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Variability of the nighttime OH layer and mesospheric ozone at high latitudes during northern winter: influence of meteorology

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Abstract. Analyses of OH zonal means, recorded at boreal high latitudes by the Aura Microwave Limb Sounder (MLS) in winters of 2005–2009, have shown medium- (weeks) and short- (days) term variability of the nighttime OH layer.

Because of the exceptional descent of air from the mesosphere-lower thermosphere (MLT) region, medium-term variability occurred during February 2006 and February/March 2009. The layer normally situated at about 82 km descended by about 5–7 km, and its density increased to more than twice January values. In these periods and location the abundance of the lowered OH layer is comparable to the OH values induced by Solar Energetic Particle (SEP) forcing (e.g., SEP events of January 2005) at the same altitudes. In both years, the descent of the OH layer was coupled with increased mesospheric temperatures, elevated carbon monoxide and an almost complete disappearance of ozone at the altitude of the descended layer (which was not observed in other years). Moreover, under these exceptional atmospheric conditions, the third ozone peak, normally at about 72 km, is shown to descend about 5 km to lower altitude and increase in magnitude, with maximum values recorded during February 2009.

Short-term variability occurred during Sudden Stratospheric Warming (SSW) events, in particular in January 2006, February 2008 and January 2009, when dynamics led to a smaller abundance of the OH layer at its typical altitude. During these periods, there was an upward displacement of the OH layer coupled to changes in ozone and carbon monoxide. These perturbations were the strongest during the SSW of January 2009; coincident upper mesospheric temperatures were the lowest recorded over the late winters of 2005–2009.

Finally, the series of SSW events that occurred in late January/February 2008 induced noticeable short-term variability in ozone at altitudes of both the ozone minimum and the third ozone peak.

These phenomena, confined inside the polar vortex, are an additional tool that can be used to investigate mesospheric vortex dynamics.

1 Introduction

The odd-hydrogen (HO_x=H+OH+HO_2) family, in particular the hydroxyl radical (OH), plays a fundamental role in the ozone balance especially in the middle atmosphere. That is because of its efficient catalytic cycles of O_3 destruction (Bates and Nicolet, 1950) and its presence in several reactions between stable and active forms of other ozone destroying components. The relevance of OH resides also in its use as a proxy for mesospheric water vapour (Summers et al., 2001), which is known to play an important role in the atmospheric thermal budget. Therefore, detailed knowledge of OH distribution and variability is needed in order to investigate the terrestrial atmosphere. Nevertheless, until a few years ago there still existed some discrepancies between modelled and measured OH concentration, the so-called HO_x dilemma (see Conway et al., 2000), and some uncertainty about its impact on O_3. The HO_x dilemma arises from previous observations of either OH or HO_2 alone which have shown poor agreement with standard chemistry (JPL recommended rates). Therefore, in order to reach better agreement, some modifications to the rate constants of HO_x partitioning reactions were suggested (e.g., Clancy et al., 1994; Summers et al., 1997). Nowadays these problems seem to be resolved by recent studies based on Aura Microwave Limb Sounder

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(MLS) OH and HO_2 data (e.g., Canty et al., 2006; Pickett et al., 2008), therefore no HO_x dilemma is present between MLS observations and the standard chemistry. The availability of MLS data has opened new scenarios since for the first time a worldwide dataset of OH and HO_2, spanning more than five years and recorded also at nighttime, is freely accessible.

The main OH source in the stratosphere is due to the reaction of water vapour with atomic oxygen from O_3 photolysis, whereas in the mesosphere it is due to the direct photolysis of H_2O. Cannibalistic reactions, e.g. between OH and HO_2, are the main sinks. Because of the short lifetime of OH, the major variability is connected to the diurnal cycle, with maximum OH abundance roughly at noon and values very low at nighttime. This maximum moves slightly towards the afternoon with increasing altitude due to the longer chemical lifetime of OH (Li et al., 2005). Stratospheric annual and semiannual oscillations of OH are of minor importance (a few percent) and mainly follow the annual trend of ozone, water vapour and ultraviolet intensity (e.g., Canty and Minschwaner, 2002).

The key feature of the OH profile recorded at nighttime is the presence of an enhanced mesospheric OH layer. It is caused by the reaction of ozone with atomic hydrogen and the consequent formation of OH* (i.e. hydroxyl radical vibrationally excited) which forms a layer at a nominal altitude of 87 km. The OH* is deactivated either by photon emission in the Meinel bands (observed in the nightglow) or by collisional quenching. The latter becomes the most important factor at lower altitudes due to the higher density, and it is the main cause of the formation of the OH layer in the ground vibrational state at about 82 km under typical atmospheric conditions. (Slight hemispheric variations of its altitude can arise from the large mesospheric temperature differences between summer and winter hemispheres, therefore pressure is a better coordinate than altitude, see Pickett et al., 2006).

The mesospheric odd-hydrogen of the Polar Regions is mainly produced in the sunlit atmosphere, transported to the polar winter thermosphere, and then descends towards the upper mesosphere. In the middle/lower mesosphere (below about 75 km) the concentration of atomic hydrogen (H) is only a small fraction of the total HO_x because the density still allows the reaction of atomic hydrogen with molecular oxygen (plus a third body) to form HO_2. When the density decreases (in the upper mesosphere), the H concentration increases and its reaction with O_3, which produces OH, becomes the main process. The lifetime of the HO_x components is very short in the middle mesosphere (it is less than 1 h at 75–80 km; see, for instance, Brasseur and Solomon, 2005), preventing transport processes from influencing the OH distribution there, but at slightly higher altitudes it grows quickly (it is ~30 days at 85 km; see Pickett et al., 2006) and dynamics could play an important role.

In Polar Regions an important source of variability of mesospheric OH stems from Solar Energetic Particle (SEP) events arising from huge explosions on the Sun. They provide additional external energy to the middle polar atmosphere and are able to produce ionizations, dissociations, dissociative ionizations and excitation phenomena by interacting with minor atmospheric constituents. The final result of these paths is an odd-hydrogen enhancement (Solomon et al., 1981); therefore OH can increase by more than one order of magnitude, although the perturbation lasts only a few days. This is particularly evident at nighttime when the OH background is low (see Storini and Damiani, 2008; Damiani et al., 2008, 2009). Since the production of SEP-induced HO_x occurs in the mesosphere via water cluster ions (Solomon et al., 1981), the upper limit of the OH enhancement is roughly confined by the mesopause. Therefore, the nighttime OH layer can be potentially influenced by incoming solar energetic particles.

