

The 27-day variations in stratospheric ozone and temperature: New MLS data

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[1] We use new data obtained by the Microwave Limb Sounder (MLS) onboard of Aura spacecraft to investigate variations in stratospheric ozone and temperature concurrent with the 27-day variations of solar UV irradiance, measured simultaneously by the Solar Radiation and Climate Experiment (SORCE) during the declining phase of solar activity. Using Empirical Mode Decomposition we determine the latitudinal and height distributions of the 27-day modes for ozone and temperature and find that these modes are enhanced in the lower tropical stratosphere, and at high latitudes in winter. **Citation:** Ruzmaikin, A., M. L. Santee, M. J. Schwartz, L. Froidevaux, and H. Pickett (2007), The 27-day variations in stratospheric ozone and temperature: New MLS data, *Geophys. Res. Lett.*, **34**, L02819, doi:10.1029/2006GL028419.

1. Introduction

[2] The responses of stratospheric ozone to variations in solar UV irradiance on the timescale of the 11-year solar cycle and of the solar rotation (27-day) have been studied since 1979 when space data became available (for a review and references see Hood [2004]). The study of the responses on the solar rotation time-scale can be performed using a relatively short series of measurements because there are about 13 solar rotations per year. In addition to the direct UV influence, the ozone concentration strongly depends on temperature, which is varying due to the UV changes and due to dynamical processes that are effective in the 27-day scale range. The sensitivity of ozone response to solar UV changes has been estimated to be highest during solar cycle maxima, reaching 0.5% in the upper stratosphere tropical regions [Hood, 2004]. The response is expected to decrease during declining phase of the cycle [Chandra *et al.*, 1996] but has not been investigated on the 27-day time scale. The horizontal and altitude resolution of previously available measurements did not allow construction of global distributions of the ozone variations. We here report on the new MLS data [Waters *et al.*, 2006], which allow the construction of these distributions throughout the stratosphere. We compare the 27-day variations in ozone and temperature, measured by MLS, and in the UV irradiance, measured simultaneously by SORCE [Rottman *et al.*, 2005] during the declining phase of solar cycle 23 (August 8, 2004–May 1, 2006).

2. Data and Method

[3] The solar UV irradiance has two major sources in the solar chromosphere: bright plages and bright active network [Lean *et al.*, 1998]. Almost all of the variations in the irradiance on the solar rotation time-scale arise due to the inhomogeneous distribution of the plages along solar longitudes. The solar UV irradiance daily record is taken from the SORCE's Solar Stellar Irradiance Comparison Experiment (SOLSTICE) (<http://lasp.colorado.edu/sorce/ssi/>). The irradiance is measured in the 115–310 nm range with spectral resolution of 0.1 nm. Following previous studies [Hood, 2004] we use the UV irradiance at 205 nm (see Figure 1, top). The power spectrum of the irradiance (not shown) has a strong 27-day peak.

[4] For stratospheric ozone and temperature we use version 1.51 MLS data obtained at the same time as the solar UV. MLS provides daily global coverage from 82°N to 82°S. A typical estimated single-profile precision for ozone is ~0.2–0.5 ppmv over the range 1 to 100 hPa, with vertical resolution ~3 km. For temperature, typical estimated single-profile precision values are 1 K at 100 hPa, 0.5 K at 10 hPa, and 0.8 K at 1 hPa with vertical resolution ~4–6 km in the stratosphere [Froidevaux *et al.*, 2006]. We average the data in 36 latitudinal bins at 13 levels from 100 hPa to 1 hPa. The Aura orbit is sun-synchronous, with a 1:45 PM ascending equator-crossing time, so that MLS measurements at a given latitude on either the ascending (day) or descending (night) sides of the orbit have approximately the same local solar time every day [Waters *et al.*, 2006]. Data from both sides of the orbit are included in calculating the averages. We interpolated between the gaps occasionally found in the data using a shape-preserving piecewise cubic interpolation method. By using zonal means the precision is improved by about an order of magnitude, since noise is reduced by the square root of the number of profiles being averaged, and typically 50–150 profiles contributed to the zonal means.

