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Stratospheric effects of 27-day solar ultraviolet variations: An analysis of UARS MLS ozone and temperature data

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Abstract. The characteristics of upper stratospheric ozone and temperature responses at low latitudes to short-term solar ultraviolet variations are studied by using 1000 days of UARS microwave limb sounder (MLS) and solar stellar irradiance comparison experiment data. Consistent with previous analyses of Nimbus 7 solar backscattered ultraviolet (SBUV) data, the high-pass-filtered solar flux in the 200–to 205–nm interval is most strongly correlated with MLS ozone measurements at tropical latitudes near 4 hPa with a sensitivity of about 0.4% for each 1% change in the solar flux. Reproducibility tests, power spectral, and coherency estimates support the reality of the observed ozone response at this level. The MLS solar UV/ozone response is significantly reduced at levels above $\sim$ 2 hPa as compared to earlier results based on SBUV data. This reduction appears to be a consequence of the ozone diurnal cycle at high altitudes combined with the necessary inclusion of nighttime records in calculating the MLS ozone zonal averages. Some evidence is obtained for an MLS solar UV/temperature response near the stratopause, but coherency tests are negative. Future analyses of independent data records having similar local time coverage as that of Nimbus 7 SBUV are needed to establish more definitively whether any significant change in the upper stratospheric UV response has occurred.

1. Introduction

The observed response of the stratosphere to 27-day solar ultraviolet variations provides one basic constraint on models that attempt to simulate solar ultraviolet forcing of the middle atmosphere on both short and long timescales [e.g., *Brasseur*, 1993; *Fleming et al.*, 1995; *Haigh*, 1994; *Chen et al.*, 1997]. While solar-induced temporal variations on short timescales are small in comparison to seasonal variations, they are not negligible on longer timescales such as that of the 11-year Schwabe activity cycle [*Chandra and McPeters*, 1994; *Hood and McCormack*, 1992; *McCormack and Hood*, 1996; *Miller et al.*, 1996; *Hood*, 1997]. Thus it is important to both characterize and understand this source of stratospheric variability. In addition, solar ultraviolet forcing can serve as a useful probe of radiative-photochemical-dynamical coupling in the stratosphere. For this purpose, accurate measurements of the phase lags as well as the amplitudes (sensitivities) of ozone and temperature responses are necessary as a function of pressure level [e.g., *Hood and Douglass*, 1988].

Previous detailed investigations of stratospheric photochemical and thermal effects of short-term solar UV variations have been based primarily on analyses of Nimbus 7 and NOAA 11 satellite remote sensing measurements [e.g., *Gille et al.*, 1984; *Hood*, 1986; *Chandra*, 1986; *Keating et al.*, 1987; *Hood and Jirikowic*, 1991; *Chandra et al.*, 1994; *Fleming et al.*, 1995]. Observations of upper stratospheric ozone profile responses to $\sim$ 27-day solar UV variations have been complemented by studies of the response of total column ozone using Nimbus 7 total ozone mapping spectrometer data [*Bjarnason and Rögnvaldsson*, 1997]. The ozone profile analyses mainly employed Nimbus 7 or NOAA 11 solar backscattered ultraviolet (SBUV) data. The SBUV instrument is a nadir-viewing UV double monochromator whose vertical resolution has been estimated to be about 8 km [*McPeters et al.*, 1984]. The SBUV measurements were necessarily acquired only during local day conditions at a range of solar zenith angles. For a recent validation analysis of current NOAA SBUV/2 operational measurements, see *Lienesch et al.* [1996]. The temperature profile analyses have mainly utilized Nimbus 7 stratosphere and mesosphere

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sounder (SAMS) data. The SAMS instrument is a limb-scanning-pressure modulating radiometer that measures CO_2 emission in the 15 μm ν_2 band [*Wale and Peskett*, 1984]. The derived temperatures are based on limb scans obtained in the afternoon and early evening hours of each day [see *Barnett and Corney* [1984, Table 1] and have a vertical resolution of 8–10 km [*Rodgers et al.*, 1984]. For orbital and geometrical reasons, SAMS measurements were obtained only between 65°N and 45°S.

Analyses of the SBUV data have shown that the maximum ozone response to short-term solar UV variations occurs near the 3 hPa level (about 40 km altitude) and amounts to approximately 0.5% for each 1% change in the 205 nm solar flux. Peak-to-peak 27-day variations in the 205 nm flux are typically several percent [*London et al.*, 1993] but can have amplitudes as large as 6-7% under solar maximum conditions [*Donnelly et al.*, 1987]. On the basis of SAMS data, evidence was also obtained for an associated temperature response with a maximum amplitude of about 0.06% ($\sim$ 0.16 K) near the 1 hPa level for a 1% change in the 205 nm flux.

In this paper, an initial detailed analysis is presented of the response of stratospheric ozone and temperature to 27-day solar ultraviolet variations using remote sensing measurements derived with the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) [*Waters*, 1989, 1993]. The UARS was launched in September 1991, about 1 year after solar maximum, while the Nimbus 7 satellite was launched in late 1978, several years before solar maximum. Like the SBUV data set, the MLS data set therefore includes a significant sample of measurements under solar maximum conditions when solar UV variations on the solar rotation timescale have their largest amplitudes. One advantage of the UARS MLS measurements is the somewhat higher vertical resolution of the ozone and temperature retrievals (about 6 km) (E. Fishbein and J. Waters, private communication, 1995). However, unlike the SBUV instrument, the MLS is capable of nighttime as well as daytime ozone measurements, and as discussed below, the number of nighttime records generally exceeds the number of daytime records. Because the ozone lifetime is less than a day in the uppermost stratosphere (leading to a significant diurnal cycle), care must be taken in comparing the resulting MLS ozone/UV response measurements at high levels (above 2 hPa) with those obtained previously from the SBUV data.

