar vortex. For example, based on balloon-borne measurements, *Engel et al.* [2006] and *Huret et al.* [2006] reported air masses with high CO mixing ratios characteristic of mesospheric air over the Arctic in 2003 at an altitude as low as 25 km. In situ observations in the lower stratosphere of air masses with mesospheric composition have been reported on other occasions [e.g., *Ray et al.*, 2002]. Satellite observations by the ACE, Microwave Limb Sounder (MLS), or MIPAS instruments of CH_4 and CO abundances in the NO_x-enriched air masses also bear the signature of the strong descents in 2004, 2006, and 2009 [*Randall et al.*, 2005; 2006; 2009; *Jin et al.*, 2005; 2009; *Manney et al.*, 2008; 2009a, 2009b].

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[4] Water vapor (H_2O) is also a widely used indicator of middle atmospheric transport processes. It is injected into the middle atmosphere through the tropical tropopause but is also produced by CH_4 oxidation in the middle atmosphere. H_2O is destroyed by ultraviolet photolysis and reaction with atomic oxygen (O^1D), and its mean mixing ratio decreases with altitude in the mesosphere, due to its photodissociation timescale decreasing rapidly from a few months in the upper stratosphere to a few days at 80 km. Upper stratospheric H_2O vapor global observations by MLS aboard the Upper Atmosphere Research Satellite were used by *Orsolini et al.* [1997] to study the 2 day wave and by *Manney et al.* [1998] to study the 4 day wave. Mesospheric H_2O is currently observed by a series of satellite instruments, using solar occultation technique (e.g., ACE, and the Aeronomy of Ice in Mesosphere Solar Occultation For Ice Experiment SOFIE), infrared limb emission (MIPAS, or the Sounding of the Atmosphere by Broadband Emission Radiometry SABER) [*Feofilov et al.*, 2009], or microwave limb emission (MLS). The measurements from the "Odin Sub-Millimeter Radiometer" instrument (SMR) belong to the latter category [*Frisk et al.*, 2003], provide near-global coverage and have been in continuous operation since November 2001.

[5] Anomalous dynamical conditions prevailed during the descent events of the late winter and spring of 2004, 2006, and 2009. *Randall et al.* [2005] noted the role of the exceptionally strong vortex in the late winter-spring 2004 in channeling the NO_x enhancements downward. On the basis of observations from MLS and SABER, *Manney et al.* [2008; 2009b] showed that the descent events in 2006 and 2009 occurred in periods when the zonal-mean zonal winds in the polar upper stratosphere-lower mesosphere (USLM) strengthen significantly, during a vortex recovery from midwinter major stratospheric sudden warmings (SSWs). They further showed that the stratopause dropped significantly during the warmings, while a cool stratopause reformed at high altitudes, around 75 km, after the warmings, and then descended over a period of 1–2 months to its climatological level near 50 km.

[6] The aim of this article was to show the evolution of mesospheric temperature and H_2O, over the period 2001–2009 using newly analyzed SMR observations. Focus will be placed on (1) the anomalous temperature and H_2O distributions during and after the stratospheric warmings in the 2003–2004, 2005–2006, and 2008–2009 winters, (2) the formation of an elevated stratopause near 75 km, and (3) the mesospheric descent of very dry air into the stratosphere, following the vortex recovery from these warmings. In section 2, we present the Odin/SMR retrievals. For the sake of clarity, we first discuss the temperature distribution in section 3, followed by the H_2O distribution in section 4. A summary is found in section 5.

2. Odin/SMR Mesospheric Water Vapor and Temperature

[7] Odin is a small Swedish-Canadian-French-Finnish research satellite dedicated to aeronomy and astronomy. The Sub-Millimeter Radiometer (SMR) is one instrument aboard Odin, which observes globally a variety of middle atmospheric minor constituents as well as temperature. The instrument scans the thermal emission at the atmospheric limb between 7 and 110 km. H_2O spectral lines are observed in different bands in the 486–581 GHz range [*Urban et al.*, 2007]. In this study we use H_2O retrievals derived from a strong line at 556.9 GHz, providing information in the ~40–100 km altitude range with an altitude resolution of ~3 km and a single-profile precision of 0.5–1 ppmv. Information on temperature is obtained simultaneously from the same band from ~50 km up to ~90 km. The horizontal resolution, determined by the path length in the tangent altitude layer is of the order of ~400 km. Retrieval and error analysis are described in detail by *Lossow et al.* [2007]. Here we analyze data from the Odin satellite launch in July 2001 to July 2009. First scientific results on mesospheric and thermospheric variability are found in the study of *Lossow et al.* [2009] and on the semiannual oscillation in the equatorial middle atmosphere in the study of *Lossow et al.* [2008].

[8] We examine only high-quality data (assigned quality flag 0) of the latest level-2 data version (v2.1) for the main mesospheric water mode (IM_AC1c). Observations for this mode were not performed daily but rather on a more irregularly basis: approximately every eighteenth day or every ninth day depending on years and seasons. However, since April 2007, the sampling frequency increased to approximately every seventh day. For example, considering the 3 years with the pronounced mesospheric descent events mentioned in section 1, there were 12 sampled days in winter (beginning of October to end of April) 2003–2004, 15 days in winter 2005–2006 and 26 days in winter 2008–2009. In several of the figures, tick marks will indicate days with measurements.

