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A partial correlation analysis of the stratospheric ozone response to 27-day solar UV variations with temperature effect removed

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Abstract. Observational detection of upper stratospheric ozone responses to 27-day solar ultraviolet (UV) variations is often inhibited by larger, dynamically induced ozone variations, which result mainly from the temperature dependence of reaction rates controlling the ozone balance. Here we show that partial correlation coefficients of solar UV and tropical upper stratospheric ozone (1–5 hPa) with the temperature effect removed are larger (07–0.8) than are total correlation coefficients of ozone and solar UV (0.4–0.6). The phase lag of ozone relative to solar UV is also increased, and the maximum ozone-UV correlation is obtained at higher altitudes, as compared with correlation analyses using ozone and solar UV data alone. Assuming that temperature variations are not forced by solar UV variations, the ozone sensitivity to solar UV and temperature can be calculated using a linear multiple regression model. The ozone sensitivity to solar UV is generally independent of time periods used for the analysis. However, the magnitude of the ozone sensitivity to temperature at 1–2 hPa increased significantly from solar cycle 21 to solar cycle 22, possibly reflecting long-term changes in the composition of the upper stratosphere.

1. Introduction

The response of stratospheric ozone to solar UV flux changes occurring on the timescale of the 27-day solar rotation period has been extensively studied since satellite data became available [*Gille et al.*, 1984; *Hood*, 1984; *Keating et al.*, 1985; *Chandra*, 1986; *Hood*, 1986; *Lean*, 1987; *Chandra and McPeters*, 1994; *Hood and Zhou*, 1998]. Statistical and spectral analyses, including cross-correlation analyses, are useful mathematical tools for such studies. However, any correlation study and its interpretation must be based on a thorough understanding of physical mechanisms of ozone variations. For instance, to minimize dynamical effects of the atmosphere, ozone data are usually averaged over the tropics, detrended, and deseasonalized before use in correlation analysis.

In the upper stratosphere, where ozone is nearly in photochemical equilibrium, temperature fluctuations produce ozone fluctuations of opposite sign because of the temperature dependence of dominant reaction rates determining the ozone balance [e.g., *Barnett et al.*, 1975]. This temperature-induced ozone variation was removed from the ozone data in early studies by using a model for the ozone-temperature relationship prior to cross-correlation analyses [*Hood*, 1984]. Later, with improved data quality in both ozone and solar UV, direct ozone data (unmodeled) have been used in correlation analysis with solar UV flux. To examine the effect of temperature, correlations of temperature and solar UV variations have been separately analyzed and incorporated into a physical model in some studies [*Hood*, 1986; *Keating et al.*, 1985]. With such a model the negative time lag of ozone relative to solar UV flux (ozone leading solar UV) found in the upper stratosphere could be explained as the result of interactions of ozone, temperature and solar UV flux [*Hood*, 1986; *Hood and Jirikowic*, 1991]. In some other studies, solar UV flux and temperature have been put together in a multiple regression model for ozone [*Chandra*, 1986]. The regression results show that ozone is more sensitive to dynamically induced changes in temperature than to changes in solar UV flux, so that ozone response to short-term solar UV change can be detectable only under favorable conditions, such as at low latitudes and during high solar UV variations.

According to statistical theory, if a correlation of two variables is influenced by other variables, the correlation coefficient of the two variables may be misleading. However, the influence of other variables can be eliminated by replacing the correlation with the partial correlation. In this paper we calculate partial correlation coefficients of ozone and solar UV with the temperature effect removed and compare them with the correlation coefficients of solar UV and ozone without removing the temperature effect (referred as to total correlation coefficients). Implicitly, we treat temperature as an independent variable similar to solar UV. Strictly speaking, temperature and solar UV flux are dependent in general. However, according to previous data analyses [*Chandra*, 1986; *Hood*, 1987] the 27-day solar UV effect on temperature is

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relatively small compared with the solar UV effect on ozone. Reasons for this characteristic may include the following: (1) Ozone is affected by solar UV in the 170–210-nm wavelength range, which is more important in the photodissociation of oxygen, while temperature is mainly affected by longer wavelengths in the 210–290-nm range, which is more important in heat absorption [*Donnelly and Heath*, 1984]. As is well known, the longer the wavelength, the smaller the variability. In fact, the 27-day variability at 210–290-nm wavelengths is only one half to one third of that at 170–210 nm wavelengths [*Rottman*, 1988; *Brasseur*, 1993]. (2) According to photochemical and radiative theory and model calculations the lifetime of ozone is several hours to 1 day in the upper stratosphere (e.g., 40–50 km), where the radiative photochemical relaxation time of temperature is 3–5 days [*Kinnersley and Harwood*, 1993; *Dickinson*, 1973]. (3) The loss rate of ozone is strongly dependent on temperature, while the temperature change rate depends not only on ozone but also on other absorptive gases (e.g., H_2O, CH_4, and CO_2). (4) Temperature is more subject to dynamical changes such as adiabatic heating or cooling associated with vertical motions. Therefore the temperature variation on the timescale of a few weeks is more likely due to internal processes such as planetary and gravity wave propagating and breaking, photochemical reactions and radiative perturbations. For instance, a major 23–24-day period has been found in the Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) temperature data [*Zhou and Miller*, 1997], which may be induced by tropical Kelvin waves [*Wallace and Kousky*, 1968].

A partial correlation analysis is more appropriate for studying how ozone responds to solar UV variations in different time periods, for example, in different stages of a solar cycle or in different solar cycles, because total correlations cannot show whether a difference between two time periods is from solar UV or from temperature effects. In addition, a partial correlation analysis can provide us an alternative way to evaluate our understanding of the solar UV and ozone relationship based on previous data analyses and theoretical explanations. For instance, would there be a negative lag of ozone to solar UV if the temperature effect is removed? On the basis of the above considerations we believe that a second look at separating the effect of temperature and solar UV changes on ozone variability is warranted using the improved satellite data records that are now available. For this purpose we will assume that the upper stratospheric ozone is dependent upon two variables: solar UV and temperature. By using partial correlation analysis the ozone response to solar UV and temperature can be more clearly separated, as discussed later. In section 2 we describe the solar UV, ozone, and temperature data used in this study and demonstrate the use of partial correlation using a simple example. The partial correlation results of actual data are discussed in section 3. A linear multiple regression of ozone is used to calculate ozone sensitivities to solar UV and temperature and modified ozone data with temperature effect removed are used to calculate coherency square of solar UV and ozone in section 4. A summary and conclusion are given in section 5.

