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Signature of the 27-day solar rotation cycle in mesospheric OH and H$_2$O observed by the Aura Microwave Limb Sounder

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Abstract. The mesospheric hydroxyl radical (OH) is mainly produced by the water vapor (H$_2$O) photolysis and could be considered as a proxy for the influence of the solar irradiance variability on the mesosphere. We analyze the tropical mean response of the mesospheric OH and H$_2$O data as observed by the Aura Microwave Limb Sounder (MLS) to 27-day solar variability. The analysis is performed for two time periods corresponding to the different phases of the 11-yr cycle: from December 2004 to December 2005 (the period of "high activity" with a pronounced 27-day solar cycle) and from August 2008 to August 2009 ("solar minimum" period with a vague 27-day solar cycle). We demonstrate, for the first time, that in the mesosphere the daily time series of OH concentrations correlate well with the solar irradiance (correlation coefficients up to 0.79) at zero time-lag. At the same time H$_2$O anticorrelates (correlation coefficients up to -0.74) with the solar irradiance at non-zero time-lag. We found that the response of OH and H$_2$O to the 27-day variability of the solar irradiance is strong for the period of the high solar activity and negligible for the solar minimum conditions. It allows us to suggest that the 27-day cycle in the solar irradiance and in OH and H$_2$O are physically connected.

1 Introduction

It is well known that the solar radiation, which is the main energy source in the terrestrial atmosphere, is variable on different time scales (see e.g. Lean et al., 2005; Krivova and Solanki, 2008; Krivova et al., 2011; Shapiro et al., 2010, 2011b; and references therein). The most important cycles in the solar UV irradiance are the 11-yr solar activity cycle, seasonal and rotational cycles. Krivova et al. (2006) showed that the variations of the Spectral Solar Irradiance (SSI) can reach up to 80 % at the Lyman-α line (121.6 nm).

These variations of the SSI may have substantial impact on chemical and physical processes in the atmosphere. During the last decade the atmospheric response to the decadal solar variability has been studied based on observations (e.g. Soukharev and Hood, 2006; Fioletov, 2009; Randel et al., 2009) and the state-of-the-art transient chemistry-climate models (e.g. Egorova et al., 2004; Rozanov et al., 2004, 2008; Schmidt et al., 2006; Marsh et al., 2007; Austin et al., 2008). The results of these efforts revealed a noticeable disagreement among model results and high uncertainty of the observed solar signal in ozone and temperature obtained from the different satellite data.

Possible reasons for this high uncertainty could be traced to the relatively short ($\sim$30 yr) and inhomogeneous observational time series, non-linearity of the atmospheric processes, contamination of the time series by volcanic eruptions, sea surface temperature anomalies and some other factors. These uncertainties can be reduced by the examination of the atmospheric response to the short-term (days-to-month) variability of the solar irradiance. The recent studies of the solar rotation cycle effects with chemistry-climate models (Rozanov et al., 2006; Austin et al., 2007; Gruzdev et al., 2009; Chen et al., 1997; Kubin et al., 2011) showed that the ozone response to the short-term solar variability is more robust and is in a better agreement with available satellite data in the middle stratosphere in comparison with the decadal scale signal. As the transport time scales are more than one day (Brasseur

and Solomon, 2005), one can expect that the uncertainries are minimal for the short-lived species and the response to the solar variability for them should be more robust.

The OH lifetime decreases with altitides reaching the value less than few seconds in the mesosphere. At these heights it is produced by the photolysis of water vapor (H_2O + $h\nu \rightarrow$ H + OH for $\lambda < 200$ nm) and $H_2O + O(^1D) \rightarrow 2OH$ (Brasseur and Solomon, 2005). Therefore OH is an ideal object for the atmospheric solar signature study in the mesosphere.

Chemistry-climate models suggest strong responses in stratospheric and mesospheric OH and H_2O mixing ratios caused by solar irradiance variability (Fleming et al., 1995; Egorova et al., 2005; Rozanov et al., 2006; Gruzdev et al., 2009). The response was also found in the observed data. The diurnal cycle of OH concentration which reflects a solar zenith angle changes was analyzed by Minschwaner et al. (2011). The response of OH from Fritz Peak Observatory (Colorado) to 11-yr solar cycle was reported by Canty and Minschwaner (2002). The H_2O response obtained from HALOE (HALogen Occultation Experiment) between 1991 and 2005 to the 11-yr solar cycle was found to be strong ("max minus min" H_2O response is about 23 % at 0.01 hPa) and negative (Remsberg, 2010). However, the responses to the 27-day solar rrotational cycle were not yet found.