[5] In the previous studies of the stratospheric response to the 27-day UV variation [Chandra, 1986; Hood, 2004] the ozone and temperature signals were band-pass filtered to remove periods longer than 35 days and shorter than 7 days. Here we use a more sophisticated method of filtering out the 27-day signals, called the Empirical Mode Decomposition (EMD) [Huang *et al.*, 1998], which is especially designed to take into account all non-linear and non-stationary features of the signals. The EMD represents the data as a sum of a small number of orthogonal empirical modes that have time-variable amplitudes and frequencies. Each mode has a symmetric envelope defined by the local maxima and minima so that its mean amplitude is zero everywhere. Its mean period can

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be determined by counting the number of peaks (maxima). Each mode is equivalent to an adaptively filtered signal in an empirically determined (not imposed!) frequency range. The last mode characterizes a nonlinear trend in the signal. The orthogonality of EMD modes guarantees that there is no power leakage into a selected mode from other modes. We found that the UV irradiance, ozone and temperature can be fully represented by seven EMD modes. To avoid overlaps of frequency ranges of adjusting modes we averaged an ensemble of 500 EMD realizations obtained from data plus white noise, as recommended by N. Huang (private communication, 2006). The white noise contribution to final modes averages to zero, but adding noise helps in ordering (along decreasing frequency range) modes extracted out of a signal that sharply changes its frequency range in time. A comparison of power of the calculated modes with the power of modes generated from white noise allows an evaluation of the statistical significance [Wu and Huang, 2004]. We find that all 27-day modes investigated here are statistically significant at the 99% level.

[6] We compare the 27-day EMD modes of ozone, temperature and the UV irradiance. Figure 1 shows the mode amplitudes and distributions of instantaneous frequencies of the UV irradiance. Mode 4 has an instantaneous frequency close to $1/27$ day. Since the solar UV flux decreases due to approaching the solar minimum (2007) the direct effect of the UV on ozone is expected to decline. Detail examples of amplitudes and instantaneous frequencies for ozone and temperature modes for the tropical upper stratosphere are shown in Figures S1 and S2 in the auxiliary material¹.

3. Spatial-Temporal Distribution of the 27-Day Modes for the Ozone and Temperature

[7] We applied the EMD to time series of ozone and temperature at each of the 13 altitudes (from 100 hPa to 1 hPa) at fixed latitudes, and to the time series corresponding to the 36 latitudinal bins (from -87.5° to 87.5°) at fixed altitudes. Figure 2 shows the height distribution of the 27-day mode (mode 4) for the ozone and temperature at three latitudinal locations. The 27-day mode of the UV irradiance for the same time period is shown in the top panel for comparison. Because the magnitude of ozone depends on altitude, we normalized the data time series at each altitude by its maximum. Shown is the amplitude of the 27-day mode relative to the ozone (and the temperature) magnitude at each given altitude.

[8] Some results are immediately apparent. The ozone and temperature modes tend to be in anti-phase in the upper stratosphere, in-phase in the lower stratosphere and strongest in the winter hemisphere. The ozone at the top of the stratosphere is in phase with the UV mode. This type of phasing of the responses confirms earlier findings [Chandra, 1986; Hood, 2004]. And we see strong ozone and temperature 27-day variations (relative to their mean values) near

