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Signature of the 27-day solar rotation cycle in mesospheric OH and H₂O observed by the Aura Microwave Limb Sounder

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The mesospheric hydroxyl radical (OH) is mainly produced by the water vapor (H₂O) 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 H₂O 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 (“solar maximum” period with a pronounced 27-day solar cycle) and from November 2008 to November 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 H₂O anticorrelates (correlation coefficients up to -0.74) with the solar irradiance at non-zero time-lag. We found that the response of OH and H₂O to the 27-day variability of the solar irradiance is strong for the solar maximum 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 H₂O 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). Two most important cycles in the solar UV irradiance are the 27-day rotational cycle and the 11-yr solar activity cycle. Krivova et al. (2006) showed that the variations of the Spectral Solar Irradiance (SSI) can reach up to 80 % at the Ly- 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

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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. So we still cannot positively answer the question whether the response of the Earth's middle atmosphere to the solar variability is completely understood.

Possible reasons for this high uncertainty could be traced to the relatively short (~ 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), the most evident response to the solar variability may be expected in the short-lived species, such as OH. The diurnal cycle of OH 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). However, the OH response to the 27-day solar rotational cycle was not yet found.

In the mesosphere OH is a main catalyst for destruction of odd oxygen (ozone and atomic oxygen). It is produced by the photolysis of water vapor ($\text{H}_2\text{O} + h\nu \rightarrow \text{H} + \text{OH}$ for $\lambda < 200$ nm) (Brasseur and Solomon, 2005). Chemistry-climate models suggest strong responses in stratospheric and mesospheric OH and H_2O mixing ratios caused by solar changes (Fleming et al., 1995; Egorova et al., 2005; Rozanov et al., 2006; Gruzdev et al., 2009). The response of H_2O obtained from HALOE (HALogen

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Occultation Experiment) between 1991 and 2005 to the 11-yr solar cycle was found to be strong (“max minus min” H₂O response is about 23% at 0.01 hPa) and negative (Remsberg, 2010).

The measurements of the odd hydrogen (fast-reacting radicals such as H, OH and HO₂) 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). Longer time series of H₂O observations are available (e.g. Russell et al., 1993).

In this paper we analyze the AURA MLS OH and H₂O 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 Spectral Solar Irradiance (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. The comparison of the OH and H₂O responses to the 27-day solar cycle for the different solar activity periods is given in Sect. 3. The sensitivity analysis is presented in Sect. 4. Our conclusions are summarized in Sect. 5.

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

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0.0032–32 hPa (about 24–89 km), and H₂O via the emission at 190 GHz in the ranges 0.002–83 and 100–316 hPa (about 18–92 and 8–16 km). We used the data (version 3.3, Livesey et al., 2011) for OH (Pickett et al., 2008) and for H₂O (Read et al., 2007; Lambert et al., 2007) at 0.0022–0.046 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 O₃ 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.

The tropical latitudes are the most affected by the solar radiation so for our analysis we used the tropical mean (27° S–27° N) OH and H₂O mixing ratios. As our analysis is

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aimed on the 27-day solar cycle we applied 20–35 day pass filter on the daily averaged SSI, OH and H₂O datasets to exclude the influence of other mesospheric cycles. The points outside of the 3 σ interval were removed.

Figure 2 presents a comparison of the Ly- α line irradiance (which dominates the UV irradiance shortward of 200 nm) with the daytime OH data (top panel) and daytime H₂O (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 H₂O, whose mesospheric lifetime is of order of one week (Brasseur and Solomon, 2005), so that H₂O is negatively correlated with SSI and phase-lagged.

The Ly- α radiation drives the production of OH which mesospheric lifetime is less than one minute. Thus in contrast with H₂O its concentration mainly varies in phase with the solar cycle. The data for 2004 and 2006 are poorly correlated with the solar irradiance. The bottom panel of Fig. 2 shows the unfiltered H₂O data at 80 km. The SAO (Semiannual Oscillation), which was found in H₂O in the mesosphere by Jackson et al. (1999), is clearly seen in the data. The downward transport of O₃ by SAO leads to the increase of O₃ concentration at 77–80 km altitude and OH production by O₃ + H \rightarrow OH + O₂ 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 H₂O 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.