[9] Water and temperature profiles of this data version have been compared to measurements of the ACE instrument and exhibit slight dry biases of 0.3–0.6 ppmv for H_2O and cold biases of about 5 K in the 45–60 km range [*Lossow et al.*, 2007; *Carleer et al.*, 2008]. The vertical resolution of SMR H_2O profiles retrieved from the 556.9 GHz line is finer than those from MLS, which increases from about 3 to 4 km in the stratosphere to 12–16 km in the pressure range 0. 1–0.01 hPa [*Lambert et al.*, 2007]; it is comparable to the one from ACE, which is 4 km in the mesosphere. Concerning temperature retrievals, SMR vertical resolution in the mesosphere is higher than MLS: *Schwartz et al.* [2008] indicate a MLS resolution of about 3 km near 30 hPa, increasing to about 13 km at 0.001 hPa.

[10] As ancillary meteorological data, we use upper stratospheric (1 hPa) zonal winds from the European Center for Medium-Range Weather Forecast (ECWMF) operational analyses over the Odin/SMR period of observation (2001–2009). For more recent years, we also use the zonal winds and temperature throughout the USLM (up to 70 km) from the NASA GEOS-5 analyses, which only began in 2004. The 1 hPa winds derived from ECMWF analyses shown here are consistent with those derived from GEOS-5. In the mesosphere, the temperature evolution and, in particular, occurrences of high-altitude stratopause reformation, are only partially captured by current meteorological analyses as demonstrated in the study of *Manney et al.* [2008]. This owes to the limited vertical extent of the analyses and also to the paucity of mesospheric observations being assimilated.

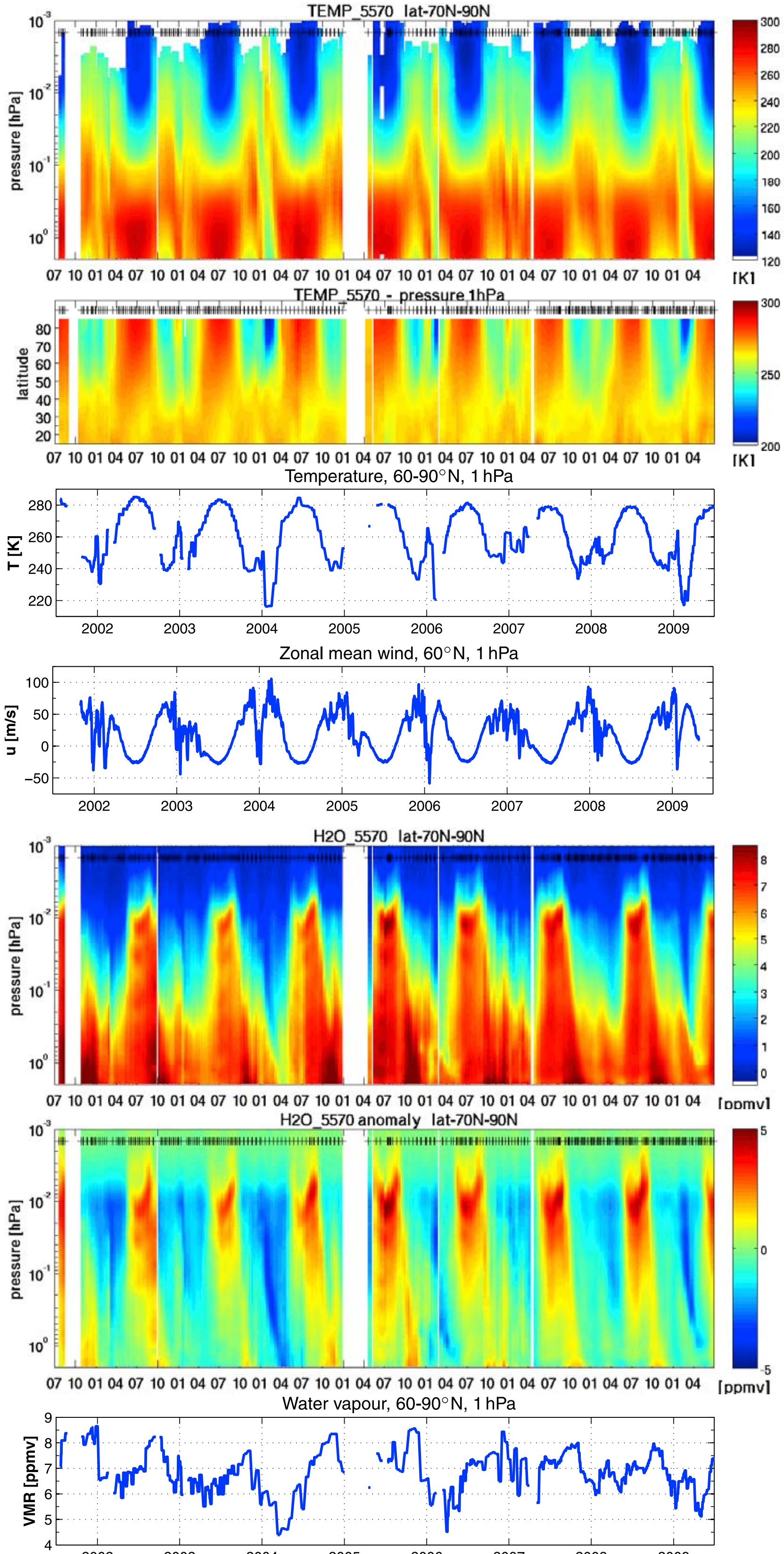
TEMP_5570 lat-70N-90N
pressure [hPa]
[K]
TEMP_5570 - pressure 1hPa
latitude
[K]
Temperature, 60-90°N, 1 hPa
T [K]
Zonal mean wind, 60°N, 1 hPa
u [m/s]
H2O_5570 lat-70N-90N
pressure [hPa]
[ppmv]
H2O_5570 anomaly lat-70N-90N
pressure [hPa]
[ppmv]
Water vapour, 60-90°N, 1 hPa
VMR [ppmv]