In addition, recent research studies pointed out that meteorological events are also sources of variability for the layer of OH*. By using SABER measurements of OH emission rates, Winick et al. (2009) showed that in the boreal winters of 2004 and 2006 the layer of OH* descended about 5–8 km to lower altitudes and the emissions were ~2–3 times as intense as normal. Since ozone can be considered to be in steady state under nighttime conditions (i.e., polar winter), this drop was attributed to strong descent of air in the MLT region leading to subsequent increased O_x ($O+O_3$) transport to lower altitudes. Since O_3 is generated through the reaction between atomic oxygen and O_2, the production of OH is proportional to [O] (the square brackets represent "concentration"). In order to move the layer toward lower altitudes a vigorous downward transport of O_x is required to maintain the abundance of O above its normal levels at anomalously low altitudes. As a result, the availability of O at lower altitudes leads to the descending O_3 and consequently the descending OH (see Winick et al., 2009).

A further meteorological trigger for variability of the nighttime OH layer is provided by Sudden Stratospheric Warming (SSW) events. In this regard, Sonnemann et al. (2006a) showed changes in the spatiotemporal characteristics of the minor constituents in the MLT region under SSW conditions (i.e., changing of the characteristics of the secondary and tertiary ozone maximum, the variation of the Meinel band emission layer and ground state OH layer and the alteration of the chemical heating rate). In particular, their modelling findings reported variation in concentration/production rate and altitude of the nighttime OH layer in both ground and vibrational states. Ground based observations (e.g., Cho and Shepherd, 2006) also showed the variability in emission rate and altitude of the OH* layer during such events. Observations of the ground-state OH layer variability due to SSW events have not been reported.

Therefore, in the MLT region there exists a strong connection between OH and O_x, and both parameters are related to the dynamics and temperature.

The present paper analyzes Aura MLS observations of nighttime OH (i.e. in the ground vibrational state), ozone, carbon monoxide (CO) and temperature from January to March for the years 2005–2009, focused on times during and after SSW events. Special attention has been paid to periods of exceptional descent of polar air from the MLT region (i.e., February 2006 and February/March 2009; see, for instance, Siskind et al., 2007; Manney et al., 2008, 2009) characterized by very high (low) temperatures in the mesosphere (stratosphere) that followed the intense SSW events that occurred in January 2006 and 2009. MLS data show changes in the above chemical constituents that are consistent with previous observations but that provide new information and details that can help fill in the picture of the dynamical-chemical processes acting during these periods.

2 MLS data used

Data used were recorded by the Microwave Limb Sounder (MLS) instrument on the Aura satellite. The NASA EOS (Earth Observing System) MLS (Waters et al., 2006) is one of the four instruments of Aura, launched on 15 July 2004 to a sunsynchronous near polar orbit. MLS scans the Earth's limb in the flight forward direction, viewing the microwave emission in different spectral regions. Measurements are performed along the sub-orbital track, and resolution varies for different parameters (typical values are: 5 km cross-track×500 km along-track×2.5 km vertical). The EOS MLS records vertical profiles of gas phase chemical abundances, temperature, and cloud ice density. Here we will focus on MLS Version 2.2 OH, O_3, CO and temperature Level 2 Data (available at: http://mirador.gsfc.nasa.gov/index.shtml; see Pickett et al., 2008; Livesey et al., 2007, for data quality). Note that MLS profiles are mostly output on a grid that has a vertical spacing of six surfaces per decade change in pressure (~2.5 km), which degrades to three surfaces per decade above 0.1 hPa. Only OH profiles maintain the higher resolution also in the middle/upper mesosphere, therefore some limited incongruities between OH and other products in the following figures may arise from this factor. The vertical width of the averaging kernel of MLS OH at pressures higher than 0.01 hPa is roughly coincident with the grid for the data (2.5 km). At the altitude of the OH layer it is slightly larger (3 km). The resolution increases to about 5 km at 0.003 hPa. The changes in vertical resolution at pressures lower than 0.01 hPa are due mainly to use of a faster operational scan rate for tangent heights above 70 km (e.g., Pickett et al., 2008).

We employed daily zonal means of MLS data recorded in the geographic latitudinal range 75–82° N and under nighttime conditions i.e., solar zenith angle (SZA)>95°, unless otherwise noted. In this way, in the investigated region, which should correspond to the inner polar vortex, we have almost complete satellite coverage up to late March, allowing the study of the February/March 2009 event. However, in choosing this SZA limit we include also some profiles recorded under twilight conditions. This occurs especially in the latter half of March, but without altering the results. (Experimental analysis with SZA>100° conducted on OH, the most reactive component, revealed that the nightly OH trend is analogous to the results presented here and the values of OH are very similar to the ones shown until about mid-March; some differences between the values recorded under conditions of SZA>95° and >100° depend on the number of samples utilized for the means.) About 200–250 (100–200) profiles per day in January (February) have been used to calculate the MLS zonal means. The number of employed profiles decreases to a few tens per day in late March due to the incoming solar illumination.

Although the upper limit generally recommended for single profiles of MLS O_3 is 0.02 hPa (Froidevaux et al., 2008), in some analysis of this paper we extended the vertical range of the zonal means in order to get at least qualitative information on the O_3 trend in the MLT region. As explained in the data quality and description document of MLS data (Livesey et al., 2007), some of the MLS observations are "noisy" in nature. A consequence of this is that the abundances of the MLS retrieval components may have negative values because MLS measurements have a poor signal to noise ratio for individual profiles. In order to avoid introducing a high bias in calculating averages, it is necessary to retain these values. For ozone, negative values occur at pressures lower than 0.02 hPa. In our case, despite the large amount of profiles utilized for the averages, some negative daily values persist but only at the altitude of the ozone minimum (0.01 hPa) and under anomalous circumstances which, as we will show in the discussion, involve an increase of OH abundance.

