Sensitivity of equatorial mesopause temperatures to the 27-day solar cycle

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[1] Night-time observations of OH(3–1) rotational temperatures with SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) on Envisat are used to study the sensitivity of equatorial mesopause temperatures to the 27-day solar forcing. Fourier and cross-correlation analysis are first used to demonstrate the presence of a solar-driven 27-day cycle in OH rotational temperatures. The temperature sensitivity to solar forcing is quantitatively evaluated based on a superposed epoch analysis that also demonstrates that the solar signal in the OH temperature time series is significant at the 99.9 % confidence level. The most remarkable result is that the temperature sensitivity to solar forcing in terms of the 27-day solar cycle ($\beta_{F10.7}$ = 2.46 ($\pm$0.93) K/(100 sfu)) agrees within uncertainties with the majority of published sensitivity values in terms of the 11-year solar cycle. This implies that the same underlying physical mechanism drives the mesopause temperature response to solar variability at both the 27-day and the 11-year time scale.

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1. Introduction

[2] The Sun's differential rotation with an effective period near 27 days gives rise to variations in solar spectral irradiance if the active solar regions are not homogeneously distributed zonally. The 27-day signature is typically the dominant component, but variations with periods near 13 days [*Donnelly and Puga*, 1990], 9 days and 7 days [e.g., *Fioletov*, 2009] are also reported.

[3] While a significant number of experimental studies investigated solar-driven 27-day variations in stratospheric and mesospheric temperatures, the number of studies dealing with mesopause temperatures is very limited. *Hood et al.* [1991] used Nimbus-7/SAMS (Stratosphere and Mesosphere Sounder) measurements at low latitudes to determine the temperature sensitivity to solar forcing at the 27-day scale for altitudes extending up to about 90 km. *Hall et al.* [2006] and *Dyrland and Sigernes* [2007] identified signatures with periods near 27 days in meteor radar temperature and ground-based OH rotational temperature measurements, respectively. *Robert et al.* [2010] identified a solar-driven 27-day signature in mesospheric temperatures at mid- and high latitudes applying a cross-correlation analysis on MLS/Aura measurements, but low latitudes were not investigated in this study.

[4] Here, we report on a 27-day signature in equatorial mesopause temperatures derived from Envisat/SCIAMACHY observations of the OH(3–1) Meinel band in the terrestrial nightglow.

2. Brief Instrumental Description

[5] SCIAMACHY, the Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY [*Bovensmann et al.*, 1999] onboard Envisat was a passive 8-channel grating spectrograph observing scattered, reflected and transmitted solar radiation in nadir, limb-scatter and solar/lunar occultation geometry in the 220 nm to 2380 nm spectral range. Additionally, limb-emission measurements were performed on the Earth's night-side covering the 75–150 km tangent height range. Moreover, SCIAMACHY provided daily measurements of spectral solar irradiance. In this study the night-time limb-emission as well as the solar irradiance measurements are used. Envisat was launched on March 1st 2002 into a polar, sun-synchronous orbit with a 10:00 a.m. descending node. SCIAMACHY routine operations started in August 2002, and the Envisat mission ended suddenly and unexpectedly on April 8, 2012 due to a major spacecraft failure.

3. Data Products

3.1. OH(3–1) Rotational Temperature Measurements

[6] OH(3–1) rotational temperatures are derived from SCIAMACHY limb-emission observations of the $P_{1/2}(2)$ to $P_{1/2}(4)$ rotational lines of the OH(3–1) Meinel band on the Earth's night side, as described by *von Savigny et al.* [2004]. Temperature is retrieved from limb emission spectra at about 85 km tangent height. The mean emission altitude–weighted by the vertical emission rate profile–is then similar to that of ground-based observations, i.e. about 87 km. The local solar time of the OH rotational temperature measurements is close to 10:00 p.m. The statistical uncertainty (due to random noise on the emission spectra) of a single temperature retrieval is about 6–9 K [*von Savigny et al.*, 2004].