The measurements of the odd hydrogen (fast-reacting radicals such as H, OH and HO_2) are very difficult due to its high reactivity in the mesosphere. Therefore the regular satellite measurements of OH at these heights started only a few years ago (e.g. Pickett et al., 2008). The nighttime OH data are available for longer period from lidar observations (Brinksma et al., 1998). However as OH lifetime in the mesosphere is a few seconds and we search for the hydroxyl response to the SSI variability we cannot use nighttime data for our analysis. H_2O concentration was measured by different instruments (e.g. Russell et al., 1993; Fischer et al., 2008) and available now for more than 20 yr. However the most of the observed data contain many gaps which could substantially spoil our analysis as we consider the response of the daily time series to the 27-day solar cycle. The AURA MLS instrument gives the best H_2O temporal caverage for the period of our interest.

In this paper we analyze the AURA MLS OH and H_2O measurements, which are available from 2004. Presently the coverage of the data is less than one 11-yr solar cycle, i.e. still insufficient for a statistical analysis of the response to the 11-yr cycle. The 27-day and 11-yr cycles have the same profile of the SSI variability as both of them originate from the evolving inhomogeneous brightness structure of the solar disc. Therefore, one can expect similarities in the responses of the atmospheric species to both these cycles in the solar irradiance. Thus, we aim our analysis on the rotational 27-day solar cycle.

In Sect. 2 we describe the data used for the analysis. Section 3 shows the correlations between the solar irradiance and the considered species. The comparison of the OH and H_2O responses to the 27-day solar cycle for the different solar activity periods is given in Sect. 4. The analysis of the obtained responses is presented in Sect. 5. Our conclusions are summarized in Sect. 6.

2   Data description

The MLS is one of the four instruments onboard Aura, which was launched on 15 July 2004 into a sun-synchronous near-polar orbit for the purpose of studying atmospheric chemistry and dynamics. The MLS instrument was designed to observe the thermal emission from the atmospheric limb in broad spectral regions centered near 118, 190, 240, and 640 GHz, and 2.5 THz (Waters et al., 2006). Stratospheric and mesospheric OH can be detected via the emission at 2.5 THz in the pressure range 32–0.0032 hPa (about 24–89 km), and H_2O via the emission at 190 GHz in the ranges 83–0.002 and 316–100 hPa (about 18–92 and 8–16 km). We used the data (version 3.3, Livesey et al., 2011) for OH (Pickett at al., 2008) and for H_2O (Read et al., 2007; Lambert et al., 2007) at 0.046–0.0022 hPa (about 70–91 km). All data used in this study were screened following the recommendations from the MLS data quality documents (e.g. Livesey et al., 2011).

The tropical mean (27° S–27° N) daily averaged OH mixing ratios from August 2004 to December 2006 at 78 km altitude are presented in Fig. 1 for both daytime-only (obtained from sunrise to sunset) and nighttime data. The mean concentration obtained with nighttime data is about six times smaller than the mean concentration calculated with daytime-only data. This is well expected as mesospheric OH is mainly produced by the water vapor photolysis and its lifetime for the layers below 80 km is only a few seconds. Thus it is mostly destructed immediately after the sunset. The nighttime profiles of OH contain a prominent peak around 82 km altitude, whose origin is different from the origin of the daytime OH (Brinksma et al., 1998; Pickett et al., 2006). As the nonzero night time OH can affect our analysis and our main goal is the analysis of the hydroxyl and water vapor responses to the SSI variability, we consider the daytime-only and nighttime data separately.