3 MLS data analysis

Figure 1 shows the time series of mesospheric daily OH abundance at 0.015 hPa (~77 km) recorded at night from January to March for the years 2005–2009. The relative precision of the zonal averages is better than 10% with at least 100 samples at pressures ≥0.01 hPa (Pickett et al., 2008). Note the error bar for the year 2005 reported as a reference. The main features of Fig. 1 are the sudden and short-lived OH increases related to the SEP events of 17 and 20 January, 2005 and the long-lasting OH enhancements during February 2006 and February/March 2009. All these OH peaks have comparable magnitude, up to five times the background values. We excluded the presence of noticeable transient solar activity (e.g. SEP events) in the winters of 2006 and 2009 by checking solar proton flux data from GOES (available at: http://www.ngdc.noaa.gov/stp/GOES/goes.html) and intense
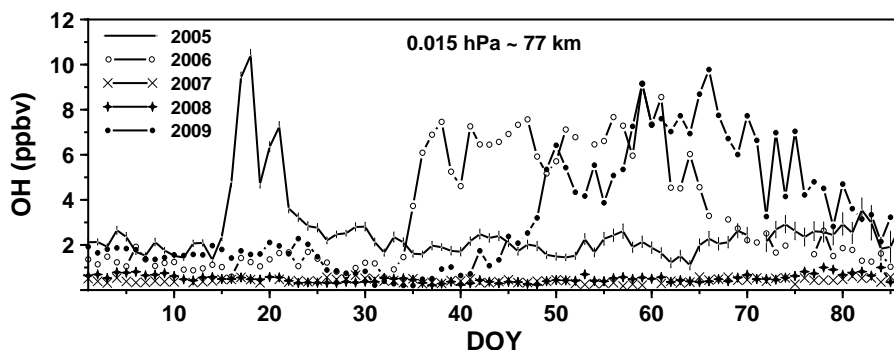
Fig. 1. Daily zonal mean nighttime OH (75–82° N) from 1 January–27 March for 2005–2009 at about 77 km (error bars for the year 2005 as a reference).

geomagnetic activity by looking at the Kp index (SEP days excepted, the highest value of the years 2005–2009 occurred on 7 March 2005, with a Kp=4.7). In addition, the position of the investigated region, roughly outside the auroral belt, should avoid important effects induced by electron precipitation. Hence the cause of such OH variability in 2006 and 2009 shown in Fig. 1 has a meteorological origin.

Figure 2 reports the geographic distribution of nighttime OH at 0.015 hPa for 19 February 2005, 2006, 2007, 2008 and 2009 (from left to right). This altitude is below the usual position of the OH layer and the typical OH abundance is ∼1 ppbv. Therefore during 2005, 2007 and 2008 there are not sensible differences in OH mixing ratio between polar and middle latitudes. In contrast, the OH abundance is higher (more than 5 ppbv) at polar latitudes in 2006 and 2009. Further elevated OH values are evident at high latitudes of the Southern Hemisphere (SH). We will examine such features in the discussion section.

Figure 3 shows MLS nighttime OH zonal means from January to March for the years 2005–2009. As for Fig. 1, the sudden OH rise in January 2005 is connected to the increased ionization induced by the SEP events. An apparent downward displacement by ∼5–7 km of the OH layer occurred during the 2006 and 2009 winters. In Fig. 3 the CO mixing ratio (white contours superimposed over the OH abundance) is used as a tracer of middle atmospheric motion (e.g., de Zafra and Muscari, 2004). Note the presence of a long-lasting tongue of CO, representative of intense vertical transport, down to at least 60 km in 2006 and 2009, and the similar trend of the OH layer in those years. Further, the short term variability of the OH layer and its upward extension on some days (e.g. around 13 and 21 January 2006, 2 and 23 February 2008, 24 January 2009; see Fig. 3) are noticeable, corresponding to SSW events that we discuss below in detail. The occurrence of major and minor SSW events is reported in Figs. 3 and 4 as black vertical solid and dashed lines, respectively (they show the date that SSW criteria were fulfilled; see Manney et al., 2009; Wang and Alexander, 2009; Xu et al., 2009, for a complete description of the events).

Expressing OH in number density units (as reported in the left panels of Fig. 4) allows the increased concentration of the OH layer at lower altitudes (∼74 km) in February 2006 and February/March 2009 (more than twice January values) to be noted more readily. In 2005 (except for January), 2007 and 2008, the OH layer was characterized by lower density and typical altitude. Because the major SSW events of January 2006 and 2009 occurred in the stratosphere on roughly the same days in both years (21 January 2006 vs. 24 January 2009; Manney et al., 2009), the delayed OH descent in 2009 compared with that in 2006 indicates that the recovery of the polar vortex in the mesosphere was faster in 2006 than in 2009, at least in the investigated region. Zonal means of temperature (middle panels of Fig. 4) reflect this delay, with higher mesospheric temperatures, which suggest intense downward transport, starting earlier in 2006 than in 2009. Moreover, the mesospheric cooling associated with the SSW occurrence is well discernible.

In the right panels of Fig. 4 we show ozone zonal means in order to get at least qualitative information on the O_3 trend in the MLT region (see Smith and Marsh, 2005), where there exists a strong relationship between O_3 and OH. In this regard, a similar trend can be seen in the upper boundary of the OH layer (reported in mixing ratio units as black contours in the middle and right panels of Fig. 4) and the lower limit of the thermospheric ozone (roughly shown by the contour of ∼3 ppmv). In addition, in February 2006 and 2009, consistent with the lowered OH layer location, which roughly coincides with the typical altitude of the minimum ozone mixing ratio, MLS showed an almost complete disappearance of ozone, not seen in other years.

Moreover, from the right panels of Fig. 4 it is evident that variability in mesospheric ozone also generally occurs around SSW events, when an increased ozone abundance is clearly discernible at the altitude of the ozone minimum (∼0.01 hPa) (e.g., in February 2005, January 2006, late January/February 2008 and January 2009).
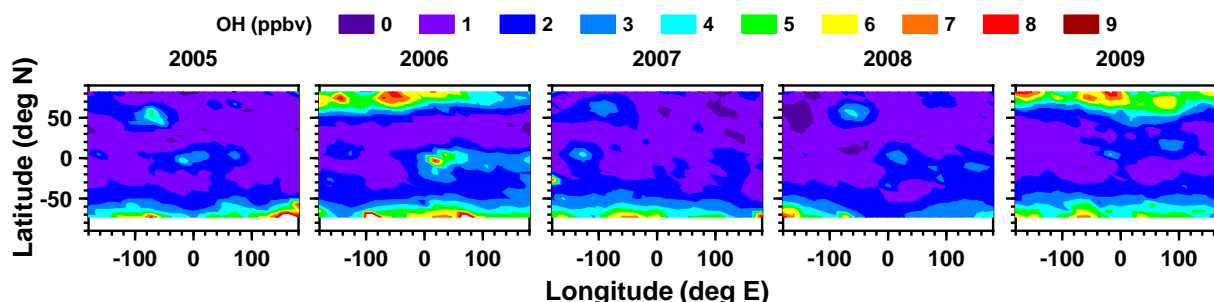
Fig. 2. Geographic distribution of nighttime OH at 0.015 hPa for 19 February 2005, 2006, 2007, 2008 and 2009 (from left to right).