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3 The OH and H₂O 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 2008–2009 minimum. The goal of this study is the analysis of the OH and H₂O responses to the SSI 27-day solar variability. This could be complicated by the possible internal variability of the atmosphere, which can have 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 H₂O 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 H₂O variabilities for the different phases of the 11-yr solar activity cycle. If 27-day cycle in OH and H₂O data is caused by the solar irradiance one can expect that it will be significantly weaker for the periods of the lower solar activity.

The MLS data are available only from August 2004, but as it was described in Sect. 2 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 November 2008 to November 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. 3 (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. 3): one calculated using the irradiance from December 2004 to December 2005 (“max” period) and another using the irradiance from November 2008 to November 2009 (“min”

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period). 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 H₂O variability during the periods of high and low solar activity we considered the daytime tropical means of OH at 78 km and H₂O at 86 km for the two aforementioned periods. 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 (solar “max” and “min”) correspond to the same QBO (quasi-biennial oscillation) phase so the atmosphere is in similar dynamical conditions (Baldwin et al., 2001).

Figure 4 presents the power spectra for OH (top panel) and H₂O (bottom panel) during the “max” and “min” periods. The OH spectrum reveals clear 27-day cycle for the “max” while in the OH data obtained during the “min” this cycle is almost disappeared. The 27–28-day solar rotational cycle in H₂O 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 and 33 days) in H₂O 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 “max” than for the solar “min” in both data sets. Thus the complementary analysis of the OH and H₂O responses during the periods of low and high solar activity allows us to conclude that they are physically connected with the solar irradiance variability.

4 Sensitivity 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 “max” period versus the solar irradiance at the Ly- α line are shown in Fig. 5 (top panel). As

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the OH lifetime at 60–80 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). 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 ($\text{H}_2\text{O} + h\nu \rightarrow \text{H} + \text{OH}$ 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. 5 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 “max” period.

The cross-correlation functions for the H₂O data obtained for the solar “max” period versus the solar irradiance at the Ly- α line are presented in the top panel of Fig. 6. They reveal a strong negative response of H₂O (up to –0.74 at 85–90 km) to the solar irradiance at levels 78–90 km, caused by the H₂O photolysis. The non-zero time-lag can be attributed to the lifetime of H₂O at these heights. The bottom panel of the Fig. 6 shows the cross-correlation functions for H₂O 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 H₂O 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 decrease the correlations and it makes the obtained correlations insignificant.

A sensitivity analysis was made both for the OH radical and for the H₂O 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. 7 (top panel). The maximum of the daytime OH response is 0.93 at ~80 km. The sensitivity of the H₂O to irradiance change (Fig. 7, bottom panel) is negative and reaches –1.2 at about 90 km. The full-day and day-time H₂O sensitivities are almost identical at levels higher than 75 km due to its long lifetime.

5 Conclusions

We analyzed the mesospheric response of the OH and H₂O 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 H₂O respond strongly (correlation coefficients up to 0.79 for OH and up to -0.74 for H₂O) to the solar irradiance variability;
- OH correlates positively and in phase with the 27-day irradiance changes;
- H₂O (above 78 km) and 27-day irradiance changes correlate negatively with phase lag of about 6–7 days;
- the OH and H₂O responses during “solar maximum” period are substantially higher than during “solar minimum” which allows us to suggest that OH, H₂O and SSI variabilities are physically connected.

The obtained results can be used for the CCM model validations. Further observations of the mesospheric OH and H₂O are needed for the better understanding of the solar-terrestrial connection.

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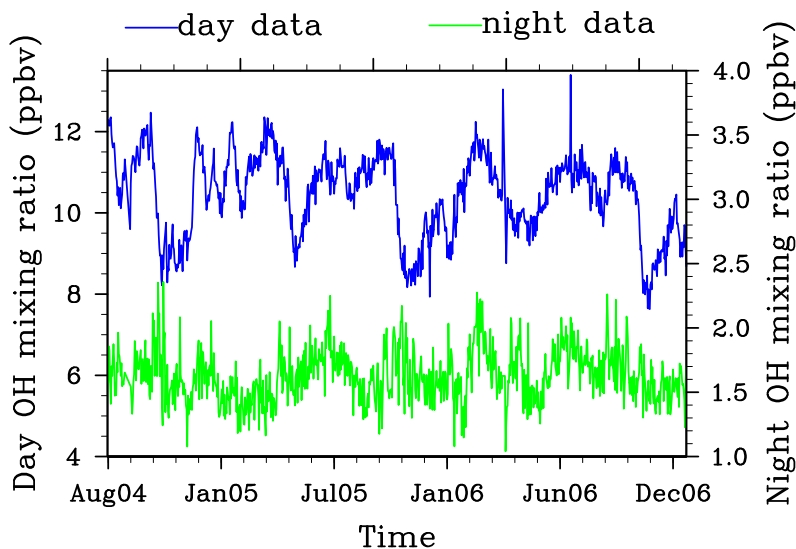


Fig. 1. Tropical mean OH mixing ratios (27° S– 27° N) at ~ 78 km altitude for the period from August 2004 to December 2006 obtained from AURA MLS. Green curve: nighttime averages. Blue curve: day-time only.