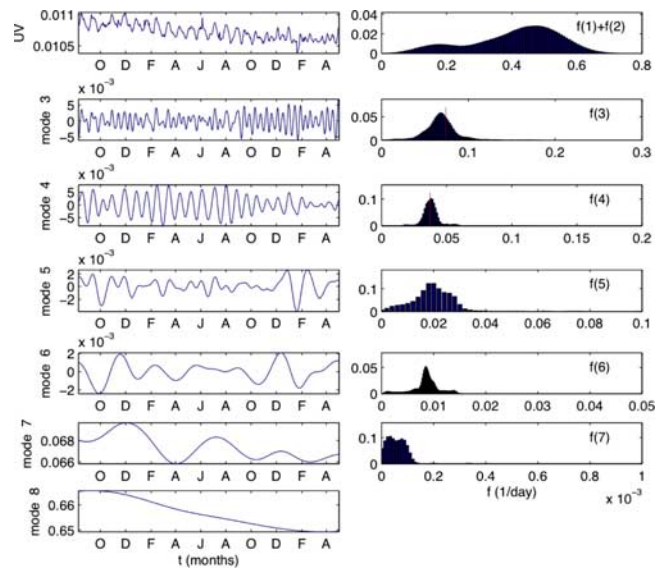


Figure 1. (top) The solar UV irradiance at 205 nm for August 8, 2004 through May 1, 2006 normalized to its maximum value. (left) The time evolution of the EMD modes, starting from mode 3. Noise-like modes 1 and 2 are not plotted. (right) The distribution of the instantaneous frequencies of each mode. The vertical line in mode 4 marks the 27-day period. The wider frequency distribution of mode 3 includes 13.5-day period. The last mode shows a nonlinear trend.

the bottom of the stratosphere. Strong 27-day modes are also seen at high latitudes in the winter.

[9] Figure 3 shows the distributions of the 27-day modes for the heights near the top, middle, and bottom of the stratosphere, at 1.5, 10, and 100 hPa. We see the strongest modes at mid and high latitudes in winter. The 27-day variations of ozone at high latitudes (up to 60°) in winter had also been noticed earlier [Hood, 2004]. Again, ozone and temperature modes tend to be in anti-phase. An important feature is the phase flip at about 45°N , also noticed in the earlier data analyses [Chandra, 1986; Hood, 2004]. A similar but weaker pattern is seen in the southern winter.

4. Discussion

[10] Interpretation of the results and answering the question what causes the 27-day variations in ozone (solar UV or dynamics) requires comparison with modeling and will be done elsewhere. Here we make only a few comments illustrating the nature of the problem.

[11] Since ozone is affected by UV and by temperature, a simple calculation of correlation coefficients between two variables, say ozone and UV, does not reflect the role of the third variable, T , which is in turn affected by the UV. Somewhat helpful is calculating partial correlation coefficients [Zhou et al., 2000] but it is based on an assumption that T is independent of UV and does not take into account nonlinear (higher-order) correlations. Additional problem is the phase drift, seen for example in the time series of ozone

¹Auxiliary materials are available in the HTML. doi:10.1029/2006GL028419.