3.2. MgII Index

[7] The MgII index is a dimensionless proxy of solar activity, and is defined as the core-to-wing ratio of the Mg^+ Fraunhofer line around 280 nm. Near the center of the Fraunhofer line a chromospheric emission doublet occurs which is more intense during periods of enhanced solar activity. For this study we employ the MgII index derived from

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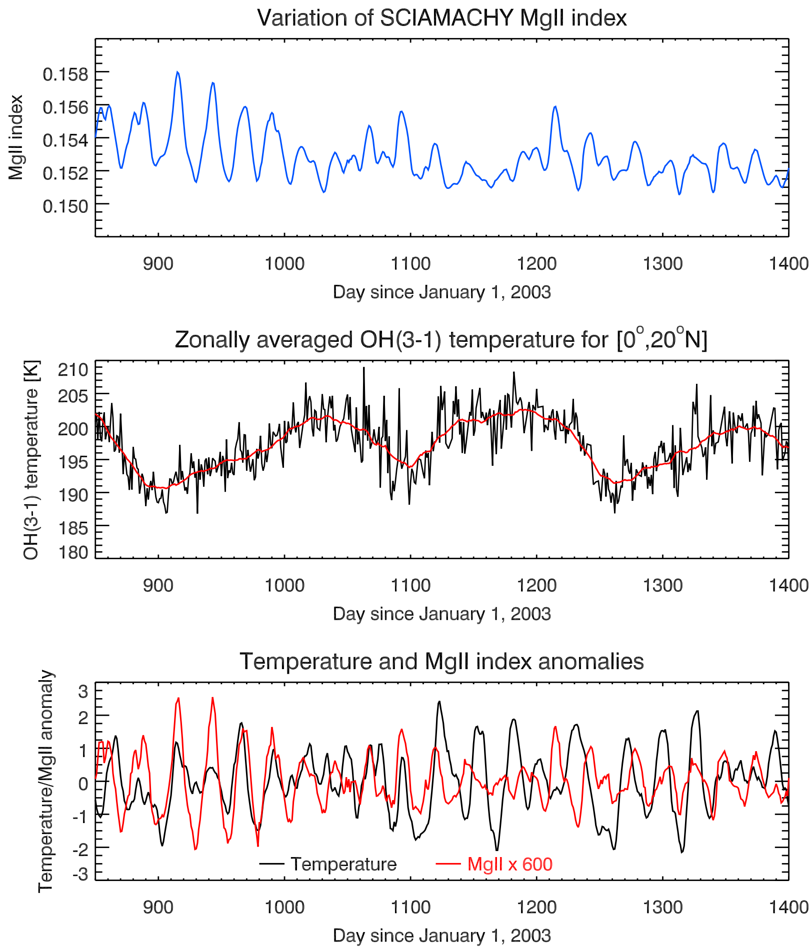

Figure 1. (top) Time series of the MgII index derived from SCIAMACHY spectral solar irradiance observations for the period analyzed here. (middle) Zonally and daily averaged OH(3–1) rotational temperatures for the 0°–20°N latitude bin (black line) and 35-day running mean (red line) for the time period analyzed. (bottom) Temperature and MgII index anomalies obtained by subtracting a 35-day running mean from the time series (the former being smoothed with a 3-day running mean filter and the latter multiplied by a factor of 600).

daily SCIAMACHY observations of solar spectral irradiance [*Weber et al.*, 2012].

4. Results

[8] The OH(3–1) rotational temperature data set is unfortunately characterized by a several data gaps of varying duration, particularly during 2003/2004, and after 2006. In order to investigate the presence of a 27-day solar cycle signature in the temperature data set a period spanning about 18 months with very few and short gaps in coverage was selected. Figure 1 shows the MgII index time series (upper panel), and the zonally and daily averaged OH(3–1) rotational temperature time series for the 0° to 20° N latitude range together with a 35-day running mean (middle panel) for the period April 2005 to October 2006. We limit the analysis to the [0°, 20°N] latitude range, because SCIAMACHY night-time observations are available all throughout the year for these latitudes. The statistical uncertainty of the daily and zonal mean OH rotational temperatures is about 1 K.

[9] In a first step we determined anomaly time series of the daily and zonally averaged OH(3–1) rotational temperature and the MgII index time series by removing a 35-day running mean, following the approach used by *Hood et al.* [1991]. The resulting anomalies are displayed in Figure 1 (bottom). Apparently, there are periods with obvious positive correlations between the temperature and MgII index anomaly time series, particularly during the first half of the period. In the second half the correlation is not as good, and solar cycles with an apparent anti-phase behavior in the temperatures exist.