Figure 1

3. Temperature Distribution in the Mesosphere From SMR

[11] Figure 1 shows different facets of the SMR-derived mesospheric temperature and H_2O in northern high latitudes, from July 2001 to July 2009, as well as upper stratospheric winds from ECWMF analyses. First, the zonal-mean temperatures (averaged between 70°N and 90°N) are shown from about 1 to 0.001 hPa; then, zonal-mean temperatures as a function of latitude are shown at 1 hPa. Finally, the zonal-mean 1 hPa temperatures averaged in latitudes (poleward of 70°N) are repeated as a line plot, to facilitate comparison with the zonal-mean zonal wind at 70°N (shown just below).

[12] The SMR observations reveal the upper mesospheric annual cycle, with cold (warm) summer (winter) temperatures associated with the ascending (descending) phase of the mean meridional pole-to-pole circulation. At 1 hPa, the low winter temperature pattern is occasionally interrupted by occurrence of a major SSW, and zonal wind reversals from westerlies to easterlies occurred in late December 2004, mid-January 2006, and late January 2009. The latter SSW was characterized by a vortex-split event while the previous two SSWs were related to vortex displacement off the pole. The wind and temperatures time series at 1 hPa in Figure 1 also show that three midwinter pronounced coolings occurred during the recovery of the westerlies, following the SSWs. Three intense cold periods stand out from the observational record: in the middle of winters 2003–2004, 2005–2006, and 2008–2009. The vortex recovery was particularly pronounced in 2004, with zonal winds higher than in the prewarming period. The 2006 and 2009 warmings were also followed by a strong vortex recovery.

[13] Figure 2 shows the October–April evolution of zonally averaged polar temperature during the 2003–2004, 2005–2006, and 2008–2009 winters (Figure 2a) as well as temperature anomalies from the winter mean (Figure 2b). Around the peak of the SSWs, in late December 2003 to early January 20004, in January 2006, and in late January 2009, warm upper stratospheric anomalies are mirrored vertically by cold anomalies aloft, throughout the mesosphere but mostly the upper mesosphere in 2009. Such polar mesospheric coolings have been observed from the ground for decades; recent radar observations during the SSW in winter 2005–2006 is given by *Hoffman et al.* [2007]. SABER also observed such a cooling during SSWs in 2002 and 2003 [*Siskind et al.*, 2005]. Present understanding of the dynamical evolution of the stratosphere-mesosphere coupling during SSWs derives from the seminal work of *Matsuno* [1971] based on a quasi-geostrophic model. Details on this coupling have been further illuminated in more recent studies using general circulation models extending up into the thermosphere [e.g., *Liu and Roble*, 2002]. During the SSW onset, damping of upward-propagating planetary waves provides westward forcing of the zonal wind that promotes the eventual polar jet reversal and warming in the USLM. The associated peak in wave flux divergence induces two vertically stacked cells of transient mean meridional circulation above and below the level where westward momentum deposition peaks, near the stratopause, as required by thermal wind balance. In the top cell, rising motions at high latitudes adiabatically cool the polar lower mesosphere. In the underlying cell, sinking motions adiabatically warms the upper stratosphere and leads to a descent of the stratopause from its normal altitude near 50 km, as first shown by *Labitzke* [1972] using rocket data. Using lidar observations, *von Zahn et al.* [1998] observed the stratopause drop by 10 km in 3 days above Andøya (Northern Norway, 69N), reaching down to 40 km during a SSW in the winter 1997–1998. Using MLS and SABER temperatures, *Manney et al.* [2008; 2009b] showed the stratopause descending by at least 30 km during the 2006 and 2009 SSWs. This stratopause drop is not readily seen in the SMR observations used here, which cover mostly mesospheric altitudes.

[14] Following the warming, the upper stratosphere cooled down to below 220 K, about 20 K below the winter climatological value (see Figure 1). At the same time, a warm mesospheric layer corresponding to an elevated zonal-mean stratopause abruptly appears near 0.01 hPa, i.e., between approximately 72 and 75 km, at what are normally mesospheric altitudes. It then descends over the next 1–2 months. Snapshots of zonal-mean mesospheric temperature meridional cross sections (Figure 3) clearly show a distinct, elevated NH polar stratopause during the vortex recovery period (on 20–21 January 2004, on 7–8 February 2006, and on 19–20 February 2009). Using the Limb Infrared Monitor of the Stratosphere data in early winter 1978–1979, *Hitchman et al.* [1989] previously noted the existence of such a well-separated polar stratopause at similar altitudes. While this separation is a climatological feature, it is found anomalously high during these three events. This was also shown in the study of *Manney et al.* [2008] in winter 2005–2006. The descent of the warm anomalies in the recovery period gives rise to the three slanted temperature patterns in the first panel of Figure 1.