The SSI data used for this study were obtained by the SOLar STellar Irradiance Comparison Experiment (SOLSTICE) instrument onboard the Solar Radiation and Climate Experiment (SORCE) satellite launched on 25 January 2003 (McClintock, 2005). The SORCE SOLSTICE measurements cover the spectral range from 115 to 320 nm and the data are available as a daily average with 1-nm spectral resolution. Shapiro et al. (2011a) showed that in the mesosphere the sensitivities of the OH and O_3 to changes in irradiance do not depend on the choice of the SSI data set if the analysis is based on the variability at the Ly-α line. Thus, we derive the solar irradiance at the Ly-α line from SOLSTICE SORCE data.
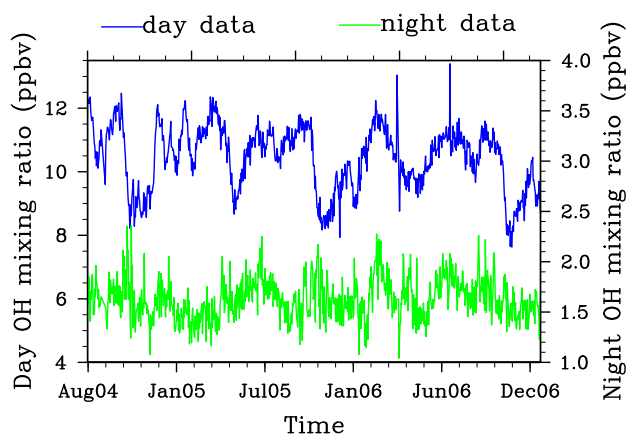
Fig. 1. Tropical mean OH mixing ratios (27° S–27° N) at ∼78 km altitude for the period from August 2004 to December 2006 obtained from AURA MLS. Green curve: nighttime averages. Blue curve: day-time only.

The tropical latitudes are the most affected by the solar radiation and using them we also avoid effects of the energetic particle precipitation. So for our analysis we used the tropical mean (27° S–27° N) OH and H_2O mixing ratios. As our analysis is aimed on the 27-day solar cycle we applied 20–35 day pass filter on the daily averaged SSI, OH and H_2O datasets to exclude the influence of other mesospheric cycles. The points outside of the 3σ interval were removed.

3   Data correlation

The solar energy emitted by the Sun penetrates the Earth atmosphere and triggers many atmospheric processes for example the production of hydroxyl via the water vapor photolysis ($H_2O + h\nu \rightarrow H + OH$ for $\lambda < 200$ nm). The irradiance at wavelengths below 200 nm is mostly absorbed in the upper atmosphere and does not reach the mesosphere. However the strong Ly-α line irradiance is able to penetrate down to the mesosphere and activate there the water vapor photolysis.

Figure 2 presents a comparison of the Ly-α line irradiance with the daytime OH data (top panel) at 78 km and daytime H_2O (center panel) at 80 km altitude. SSI and both species show a pronounced 27–28 days periodicity, which resembles the solar rotational cycle.

The Ly-α radiation drives the destruction of H_2O, whose mesospheric lifetime is of order of one week (Brasseur and Solomon, 2005), so that H_2O is negatively correlated with SSI and phase-lagged (Fig. 2, central panel). The Ly-α radiation drives the production of OH which mesospheric lifetime is less than one minute. Thus in contrast with H_2O its concentration mainly varies in phase with the solar cycle (Fig. 2, top panel).

The OH data for 2004 and 2006 are poorly correlated with the solar irradiance. It is clearly seen from Fig. 2 that the
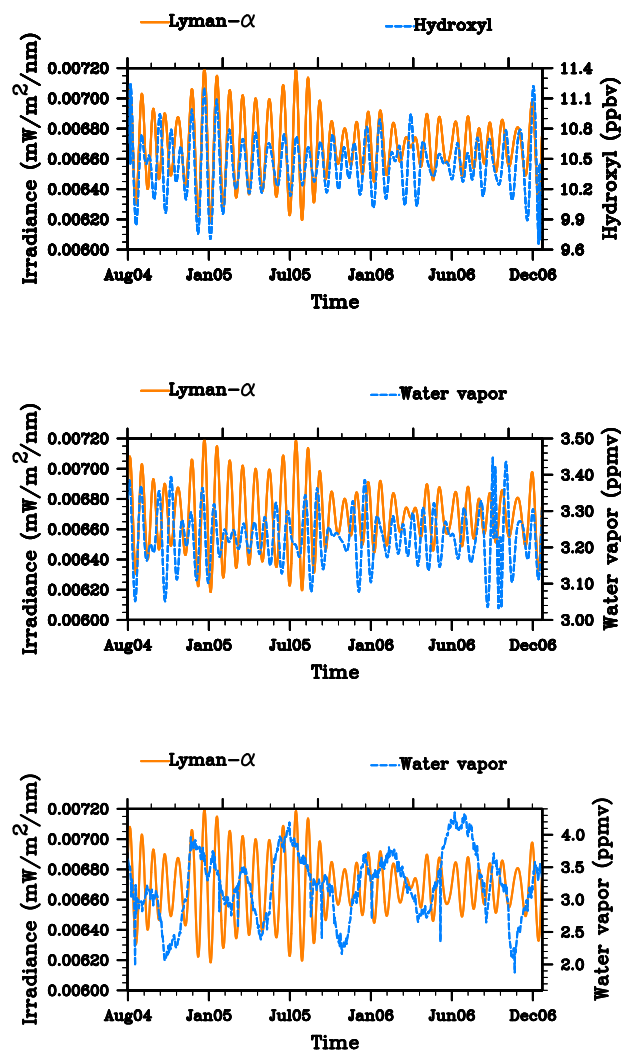
Fig. 2. Comparison of the tropical mean daytime averaged and 20–35 day filtered MLS OH at ∼78 km altitude (upper panel) and filtered (central panel) and unfiltered (lower panel) H_2O at ∼80 km altitude with SOLSTICE Ly-α line irradiance. The comparison is performed for the period from August 2004 to December 2006.