2. Data Description

The UARS satellite was launched on September 12, 1991, into a 57° inclination, 585-km altitude orbit [e.g., *Reber et al.*, 1993]. The MLS instrument is one of 10 UARS instruments and one of two limb-scanning sensors of composition and physical conditions in the stratosphere. The other limb-scanning sensor is CLAES (cryogenic limb array etalon spectrometer) whose vertical resolution is estimated as about 2.5 km [*Roche et al.*, 1993]. (CLAES ceased operations in May 1993 and has a total data length of 602 days.) In principle, an investigation of solar UV effects on the stratosphere could employ either MLS or CLAES data. For the present analysis, however, only MLS data are considered.

The microwave limb-sounding technique applied by the MLS instrument has been described in detail by *Waters* [1989, 1993]. Retrieved ozone mixing ratios and temperatures are obtained at stratospheric pressure levels p of 0.46, 1, 2.2, 4.6, 10, 22, and 46 hPa so that the vertical resolution is $\Delta \log_{10}(p) = 0.33$, or about 6 km. The temperature retrieval utilizes a sequential estimation algorithm with an a priori estimate based on a combination of climatological temperatures and National Centers for Environmental Prediction (NCEP, formerly NMC) daily analyses. The 1σ precision for single temperature profiles ranges from 3 K at 0.46 hPa to 1.5 K at 2.2 hPa and at lower levels (E. Fishbein and J. Waters, private communication, 1995). The ozone retrieval is based on 205 GHz radiances and also utilizes a sequential estimation algorithm with an initial guess based on climatology. The 1σ precision for single ozone mixing ratio profiles is 0.5 ppmv at 0.46 hPa, 0.3 ppmv at 1–4.6 hPa, and 0.2 ppmv at 10–46 hPa.

Because the tangent point of the limb-scanning observation path for MLS is approximately 23° away from the satellite orbit track, the 57° orbit inclination causes measurements to be obtained between 34° latitude on one side of the equator and 80° latitude on the other side. To allow more equal coverage of both hemispheres, the UARS performs a "yaw maneuver" which changes its orientation by 180° 10 times a year. The net effect is that latitudes greater than 34° are covered only in alternate hemispheres with an approximate period of 36 days. Consequently, the present analysis is limited to latitudes less than 34° where the data record is nearly continuous in time. This does not represent a major problem since previous studies of Nimbus 4 and 7 data have shown that the stratospheric response to solar UV variations is most easily detectable at latitudes less than about 30° where dynamically induced variability is smaller [e.g., *Hood*, 1984; *Chandra*, 1986].

A more serious problem related to the UARS yaw maneuver cycle is that an artificial 36-day periodicity is present in daily zonal averages of the MLS ozone and temperature data even at tropical latitudes where the data record is continuous in time. As shown by spectral analysis, the amplitude of this periodicity increases with increasing altitude in the upper stratosphere. The explanation involves a combination of viewing geometry changes from one yaw cycle to the next and the presence of an ozone diurnal cycle with increasing altitude. Specifically, an MLS zonal average for a given day includes both daytime and nighttime measurements, and the ratio of daytime to nighttime records varies with a 36-day period. Because of the diurnal cycle at high altitudes, a 36-day periodicity is then introduced into the zonal mean time series of either ozone or temperature. Ideally, this problem could be remedied by restricting the zonal average to include only daytime measurements near a single local time. This would effectively convert the MLS measurements to values roughly comparable to those derived from the SBUV instrument, for example. However, the fraction of daytime measurements in a given daily zonal average varies from 0% to 50% with a mean near 30%. Consequently, a zonal mean time series constructed only from daytime measurements within a restricted local time range would be based on a small fraction of the available data. This would lead to much larger sampling errors and time gaps in the zonal averages.

On the basis of the above considerations we have elected to adopt the MLS zonal mean measurements as weighted averages of both night and day records and to minimize the 36-day variation mathematically using a band-pass filter. This means that the MLS ozone and temperature zonal mean measurements are not identical to those derived from the SBUV instrument (daytime measurements only) at those levels where a significant diurnal cycle is present (above 2 hPa). This is an important consideration for interpreting the resulting UV responses, as will be discussed further in a later section. The band-pass filtering procedure is described in detail by *Murakami* [1979] and has been applied previously by *Zhou et al.* [1997]. The procedure is as follows: First, the mean value and linear trend are removed from the time series. The residual is then processed by convolving the time series with a special weighting function of the band-pass filter. The weighting coefficients are computed with a specified central period (100% response) and bandwidth (> 50%). In this case, the central period is 36 days and the bandwidth is 2 days (i.e., 35 to 37 days). The output time series is reversed in time and processed again to obtain the final filtered time series. This procedure has little effect on the 27-day period at which the response is less than 1% (0.0092).

Solar spectral irradiance variability over the 115–420 nm interval is measured by two instruments on UARS. These are the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE) [*Rottman et al.* [1993] and the solar ultraviolet spectral irradiance monitor (SUSIM) [*Brueckner et al.* [1993]. In this paper, only the SOLSTICE measurements will be considered. SOLSTICE observations began on October 3, 1991, and were continuous thereafter except for the period from June 3 to July 17, 1992, when the operation of the UARS solar array drive was anomalous. Although solar radiation varies at all ultraviolet wavelengths on the 27-day timescale (with an amplitude that increases with decreasing wavelength), it is conventional to choose the solar spectral irradiance at 205 nm as a reference value. Variations at this wavelength are representative of those in the photochemically important 183- to 205-nm Al I continuum [*Heath et al.*, 1984]. If the 205 nm flux is known as a function of time, it is straightforward to estimate the variation with time at other ultraviolet wavelengths on the 27-day timescale using appropriate scaling factors [e.g., *Heath and Schlesinger*, 1986, Figure 3; *Haigh* [1994, Figure 1]. In particular, the variation can be estimated at all wavelengths less than 242 nm where photodissociation of molecular oxygen occurs in the stratosphere. Therefore for the purposes of this analysis, only the integrated flux in the 200–205 nm band will be utilized.