[15] The mesospheric temperatures measured by SMR during these three SSW events are quantitatively consistent with previous observations. Using SABER data, *Hauchecorne et al.* [2007] and *Siskind et al.* [2007] showed a descending mesospheric warm layer during the vortex recovery in 2004 and 2006, respectively; a zonal-mean

Figure 1. From top to bottom with a common horizontal axis indicating time from July 2001 to July 2009: Pressure (2 hPa to 0.001 hPa) versus time cross section of temperature in the NH high latitudes (poleward of 70°N); latitude versus time cross section of zonal-mean temperature at 1 hPa; time evolution of temperatures in the NH high latitudes (poleward of 60°N) at 1 hPa; time evolution of zonal-mean zonal winds at 60°N and 1 hPa; pressure (2 hPa to 0.001 hPa) versus time cross section of water vapor mixing ratio in the NH high latitudes (poleward of 70°N); pressure (2 hPa to 0.001 hPa) versus time cross section of water vapor anomalies, i.e., departures from the entire time mean, in the NH high latitudes (poleward of 70°N); and time evolution of water vapor mixing ratio in the polar cap (poleward of 60°N) at 1 hPa. In this figure and the following ones, tick marks (plus) at top of diagram indicate days with measurements.

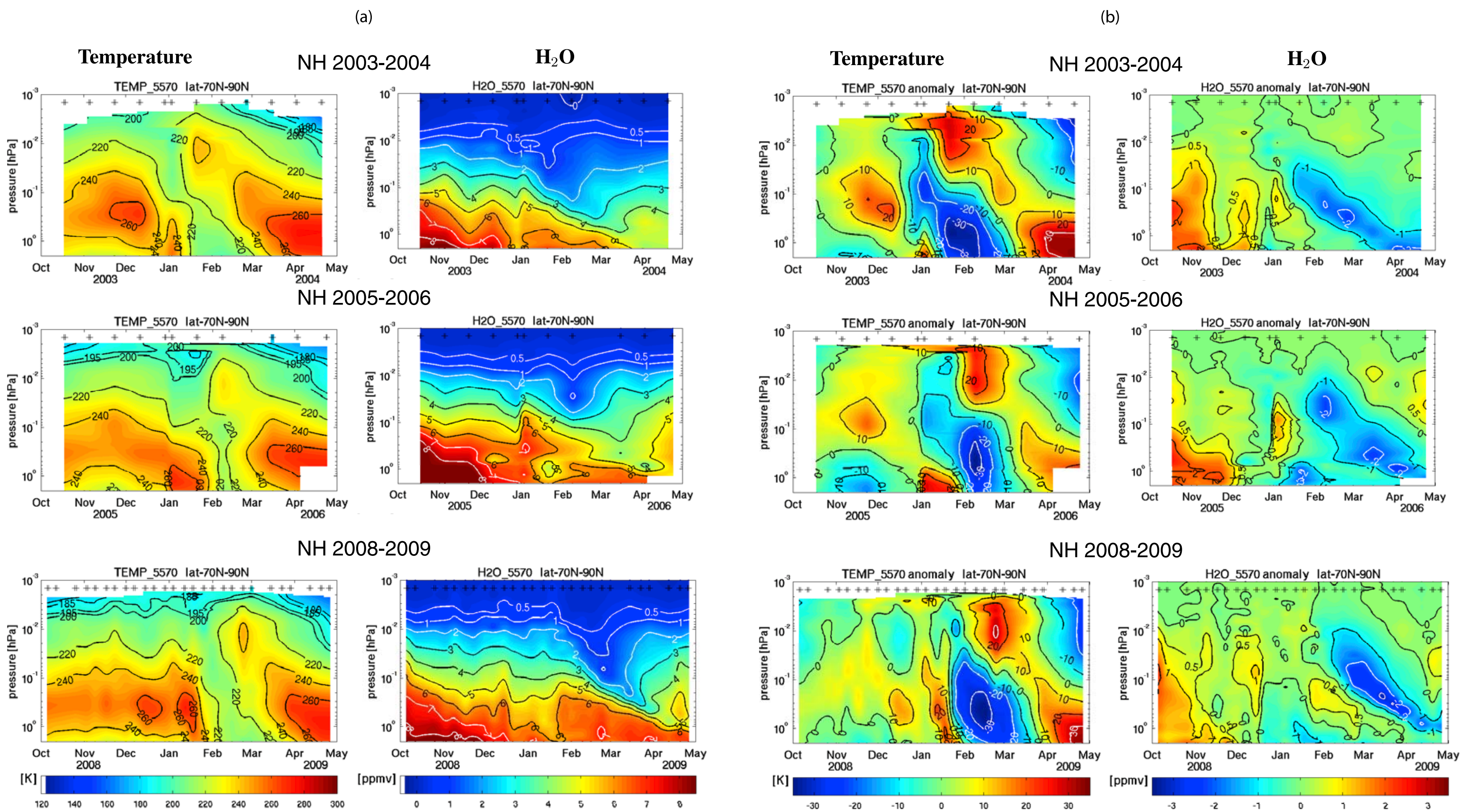

Figure 2. (a) Pressure (2 hPa to 0.001 hPa) versus time (October–April) cross sections of (left) zonal-mean mesospheric temperature and (right) water vapor mixing ratio in the NH high latitudes (poleward of 70°N) through winter 2003–2004, 2005–2006, and 2008–2009. (b) Same with temperature or water vapor expressed as anomalies from the corresponding winter mean.