solar rotational cycle in the end of 2004 and in 2006 is not as strong as in 2005. That can lead to weakening the considered correlation and strengthening the role of the OH production by non-solar mechanisms. One of such mechanisms can be downward O_3 propagation due to the SAO (Semiannual Oscillation). The SAO, which was found in H_2O in the mesosphere by Jackson et al. (1999), is clearly seen in the unfiltered H_2O data at 80 km (Fig. 2, bottom panel). The downward transport of O_3 by SAO leads to the increase of O_3 concentration at 77–80 km altitude and OH production by $O_3 + H \rightarrow OH + O_2$ reaction during the easterly SAO phase (such as September–December 2004). OH produced by the latter reaction does not correlate with the solar irradiance. Thus the mixing of this OH with one produced by the H_2O
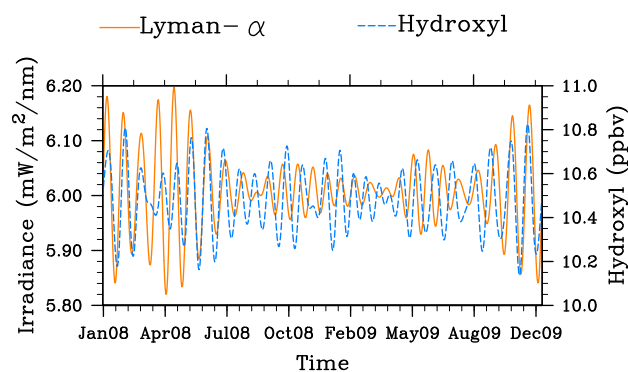
Fig. 3. Comparison of the tropical mean daytime averaged and 20–35 day filtered MLS OH at ∼78 km altitude with SOLSTICE Ly-α line irradiance for 2008–2009.

Fig. 4. The wavelet analysis (top panel) and the normalized power spectra (bottom panel) of the unfiltered Ly-α irradiance as measured by SOLSTICE/SORCE.

photolysis leads to the weakening of the correlation between OH and the solar irradiance. Worsening of the correlation for 2006 is due to the strong decrease of the solar activity. Taking both these factors into account we used only the data from December 2004 to December 2005 for our analysis.

All data were produced with the 20–35 day band pass filter. The analysis covers 14 rotational cycles (13 months) and therefore is sufficient for statistical analysis. Both periods (the solar "high activity" period and "solar minimum") correspond to the same QBO (quasi-biennial oscillation) phase so the atmosphere is in similar dynamical conditions (Baldwin et al., 2001).