In preparation for cross correlation and regression analyses, the band-pass-filtered MLS ozone and temperature data at individual pressure levels were first interpolated to a 2.5° × 2.5° latitude-longitude grid using a successive correction method. The data were then averaged zonally on five 10° latitude bands centered at 25°S, 15°S, 0°, 15°N, and 25°N. Finally, a tropical average from 30°S to 30°N was calculated. Ozone data were analyzed at levels ranging from 31.6 to 0.46 hPa ($\simeq$ 23 to 55 km altitude). Temperature data were analyzed from 21.5 to 0.46 hPa ($\simeq$ 26 to 55 km).

For cross-correlation and cross-spectral analysis we specifically consider the 1000-day time period beginning on October 20, 1991, and ending on July 15, 1994. To form a continuous time series, the solar UV, ozone, and temperature data were first interpolated and smoothed by using a 7-day running average algorithm. Following previous work, to allow an analysis of 27-day variability, we remove a 35-day running average from each time series to minimize longer-period variations [*Hood,* 1984, 1986; *Chandra*, 1986; *Keating et al.*, 1987]. In the time domain this is roughly equivalent to high-pass filtering in the frequency domain with a lower cutoff frequency corresponding to a period near 35 days. The 45-day gap in the SOLSTICE data beginning on June 3, 1992, was filled by linear interpolation.

3. Data Analysis

Plots of the resulting tropically averaged ozone and UV deviation time series at 0.46, 1.0, 2.2, and 4.6 hPa are shown in Figure 1. Positive correlations between the UV deviations and the ozone deviations are evident especially at the 4.6 hPa level (bottom panel). However, at higher altitudes, these correlations are not so large as found in the SBUV data for the 1979 to 1982 time period [*Hood and Cantrell,* 1988, Figure 1]. To quantify the extent of the observed correlation as a function of pressure level and phase lag, Figure 2 shows the cross-correlation function computed from the tropically averaged data between 0.46 and 31.6 hPa. The maximum correlation is approximately 0.35 at zero lag at 4.6 hPa. For comparison the maximum correlation obtained between SBUV ozone and the 205 nm flux during the 1979–1980 period was about 0.6 at zero lag in the 3- to 4-hPa pressure range [*Hood*, 1986, Figure 4]. In addition, although the variation of phase lag with altitude shown in Figure 1 is similar to that obtained previously (negative lags above the 3 hPa level and positive lags below 3 hPa), there are several differences. Most importantly, there is little correlation above 1.5 hPa in Figure 2, whereas correlation coefficients exceeding 0.5 were obtained in the SBUV analyses referred to above.

Plots of tropically averaged temperature and UV de-

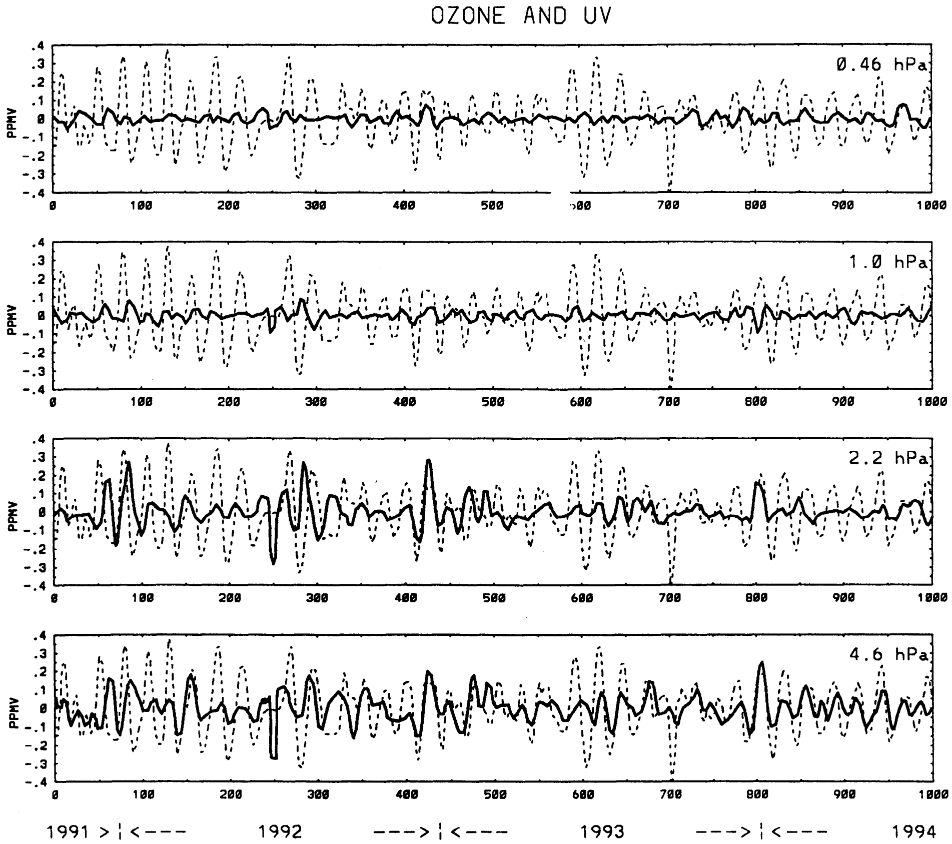

Figure 1. Comparison of 35-day running mean deviations of microwave limb sounder (MLS) zonal mean ozone mixing ratio (solid lines) and solar stellar irradiance comparison experiment (SOLSTICE) 200-205 nm solar flux (– lines) at four pressure levels in the upper stratosphere. The ozone mixing ratios have been averaged between 30°S and 30°N; the units are in ppmv. The UV units are 0.25×10^7 W m^{-3}. The 1000-day interval begins October 20, 1991, and ends July 15, 1994.