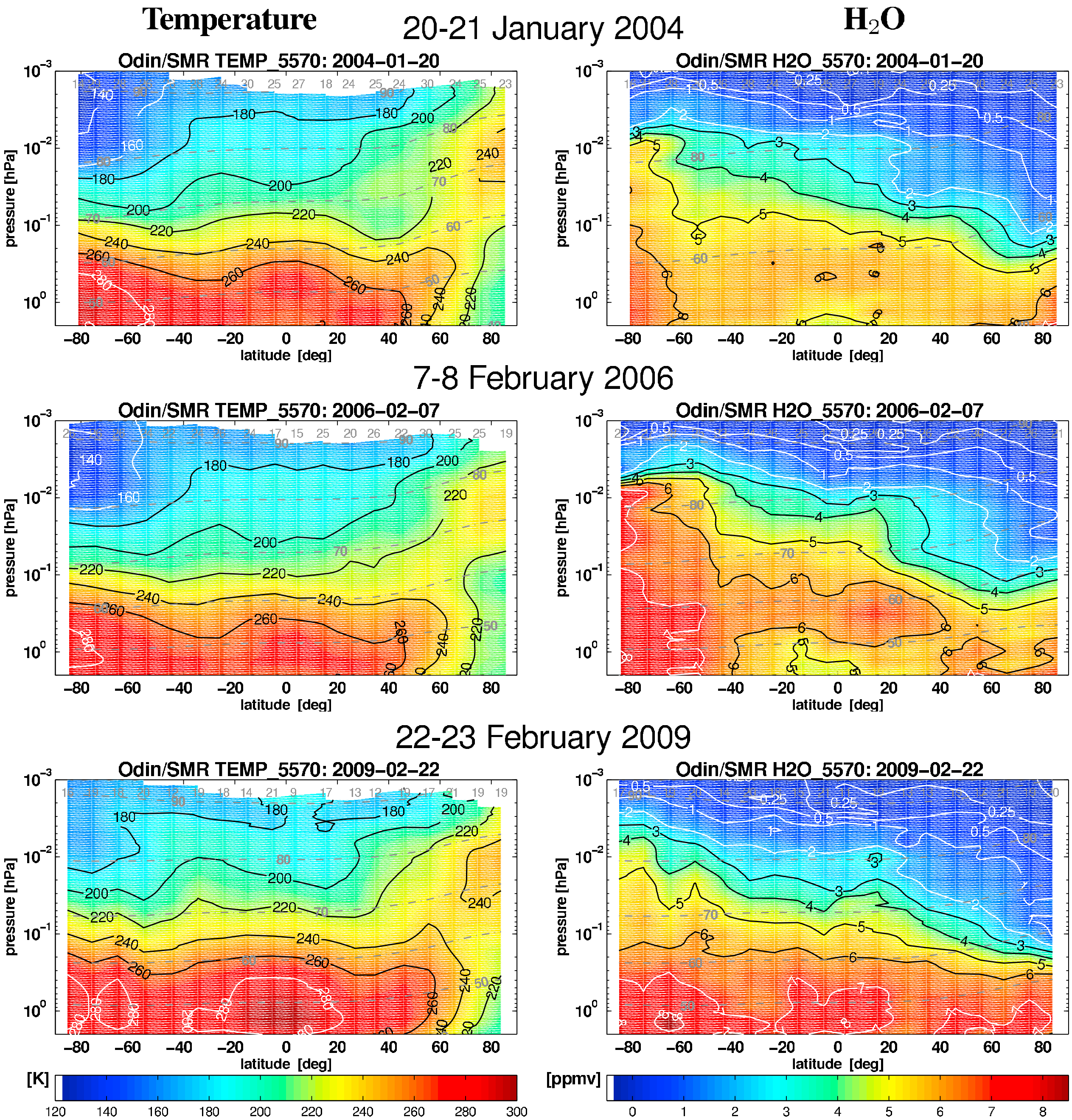

Figure 3. Pressure (2 hPa to 0.001 hPa) versus latitude cross sections of (left) zonal-mean mesospheric temperature and (right) water vapor mixing ratio on (top row) 20–21 January 2004, 7–8 February 2006, and (bottom row) 22–23 February 2009. Dot-dashed lines are approximate altitudes in kilometer.

temperature cross section on 20 January 2004 in the study of *Hauchecorne et al.* [2007] shows mesospheric temperatures around 250 K at altitudes near 75 km. In the 2005–2006 winter, SMR temperatures near 230 K around 0.01 hPa (Figure 2) are in good agreement with the MLS and SABER temperatures in the study of *Manney et al.* [2008].

[16] In Figure 4, we show the October–April evolution of zonally averaged temperature, for the 8 NH winters observed by SMR (as in Figure 2). The stratopause high-altitude reformation and strong descent events only occurred during the 2003–2004, 2005–2006, and 2008–2009 winters.