## 4 The OH and H$_2$O responses during the periods of the high and low solar activity

Solar cycle 23 extends from 1996 solar minimum through the maximum at 2000–2002 to the solar minimum 2008–2009. The goal of this study is the analysis of the OH and H$_2$O responses to the SSI 27-day solar variability. The strongest response to the solar variability could be expected during the period of the high solar activity. However if we considered only the period of the high solar activity the obtained response could be contaminated by the internal variability of the atmosphere, if it has periods close to 27 days. Then the correlation between hydroxyl and water concentrations and the solar irradiance would be artificially high even in absence of any physical connection. This means that the good correlation of the OH and H$_2$O with the solar irradiance presented in Fig. 2 could not be considered as an unambiguous evidence of the connection between the solar irradiance and considered species. One way to prove the connection is to analyze OH and H$_2$O variabilities for the different phases of the 11-yr solar activity cycle. If the 27-day cycle in OH and H$_2$O data is caused by the solar irradiance one can expect that it will be significantly weaker for periods of lower solar activity. The comparison of the Ly-α line irradiance with
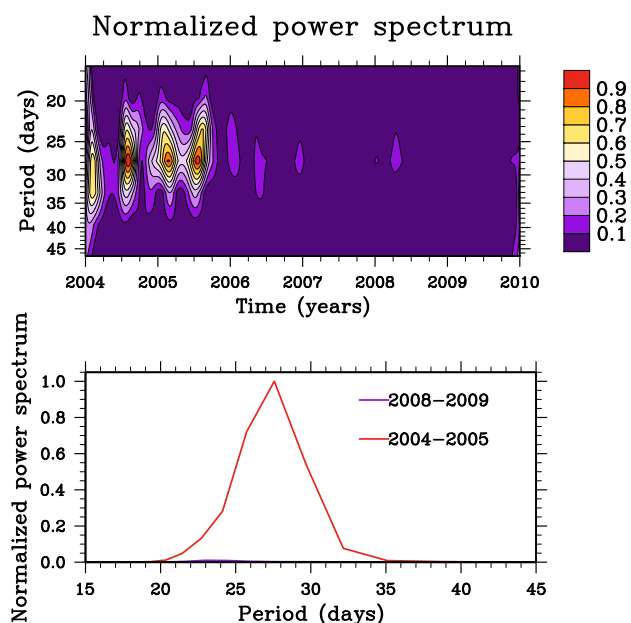
the daytime OH data at 78 km for the solar minimum period (2008–2009) is presented in Fig. 3. It is seen that the correlation in the first half of 2008 and in the end of 2009 is noticeable as some solar activity can be observed in this period. While for the period from June 2008 to October 2009 the solar rotational variability is negligible. The OH response in this period does not show any correlation with the solar irradiance and can be rather qualified as a filtered noise.
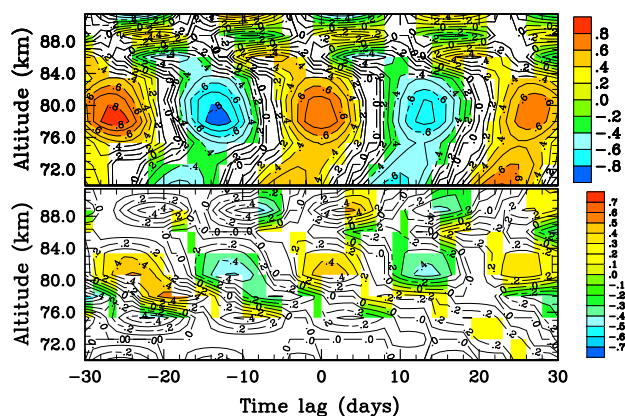
The MLS data are available only from August 2004, but as it was described in Sect. 3 the data for 2004 are strongly affected by the SAO activity. So we used the data from December 2004 to December 2005 to estimate the atmospheric response in the period of high solar activity (sunspot number is about 50) and the data from August 2008 to August 2009 for the solar minimum. The wavelet power spectrum of the Ly-α irradiance for the period from 2004 to 2010 is shown in Fig. 4 (top panel). The analysis was made using the Morlet wavelet with a wavenumber equals to 6, the smallest resolvable scale equals to 1 day. The larger scales were chosen as power-of-two multiples of the smallest scale (Torrence and Compo, 1998). The spectrum reveals a well pronounced 27-day solar rotational cycle until 2006 and strong weakening of the cycle from 2006 to 2010. To directly compare the strength of the 27-day cycle during the periods of low and high solar activity we present two power spectra (lower panel of Fig. 4): one calculated using the unfiltered irradiance from December 2004 to December 2005 ("high activity" period) and another using the unfiltered irradiance from August 2008 to August 2009 ("min" period). The spectra
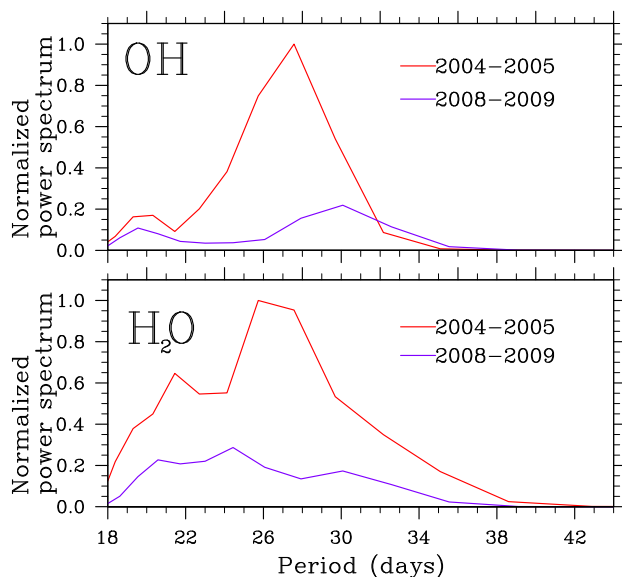
Fig. 5. The normalized power spectra of the tropical mean unfiltered daytime OH (top panel) and H_2O (bottom panel).