2. Data and Method of Analysis

We study the ozone response to solar UV variations in two major periods of solar cycles 21 and 22. Each period includes 2000 days, i.e., from January 12, 1980, to July 3, 1985, for the solar cycle 21 period and from January 23, 1989, to July 15, 1994, for the solar cycle 22 period. For statistical purposes we divide each period into two 1000-day subperiods and denote them as S21 period 1, S21 period 2, S22 period 1, and S22 period 2, respectively. We use Mg II index (R. P. Cebula and M. T. DeLand, personal communications, 1997) as a proxy for solar UV flux changes [*Heath and Schlesinger*, 1986], as shown in Figure 1. Note that there are more missing data of the Mg II index in solar cycle 21 than in solar cycle 22; we use linear interpolation for a continuous time series. In general, S21 period 1 and S22 period 1 correspond to solar maximum conditions with larger UV variability, and S21 period 2 and S22 period 2 correspond to declining stages of the solar cycles with smaller UV variability. We use the upper stratospheric ozone mixing ratio profiles measured by the solar backscattered ultraviolet (SBUV and SBUV/2) instruments on the Nimbus 7 and NOAA 11 satellites. The version 6 SBUV ozone data are used in this study, which is appropriate for comparison with previous results using the same version of data. We use the National Centers for Environmental Prediction (NCEP) temperature data, which are available from 1000 to 0.4 hPa since 1979. In addition, we use the UARS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) 200–205-nm UV flux and MLS ozone and temperature data [*Rottman et al.*, 1993; *Waters*, 1993] in S22 period 2 for a comparison.

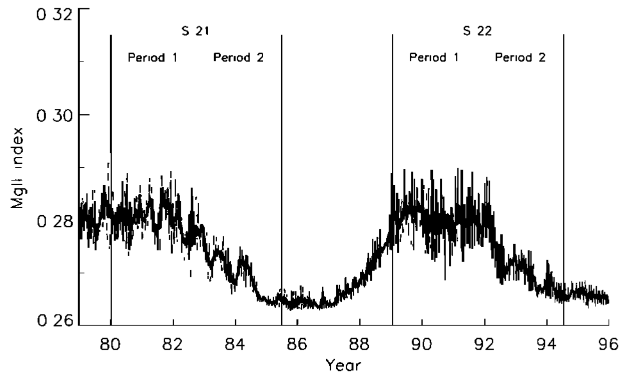

Figure 1. Daily Mg II index from 1979 to 1995. Gaps indicate where data are missing. The thick line is the 35-day running average. The vertical lines mark the four periods studied, corresponding to the solar maximum and declining stages in solar cycles 21 and 22.

The ozone and temperature data are averaged over the 30°S–30°N tropical area to minimize dynamical effects. All data are then detrended and deseasonalized by subtraction of a 35-day running average and smoothed by a 7-day running average. This procedure has been commonly used in previous studies [e.g., *Hood*, 1986; *Chandra*, 1986] to filter long-term variations, such as annual and seasonal changes, as well as to filter very short term fluctuations (noises). However, when a time series is filtered and smoothed, the number of independent data points is inevitably altered. Therefore a proper significance level needs to be determined for correlation coefficients. In this study the significance level is ascertained in the following method. We first choose three random time series of the same length of actual data (1000 points each) and use the same filtering and smoothing procedure on the random data as is used on the actual data. Then we calculate total and partial correlation coefficients for the three random time series. This calculation is repeated for numerous times, with different random data at each time, until a clear Gaussian distribution of correlation coefficients is established (800 times have been repeated for convergence). The distribution of correlation coefficients indicates a mean value of 0.0 and a standard deviation of 0.076 for both total and partial correlation analyses. Therefore we may cite 0.15 (two standard deviation value) as the 95% significance level for the actual data analysis.

In the case of three variables the partial correlation coefficient is calculated by

$$r_{ij\cdot k} = \frac{r_{ij} - r_{ik}r_{jk}}{\sqrt{(1 - r_{ik}^2)(1 - r_{jk}^2)}}, \tag{1}$$

where r_{ij}, r_{ik}, and r_{jk} are correlation coefficients between two variables, and $r_{ij\cdot k}$ is the partial correlation coefficient between variables i and j with the effect of variable k removed [*Hald*, 1952]. To illustrate partial correlations, we give a simple example. Given three time series with data length of N,

$$x_i(n) = \sin\frac{2n\pi}{27},$$

$$x_k(n) = \frac{2}{3}\sin\left(\frac{2n\pi}{24} - \frac{7\pi}{6}\right), \tag{2}$$

$$x_j(n) = x_i(n) + x_k(n), \qquad n = 1,2,\cdots, N,$$

as shown in Figure 2. Here x_i has a 27-day period, which may be considered as "solar UV," x_k has a 24-day period with a 14-day phase lag to x_i, which may be considered as "temperature," and x_j is a linear combination of x_i and x_k, which may be regarded as "ozone." (The actual variations of solar UV, ozone, and temperature are also shown in Figure 2.) If there is no temperature effect, i.e., $x_j = x_i$, then ozone and solar UV are perfectly correlated. With the temperature effect the total correlation coefficient of ozone and solar UV is <1 (0.78). With the temperature effect removed using (1) the partial correlation coefficient of ozone and solar UV becomes 1; that is, the real relationship of ozone and solar UV is revealed. In reality, ozone change is not necessarily a linear combination of solar UV flux and temperature changes. However, (1) should work for either linear or nonlinear cases.