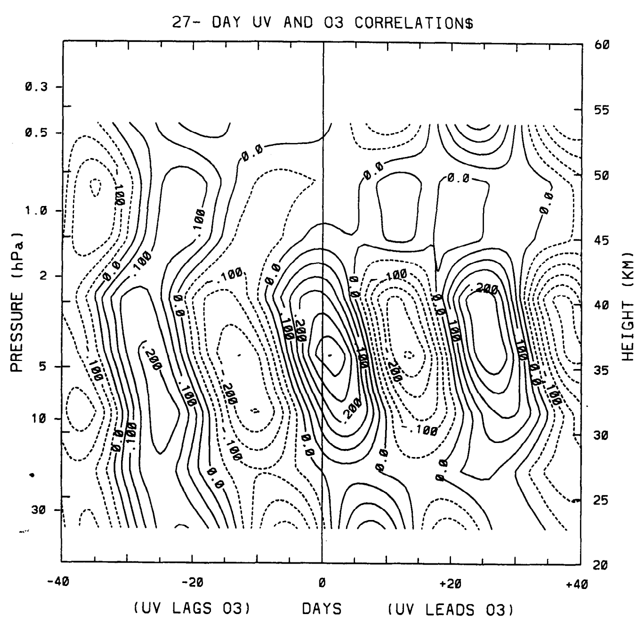

Figure 2. Cross-correlation function for 35-day running mean deviations of MLS zonal mean ozone versus SOLSTICE 200-205 nm solar flux for the 1000-day interval shown in Figure 1. The ozone data have been averaged between 30°S and 30°N.

viations at 0.46, 1.0, 2.2, and 4.6 hPa are shown in Figure 3. As was the case in earlier studies of Nimbus 7 SAMS data, only a weak correlation is present. As shown in Figure 4, the maximum correlation coefficient is 0.20–0.25 near zero lag at approximately the stratopause level. The correlation amplitude and pressure level of maximum correlation are in agreement with earlier analyses [*Hood*, 1986, Figure 8]. However, the phase lag obtained previously (5-6 days at the stratopause) differs significantly from the phase lag deduced from the MLS data (approximately 0 days at the stratopause).

To test the reproducibility of the cross-correlation functions of Figures 2 and 4, the time series shown in Figures 1 and 3 were divided into two equal parts, (days 1 to 500 and 501 to 1000) and the functions were recalculated. Figures 5a and 5b show the resulting functions for the ozone-UV correlation, while Figures 6a and 6b show the temperature-UV correlation functions. In Figures 5a and 5b the vertical structures of the cross-correlation functions are each similar to those of Figure 2, supporting the reality of the correlation. However, the correlation at 4.6 hPa is noticeably larger during the second half of the record ($R_{max} = 0.5$) than during the first half of the record ($R_{max} = 0.25$). Since solar

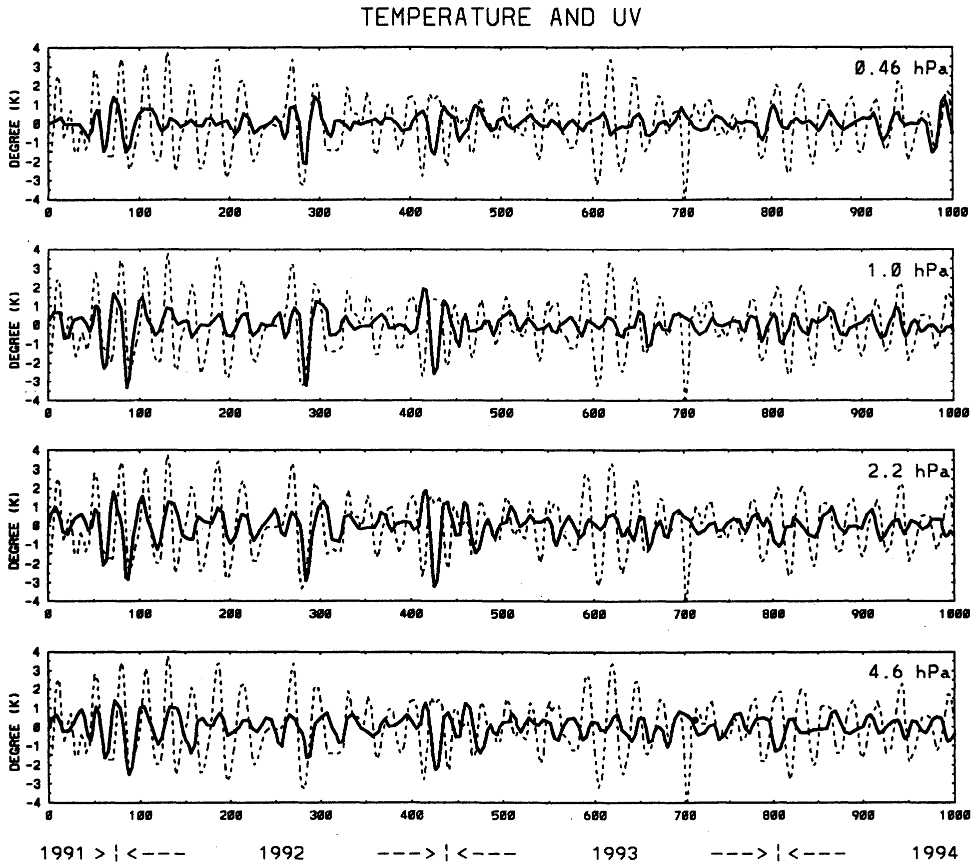

Figure 3. Same format as Figure 1 but for MLS temperatures. The UV units are 0.25 × 10^6 W m^{-3}.

UV forcing is closer to solar maximum and presumably stronger during the first half of the data record, this result is unexpected. It may be speculated that either instrumental or geometric (local time coverage) problems may have affected the earliest part of the record more than the later part. In Figures 6a and 6b the correlations near the stratopause are each similar to those of Figure 4. However, at lower levels the phase lags of maximum correlation differ markedly. The reality of the temperature-UV correlation near the stratopause is therefore supported but that at lower levels is not supported. It should be noted that a similar test of the reproducibility of SBUV ozone and SAMS temperature cross-correlation functions was carried out by *Hood and Cantrell* [1988]. Both the ozone-UV and temperature-UV correlations were found to be reproducible approximately as a function of pressure and phase lag in separate 22-month time intervals.