Fig. 6. Cross-correlation functions between tropical (27° S–27° N) mesospheric OH and SOLSTICE/SORCE Ly-α irradiance as function of altitude and response time-lag. Daytime OH for the solar "max" (top panel) and "min" (bottom panel)". Colored areas: significance ≥ 0.99.

were normalized to the maximum of the strongest spectrum for the periods from 20 to 35 days. One can see that the cycle is significantly stronger when the solar activity is high. So the 27-day harmonic for 2008–2009 period is barely visible in comparison with the harmonic for 2004–2005 period.

To analyze the OH and H_2O variability during the periods of high and low solar activity we considered the daytime tropical means of OH at 78 km and H_2O at 86 km for the two aforementioned periods. Figure 5 presents the power spectra for OH (top panel) and H_2O (bottom panel) during the "high activity" and "min" periods. To make the comparison of the spectra more robust we produced them with the unfiltered data. The spectra were normalized as it was made for the spectra of the solar irradiance. The OH spectrum reveals a clear 27-day cycle for the "high activity" while in the OH data obtained during the "min" this cycle is almost disappeared. The 27-day solar rotational cycle in H_2O is less pronounced for the period of the high solar activity than that one for OH and almost disappears during the low activity. Besides there are some periods (e.g. 22 days) in H_2O which most probably cannot be attributed to the solar variability. It is clearly seen that the 27-day solar rotational cycle is more pronounced for the solar "high activity" than for the solar "min" in both data sets. Thus the complementary analysis of the OH and H_2O responses during the periods of low and high solar activity allows us to conclude that they are physically connected with the solar irradiance variability.

5 Analysis

The sensitivity analysis of the mesospheric OH concentrations to the short-term solar variability is based on cross-correlation functions, which we calculate according to Chatfield (1982), and on the linear regression technique proposed by Hood (1986).

The cross-correlation functions for the daytime OH data obtained for the solar "high activity" period versus the solar irradiance at the Ly-α line are shown in Fig. 6 (top panel). As the OH lifetime at 75–85 km is very small in comparison to the 27-day rotational cycle, the response reaches its maximum at about zero time-lag. The response is positive and the level of statistical significance for the colored areas is 0.99 (the statistical significance is calculated using the two-sided statistical test $r * \text{sqrt}((N-2)/(1-r^2))$, where r is Pearson's correlation coefficient and N is the number of pairs that were used for the r computation). The positive correlation (more than 0.7 at 76–82 km) can be explained by the production of the OH radical due to photolysis of the water vapor ($H_2O + h\nu \rightarrow H + OH$ for $\lambda < 200$ nm) at these altitudes. The correlation decreases at lower altitudes, as the Ly-α line irradiance does not penetrate there. The bottom panel of Fig. 6 shows the cross-correlation functions for the daytime OH obtained for the solar "min" period versus the solar irradiance at the Ly-α line. One can see that the correlations are substantially weaker for the solar "min" than for the solar "high activity" period.