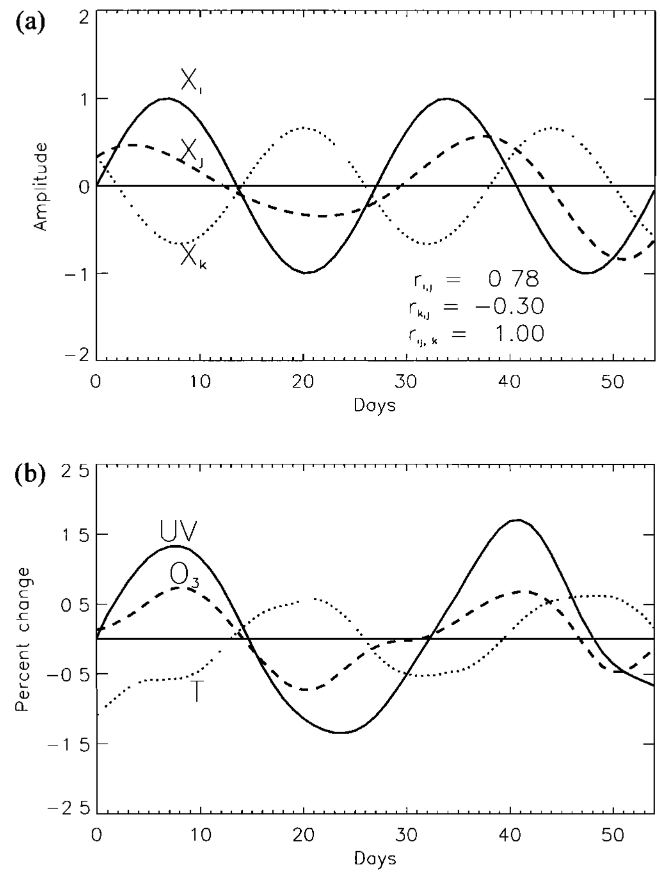

Figure 2. (a) Example data to illustrate partial correlation of x_i and x_j with the effect of x_k removed, where x_i and x_k are two independent variables and x_j is a dependent variable (see text). (b) Actual data of variations of solar ultraviolet (UV), ozone, and temperature at 2 hPa from May 2, 1989, to June 2, 1989. Note that the temperature variation is amplified by a factor of 10 for clear illustration.

3. Partial Correlation Results

Results of the partial correlation analysis are given in Figure 3 and Table 1 for the two periods in solar cycle 21. Those results are compared with the total correlation coefficients of ozone and solar UV at five pressure levels (1, 2, 5, 10, and 30 hPa). In calculating lag correlations the same time lag relative to solar UV is used for ozone and temperature. In general, the partial correlation coefficients of ozone and solar UV (solid lines) are considerably larger than the total correlation coefficients (dashed lines) near zero lag. For instance, in S21 period 1 the maximum partial correlation coefficients are 0.73, 0.77, and 0.79 at 1, 2, and 5 hPa, while the maximum total correlation coefficients are 0.58, 0.58, and 0.63 at the same pressure levels. The partial correlation coefficients in S21 period 2 are smaller than those in S21 period 1. This may reflect the reduced ratio of solar UV-ozone "signal" to temperature-induced ozone "noise" during the solar maximum stage as compared to the declining stage. For instance, we can define the snr as the ratio of average solar UV variability (percent change) and temperature variability over the period. Table 2 gives values of the snr at 2 hPa, which shows that the ratio in S21 period 2 (2.7) is much smaller than that in S21 period 1 (7.7). The reduced snr in S21 period 2 is in part due to the weakened solar UV variability (~50% decrease) and in part due to the enhanced temperature variability (~40% increase) for which the cause is unclear. The time lags of maximum solar UV-ozone partial correlations are very similar in S21 period 1 and S21 period 2; they are 1–3 days in the upper stratosphere (1–5 hPa). However, the time lags of solar UV-ozone total correlations are different in the two periods. In particular, the time lag becomes negative (ozone leads solar UV) at 1 and 2 hPa in S21 period 2. The difference in time lag is consistent with the theoretical interpretation that temperature effect can shift the maximum ozone response to earlier times [*Hood*, 1987]. In both the periods the total correlation coefficients peak at 5 hPa, while the partial correlation coefficients have similar values at 2 and 5 hPa. At 10 hPa the partial and total correlations are almost identical, implying that the temperature effect is negligible at that level. Down to 30 hPa the partial correlation differs again from the total correlation, but both coefficients are much smaller than those at upper levels.

Similar results for the solar cycle 22 period are shown in Figure 4 and Table 1. All partial correlation coefficients from 1 to 5 hPa are larger than the corresponding total correlation