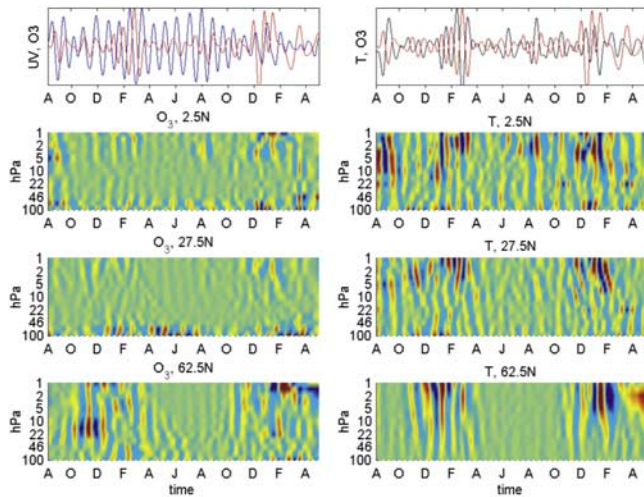


Figure 2. Height distributions of the 27-day mode for ozone and temperature at tropical (2.5°N), subtropical (27.5°N), and high (62.5°N) latitudes. The (top left) 27-day modes for UV (blue), ozone (red) at 1.5 hPa, 2.5°N and (top right) ozone (red) and temperature (black) in are shown to guide the phase comparison. In the panels below the colors are linearly scaled between the maximum and minimum of the plotted variables. To evaluate the absolute strength one should multiply each row of map by the maximum (over the 360 days) magnitude of the mode at this height. At 2.5° N these magnitudes are: [0.007, 0.029, 0.084, 0.167, 0.276, 0.392, 0.435, 0.426, 0.388, 0.293, 0.232, 0.164, 0.125] ppmv for ozone, and [0.88, 0.92, 0.93, 0.96, 0.99, 1.02, 1.06, 1.08, 1.11, 1.17, 1.20, 1.20, 1.21] K for temperature, at 100 to 1 hPa respectively.

shown in upper panels of Figures 2, 3, that makes correlation coefficients between the 27-day UV and ozone modes small. To illustrate (in a simplified manner) how the drift could appear let us consider the evolution of perturbations of ozone mixing ratio (μ') forced with the same 27-day frequency ω by changes in UV flux and temperature in the upper stratosphere

$$\frac{\partial \mu'}{\partial t} + \alpha \mu' = a \sin \omega t - b \sin(\omega t - \varphi), \quad (1)$$

where α is the chemical rate of ozone loss, a is the amplitude of the UV forcing and b , φ are the amplitude and phase of temperature perturbations. [It can be shown that for the height dominated by Chapman chemistry $\alpha = 4(\frac{k_{O+O_3}}{k_{O+O_2}} J_2 J_3)^{1/2}$, $a = 2(\epsilon_2 - \epsilon_3) J_2 O_2$, $b = J_2 O_2 \delta(\frac{k_{O+O_2}}{k_{O+O_3}})^2 / \delta T$, where ϵ 's are the amplitudes of the UV flux in the wavelength range responsible for ozone production (J_2) and destruction (J_3), and k 's are the rates of O , O_2 , O_3 collisions.] Since in the upper stratosphere the rate of chemical losses of ozone is much faster than the 27-day variation, the solution of equation (1) has the form

$$\mu' = A \sin(\omega t - \Phi), \quad A = \alpha^{-1} (a^2 + b^2 + ab \sin 2\varphi)^{1/2}, \quad \Phi = a \tan\left(\frac{b \sin \varphi}{a + b \cos \varphi}\right). \quad (2)$$

Hence, slow (compared with 27-day) changes in the amplitudes of forcings ($a(t)$, $b(t)$) could cause a drift in the phase Φ .

[12] In the lower stratosphere, where the ozone production P is not compensated by its chemical loss, the dynamics becomes critically important. In the tropics the transport of ozone is mostly provided by the vertical velocity w [Dessler, 2000]. Using the NCEP Reanalysis data we found that w indeed has a 27-day mode in the low stratosphere (Figure S3 in the auxiliary material). The origin of the velocity variation on this time scale is not clear. It could be present in wave disturbances traveling up from the troposphere or induced by changes in upwelling rates induced by the solar UV variations in the upper stratosphere [Hood, 2003].

[13] The variations found at high latitudes in winter also cannot be induced photochemically and should be caused by dynamics. The major component of the dynamics, planetary waves, does not show 27-day variation in the troposphere but this variation appears in the stratosphere (Figure S4 in the auxiliary material). If caused by the interaction between planetary waves and mean zonal flow this would suggest involvement of the North (South) Annular Mode (NAM, SAM) driven by this interaction [Limpasuvan and Hartmann, 2000]. An additional argument is positioning of the NAM between 20° and the pole (with sign change at about 45°–50°) where the phase flip in ozone and temperature is seen. The solar variability level does influence the NAM [Ruzmaikin and Feynman, 2002], however the effect has not been studied on the 27-day scale. Conceivably, the 27-day variations in temperature induced by the solar UV at the lighted (equatorial) side of the annular mode could propagate through the whole mode structure to its polar part. More detailed investigation and comparison with models is needed.