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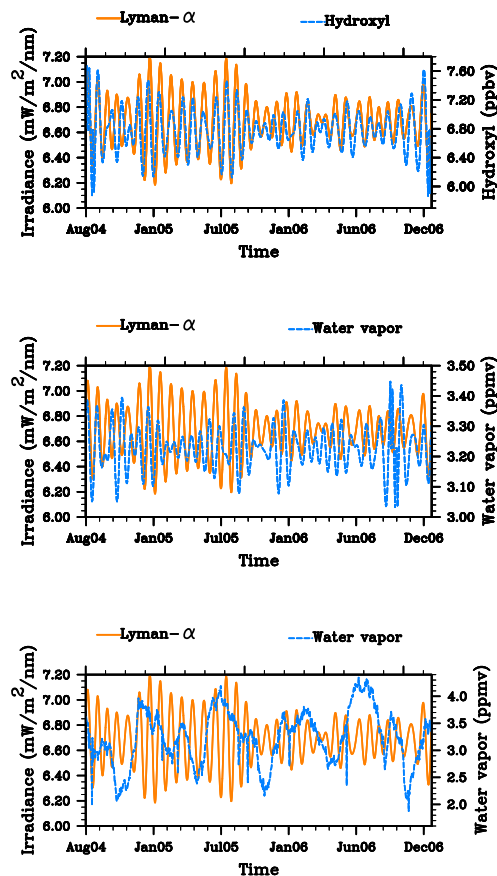


Fig. 2. Comparison of the tropical mean daytime averaged and 20–35 day filtered MLS OH (upper panel) and H₂O (centered panel) and unfiltered H₂O (lower panel) with SOLSTICE Ly- α line irradiance. The comparison is performed at ~ 80 km altitude for the period from August 2004 to December 2006.

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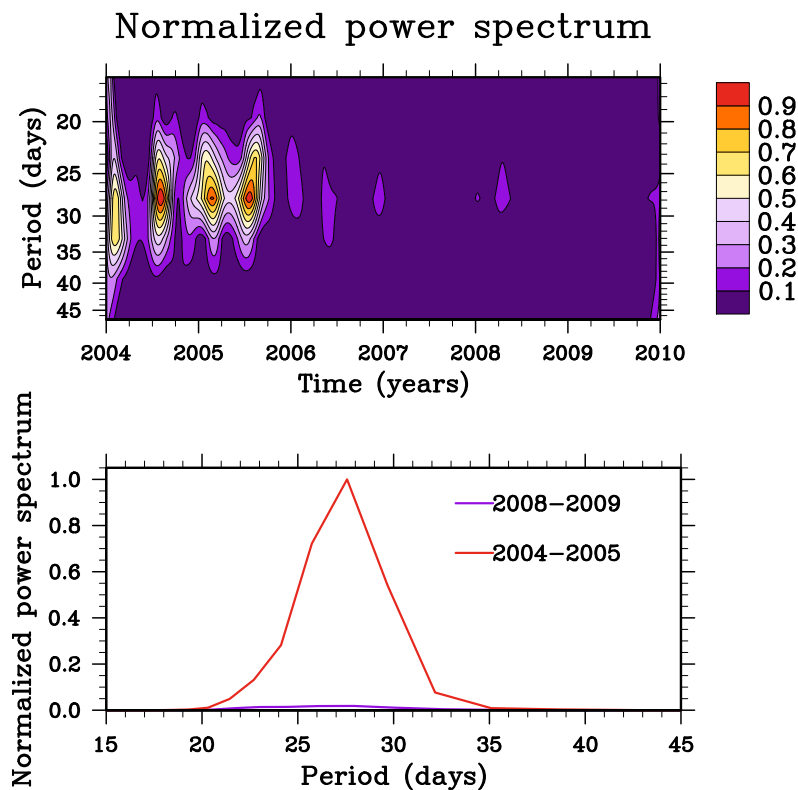


Fig. 3. The wavelet analysis (top panel) and the normalized power spectra (bottom panel) of the Ly- α irradiance as measured by SOLSTICE/SORCE (top panel).