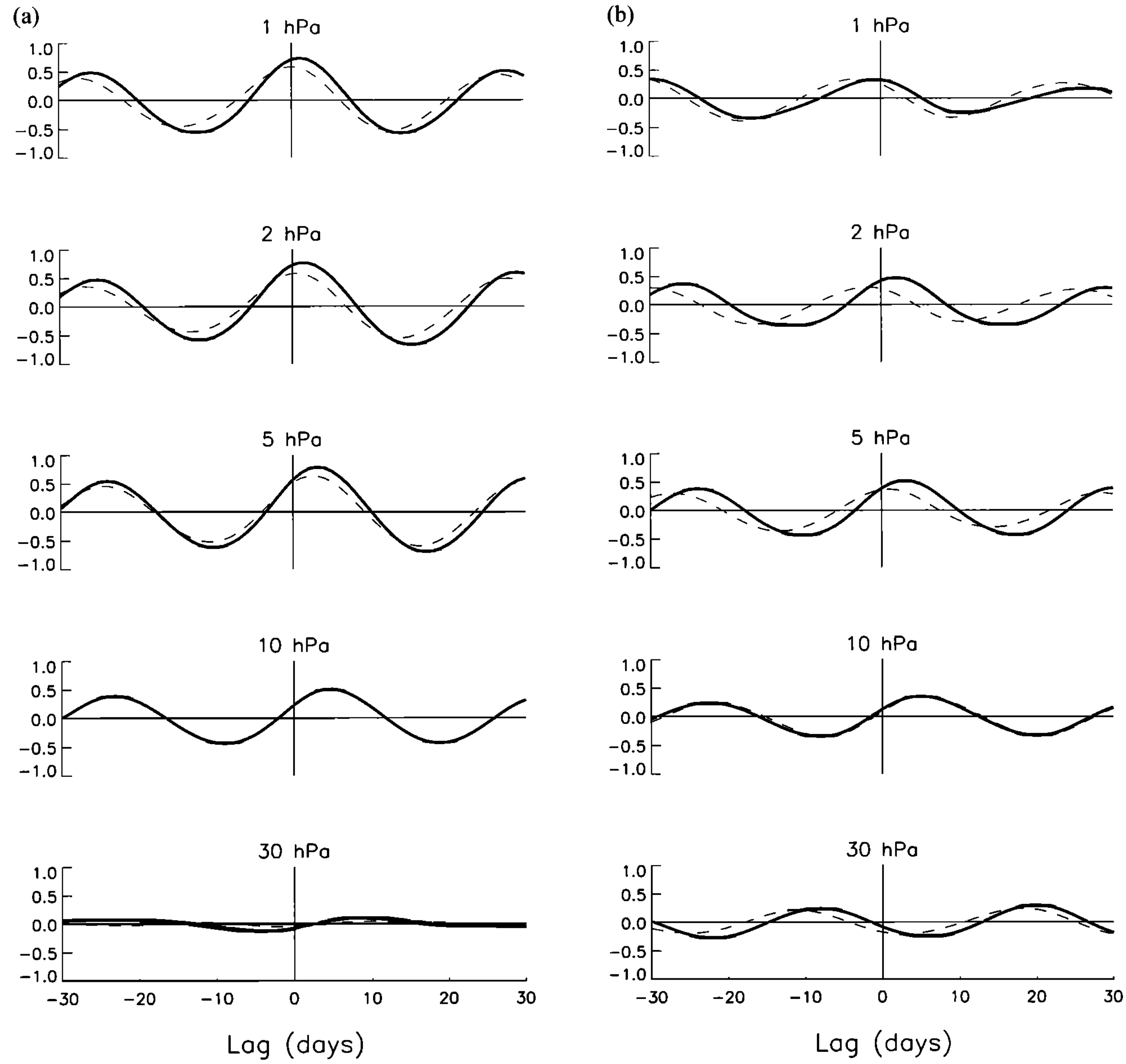

Figure 3. Partial (solid lines) and total (dashed lines) correlation coefficients of solar backscattered ultraviolet (SBUV)/2 ozone (30°N–30°S) and solar UV (Mg II index) as a function of time lag for the two periods in solar cycle 21: (a) S21 period 1 and (b) S21 period 2.

coefficients. Time lags of partial correlations are all positive and 1 day longer than those of total correlations. In S22 period 1 both partial and total correlations are very close to those in S21 period 1, for example, the maximum partial correlation coefficients are 0.74, 0.77, and 0.78 at 1, 2, and 5 hPa, respectively, with time lags of 2–3 days. The snr in this period is also close to that in S21 period 1, as shown in Table 2. In S22 period 2 the partial correlation coefficients are smaller than those in

Table 1. The Maximum Total and Partial Correlation Coefficients and Corresponding Ozone Lag Days to Solar UV Variations

	S21 Period 1		S21 Period 2		S22 Period 1		S22 Period 2	
P, hPa	Total	Partial	Total	Partial	Total	Partial	Total	Partial
1	0.58(0)	0.73(1)	0.34(−3)	0.33(0)	0.45(1)	0.74(2)	0.15(0)	0.65(1)
2	0.58(1)	0.77(2)	0.31(−2)	0.48(2)	0.52(1)	0.77(2)	0.27(0)	0.73(1)
5	0.63(3)	0.79(3)	0.37 (1)	0.52(3)	0.61(3)	0.78(3)	0.37(1)	0.59(2)
10	0.51(5)	0.50(5)	0.38 (5)	0.38(5)	0.35(5)	0.35(5)	0.19(3)	0.19(3)

Ozone lag days are in parentheses. Two standard deviations for all coefficients is ±0.15.

Table 2. Average Solar UV Variability (Percent Change), Temperature Variability at 2 hPa, and the snr in the Four Periods Studied

	S21 Period 1	S21 Period 2	S22 Period 1	S22 Period 2
Mg II index	2.5	1.2	3.2	1.7
Temperature	0.32	0.44	0.38	0.41
snr	7.7	2.7	8.4	4.2

S22 period 1 because of the reduced snr, as in the solar cycle 21 period. However, these coefficients are not as small as those in S21 period 2, and there is a maximum of 0.73 at 2 hPa. This is consistent with the difference in the snr, which is relatively larger in S22 period 2 than in S21 period 2. This larger snr in S22 period 2 is mainly due to the smaller change in temperature variability (~10% increase) because solar UV variability has a similar reduction (~50%) from period 1 to period 2 in both solar cycles (Table 2).

Using independent data sets of solar UV, ozone, and temperature from the UARS measurements for S22 period 2, we have done a similar analysis in which ozone and temperature are taken from MLS data and solar UV is represented by SOLSTICE 200–205-nm flux. Because the MLS ozone and temperature data in the tropical upper stratosphere are overwhelmed by the 36-day satellite yaw period, which results from the diurnal cycle at high altitudes combined with the necessary inclusion of nighttime records in calculating zonal averages