The presence of the Third Ozone Peak (Marsh et al., 2001, hereafter called TOP) at the nominal altitude of 72 km is clearly visible, even though each year exhibits different intensity. Here we want to emphasize the presence of the TOP also at very high latitudes in every year and, after the vortex recovery of February 2006 and 2009, its descent (by about 5 km) and settling at lower altitudes with an increased mixing ratio. The sudden disappearance of the TOP during some SSW events (e.g. in February 2008) is also evident.

Table 1 shows the linear correlation among temperature, OH and O_3 in "quiet" years (i.e. those not characterized by strong vertical air descent, as for 2005, 2007, and 2008; SEP days excluded) and "disturbed" years (i.e. for 2006 and 2009 when atypical conditions are present; SSW days excluded) at different pressure surfaces (i.e., at 0.02 hPa, 0.01 hPa and 0.004 hPa) for January-February 2005–2009. The correlations for temperature vs. ozone and temperature vs. hydroxyl have opposite signs. Note also the reversing trends above 0.01 hPa reflecting the importance of dynamics in the middle and upper mesosphere, especially during "disturbed" years. In contrast, the correlation between OH and O_3 remains roughly negative for all the investigated altitudes. The positive correlation between temperature and OH is most evident at 0.01 hPa (~79 km). Although this apparent linkage exists also during "quiet" years, the correlation coefficient is higher ($r=0.86\pm0.05$) during "disturbed" years. Considerable ozone variability in response to temperature changes at 0.01 hPa during "quiet" years ($r=-0.74\pm0.05$) becomes somewhat more intense during "disturbed" years ($r=-0.83\pm0.06$). This anti-correlation between temperature and ozone is less evident around the altitudes of the TOP. In general, the correlation coefficients in "disturbed" years, characterized by very high altitude of the stratopause, are higher than in "quiet" years at all selected altitudes. It is, therefore, suggested that the descent of air during "disturbed" years strengthens the above-discussed correlations.

Further correlations as in Table 1 (not illustrated) made for the quiet days of "quiet" years with totally stable conditions (i.e., days of January–February 2005, 2007 and 2008 not affected by SSWs) showed coefficients slightly lower than in "quiet" years (with SSW days included). Therefore, the presence of SSWs can also influence the correlation result.

4 Discussion

February 2006 and 2009 correspond to periods with strong winter polar vortices in the upper stratosphere following intense SSW events that occurred in January of those years (Siskind et al., 2007; Manney et al., 2008, 2009). SSWs are extreme meteorological events that impact the winter middle atmosphere and involve changes in temperature, wind and circulation. Planetary waves propagating from the troposphere to the stratosphere induce polar vortex disturbances by interacting with the mean flow. This interaction decelerates or reverses the stratospheric eastward winds and provokes downward (upward) circulation and adiabatic heating (cooling) in the stratosphere (mesosphere) (Matsuno, 1971). In addition, in order to explain the mesospheric cooling, it is important to mention also the role of gravity waves during SSW events. Indeed, SSWs influence their propagation and transmission in the middle atmosphere. As pointed out by Holton (1983), the reversal of stratospheric winds reduces/eliminates the flux of gravity waves entering the mesosphere. Accordingly, the reduction in gravity wave drag causes a reduced meridional circulation and hence a cold polar mesosphere.

The SSW events that occurred in January 2006 and 2009 were followed in February by upper stratospheric/mesospheric vortex recovery accompanied by low planetary wave activity, increased mesospheric temperatures, and the start of intense diabatic descent of air from the MLT region to the stratosphere (Manney et al., 2009). Moreover, during both the 2006 and 2009 major SSWs, the stratopause dropped dramatically, almost completely broke down, and then reformed at very high (~75–80 km) altitude (Manney et al., 2009), affecting the temperature structure and trace gas distributions. These periods, together with part of the Northern polar winter 2004, have been extensively investigated because they were characterized by large descent of the constituents of the NO_y family (including NO, NO_2, HNO_3
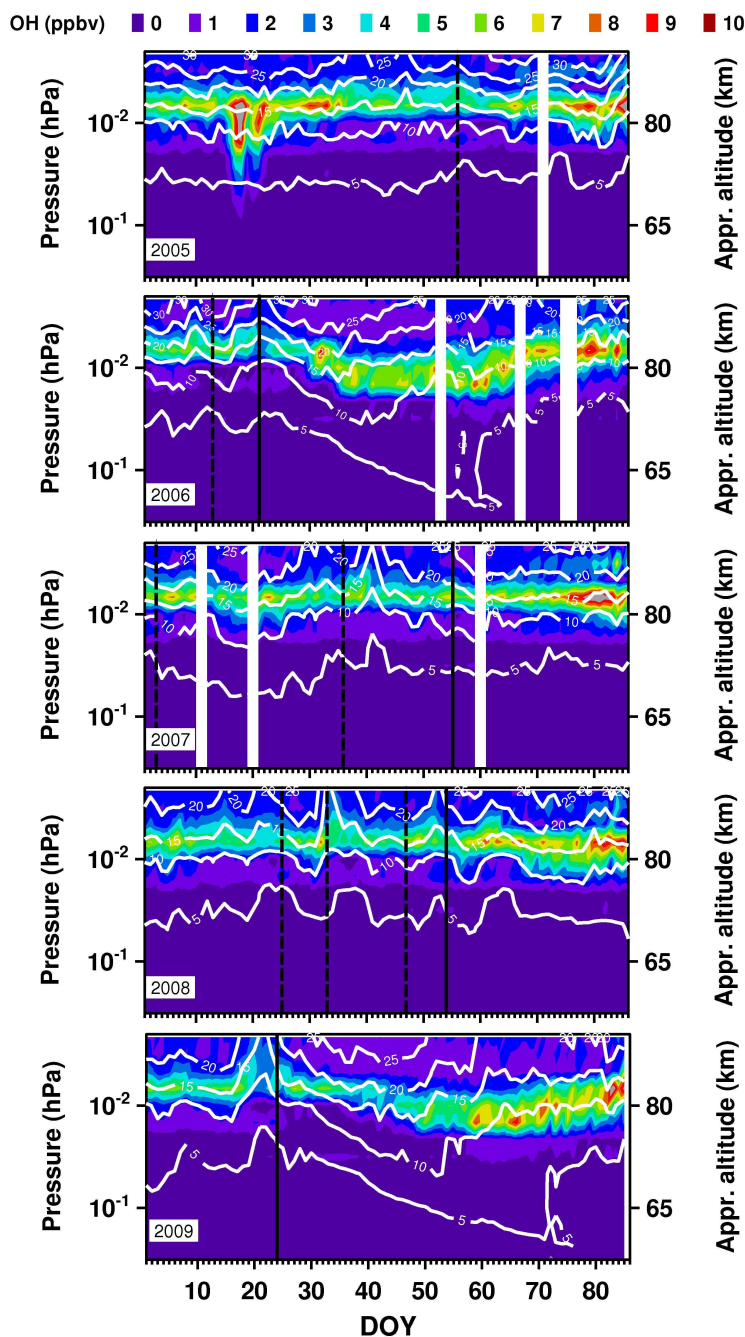
Fig. 3. Color contours: zonal mean nighttime OH (75–82° N) from 1 January–27 March for 2005–2009 (top to bottom). Gray regions: values outside the colorbar scale range; data gaps are shown as white areas. White contours: zonal mean nighttime CO expressed in ppmv. The vertical scale is from ~57 to ~90 km. Black vertical solid (dashed) line: major (minor) SSWs.