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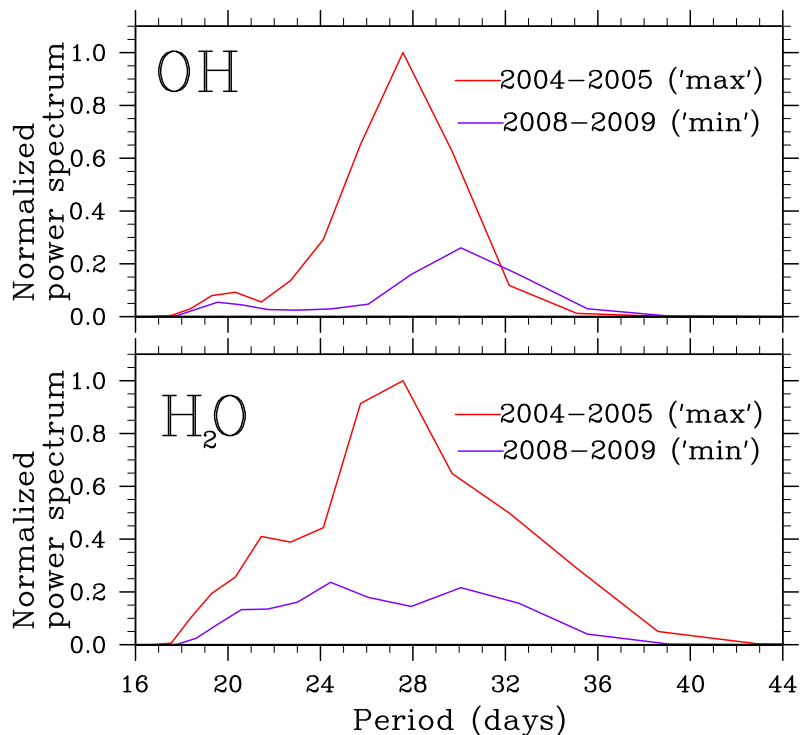


Fig. 4. The normalized power spectra of the tropical mean daytime OH (top panel) and H₂O (bottom panel).

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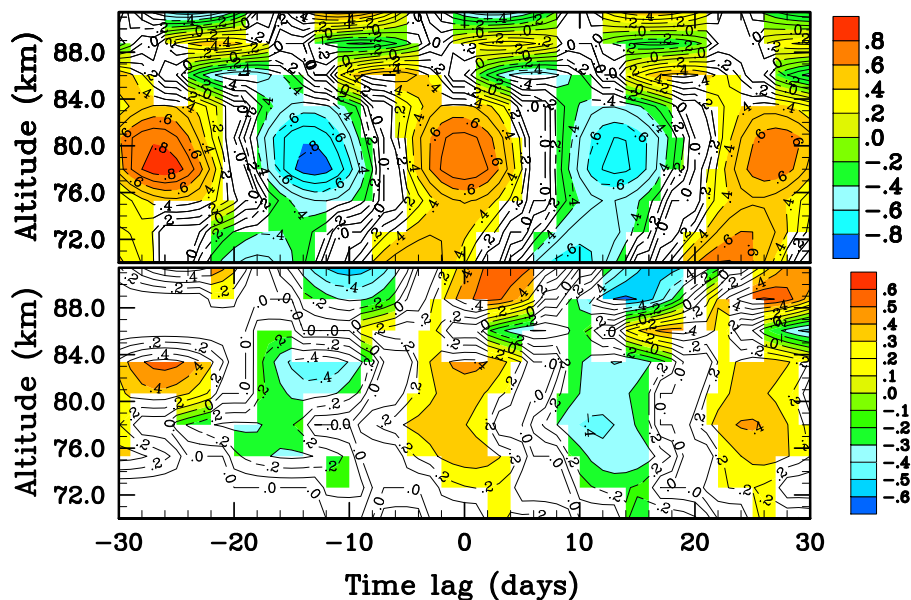


Fig. 5. Cross-correlation functions between tropical (27° S–27° N) mesospheric OH and SOLSTICE/SORCE Ly- α irradiance as function of altitude and response time-lag. Daytime OH for the solar “max” (top panel) and “min” (bottom panel)”. Colored areas: significance ≥ 0.99 .