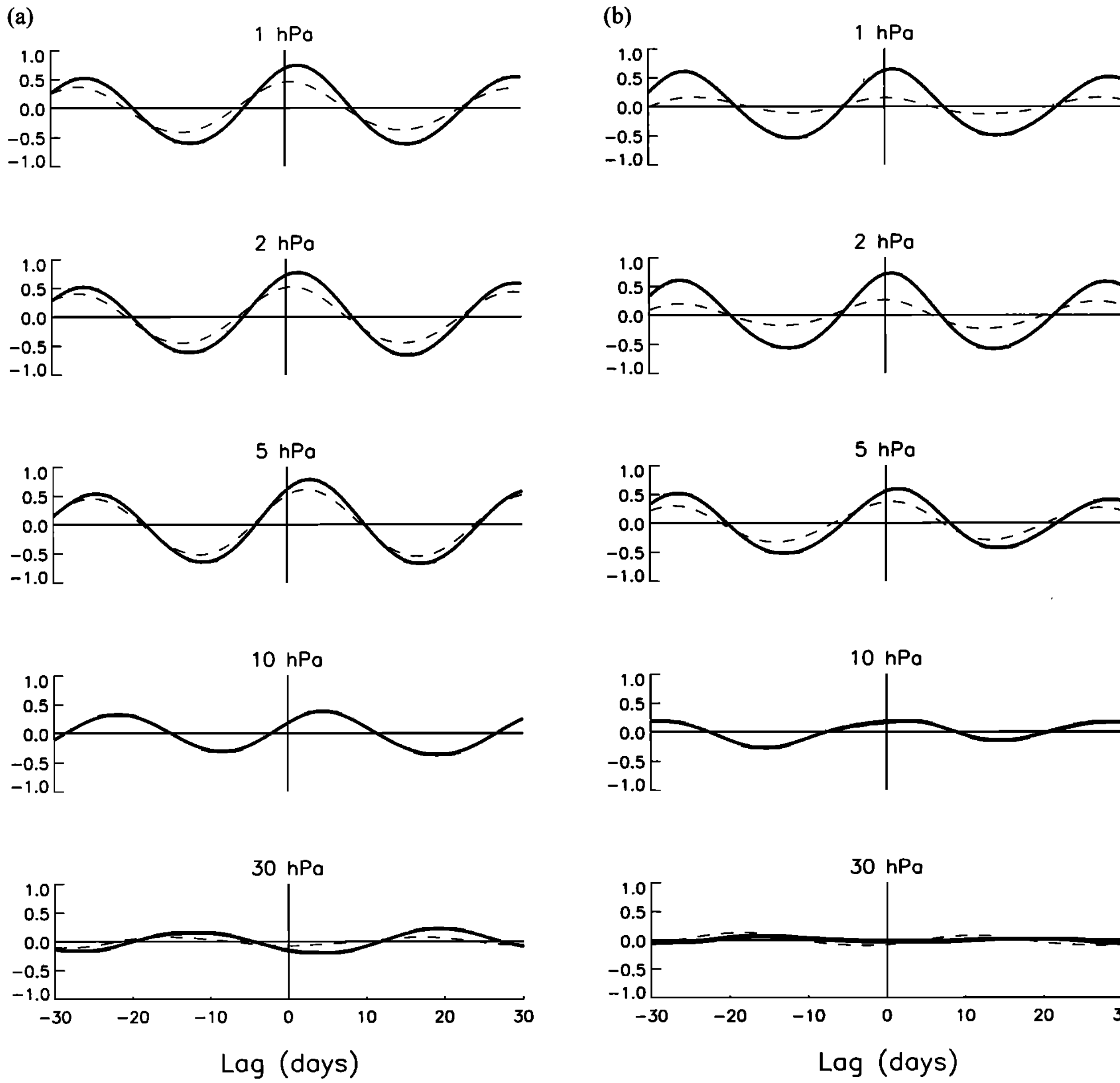

Figure 4. Same as Figure 3 except for the two periods are (a) S22 period 1 and (b) S22 period 2.

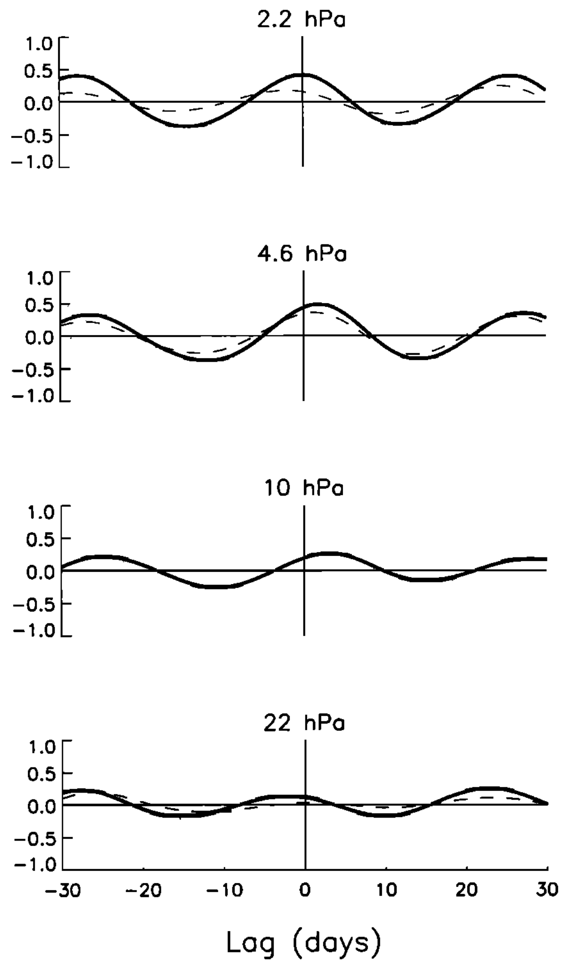

Figure 5. Partial (solid lines) and total (dashed lines) correlation coefficients of solar UV Upper Atmosphere Research Satellite ((UARS) Solar Stellar Irradiance Comparison Experiment (SOLSTICE)) and ozone (UARS Microwave Limb Sander (MLS)) in S22 period 2.

[*Hood and Zhou*, 1998], we only use MLS ozone data below 2 hPa. Below 2 hPa the 36-day period still exists but is weaker than at higher altitudes. Moreover, we use an additional bandpass filter [*Murakami*, 1979; *Zhou et al.*, 1997] on the time series of ozone residuals after subtraction of the 35-day running average and smoothing by a 7-day running average to remove this artificial 36-day period. A narrow band of 4-day window centered at 36-day is used in the filtering, which effectively removes the 36-day period with little effect on the 27-day period.

The partial and total correlation results are shown in Figure 5. Qualitatively, they are in good agreement with the previous results obtained from Mg II index, SBUV/2 ozone, and NCEP temperature. The partial correlation coefficients are larger than the total correlation coefficients at 2.2 and 4.6 hPa. For instance, at 2.2 hPa the maximum partial correlation coefficient (0.40) is larger than the total correlation coefficient (0.18) by a factor of 2. However, the partial correlation coefficients of ozone and solar UV are smaller than that with Mg II index and SBUV/2 ozone. The difference is not due to the different solar UV data used here because the results would remain almost the same if we replace the SOLSTICE data with the Mg II index data. It is not due to the difference of MLS and NCEP temperature either. We have repeated the calculation with the UARS solar UV and ozone data replacing the MLS temperature with the NCEP temperature. The partial correlation coefficients are only enhanced slightly, for example, the maximum coefficient at 2.2 hPa is increased from 0.40 to 0.42. Therefore the difference is probably due to different ozone measurements. The SBUV/2 instrument measures ozone in middle to late afternoon, which is a favorable condition to detect solar signal, while the MLS instrument measures ozone at different times of the day. In fact, the MLS data includes a large portion of nighttime measurements, which have a much weaker correlation with solar UV than the SBUV/2 daytime measurements in the total correlation analysis [*Zhou and Miller*, 1997]. Nevertheless, the partial correlation analysis has made the solar UV-ozone relationship more apparent in the MLS data (as well as in the SBUV/2 data).