and N_2O_5) from the mesosphere to the stratosphere (see, for instance, Randall et al., 2005, 2006, 2009; Natarajan et al., 2004; Clilverd et al., 2006; López-Puertas et al., 2007; Seppälä et al., 2007; Siskind et al., 2007; Hauchecorne et al., 2007; Funke et al., 2008; Orsolini et al., 2009). As pointed out by Randall et al. (2009), it is atypical for such events to occur in the Northern Hemisphere (NH) three times in six

years. Until a short time ago, nitrogen descent was believed to take place primarily in the Southern Hemisphere because the strength and stability of the SH vortex facilitated transport from the MLT, the source region of NO_x production induced by auroral activity (Barth et al., 2001), to the stratosphere. However, the occurrence of these events in 2004, 2006 and 2009 winters has shifted attention to the NH.
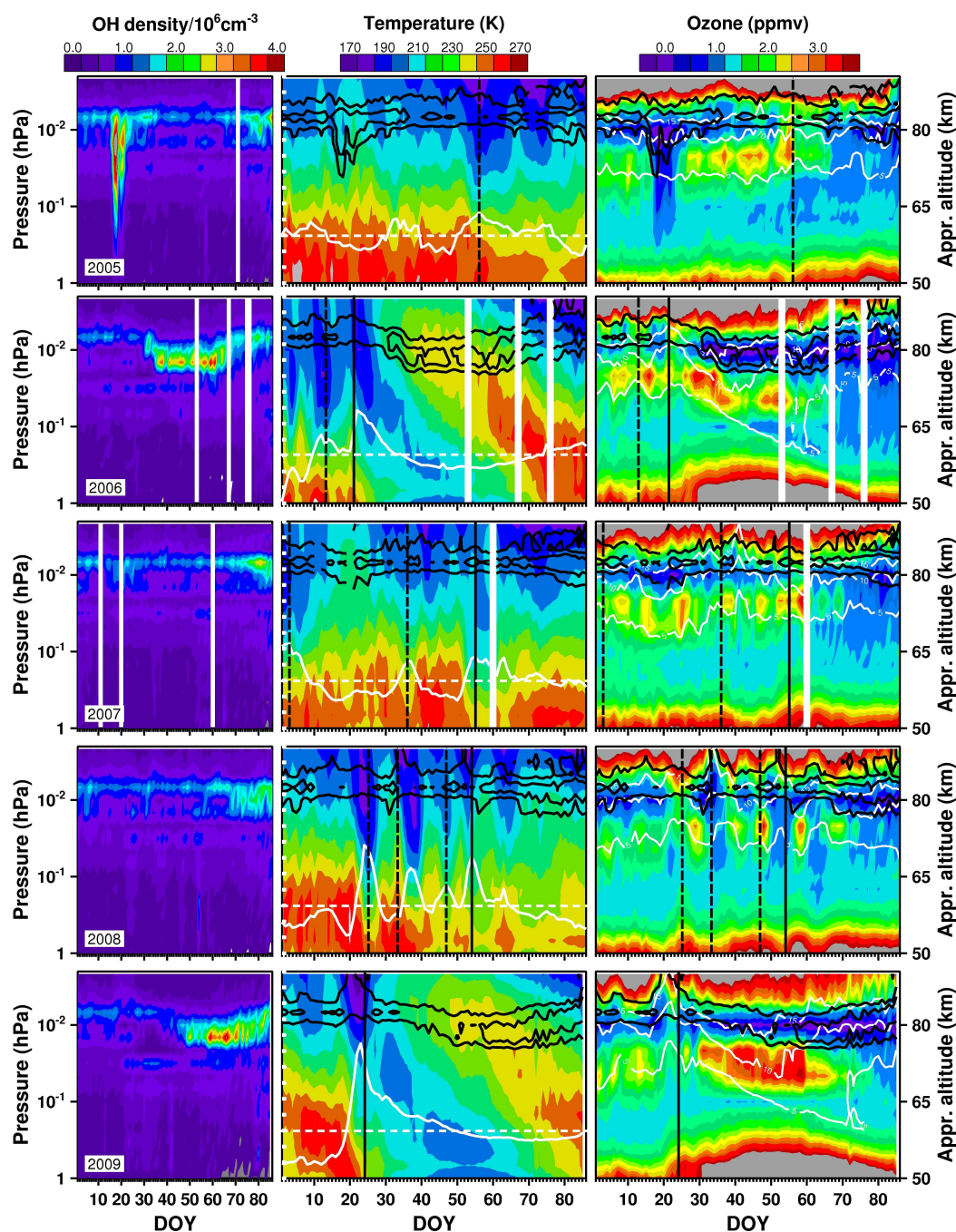
Fig. 4. (Left panels) Color contours: as in Fig. 3, except OH given in density units. (Central panels) Color contours: zonal mean nighttime temperature; black contours: zonal mean OH (we show 3 and 6 ppbv levels of OH mixing ratio); white lines: residual zonal mean temperature time series at 10 hPa (see the text. Zero is marked by the horizontal white dashed line. Note the white vertical scale on the left axis, with one unit denoting 10 K). (Right panels) Color contours: zonal mean nighttime ozone; black contours: zonal mean OH; white contours: zonal mean CO (5, 10, 15 ppmv). Black vertical solid (dashed) line: major (minor) SSWs. Gray regions: values outside the colorbar scale range; data gaps are shown as white areas.