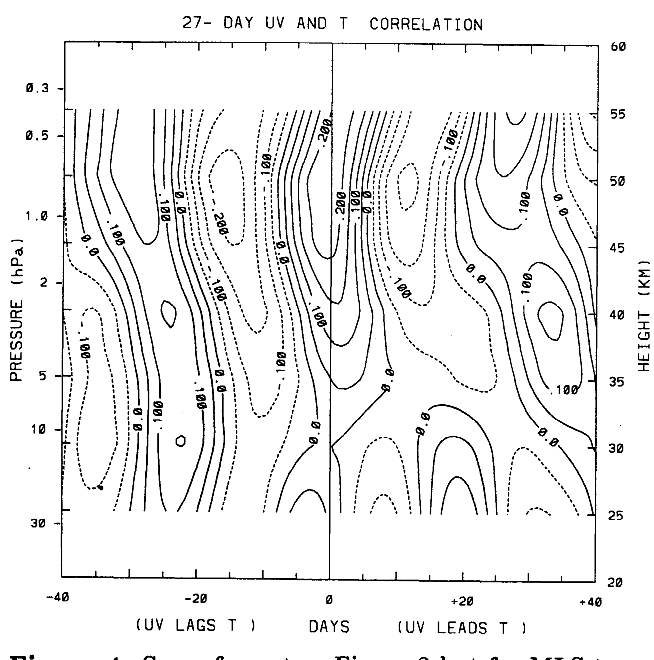

Figure 4. Same format as Figure 2 but for MLS temperatures.

To estimate the power spectra of the UV, ozone, and temperature time series, the autocorrelogram was harmonically analyzed by using a fundamental period of 432 days. The spectral coefficients were then smoothed using a (1,2,1) filter. Figures 7 and 8 show the resulting power spectra for ozone and temperature, respectively, at 2.2, 4.6, and 10 hPa. Also shown in Figures 7 and 8 is the UV spectrum with a pronounced maximum at a period of 27 days. As seen in the figures, there is no significant spectral peak at the yaw period of 36 days in either the MLS ozone or the temperature data. At the solar rotation period near 27 days the ozone power spectra of Figure 7 exhibit well-defined, single maxima at each of the pressure levels shown (2.2, 4.6, and 10

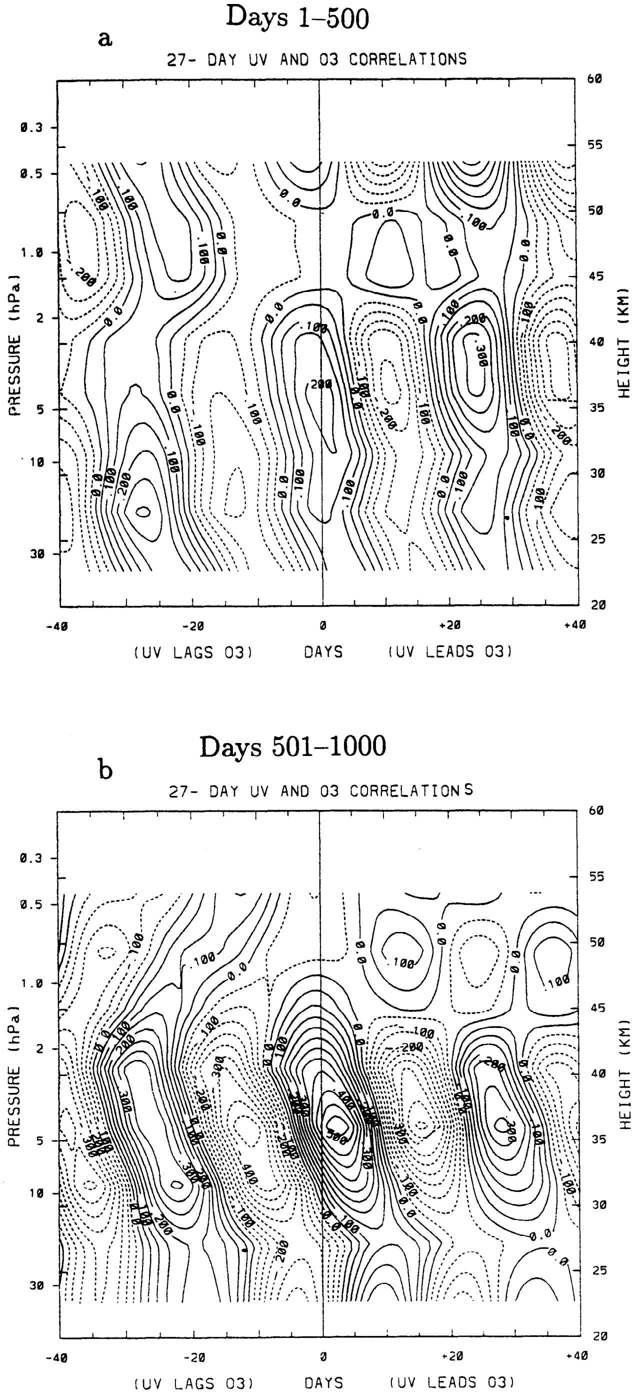

Figure 5. Same format as Figure 2 (ozone-UV cross-correlation functions) but for separate halves of the 1000-day interval: (a) days 1–500, (b) days 501–1000.

hPa). The temperature spectra of Figure 8 contain a series of maxima at periods ranging from 23 to 35 days. The central maximum occurs at periods ranging from 27 days (4.6 hPa) to 29 days (2.2 and 1.0 hPa).