4. Linear Regression Results

In addition to correlation analysis, ozone response to solar UV flux changes is measured in terms of sensitivity, or percent change in ozone per 1% change in solar UV. In some studies, ozone sensitivity was calculated by linear regressions in which only one independent variable (solar UV flux) was considered [*Hood and Cantrell*, 1988; *Hood and Jirikowic*, 1991; *Fleming et al.*, 1995]. On the other hand, *Chandra* [1986] used a multiple regression, in which temperature is treated as another independent variable, to study ozone sensitivities to both solar UV and temperature changes because the short-term temperature oscillations are more likely associated with dynamical changes and are less sensitive to changes in solar activity. Here we compare single-variable regression and multiple (two-variable) regression results using the same data sets used for partial correlation analyses. The purpose is to examine from another aspect how temperature affects ozone response to solar UV changes at different altitudes and at different time periods. The ozone regression equation is written as

$$O_3 = A_0 + A_1 S + A_2 T, \qquad (3)$$

where O_3, S, and T denote percent changes in ozone, solar UV, and temperature, respectively, A_0 is a constant, A_1 is equivalent to ozone sensitivity to solar UV, and A_2 is equivalent to ozone sensitivity to temperature. This equation is the same one used by *Chandra* [1986], who calculated the ozone sensitivity to solar UV and temperature using SBUV ozone, 205 nm solar UV flux, and Stratospheric and Mesospheric Sounder (SAMS) temperature in a 30-month period (December 1978 to May 1981). The ozone sensitivity to solar UV (A_1) obtained by Chandra is 0.43 ± 0.11, and the ozone sensitivity to temperature (A_2) is −2.96 ± 0.55, both at 3 hPa.

We show the ozone sensitivity to solar UV change (A_1) in the four periods studied in Figure 6. Time lags are not considered in the regression. The vertical distributions and magnitudes from 1 to 30 hPa are very similar in those periods despite solar UV changes, which are different. For instance, the ozone sensitivity to solar UV change has a maximum value of 0.46 ± 0.03 at 2 hPa and decreases to near zero at 30 hPa. Our result is in good agreement with that calculated by *Chandra* [1986]. When ozone is regressed using solar UV only, i.e., the last term in (3) is omitted, we find that there are little differences from the results of multiple regressions in the periods with solar

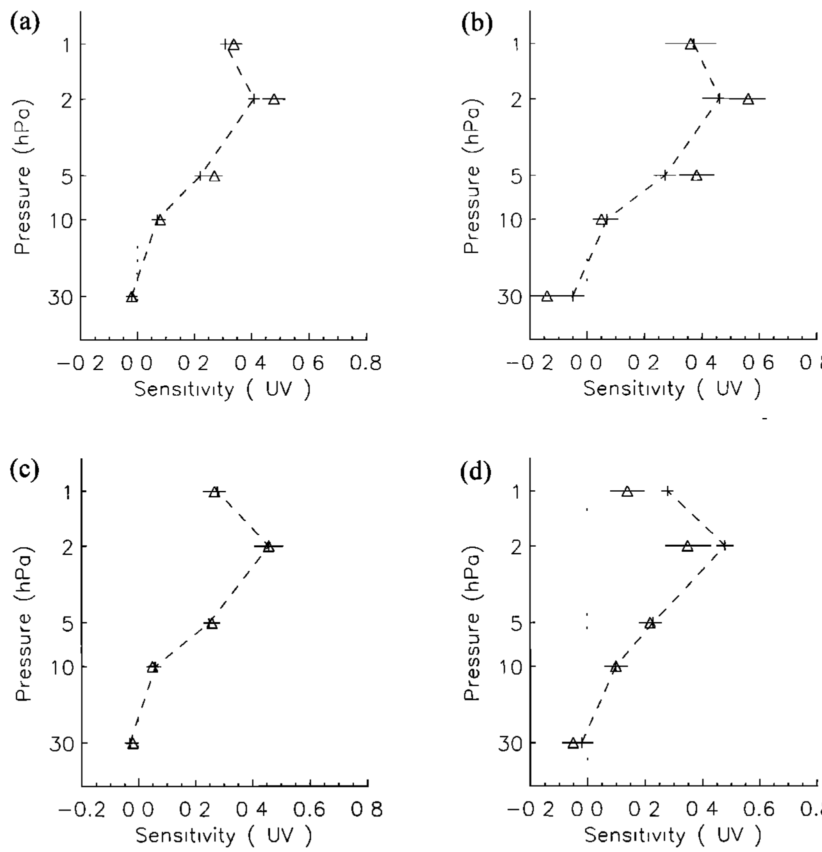

Figure 6. Ozone sensitivity to solar UV from 1 to 30 hPa: (a) S21 period 1, (b) S21 period 2, (c) S22 period 1, and (d) S22 period 2. The dashed lines are calculated from the linear multiple regression, while the triangles are calculated without including temperature variations. Horizontal bars indicate two standard deviations.

maximum (period 1). However, the differences become larger in the upper stratosphere in the declining stage of a solar cycle (period 2). The ozone sensitivity to solar UV becomes larger at 2 and 5 hPa in S21 period 2 and smaller at 1 and 2 hPa in S22 period 2 than the multiple regression results. This comparison indicates that ozone sensitivity to solar UV changes obtained in early studies would be accurate only under the condition of solar maximum if temperature effect was not considered; otherwise, the sensitivity might be overestimated or underestimated.

The ozone sensitivity to temperature (A_2) is shown in Figure 7. The vertical distribution is also similar for the four periods. The maximum negative sensitivity is at 2 hPa, and it decreases downward and becomes positive at 30 hPa because different photochemical and dynamical processes in the upper and lower levels. The sensitivity is near zero at 10 hPa, which is consistent with the partial correlation results that are almost identical to the total correlation results. The magnitude of ozone sensitivity to temperature is about the same within the same solar cycle but is different from solar cycle 21 to solar cycle 22. The sensitivity at 2 hPa ranges from -4.1 ± 0.2 to -3.8 ± 0.1 (or -1.5% change in ozone per 1 K change in temperature) in solar cycle 21. If we interpolate this value to 3 hPa, we obtain $-3.1 \pm 0.2 \sim -2.7 \pm 0.1$, which is very close to the value calculated by *Chandra* [1986]. However, the sensitivity has apparently increased in solar cycle 22, becoming $-4.7 \pm 0.2 \sim -4.8 \pm 0.1$ at 2 hPa. The differences are even larger at 1 hPa; for example, the sensitivity is -2.1 ± 0.2 in S21 period 2 and -4.5 ± 0.1 in S22 period 2. The positive sensitivity at 30 hPa is also larger in solar cycle 22 than in solar cycle 21.

It is interesting to see how the ozone variations can be represented by the two-variable regression equation. In Figure 8 we show the results of 2 hPa ozone regressions in the S22 period 1 (results are similar at 1 and 5 hPa). If the temperature effect is not included, the regressed ozone follows the solar UV variation approximately but does not predict the large amplitudes in the ozone change. The correlation coefficient between the regression model and the data is 0.51. When temperature is included in the regression model, most of the large amplitudes in the actual ozone data are predicted, except for a short time interval in March 1991, where the large discrepancy is probably attributed to the missing data in the Mg II index. The multiple correlation coefficient is increased to 0.87. Though similar results are found for other periods, the effect of including temperature in the regression equation is more pronounced in the second period of both solar cycles 21 and 22, when the temperature effect is relatively larger. This is also consistent with previous results of partial correlation analysis.