Taking into account the above research, Winick et al. (2009) interpreted the lowering of the OH* layer as being due to the strong air descent and the consequent O_x transport in

the upper mesosphere. As described in Sect. 3, we note that in 2006 also the layer of ground state OH, normally situated about 5 km below the Meinel band emission layer, descended

Table 1. Linear correlation among temperature, OH and O_3 in "quiet" years (QY) and "disturbed" years (DY) at different pressure surfaces for January–February 2005–2009 (see the text). From left to right columns: parameters, pressure surface, correlation coefficient with standard error (r) and number of samples (n) for QY and DY.

Parameters	Pressure (hPa)	QY r	n	DY r	n
T vs. OH	0.004	−0.63±0.06	165	−0.83±0.06	85
	0.01	+0.70±0.05	165	+0.86±0.05	85
	0.02	+0.47±0.07	165	+0.70±0.08	85
T vs. O_3	0.004	+0.04±0.08	167	+0.71±0.08	85
	0.01	−0.74±0.05	167	−0.83±0.06	85
	0.02	−0.24±0.07	167	−0.42±0.10	85
OH vs. O_3	0.004	−0.57±0.06	165	−0.78±0.07	85
	0.01	−0.62±0.06	165	−0.80±0.06	85
	0.02	−0.31±0.07	165	−0.55±0.09	85

a few kilometers. The same phenomenon occurred in 2009, when similar atmospheric conditions prevailed in the MLT region. In both years the OH concentration was more than twice January values during the entire period of low OH layer location. Employing CO mixing ratio as a tracer of the atmospheric motion, we showed that a descending trend of CO is coupled to the lowering of the OH layer. This is further corroboration of the interpretation by Winick et al. (2009).

Figure 2 shows that high OH values are not confined to the narrow latitudinal band analyzed with the zonal averages (i.e., 75–82° N) but seem to involve a larger area of the northern Polar Regions. In addition, it is interesting to note the elevated OH values recorded in the high latitudes of the SH. In this case the descent of the OH layer is not connected to the raised OH abundance because it occurs in the summer hemisphere. There, nighttime OH may come from two sources: the nighttime production of OH by the reaction of ozone and atomic hydrogen and the daytime OH production via water vapour photolysis which lasts a few hours after sunset. In the mesosphere (around 75–80 km), the HO_x chemical lifetime of a few hours (longer than in the stratosphere where, for example, the HO_x lifetime is a few minutes at around 60 km) preserves the daytime OH abundances some hours after sunset. MLS nighttime OH data at southern high latitudes are recorded with SZA close to 95°, therefore close to the local sunset, whereas at middle and low latitudes data are recorded with a higher SZA (e.g., SZA is about 160° around the equator), so only nighttime OH production has contribution and OH concentrations appear to be lower.

Figure 4 (middle panels) shows that mesospheric temperature was higher than climatology during the descent of the OH layer. Although there has been only limited observational evidence determining the link between the temperature and the OH layer at 82 km because few instruments were able to measure nighttime OH before the start of the Aura MLS

mission, previous analyses were performed on the emission rate of OH nightglow (e.g., Liu and Shepherd, 2006; Cho and Shepherd, 2006). They showed that the integrated emission rate is related negatively to the altitude and positively to the temperature, and they suggested vertical motions as the most likely candidate to explain such behaviour. These studies were carried out on periods not characterized by the strong vertical transport seen during the 2006 or 2009 Northern winters, but nevertheless similarly highlighted the described features. In particular, as already noted by Winick et al. (2009), it is interesting that the high positive correlation between OH emission rate and temperature ($r=0.89$) reported by Cho and Shepherd (2006) for December 2001 included a SSW event, and therefore very low mesospheric temperatures. In addition, Winick et al. (2009) showed high temperatures connected to increased OH emission, consistent with the descended OH* layer.

Observations of mesospheric cooling associated with SSW events are present in the literature (Siskind et al., 2005), but often these studies focused on one or a few events. Figure 4 presents an overview of the SSW occurrence during five winters (2005–2009). In general, the temperature decrease starts at higher altitudes and propagates downward, with slightly different intensity and altitudinal range from one event to another. The SSWs in February 2007 are an exception since they occurred in the middle of a pre-existing decreasing trend in temperature; in this case the SSW events seem not to have affected deeply the investigated region. Generally, the occurrence of mesospheric cooling is associated with almost all SSW events, whether major or minor. In order to isolate the short-term dynamical response of the atmosphere, we subtracted a linear fit from the temperature time series at 10 hPa, and we reported the residual zonal mean temperature time series for each year as a white line in the central panels of Fig. 4. In almost all cases the mesospheric cooling seems to start at about the same time as the stratospheric temperature increases.

Shepherd (2000) pointed out that the winter (summer) westerlies (easterlies) in the middle atmosphere filter out fluxes of gravity waves of the same sign, leading to net westward (eastward) angular momentum at mesopause altitudes. The effect drives the summer-to-winter-pole meridional circulation in the mesosphere that is responsible for reversing the meridional temperature gradient at these altitudes. Liu and Roble (2002) showed that the gravity wave filtering effect should also operate on shorter time scales (i.e., SSWs). During SSW events the stratospheric wind reversal induced by planetary waves also changes the filtering of gravity waves, blocking gravity wave components with westward phase while allowing more eastward gravity waves to enter the MLT, with consequent reversal of the MLT jet. In this way the meridional circulation changes its regime from downward to upward, the thermospheric O_x concentration diminishes and also the temperature starts to decrease (see also Ren et al., 2008).