The cross-correlation functions for the H_2O data obtained for the solar "high activity" period versus the solar irradiance at the Ly-α line are presented in the top panel of Fig. 7. They reveal a strong negative response of H_2O (up to -0.74 at 90 km) to the solar irradiance at levels 78–90 km, caused by the H_2O photolysis. The non-zero time-lag can be attributed
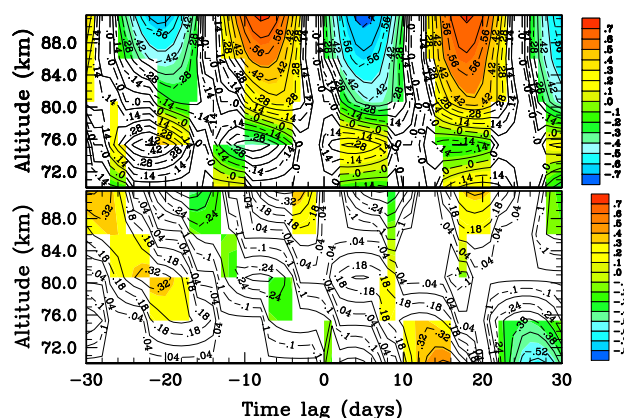
Fig. 7. The same as Fig. 5, but for H_2O.

Fig. 8. OH (upper panel) and H_2O (lower panel) sensitivities (in %) to 1 % change of the SOLSTICE /SORCE Ly-α irradiance.

to the lifetime of H_2O at these heights. The bottom panel of the Fig. 7 shows the cross-correlation functions for H_2O data observed during the solar "min" period versus the solar irradiance at the Ly-α line. As mentioned before, the 27-day period is less pronounced in H_2O data than in OH. Moreover other cycles with periods between 20 and 35 days can affect our analysis especially for the solar "min". All these effects can make the correlations less pronounced.

A sensitivity analysis was made for the "high activity" period both for the OH radical and for the H_2O responses. The sensitivities were calculated at time-lags that correspond to the maximum correlation between the species and Ly-α irradiance. The sensitivity of OH concentrations to irradiance changes is presented in Fig. 8 (top panel). The maximum of the daytime OH response is 0.93 % per 1 % change in Lyman-α irradiance and is reached at $\sim$80 km. The sensitivity of the H_2O to irradiance change (Fig. 8, bottom panel) is negative and reaches -0.95 % at about 90 km.

6 Conclusions

We analyzed the mesospheric response of the OH and H_2O mixing ratios derived from AURA/MLS data to the 27-day solar rotational cycle as measured by SOLSTICE/SORCE. The analysis was performed for the different phases of the solar activity. We showed that

– both OH and H_2O respond to the solar irradiance variability (correlation coefficients up to 0.79 for OH and up to -0.74 for H_2O);

– OH correlates positively and in phase with the 27-day irradiance changes;

– H_2O (above 78 km) and 27-day irradiance changes correlate negatively with a phase lag of about 6–7 days;

– the OH and H_2O responses during period of high solar activity are substantially higher than during "solar min-
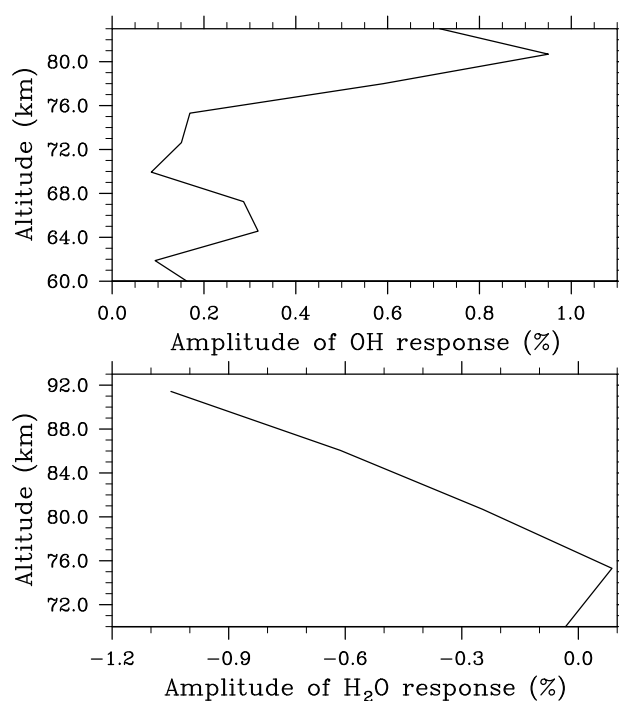
imum" which allows us to suggest that OH, H_2O and SSI variabilities are physically connected.

The obtained responses can be compared with CCM model results calculated in the same atmospheric conditions, i.e. used for the model validations. Further observations of the mesospheric OH and H_2O are needed for a better understanding of the solar-terrestrial connection.

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