[17] As first emphasized by *Manney et al.* [2008], only certain SSW episodes lead to the stratopause displacement well into the lower mesospheric altitudes (72 or 75 km), and its eventual returning descent over 1–2 months thereafter. Figure 5 provides an overview of the stratospheric and lower mesospheric zonal-mean zonal wind and temperature evolution at 70°N for December–March for the last six winters. Data are from the NASA GEOS-5 analyses, which

were not available in prior winters. Several instances of polar wind weakenings and reversals occur during the period, and noteworthy are the major midwinter SSWs in 2003–2004, 2005–2006, and 2008–2009. In the later case, consistent with *Manney et al.* [2009a] and *Lee et al.* [2009], we note that incipient polar wind reversal to easterlies appear first in the mesosphere, and a major SSW results about a week later when this wind reversal penetrated down to 10 hPa. Meteor radar wind observations by *Hoffmann et al.* [2007] also showed the mesospheric wind reversal in January 2006 leading the stratospheric wind change by 6 days. Other wind reversals initiated in the mesosphere do not lead to major SSWs since the wind reversal do not reach the 10 hPa level. In both winters 2006–2007 and 2007–2008, major SSWs occurred later in the season but the extension of the wind reversals was not deep, eventually leading into the final warming phase without a vortex recovery. In 2007–2008, a series of wind reversals reached down to only 5 hPa leading to minor depressions of the stratopause. In cases when the wind reversal reaches the lower stratosphere and persists (i.e., major SSW occurrences during 2003–2004, 2005–2006, and 2008–2009), strong vortex recovery ensues (note the magenta color in the Figure 5 wind field) along with the stratopause high-altitude reformation.

[18] In addition to forming of a critical level for planetary waves, it is likely that the persistent layers of easterlies during these remarkable SSWs modify the interaction of gravity waves (GWs) and the mean zonal flow. The breaking of GWs, mostly of orographic origin, provides a mean momentum drag capping the westerly jet in the mesosphere [*Leovy*, 1964]. During the major SSWs, the descending zonal wind reversal to easterlies inhibit the upward propagation of gravity waves, by filtering out the orographic GWs with zero phase speed and nonorographic GWs with negative phase speeds [*Liu and Roble*, 2002]. In the absence of the gravity wave drag, radiative cooling promotes vortex recovery (westerlies regaining strength). The breaking of upward-propagating gravity waves with eastward phase speeds could further contribute to the acceleration of the mean flow, the driving of mean meridional circulation cells, and the vertical expansion of mesospheric coolings, as nicely demonstrated in the study of *Ren et al.* [2008]. *Hoffman et al.* [2007] observed indeed strong gravity wave activity in their radar observations at Andenes (Northern Norway, 69°N) in the recovery phase of the 2006 event. Based on a 3-D primitive equation model, *Siskind et al.* [2007] showed that an orographic gravity wave parametrization accounting for such flow dependence is needed to reproduce the elevated polar stratopause following the 2005–2006 SSW.

4. Water Vapor Distribution in the Mesosphere From SMR

[19] Mesospheric zonal-mean H_2O mixing ratios (averaged in between 70°N and 90°N) are shown in Figure 1 from July 2001 to July 2009, as well as their anomalies expressed as departures from the multiannual mean. SMR captures well the annually varying mesospheric distribution of H_2O driven by the mean meridional circulation in the polar regions, where ascent (descent) in the summer (winter) hemisphere leads to higher (lower) H_2O mixing ratios. High degree of interannual variability is apparent in the descent of dry air into the USLM winter polar regions. The late winters of 2003–2004, 2005–2006, and 2008–2009 exhibit three periods with anomalously dry air in the USLM, which stand out in the 8 year SMR record analyzed here. Latitude-averaged (70°N–90°N) H_2O mixing ratios near or below 5 ppmv are found at 1 hPa shortly after the vortex recovery in these 3 years (Figure 1). Figures 2, 3, and 4 show the winter evolution as well as snapshots of zonal-mean H_2O mixing ratios or anomalies in the mesosphere, next to the temperature plots. At a given pressure level, mixing ratios gradually drop in time as result of early winter descent of dry air. This evolution is interrupted by a brief increase in mixing ratios during SSW events. Thereafter, as the vortex recovers, the dry air continues to sink at slightly faster rate in the warming layer. A similar sequence but with opposite polarity has been shown for CO in the study of *Manney et al.* [2008; 2009b]; early winter descent bringing CO-rich air is interrupted by abrupt CO decrease and followed by renewed descent and CO increase. The coherent behavior of CO and H_2O is consistent with vigorous mixing of vortex and extravortex air after the warming, just prior to vortex recovery. The timing of the H_2O anomalies in Odin/SMR presented here agrees with the NO_2 and CO anomalies from GOMOS or ACE [*Randall et al.*, 2006; *Hauchecorne et al.*, 2007], and the H_2O anomalies from MLS, ACE [*Manney et al.*, 2008b], and SABER [*Feofilov et al.*, 2009]. In the 2005–2006 case, the MLS observations show the 4 ppmv H_2O isopleth reaching down to pressure levels as high as 0.7 hPa in mid-March.