[10] Figure 2 (top) shows Fourier-spectra of the temperature and Figure 2 (bottom) shows the MgII index anomaly time series displayed in Figure 1 (bottom). The Fourier spectra clearly show signatures with periods near 27-days (red line) present in both time series. The MgII Fourier spectrum also shows evidence of the known signature near 13.5 days (blue dashed line) [*Donnelly and Puga*, 1990]. The temperature Fourier spectrum exhibits a signature at a slightly larger period, but it is currently not known, whether this is related to the 13.5 day signature in the solar proxy. The Fourier analysis allows us to establish the presence of a 27-day signature in the SCIAMACHY OH rotational temperature time series, but it does not permit investigating the phase relationship relative to the solar forcing. For this purpose we used cross-correlation analysis as well as the superposed epoch analysis method

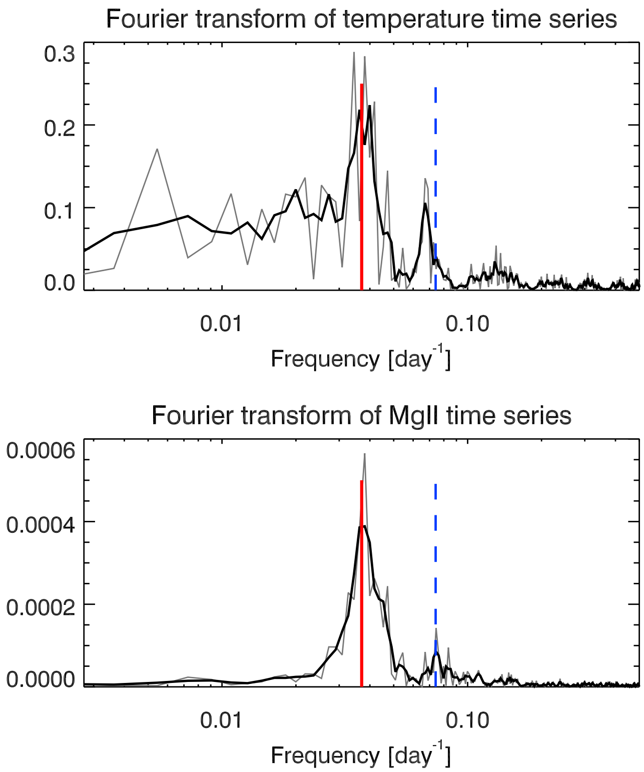

Figure 2. Fourier transforms of (top) the OH(3–1) rotational temperature and (bottom) the MgII index anomaly time series – unsmoothed (grey line) and smoothed (black line) with a 3-point running mean filter. The red solid line indicates a period of 27 days, and the blue dashed line a period of 13.5 days.

[*Chree*, 1912]. Figure 3 (top) shows the cross-correlation between the MgII index and the OH rotational temperature anomaly time series for time lags between −15 and +15 days. The maximum positive cross-correlation occurs at a time lag of 0 days, and this value is significant at the 93 % confidence level. The significance testing was performed with the random phase test introduced by *Ebisuzaki* [1997]. This technique produces random time series with the same autocorrelation as the original time series by adding a random phase in Fourier-space. The purpose of the superposed epoch technique [*Chree*, 1912] is to identify weak signatures in time series affected by variability from different sources. In a first step so-called epochs centered around forcing dates–here defined by local maxima in the MgII index time series shown in Figure 1 (top)–are defined. Each epoch lasts from day −25 to day +25 relative to the corresponding forcing date. In a second step the selected epoch time series are averaged in the following way: the values at day *n*–relative to the forcing dates–of all epochs are averaged, with $n \in [-25, +25]$.

[11] The resulting epoch-averaged temperature and MgII index anomalies are shown in Figure 3 (bottom). The MgII index anomaly exhibits very symmetric behavior with a maximum at zero day time lag and minima near ±13 days, as expected. The epoch-averaged temperature anomaly also shows a clear maximum at zero day time lag, indicating that the response in mesospheric temperature to the solar forcing occurs instantaneously, i.e. within a day at most. The regular structure of the epoch-averaged temperature time series is an unambiguous proof of the presence of a 27-day signature in equatorial mesopause temperature, and the near-zero time lag strongly suggests that this signature is solar driven. The *Ebisuzaki* [1997] random phase method was also applied to the epoch-averaged temperature and MgII anomalies, and the cross-correlation coefficient (χ = 0.928) between the anomalies was found to be significant at the 99.9 % confidence level.