We observe decreased abundances of the OH layer during or right after mesospheric temperature decreases coupled with SSWs (e.g., January 2006 and 2009, see Fig. 3). The remarkable upward extension of the OH layer and its decreased mixing ratio during the 2009 SSW seem to reflect the upward air circulation (see also the CO contours in Fig. 3). Note that above 0.01 hPa, during the SSW periods, the stronger and longer-lasting temperature decrease of 2009 compared with other events (see Fig. 4) is coupled to a major reduction and a more evident upward extension of the OH layer. Indeed, during SSW events at about 90 km the absolute temperature in 2009 was ∼15 degrees cooler than in 2006. This suggests a stronger upward air circulation because it can be interpreted in terms of adiabatic cooling. All these features seem to be in accordance with the above findings about the variability of the OH emission rate induced by vertical motions. However additional information is needed in order to distinguish between a reduction in the downwelling and an actual upwelling.

In general we can state that both "quiet" years and "disturbed" years have an intrinsic anomaly. The anomaly of "quiet" years is represented by the SSW-influenced days when we see low temperatures and a probable upward vertical motion in the mesosphere. The anomaly of "disturbed" years is determined by the very high temperature and the strong vertical air descent roughly during February 2006 and 2009. The variability is stronger and longer lasting during "disturbed" years. The enhanced correlation values of Table 1, observed during "disturbed" years, could be potentially related to the larger number of anomalous days compared with "quiet" years; nevertheless, it should be noted that other sources of variability (such as noise), could be different in the two datasets. The roughly constant increase of the coefficients in "disturbed" years at all selected pressures (see for example the correlation between OH and O_3) means that the presence of some days of noisy ozone (only at 0.01 hPa) does not noticeably influence our results. Therefore although the correlation coefficients of Table 1 are similar in both "quiet" and "disturbed" years, the cause of such values are very different. For example, at 0.01 hPa we note a positive correlation in both "quiet" and "disturbed" years. As far as "disturbed" years are concerned, both temperature and OH abundance during February are increased compared with those for January. Instead, for "quiet" years, temperature and OH abundance in SSW-influenced days are both decreased compared with those under normal conditions (i.e., absence of SSWs). On the other hand, temperatures and O_3 at the same altitude are also driven by chemistry, due to the short lifetime of O_3, so we have low temperatures and high O_3 during "quiet" years but high temperatures and low O_3 during "disturbed" years. The reversal in sign of the correlations in both analyzed periods at 0.004 hPa, an altitude normally above the OH layer at ground vibrational state and close to the lower limit of the thermospheric ozone maximum, arises for different reasons. During "quiet" years we

have some days characterized by SSW-induced cooling and uplift of the OH layer and therefore we obtain a negative coefficient between temperature and OH abundance; in contrast during "disturbed" years we have many days with the temperature higher than the climatology and the contemporaneous low OH abundance (due to layer descent) but again a negative coefficient. Moreover it is interesting to note the high positive correlation between temperature and ozone at 0.004 hPa. This feature is present only during "disturbed" years and, as shown by Smith et al. (2009), it is mainly due to the thermospheric ozone descent during periods of very high temperature. We will return to this point below. The mesospheric ozone behaviour warrants a parallel discussion for its connection with OH and transport.

Due to photolysis processes, under solar illumination the lifetime of O_3 is very short throughout the entire mesosphere (see, among others, Brasseur and Solomon, 2005). During polar night the absence of sunlight favours a longer chemical lifetime (many weeks) of O_3 molecules, especially in the middle mesosphere (below about 70 km). In nighttime the minimum abundance of ozone is roughly situated at ∼80 km (∼0.01 hPa) because there the lifetime of O_3 is the shortest (Smith et al., 2009). At lower altitudes the most important feature of the O_3 profile is the presence of the TOP. The TOP is due to the fact that solar radiation dissociates less water vapour than molecular oxygen with increasing SZA. Therefore we have ozone production but reduced ozone destruction because of the low concentration of hydroxyl radicals (Sonnemann et al., 2006b). Because of the longer chemical lifetime of ozone in the middle mesosphere, transport processes become dominant over local photochemistry at the altitude of the TOP. The altitude and abundance variability of the TOP induced by downward transport of polar air was recently discussed by Sofieva et al. (2009) and Smith et al. (2009) using data recorded by GOMOS and SABER instruments, respectively. The right panels of Fig. 4 extend the periods examined in the above papers and show that also MLS observes intense variability in the third ozone peak in February 2006 and 2009. In late February 2009 the TOP reaches the highest values of years 2005–2009, in accordance with the long lasting transport phenomena at similar heights highlighted by CO. (See the 5, 10 and 15 ppmv levels of CO mixing ratio reported as white contours on the right panels of Fig. 4.) Therefore, the higher values of the TOP in 2006 and 2009 are probably mainly due to downward transport of ozone because of its longer chemical lifetime under such conditions. Moreover, also the descent of atomic oxygen could play a nonnegligible role through combination with molecular oxygen.

While transport plays an important role at the altitude of the TOP where the nighttime O_3 lifetime is long, chemistry becomes important around 0.01 hPa, where O_3 lifetime is shorter. Ozone increases correspond to the sudden temperature decreases in the MLT during or right after the SSWs. This is evident at ∼0.01 hPa in 2006 and 2009, as a consequence of the increased rate of ozone production due to de-

creased temperature (Sonnemann et al., 2006b). Indeed both ozone production and ozone loss reactions are temperature dependent. In the former the reaction rate increases with decreasing temperature, whereas in the latter it decreases with decreasing temperature. Since during polar night conditions the ozone production is low, the main reason for the expected ozone-temperature anticorrelation is the temperature dependence of the ozone loss reaction. Other events of sudden mesospheric ozone rise associated with temperature decrease are evident also in late February 2005, late January 2008 and February 2008. (Note that only two SSW events, i.e., the minor SSW of early February 2007 and the major SSW of late February 2008, are not associated with increased ozone at ∼0.01 hPa, but in both cases the temperatures were not so low as in other events.) In particular, in February 2008 the high and low abundances of ozone are clearly emerging at the typical altitude of its minimum. These episodes of mesospheric O_3 variability follow periods when MLS recorded at 0.01 hPa the lowest mesospheric temperature of years 2005–2009. Note the further variability of the TOP under SSW conditions, with O_3 depletion occurring during the event and generally before the O_3 increase at 0.01 hPa. Since temperature decreases foster ozone production, events of low abundance of the TOP may be related to dynamics. Air poor in ozone from low latitudes entering the investigated region could explain the observed decreases.