The coherency square for MLS ozone and temperature versus SOLSTICE 200–205 nm UV flux was calculated using the cross-correlation coefficients to estimate the cospectrum and quadrature spectrum. A (1,2,1) smoother was applied to the coherency estimates, as before. The resulting coherency spectra for ozone and UV are shown in Figure 9 and those for temperature and UV are shown in Figure 10. In the case of the ozone-UV spectra, maxima exceeding the 80% confidence level are found at 10 and 4.6 hPa, while no significant coherency peak is present at 2.2 hPa. This is consistent with the ozone-UV cross-correlation function plotted versus pressure level in Figure 2. In the case of the temperature-UV spectra, no coherency maxima at periods near 27 days exceed the 80% confidence level.

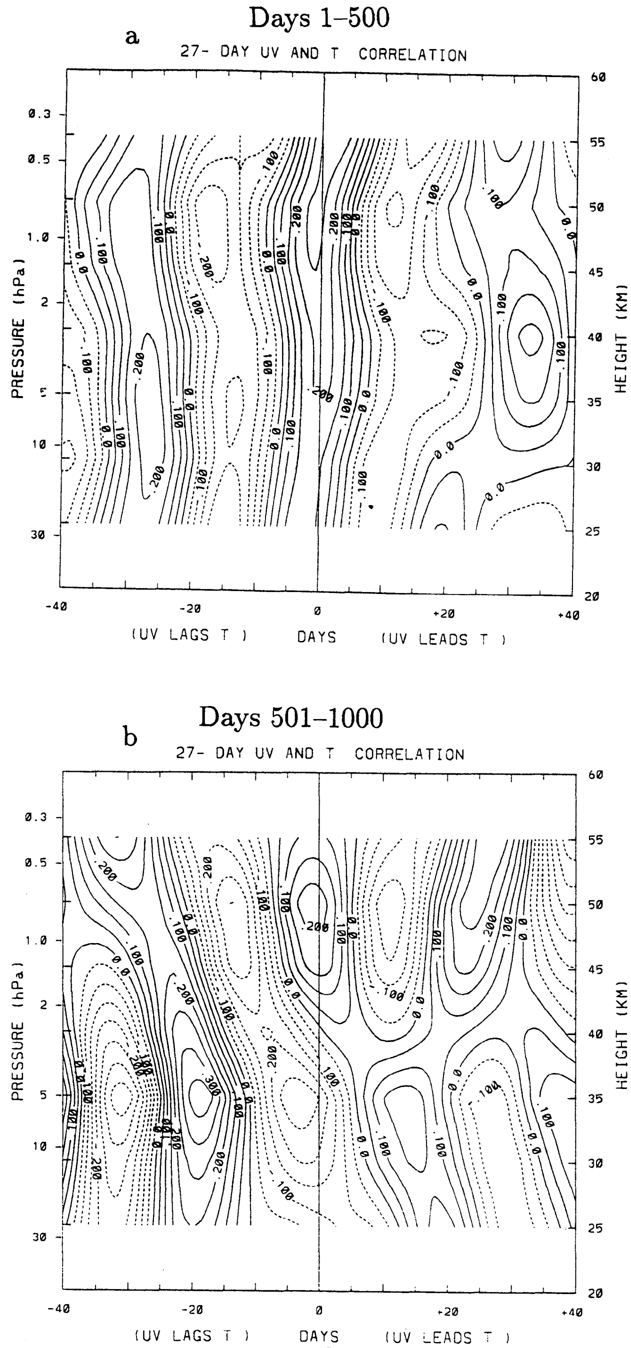

Figure 6. Same format as Figure 3 (temperature-UV cross-correlation functions) but for separate halves of the 1000-day interval: (a) days 1–500, (b) days 501–1000.

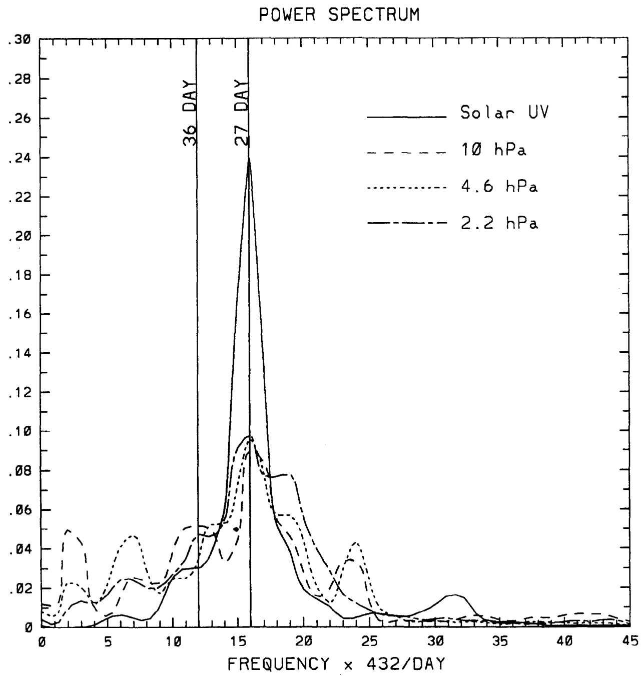

Figure 7. Power spectra of 35-day deviation MLS ozone at the indicated levels and SOLSTICE 200–205 nm solar flux. Vertical lines indicate the approximate UARS yaw maneuver period and the approximate mean solar rotation period, respectively.

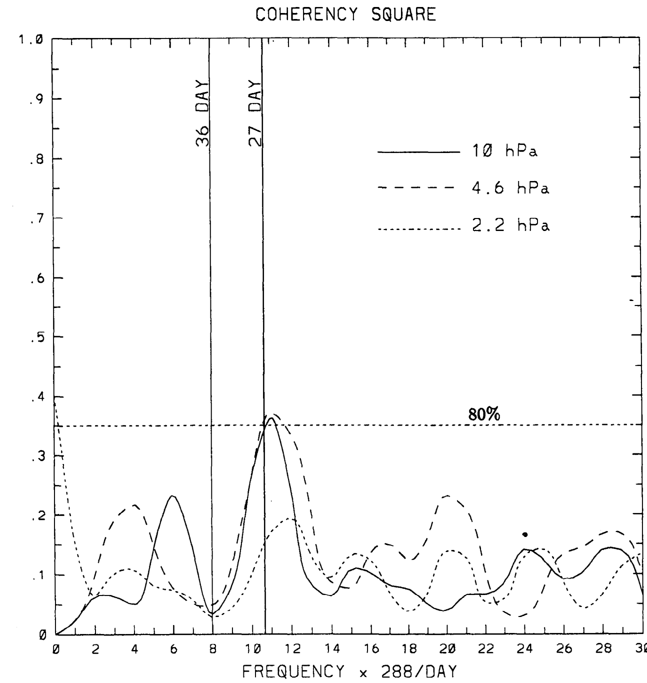

Figure 9. Mean square coherency between MLS ozone and SOLSTICE UV deviations as a function of frequency. The 80% confidence level for significant coherency is also indicated.