[20] Figure 2 suggests that the late winter descent of H_2O-poor air is more extensive in 2003–2004 than in 2005–2006 or 2008–2009. In the former, dry air with mixing ratios near 4 ppmv penetrates down to 1 hPa near mid-March, and this deep descent coincides with the lowest polar temperatures and strongest vortex recovery (see also Figure 1).

[21] We further note that the model used in the study of *Liu and Roble* [2002] exhibited yet another stacked cell during the SSWs, with descent and warming in the lower thermosphere. The SMR observations of H_2O did not allow us to reveal the signature of these motions due to the very low mixing ratios in the upper mesosphere and lower thermosphere.

5. Summary

[22] The aim of this paper was to show that satellite observations of mesospheric H_2O and temperature in the microwave spectral range by the SMR instrument aboard the Odin satellite allow us to distinguish the formation of an anomalously elevated polar stratopause, and the anomalous descent of dry mesospheric air into the polar stratosphere during the late winter of 2003–2004, 2005–2006, and 2008–2009. These 3 years are characterized by midwinter major SSWs that stand out in the 8 year (2001–2009) Odin/SMR record. These characteristics are furthered elucidated by concurrent examination of meteorological analyses. Consistent with the results from the study of *Manney et al.* [2008; 2009a, 2009b] using MLS and SABER data, in these three periods, the SMR temperatures show the elevated

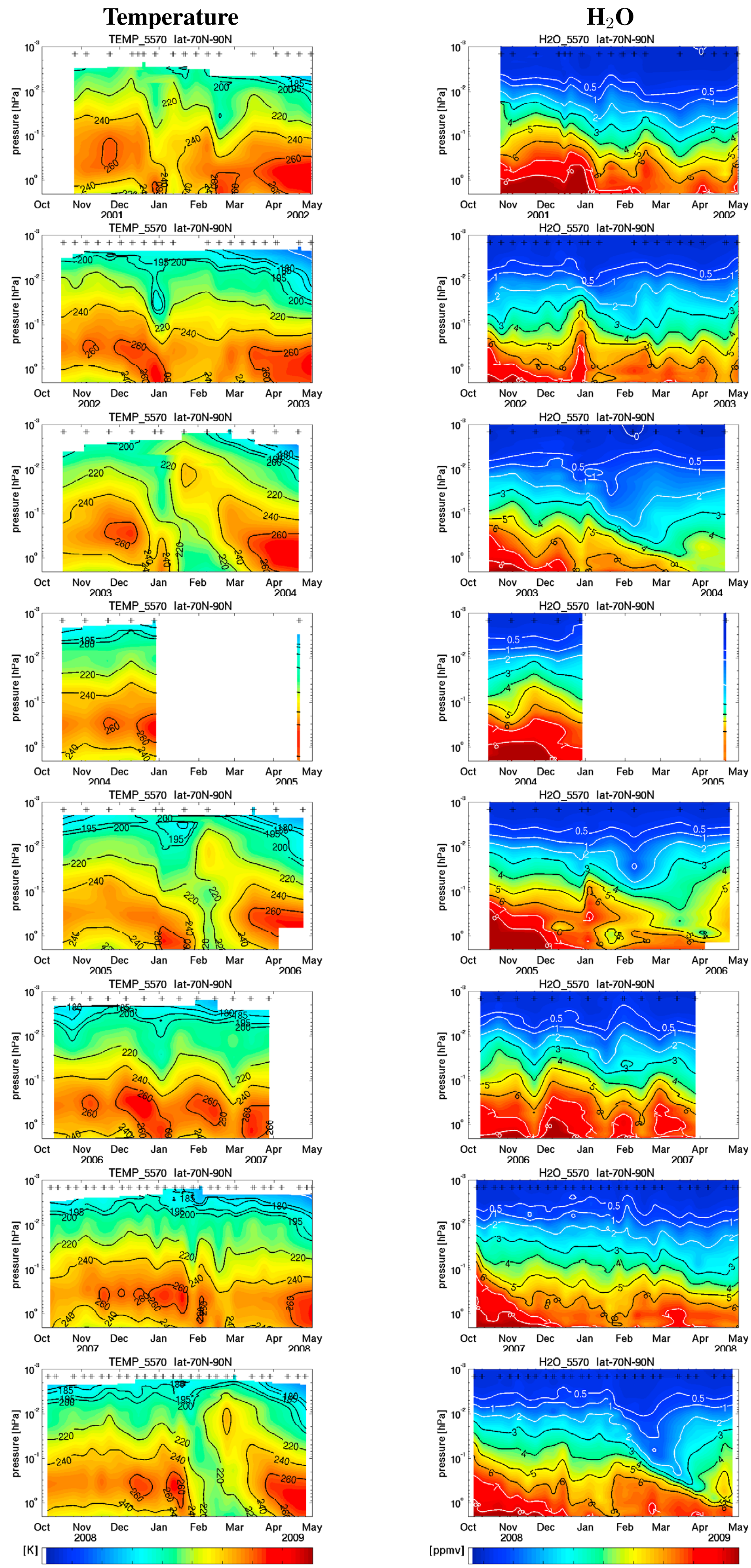

Figure 4. Pressure (2 hPa to 0.001 hPa) versus time (October–April) cross sections of zonal-mean mesospheric temperature (left) and water vapor mixing ratio (right) in the NH high latitudes (poleward of 70°N) through 8 winters measured by Odin/SMR (2001–2002 through and 2008–2009).