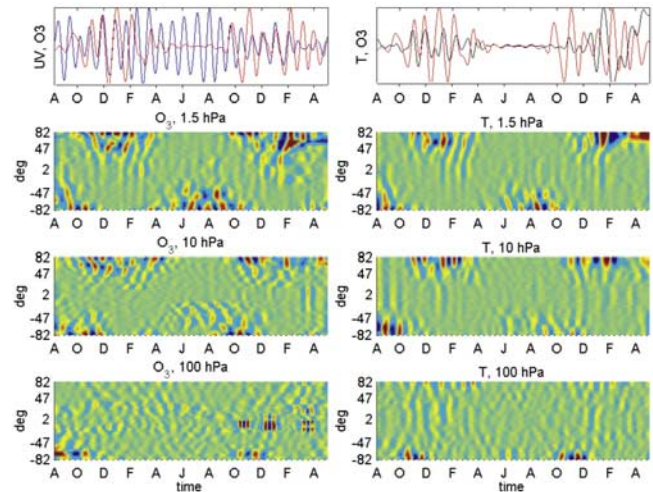


Figure 3. Latitudinal distribution of the 27-day mode for ozone and temperature at three selected heights: 1.5, 10, and 100 hPa. Here the ozone and temperature data are normalized by the factor 10^{-6} and 100 correspondingly. The 27-day UV (left, blue), ozone (red) and temperature (right, black) modes at 77.5°N, 1.5 hPa are shown in the top panels to guide the phase comparison.

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References

- Chandra, S. (1986), The solar and dynamically induced oscillations in the stratosphere, *J. Geophys. Res.*, **91**, 2719–2734.
- Chandra, S., L. Froidevaux, J. W. Waters, O. R. White, G. J. Rottman, D. K. Prinz, and G. E. Brueckner (1996), Ozone variability in the upper stratosphere during the declining phase of the solar cycle 22, *Geophys. Res. Lett.*, **23**, 2935–2938.
- Dessler, A. (2000), *The Chemistry and Physics of Stratospheric Ozone*, Elsevier, New York.
- Froidevaux, L., et al. (2006), Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite, *IEEE Trans. Geosci. Remote Sens.*, **44**, 1106–1112.
- Hood, L. L. (2003), Thermal response of the tropical tropopause region to solar ultraviolet variations, *Geophys. Res. Lett.*, **30**(23), 2215, doi:10.1029/2003GL018364.
- Hood, L. L. (2004), Effects of solar variability on the stratosphere, in *Solar Variability and its Effects on Climate*, *Geophys. Monogr. Ser.*, vol. 141, pp. 283–303, AGU, Washington, D. C.
- Huang, N. E., Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N.-C. Yen, C. C. Tung, and H. H. Liu (1998), The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis, *Proc. R. Soc., Ser. A*, **454**, 903–995.
- Lean, J., J. Cook, W. Marquette, and A. Johannesson (1998), Magnetic sources of the solar irradiance cycle, *Astrophys. J.*, **492**, 390–401.
- Limpasuvan, V., and D. L. Hartmann (2000), Wave-maintained annular modes of climate variability, *J. Clim.*, **13**, 4414–4429.
- Rottman, G., T. W. Woods, and V. George (Eds.) (2005), Solar radiation and climate experiment, *Sol. Phys.*, **230**, special issue, 185 pp.
- Ruzmaikin, A., and J. Feynman (2002), Solar influence on major mode of atmospheric variability, *J. Geophys. Res.*, **107**(D14), 4209, doi:10.1029/2001JD001239.
- Waters, J. W., et al. (2006), The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite, *IEEE Trans. Geosci. Remote Sens.*, **44**, 1075–1092.
- Wu, Z., and N. E. Huang (2004), A study of the characteristics of white noise using the empirical mode decomposition method, *Proc. R. Soc., Ser. A*, **460**, 1597–1611.
- Zhou, S., A. Miller, and L. L. Hood (2000), A partial correlation analysis of stratospheric ozone response to 27-day solar UV variations, *J. Geophys. Res.*, **105**, 4491–4500.

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