This result contrasts with analyses of Nimbus 7 SAMS data for a 4-year time interval centered on the 1980 solar maximum which yielded coherency values significant at the 95% confidence level [*Hood and Jirikowic*, 1991].

Finally, Tables 1 and 2 summarize the tropically averaged MLS temperature-UV and ozone-UV correlation coefficients, phase lags, and sensitivities as a function of pressure level. As in previous work [e.g., *Keating et al.*, 1987], sensitivities are calculated by linear regression and are defined as the percent change in ozone or temperature for a 1% change in the 200-205 nm solar

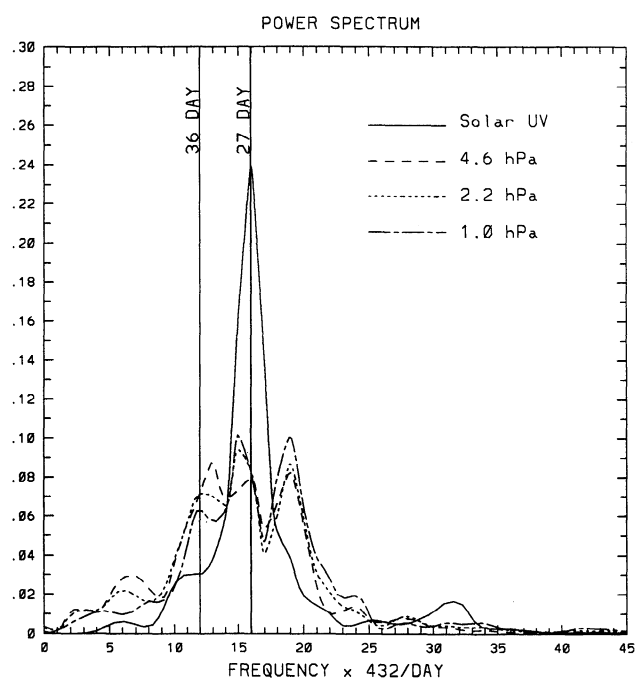

Figure 8. Same format as Figure 7 but for MLS temperature.

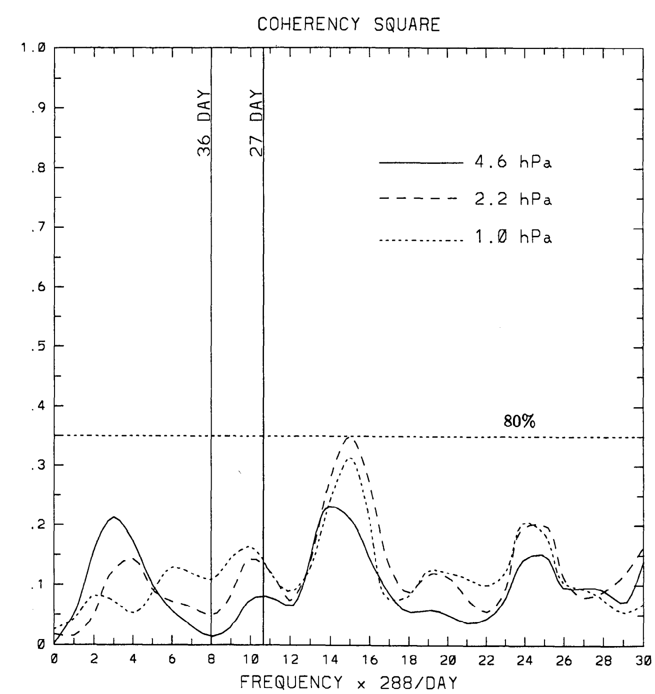

Figure 10. Same format as Figure 9 but for MLS temperature.

Table 1. MLS Ozone and SOLSTICE UV Correlation and Regression Parameters

P, hPa	Phase Lag, days	Coefficient	Sensitivity
0.46	9.4 +/- 2.1	-0.13 +/- 0.030	-0.231 +/- 0.053
1.00	2.8 +/- 4.7	-0.14 +/- 0.019	0.139 +/- 0.038
2.15	-1.2 +/- 0.4	0.16 +/- 0.044	0.267 +/- 0.047
4.64	1.0 +/- 0.6	0.33 +/- 0.048	0.404 +/- 0.033
10.00	2.8 +/- 1.2	0.25 +/- 0.020	0.165 +/- 0.019
21.54	1.8 +/- 2.2	0.06 +/- 0.049	0.031 +/- 0.028
31.62	7.4 +/- 2.2	0.14 +/- 0.051	0.145 +/- 0.027

MLS, microwave limb sounder;
SOLSTICE, solar stellar irradiance comparison experiment.

flux. The sensitivities and phase lag estimates may be directly compared to earlier determinations based on SBUV and SAMS data [e.g., *Hood,* 1986, Tables 1 and 2].