Moreover, in February 2006 and 2009, a noticeable O_3 decrease around 0.01 hPa, starting with the polar vortex recovery, and the almost contemporaneous descent of the OH layer are discernible on the right panels of Fig. 4. Indeed, during "disturbed" years, when the OH layer is at lower altitudes, O_3 is almost completely depleted at similar heights. Even though MLS data do not allow a precise quantitative evaluation of the ozone mixing ratio at this pressure surface, we point out that in this region higher ozone mixing ratios are present in February during "quiet" years. In contrast, during "disturbed" years the ozone abundance is so low that the concentrations are below the noise level of MLS, resulting in a mix of positive and negative values on some days in February. Table 1 shows that during "quiet" years the correlation between OH and O_3 is considerably lower ($r=-0.62\pm0.06$) than during "disturbed" years ($r=-0.80\pm0.06$) at 0.01 hPa. Increased temperatures should enhance the reaction rate of ozone destruction via hydrogen atoms, with consequent OH production. Moreover, we have to take into account also the large downward transport of O_x. On one hand this could lead to an increased ozone production, on the other hand this could contribute to its depletion. In the middle/lower mesosphere the catalytic cycles of O_3 destruction by odd-hydrogen are not very efficient under typical polar night conditions because of the low concentration of atomic oxygen. In contrast, in the upper mesosphere, above about 80 km, atomic oxygen has a long lifetime and high abundance due to downwelling. In February 2006 and February/March 2009 the anomalous increased availability of atomic oxygen could

allow enhanced ozone destruction via the above catalytic cycles. The comparable magnitude of SEP- and meteorology-induced OH enhancement (shown at the same pressure level in Fig. 1), both associated with the same strong ozone depletion (see Fig. 4, right panels; compare, for example, January 2005 and February 2009), further suggests enhanced O_3 depletion by HO_x. Finally, the enhanced vertical transport in February could contribute to shifting the mesospheric ozone minimum towards lower altitudes (Smith et al., 2009) and help explain such features. Specific modelling studies and/or additional satellite data are needed in order to quantitatively assess described features.

5 Conclusions

Time series of MLS OH nighttime zonal means from January to March for the years 2005–2009 have shown that the OH layer inside the polar vortex, situated at a nominal altitude of 82 km, was subject to short- and medium-term variability. The former occurred during SSW events, whereas the latter occurred after SSWs, under conditions of exceptional air descent from the mesosphere to the stratosphere (e.g., in February 2006 and 2009). The changes affected both the altitude and the abundance of the OH layer and were coupled with strong temperature variations.

In February 2006 and February/March 2009 the OH layer underwent medium-term variation. It was displaced from ∼81 km (in January) down to ∼74 km (in February), and its density increased to more than twice January values, lasting more than one month. Such displacement was caused by increased intensity of the meridional circulation indicated by elevated CO abundance and by temperatures higher than climatology in the middle mesosphere with consequent large transport of O_x at similar altitudes.

Previous work has highlighted SEP-induced OH increases seen in nighttime MLS data. Our analysis here has revealed that meteorological factors can also lead to substantial changes to the mesospheric part of the nighttime OH profile and that the OH changes at 0.015 hPa provoked by the January 2005 SEP events are comparable to the OH increase induced by the descent of the OH layer that occurred during the 2006 and 2009 winters.

We observed short-term upward extensions of the OH layer and a decreased abundance at its typical altitude during or just after SSW events, when the mean meridional circulation was ascending and the temperatures were lower than climatology. Changes in OH during the SSW events of January 2006, February 2008 and January 2009 are clearly evident. In particular, the anomalous upward extension of the OH layer around the time of the SSW in January 2009 was associated with the lowest temperature of the years 2005–2009 at ∼90 km. This suggests a strong vertical air transport, which moved air and O_x upward and led to larger (smaller) abundances of the OH layer at higher (typical) altitudes.

In addition we examined qualitatively the connections among OH, O_3 and temperature. The OH layer follows the displacement of thermospheric ozone; moreover, periods of high (low) OH concentration occur during times of high (low) temperature. A further proof of the close relationship among these three elements is provided by the correlation performed for January-February at 0.01 hPa (where the mesospheric ozone minimum is roughly situated) in "disturbed" years (2006+2009, periods characterized by very high altitude of the stratopause) and "quiet" years (2005+2007+2008) separately. A positive correlation between temperature and OH and a negative one between temperature and O_3 are usually present during "quiet" years ($r=0.70\pm0.05$ and $r=-0.74\pm0.05$), but the correlation coefficients are substantially increased during "disturbed" years ($r=0.86\pm0.05$ and $r=-0.83\pm0.06$). The trend reversing at 0.004 hPa suggests the importance of transport processes for explaining these phenomena. The weaker correlation between OH and O_3 during "quiet" years also becomes stronger during "disturbed" years ($r=-0.82\pm0.05$).

This high correlation between OH and O_3 can indicate that catalytic cycles are responsible, at least in part, for the almost complete ozone depletion that occurred around 0.01 hPa only during "disturbed" years, when the OH layer was situated at these heights. The formation of OH at ozone's expense is favoured by the elevated mesospheric temperatures that followed the SSW events. Moreover, the increased availability of atomic oxygen, induced by the intense transport from the MLT region, could lead to ozone destruction greater than average. This is because the HO_x catalytic cycles of O_3 depletion via OH production could be enhanced by the larger availability of atomic oxygen in February 2006 and 2009. The comparable magnitude of SEP- and meteorology-induced OH enhancement, both associated with the same strong O_3 depletion, further may be indicative of the enhanced O_3 depletion by HO_x. Finally, the enhanced vertical transport in February also could have contributed to changing the mesospheric ozone minimum mixing ratio.

The intense period of diabatic descent that occurred in February after recovery from the SSWs led to a more rapid displacement of the OH layer in 2006 than 2009. Further, the TOP has also experienced similar behaviour, with a descent of more than 5 km in both 2006 and 2009. MLS O_3 data showed that in February 2009 the TOP reaches the highest abundance of the period 2005–2009. That is a direct consequence of the stronger vertical transport of ozone and atomic oxygen at such altitudes and time.

Variations of ozone abundance during SSW events are evident both at its minimum ($\sim$80 km) and at the TOP ($\sim$72 km). Very low temperatures and the transport of ozone-poor air from low latitudes could be responsible for this O_3 variation at the minimum and TOP altitudes, respectively.

To our knowledge, these features are among the first experimental confirmations of the influence of meteorology on the OH layer in Polar Regions. Therefore, they are an addi-

tional tool that can be used to investigate mesospheric vortex dynamics.

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