Using the multiple regression results, we also performed cross-spectral analysis to see how the solar UV and ozone coherency is influenced by temperature variations. The coherency is analogous to the square of a correlation coefficient, except that the coherency is a function of frequency. Because ozone variations are very well represented by the linear combination of solar UV and temperature, we can remove the temperature effect by subtracting the portion of regressed

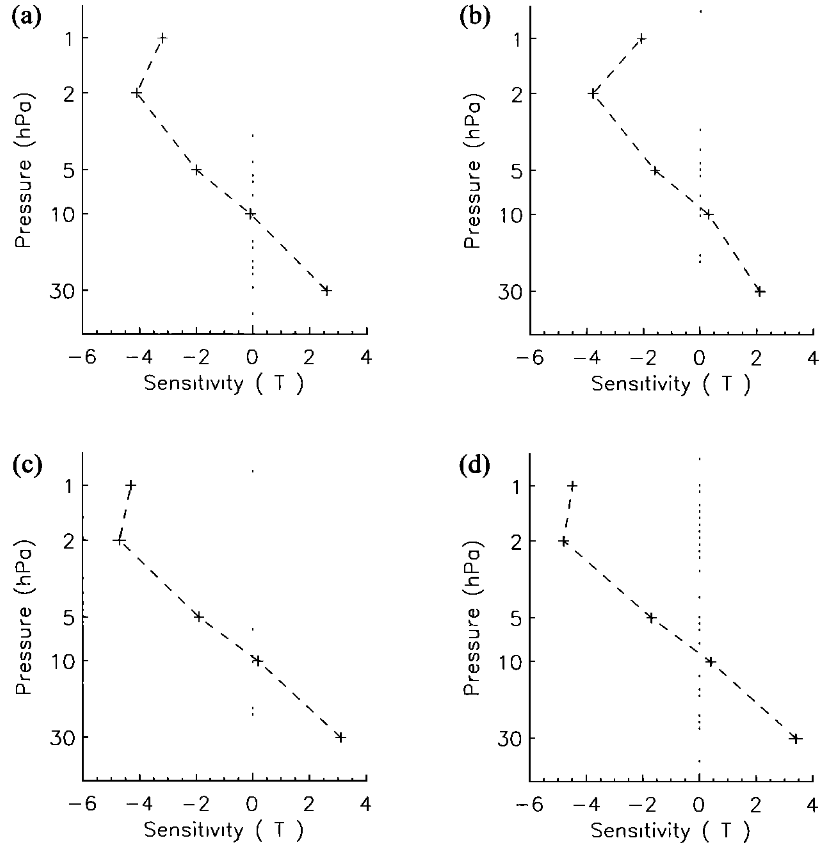

Figure 7. Same as Figure 6 except for ozone sensitivity to temperature.

ozone due to temperature variations. The remainder then includes portions due to solar UV and other secondary factors. We then calculate the coherency square using solar UV and the modified ozone for the four periods. The results at 5 hPa are shown in Figure 9 (solid lines). In all of the periods, there is a peak at or near the 27-day period, with a confidence level of at least 95%. The coherency square is larger in the solar maximum than in the declining stage of a solar cycle. For a comparison, we also calculated coherency square using unmodified ozone data (dashed lines). When the temperature effect is not removed, the coherency square is significantly reduced, though there is a peak at or near the 27-day period. In the periods of solar maximum the confidence level for this peak is above 95%. However, in the declining stage of a solar cycle the coherency square is too small to meet the statistically significant confidence level, and the peak is sometimes shifted off the 27-day period (e.g., in S22 period 2) if the temperature effect is not removed. Therefore coherency studies using direct ozone and solar UV could detect the 27-day solar modulation only under favorable conditions, such as in a solar maximum period.

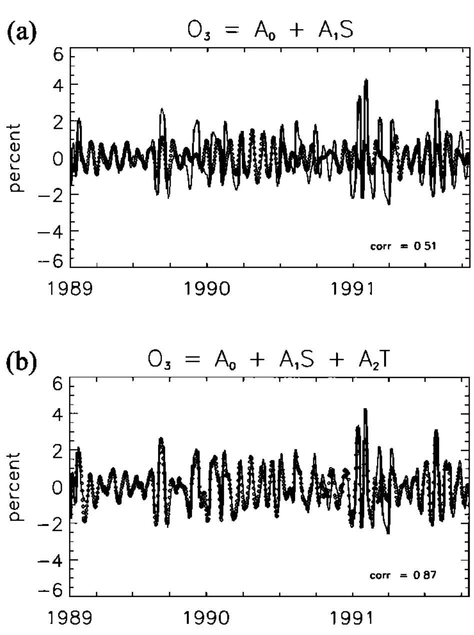

Figure 8. Daily ozone percent change at 2 hPa in S22 period 1. The solid lines are actual data, and the diamonds are linear regressions from (a) solar UV only and (b) solar UV and temperature.

5. Conclusions

On the basis of the facts that upper stratospheric ozone photochemistry is strongly dependent on solar UV and temperature and that the response of temperature itself to the 27-day solar UV variation is relatively weak, we have extended previous correlation and regression studies of stratospheric ozone response to solar UV variations to incorporate temperature as an independent variable. We examined four different periods corresponding to solar maximum and declining stages in solar cycles 21 and 22. The partial correlations of ozone and solar UV with temperature effect removed have the following common features: (1) The partial correlation coefficients are