[12] The epoch-averaged temperature and MgII index anomalies are now used to determine the sensitivity of tropical mesopause temperature to changes in solar activity represented here by the MgII index. Figure 4 (left) shows a scatter plot of the temperature and MgII index anomalies displayed in Figure 3 (bottom). The sensitivity is directly determined by the slope of a linear regression line to the data points. The sensitivity with respect to the MgII index is β_{MgII} = 182 (±69) K/(MgII index unit), which translates to the following sensitivity value in terms of the F10.7 cm radio flux: $\beta_{\mathrm{F10.7}}$ = 2.46 (±0.93) K/(100 sfu) (sfu: solar flux units). The relationship between the MgII index and the

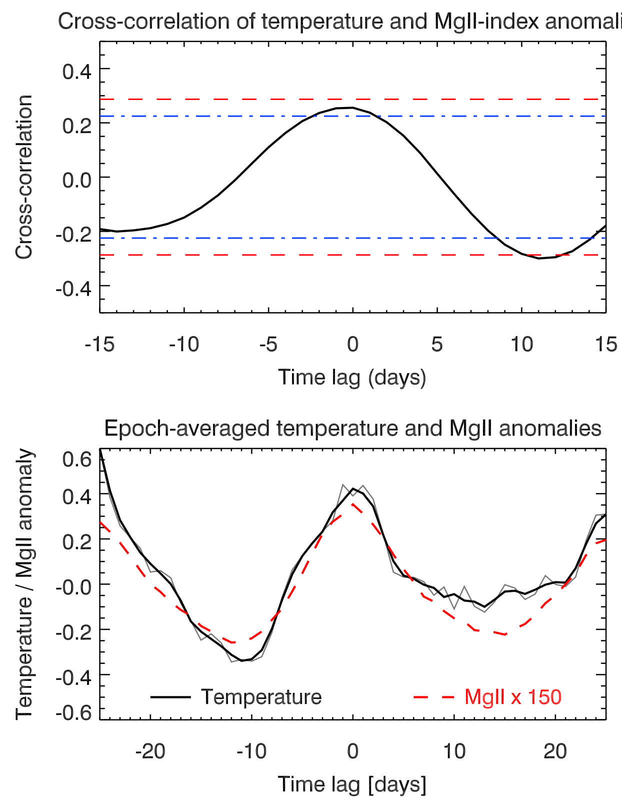

Figure 3. (top) Cross correlation between the OH(3–1) rotational temperature and MgII index anomaly time series for time lags between −15 and +15 days. The blue dash-dotted lines and the red dashed lines, respectively, correspond to the negative and positive correlation coefficients significant at the 90% and 95% confidence levels, respectively. (bottom) Epoch-averaged MgII index (red dashed line) and temperature anomalies–unsmoothed (grey line) and smoothed with a 3-point running mean (black line) – for time lags ranging from −25 days to +25 days. The MgII index anomaly is dimensionless, and the averaged temperature anomaly is given in K.

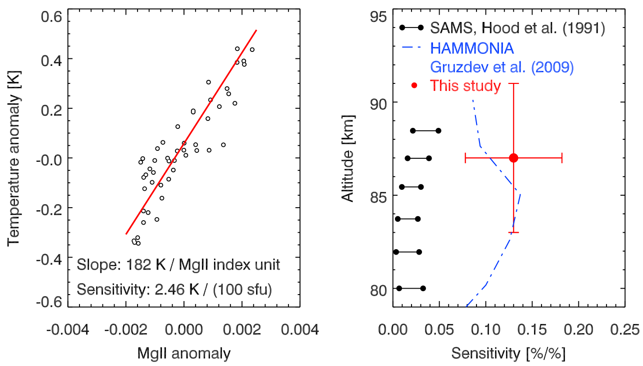

Figure 4. (left) Scatter plot of the temperature and MgII anomalies based on the epoch averages displayed in Figure 3 (bottom). (right) Comparison of upper mesospheric temperature sensitivity to solar forcing from this work and other studies (sensitivity expressed as % change of temperature per % change in solar UV flux at 205 nm).

F10.7 cm radio flux was established by a linear regression to annually averaged values for the years 2003 to 2010. The uncertainties given in parentheses correspond to the standard deviation of the sensitivity determined from a linear regression to the data points. Using the MgII index rather than the F10.7 cm radio flux in the above superposed epoch analysis is justified, because the MgII index was found to be more representative of upper atmospheric heating than the F10.7 cm radio flux [*Thuillier and Bruinsma*, 2001]. However, we also applied the superposed epoch analysis to the temperature and F10.7 cm flux anomalies directly and a sensitivity value of 2.96 K/(100 sfu) was obtained, in good agreement with the value above.