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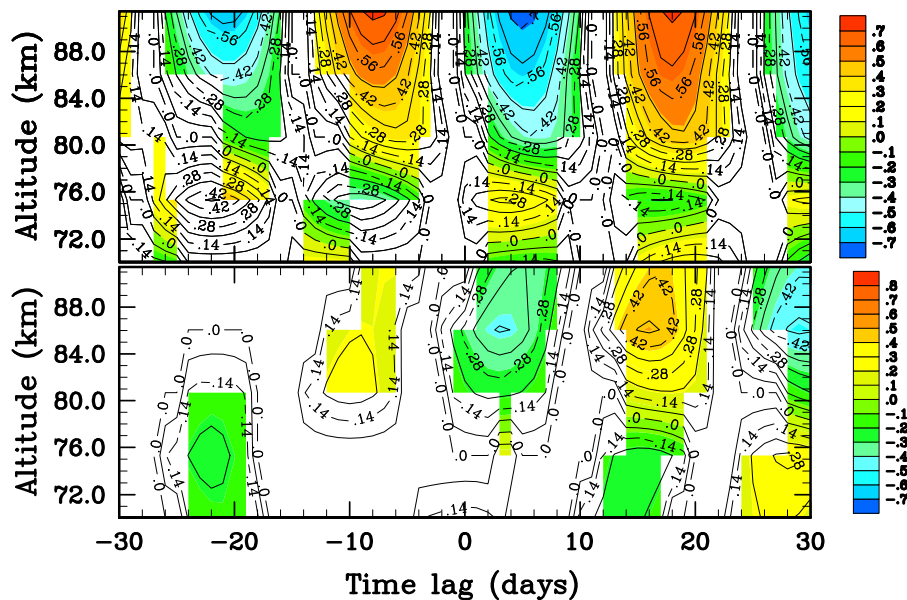


Fig. 6. The same as Fig. 5, but for H₂O.

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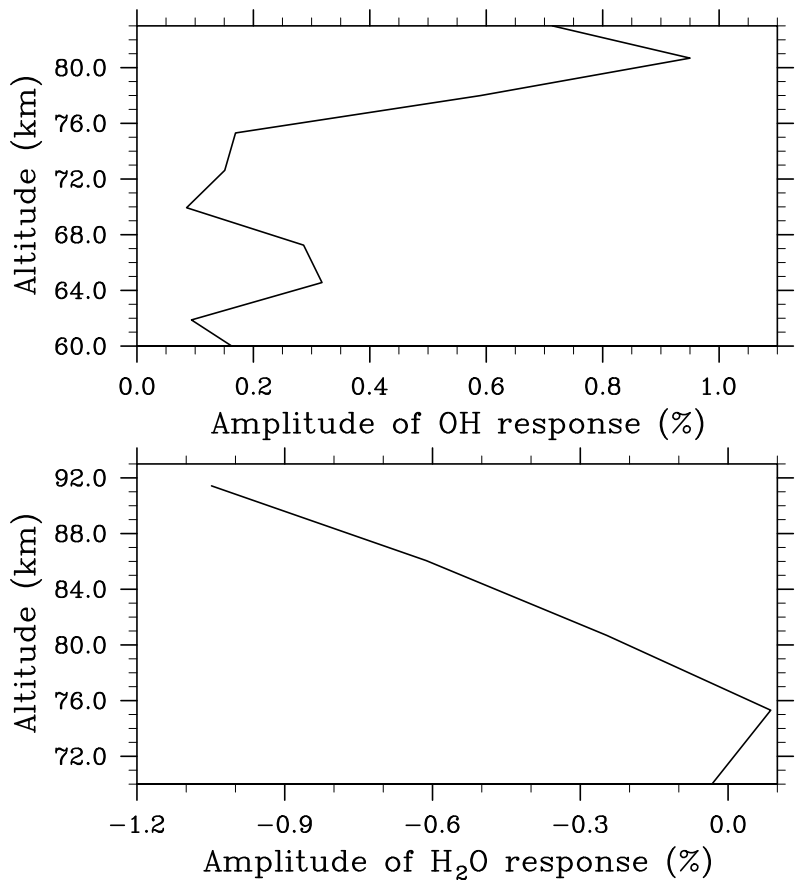


Fig. 7. OH (upper panel) and H₂O (lower panel) sensitivities (in %) to 1% change of the SOLSTICE /SORCE Ly- α irradiance.

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