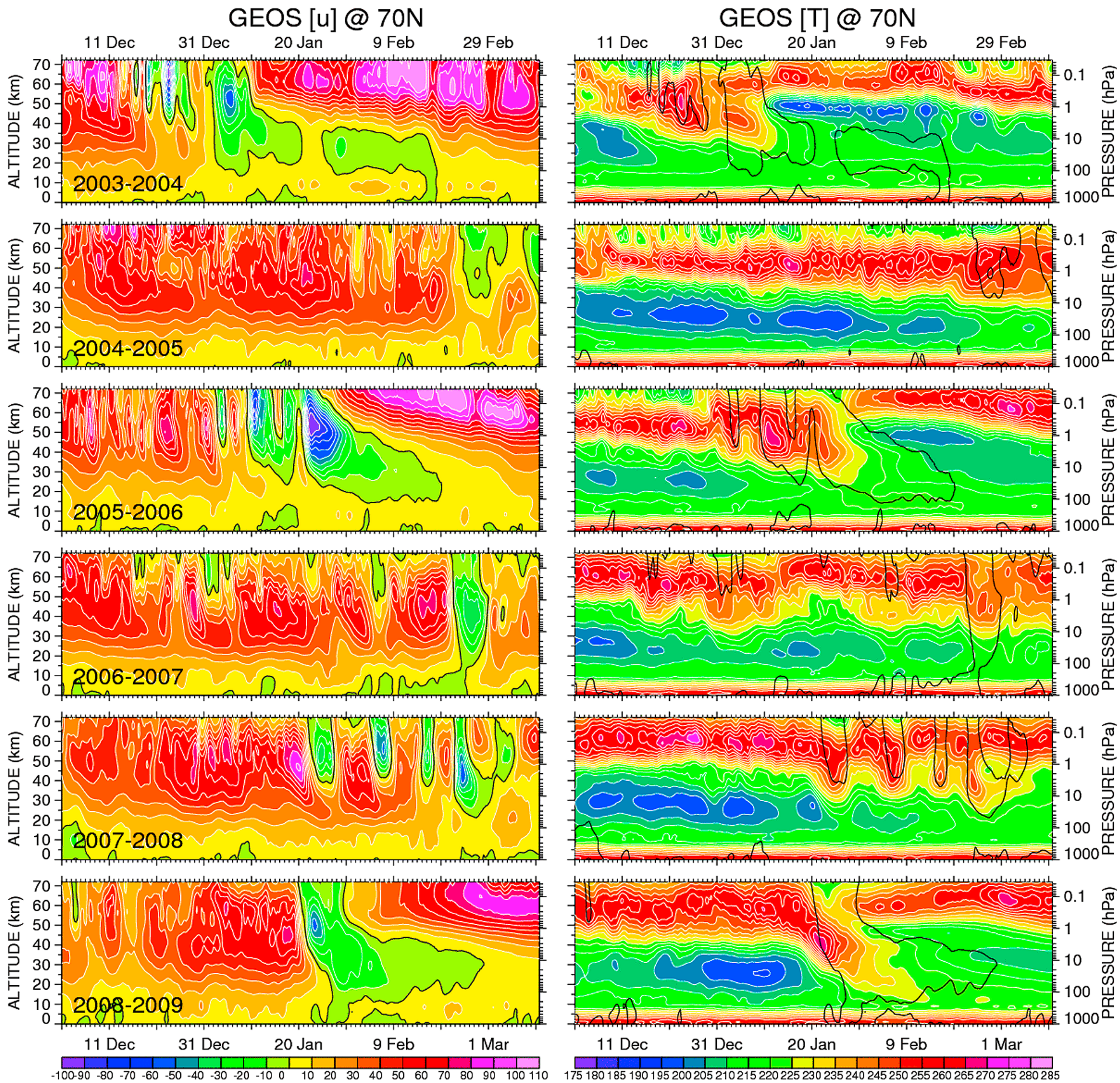

Figure 5. Altitude-time cross section of zonal-mean zonal wind (left) and temperature (right) from NASA GEOS-5 analyses at 70°N, from ground up to 70 km, from December to March for winters 2003–2004 to 2008–2009.

zonal-mean polar stratopause near 72 to 75 km, at what are normally associated with mesospheric altitudes. The restoration of a strong stratospheric vortex in the aftermath of a midwinter major SSW plays an important role in modulating the descent of minor constituents from the polar mesosphere to the stratosphere. The 2003–2004 descent was the strongest, in terms of the dryness of air reaching 1 hPa, but in 2009, the descent was comparable throughout the mesosphere but exhibited tighter vertical gradients in the USLM. Through the SSWs development, from the initial wind reversal in the mesosphere to the postwarming recovery, the temperature anomalies exhibit a quadrupole structure, shown to some extent in Figure 2b.

[23] Previous studies of the USLM, and in particular of the stratopause behavior during major SSWs, had been hampered by the restricted number of global observations. In recent years, new observations of temperature and minor constituents from, e.g., SABER and MLS [*Siskind et al.*, 2005; *Manney et al.*, 2008], and from SMR, as shown here, allow new insights into the dynamics and transport in the mesosphere.

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