4. Discussion

The UARS MLS/SOLSTICE results of section 3 are broadly consistent with earlier analyses of Nimbus 7 SBUV and SAMS data in indicating the existence of a detectable upper stratospheric response to 27-day solar UV variations. Moreover, the sensitivity estimates of Tables 1 and 2 are also in the same range as estimated from the SBUV and SAMS data [e.g., *Hood,* 1986; *Keating et al.,* 1987]. For example, the maximum ozone-UV sensitivity in Table 1 is 0.40 ± 0.03 near zero lag at 4.6 hPa while that derived from the SBUV data was 0.49 ± 0.04 at 3 hPa. Also, the temperature-UV sensitivity at 1 hPa in Table 2 is 0.077 ± 0.010 while that estimated from the SAMS data was 0.063 ± 0.014. However, a number of differences between the cross-correlative, cross-spectral, and regression analyses of the MLS data and those of the SBUV and SAMS data are also apparent.

With respect to the ozone correlation and response results, a major difference is that there is no significant response to 27-day UV variations at pressure levels above $\sim$ 2 hPa in the MLS data. On the other hand, previous analyses of SBUV measurements have identified a clear solar signal at levels up to at least the stratopause. One possible explanation for this apparent difference is that the MLS zonal means include a majority fraction of nighttime records, whereas the SBUV zonal means were necessarily calculated entirely from daytime records (see section 2). The 27-day UV signal in ozone is of course driven by UV photodissociation of molecular oxygen which produces odd oxygen in the upper stratosphere. Because the photodissociation of molecular oxygen is a strong function of solar-zenith angle, falling to zero at night, and since the ozone lifetime is much less than a day near the stratopause, the ozone mixing ratio response at this level to UV increases is detectable only during the day at any given longitude. Therefore the MLS zonal means, which are based mainly on nighttime records, will not easily detect the solar signal at higher levels in the upper stratosphere. As mentioned in section 2, it would be difficult to construct a valid daytime zonal mean time series from MLS measurements, especially if only a narrow range of local times is desired. Consequently, the derived ozone response measurements represent a weighted mean of the nighttime and daytime response of the upper stratosphere to solar UV variations on the 27-day timescale. This should be taken into account when comparisons are made with theoretical model predictions [e.g., *Brasseur,* 1993; *Fleming et al.,* 1995]. Another minor difference between the MLS and the SBUV ozone response measurements is that the maximum correlation coefficient is only about 0.35 for the MLS data (Figure 2) while that for the SBUV data was about 0.60

Table 2. MLS Temperature and SOLSTICE UV Correlation and Regression Parameters

P, hPa	Phase Lag, days	Coefficient	Sensitivity
0.46	0.2 +/- 2.1	0.20 +/- 0.051	0.056 +/- 0.008
1.00	-1.4 +/- 1.6	0.21 +/- 0.033	0.077 +/- 0.010
2.15	0.4 +/- 0.8	0.14 +/- 0.043	0.060 +/- 0.011
4.64	2.0 +/- 1.4	0.10 +/- 0.020	0.020 +/- 0.010
10.00	4.8 +/- 5.6	0.05 +/- 0.031	0.004 +/- 0.008
14.68	-0.4 +/- 1.2	0.06 +/- 0.039	0.007 +/- 0.008
21.54	-1.6 +/- 0.5	0.08 +/- 0.039	0.016 +/- 0.009

[*Hood and Cantrell*, 1988]. This difference may be due, at least in part, to the fact that the MLS data begin somewhat after solar maximum and therefore do not include as long an interval of large-amplitude solar UV variations as the SBUV data set. However, it may also be due in part to the inclusion of nighttime measurements at all levels in the MLS zonal averages, the effect of which may be to reduce the correlation even at levels as low as 4.6 hPa.

With respect to the temperature response measurements the temperature phase lag at the stratopause estimated from the MLS data (Table 2) is nearly zero (while that estimated from the SAMS data was about 6 days. Also, in general, the correlation of MLS temperature with the 200-205 nm solar flux is lower during the 1000-day interval considered here than was the case for the SAMS data during the period centered on the 1980 solar maximum. Although the MLS temperature data produce a weak 27-day power spectral maximum at 1 hPa (Figure 8), no significant coherency maximum is obtained (Figure 10), so the detection of an MLS temperature response to 27-day solar UV forcing is questionable. Again, the existence of a significant diurnal cycle in the uppermost stratosphere and the necessary inclusion of both day and night measurements in MLS zonal means may provide at least a partial explanation for why a clear MLS temperature response was not detected.

In conclusion, when differences in local time sampling and measurement period are considered, there is no clear inconsistency between the upper stratospheric response to solar UV variations as derived from MLS during solar cycle 22 and SBUV/SAMS data during solar cycle 21. The observed response during solar cycle 21 therefore remains as the best available constraint on stratospheric model calculations of solar ultraviolet forcing [e.g., *Brasseur*, 1993; *Chen et al.*, 1997].

It should be emphasized, however, that analyses of independent data sets having similar local time coverage as that of Nimbus 7 SBUV are necessary to determine definitively whether the upper stratospheric UV response has changed between solar cycles 21 and 22. In this regard, it should be noted that several analyses of NOAA 11 SBUV/2 data for 1989-1990 have suggested significant differences between the ozone response during cycle 22 as compared to that of cycle 21 [*Chandra et al.*, 1994; *Fleming et al.*, 1995]. The differences reported by *Chandra et al.* [1994] were especially large and, according to the authors, are attributable partly to a bias caused by using weekly rather than daily values of the solar irradiance in the initial SBUV/2 ozone retrieval algorithm. *Fleming et al.* [1995] analyzed a later, reprocessed version of the SBUV/2 data and reported smaller differences, including a 25–40% lower ozone-UV sensitivity at 1–2 hPa for 1989-1990 compared with 1979-1983 (see their Figure 6). If real, such a difference might indicate that long-term changes in stratospheric composition (e.g., chlorine loading) may be modifying the UV response. However, further analyses of daily Nimbus 7 SBUV data (available through June 1990), NOAA 11 SBUV/2 data, and independent UARS (CLAES) data records are needed to test this provisional result. As shown by the present analysis of MLS data, because of the strong ozone diurnal cycle near the stratopause, future analyses must carefully account for differences in local time coverage when comparing UV response measurements derived from different satellite data records.

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