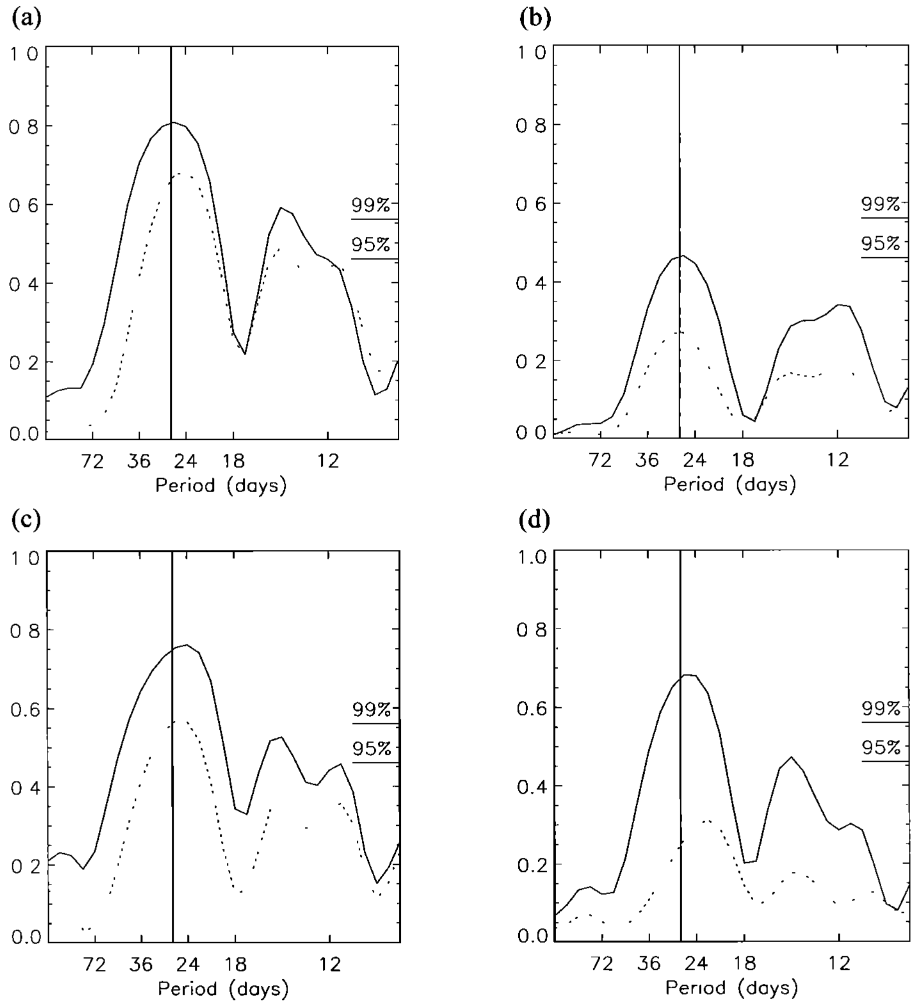

Figure 9. Coherency square calculated from solar UV and modified ozone with temperature effect removed (solid line) and from solar UV and unmodified ozone (dashed line) (a) S21 period 1, (b) S21 period 2, (c) S22 period 1, and (d) S22 period 2. The vertical lines indicate the 27-day period. The confidence levels are marked at the right side.

considerably larger than the total correlation coefficients in the upper stratosphere (1 ~ 5 hPa). The maximum partial correlation coefficients are 0.7 ~ 0.8, while the total correlation coefficients are 0.4 ~ 0.6. (2) The time lag of ozone to solar UV in the partial correlation is longer than that of the total correlation, so that there is essentially no negative time lag (ozone leading UV) for the partial correlation in the upper stratosphere. (3) The maximum ozone-UV correlation occurs at somewhat higher altitudes between 2 and 5 hPa when the temperature effect is removed. (4) The temperature effect is a minimum at 10 hPa, so that the partial and total correlations are nearly identical. This is consistent with the hypothesis that the 10 hPa level is near the lower boundary of the chemical regime for ozone production. These features are physically meaningful and consistent with theoretical results.

By including temperature variations in the ozone regression equation we find that (1) in the upper stratosphere, ozone variations on a timescale of a few weeks can be well represented by only two variables: solar UV and temperature. In particular, the large amplitudes in ozone variations are closely related to temperature variations [cf. *Barnett et al.*, 1975; *Hood*, 1984]. (2) The ozone sensitivity to solar UV is generally independent of time periods used for analyses, although solar UV variations may be very different during different time periods. (3) The ozone sensitivity to temperature is almost the same within the same solar cycle but is larger in solar cycle 22 than in solar cycle 21. (4) The coherency square of solar UV and ozone is significantly increased when temperature effect is removed, and the 27-day peak has a confidence level of 95% or higher for all the periods studied. These results confirm that solar UV and temperature are indeed two dominant factors in the upper stratosphere ozone variation and temperature can be approximately treated as an independent variable like solar UV.

The extent of ozone response to solar UV in a given time period depends on the relative magnitude of solar UV changes and temperature changes, which is indicated by a snr in this paper. The partial correlation coefficients and the coherency square of solar UV and ozone are qualitatively determined by the snr. When this ratio is large, as in solar maximum conditions, these statistical quantities are very similar in solar cycles 21 and 22. Although removing the temperature effect would enhance the solar signal, we are able to detect the 27-day solar UV modulation on ozone from direct ozone and solar UV data but only in the solar maximum period when temperature effect is relatively small. In the declining stage of a solar cycle, however, it is necessary to remove temperature effect in correlation and cross-spectral analyses. Ozone sensitivity to solar UV seems to be independent of the snr when calculated using a multiple regression equation in which temperature effect is separated.

The ozone sensitivity to temperature is significantly larger in solar cycle 22 than in solar cycle 21. Note that similar results have been reported by *Chandra et al.* [1994], who calculated the ozone sensitivity to temperature using ozone and temperature time series only. Although a thorough investigation of the cause for this difference is beyond the scope of this paper, a possible explanation is that the chemical components of atmosphere have changed from solar cycle 21 to solar cycle 22; for example, the enhanced chlorine level may have influenced ozone variations under certain temperature conditions. Ozone loss rates are generally proportional to the product of rate constants, which are temperature-dependent, for example, exp $(-2060/T)$ for $O + O_3$, and amount of those species reacting with ozone. From solar cycle 21 to solar cycle 22 the stratospheric temperature has decreased because of natural and anthropogenic effects, with maximum cooling observed in the middle to high latitudes. The decreased temperature tends to produce a smaller sensitivity in the rate constant. However, in the same time some chemical species that are actively involved in ozone photochemistry (e.g., NO_x, HO_x, and ClO_x) have increased, which may exceed the temperature effect on the rate constant and result in a larger sensitivity.

Clearly, the conclusions drawn here are for the tropical mean upper stratosphere (1 − 5 hPa). However, partial correlation and multiple regression analysis could be applied elsewhere, such as the lower mesosphere, where other independent variables (e.g., water vapor) may be taken into account in addition to solar UV and temperature. The method may also be applied to tropical column ozone and midlatitude stratospheric ozone if we can identify those independent variables that affect ozone variations.

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