5. Discussion and Implications

[13] The most remarkable finding of the present study is that the sensitivity of mesopause temperatures to solar forcing on the 27-day time scale agrees within uncertainties with the majority of published sensitivity values in terms of the 11-year solar cycle. *Beig et al.* [2008] provided a compilation of the existing studies quantifying the sensitivity of middle atmospheric temperatures to solar activity in terms of the 11-year solar cycle. The reported sensitivity values for mesopause altitudes in the northern hemisphere vary between 2 K/(100 sfu) and 4 K/(100 sfu) for mid-latitudes and values close to 0 K/(100 sfu) at polar latitudes. In the southern hemisphere the sensitivity values scatter between 0 and 13.5 K/(100 sfu) with no clear latitudinal dependence. The few available low latitude satellite observations of mesospheric temperature sensitivity to the 11-year solar cycle yield values of 1–3 K/(100 sfu) [*Beig et al.*, 2008]. Despite the scatter of values the majority of sensitivity values for low and mid latitudes is in the range 1–5 K/(100 sfu), in good agreement with the sensitivity found in this study for the 27-day solar cycle. The finding that the mesopause temperature sensitivity in terms of the 27-day cycle is similar to reported values of the 11-year solar cycle implies that the same physical/chemical processes drive the variability in the temperature field in terms of the 27-day and the 11-year solar cycle. In this context it is also noteworthy that similar sensitivities in terms of the solar 27-day and the 11-year cycles were recently identified for stratospheric ozone [*Fioletov*, 2009] and noctilucent cloud (NLC) albedo [*Robert*, 2010].

[14] An obvious question is what processes actually cause the solar-driven variability in mesopause temperatures. Temperature is directly affected by changes in the amount of solar energy deposited in the mesopause region. Additionally, solar-driven photochemical composition changes will affect diabatic heating (by, e.g., O_3) or radiative cooling (by, e.g., O_3, H_2O). In this context *Shapiro et al.* [2012] recently identified a solar driven 27-day signature in OH and H_2O in the tropical mesopause region. Changing chemical composition can furthermore affect heating rates associated with exothermic chemical reactions, and solar-driven dynamical changes can alter adiabatic heating/cooling rates. The exact contributions of these processes to the actual solar-driven temperature changes are not well understood.

[15] In order to compare the temperature sensitivity derived in this study with the–to our best knowledge–only other experimental result based on Nimbus-7 SAMS measurements [*Hood et al.*, 1991] as well as the recent modelling study by *Gruzdev et al.* [2009]-based on HAMMONIA simulations–we convert the sensitivity to % change in temperature per % change in solar UV flux at 205 nm. The conversion is based on a correlation derived from MgII index and the UV irradiance between 200 and 205 nm measured by UARS/SOLSTICE during the period 1991–1994. The percent temperature changes were determined using the mean temperature for the [0°, 20°N] latitude bin and the time period considered (see Figure 1). The resulting sensitivity value is β_{205nm} = 0.13 (±0.052) %/% (% temperature change/% change in UV irradiance at 205 nm). In Figure 4 (right) we compare the value derived in this study with the SAMS result [*Hood et al.*, 1991] and the recent model result based on the CCM HAMMONIA [*Gruzdev et al.*, 2009]. The horizontal error bars on the sensitivity derived from SCIAMACHY temperature measurements are based on the standard deviation of the sensitivity derived from the linear fit in Figure 4 (left). The vertical error bars indicate, that the temperature is based on the OH emission that has a typical vertical extent of about 8–10 km. The HAMMONIA results–for local midnight at tropical latitudes–shown in Figure 4 (right) were taken from Figure 14 in *Gruzdev et al.* [2009]. Overall, we find that the sensitivity derived in this study is significantly larger (almost an order of magnitude) than the *Hood et al.* [1991] value. The reasons for this discrepancy are not known. The agreement with the HAMMONIA model, however, is very good.

6. Conclusions

[16] A solar-driven 27-day signature was identified in SCIAMACHY night-time OH(3–1) rotational temperature measurements near the equatorial mesopause. This study provides one of very few existing experimental determinations of the sensitivity of mesopause temperatures to solar forcing on the 27-day time scale. The sensitivity of temperature to solar forcing in terms of the 27-day solar cycle is with $\beta_{F10.7}$ = 2.46 (±0.93) K/(100 sfu) consistent with the majority of published sensitivity values in terms of the 11-year solar cycle, implying similar processes causing the solar-driven temperature variability on the 27-day and the 11-year time scales.

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