JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. D21, PAGES 26,473-26,479, NOVEMBER 20, 1999

Stratospheric effects of 27-day solar ultraviolet variations: The column ozone response and comparisons of solar cycles 21 and 22

L. L. Hood

Lunar and Planetary Laboratory, University of Arizona, Tucson

S. Zhou

National Oceanic and Atmospheric Administration, Camp Springs, Maryland

Abstract. Two unresolved observational issues concerning the response of stratospheric ozone to 27-day solar ultraviolet variations are as follows: (1) the amplitude of the column ozone response and whether it is consistent with the predictions of current two-dimensional stratospheric models and (2) whether the ozone profile response in the upper stratosphere differed appreciably during the solar cycle 22 maximum period (around 1990) as compared with the solar cycle 21 maximum period (around 1980). To investigate these issues, two separate 4-year intervals (1979 - 1982 and 1989 - 1992) of daily zonal mean Nimbus 7 Total Ozone Mapping Spectrometer, Nimbus 7 solar backscattered ultraviolet (SBUV), and/or NOAA 11 SBUV/2 data for tropical latitudes (30°S to 30°N) are analyzed using cross correlation and cross-spectral and regression methods. The Mg II core-to-wing ratio is employed as a measure of solar UV variations near 200 nm. Results show that the mean tropical column ozone sensitivity (percent change of ozone for a 1% change in solar flux) is 0.09 ± 0.01 at a lag of 4–6 days during both intervals and is approximately consistent with model predictions. Ozone profile sensitivities and phase lags are also in agreement between the two 4-year intervals when statistical uncertainties and differences in data processing algorithms are considered.

1. Introduction

An accurate observational determination of the response of the stratosphere to changes in solar spectral irradiance is needed as a constraint on models that attempt to simulate the influence of solar variability on the lower atmosphere [e.g., *World Meteorological Organization,* 1995; *Intergovernmental Panel on Climate Change,* 1996]. Variations in solar spectral irradiance at ultraviolet (UV) wavelengths directly influence the stratosphere through changes in the photochemical production of ozone, a trace gas that is largely responsible for radiative heating of the middle atmosphere. Resulting changes in latitudinal temperature gradients in the winter hemisphere can perturb upper stratospheric zonal winds [*Huang and Brasseur,* 1993; *Kodera and Yamazaki,* 1990]. It is possible that these nonlinear dynamical perturbations in the upper stratosphere are sufficient to affect the selection of preferred internal modes in the winter lower stratosphere; this would be analogous to the mechanism by which the equatorial quasi-biennial wind oscillation affects the winter polar stratosphere [*Holton,* 1994; *Kodera,* 1995]. Such a process may ultimately help to explain how relatively weak solar forcing in the upper stratosphere could produce detectable dynamical effects in the lower stratosphere and upper troposphere (as reported, for example, by *van Loon and Labitzke* [1998]).

A fundamental constraint on models for the response of the stratosphere to solar variability is the sensitivity of ozone to solar ultraviolet variations occurring on the timescale of the solar rotation period [*Brasseur,* 1993; *Fleming et al.,* 1995; *Chen et al.,* 1997]. Unlike the timescale of the 11-year solar activity cycle, the 27-day timescale is amenable to more rigorous statistical examination of measured atmospheric quantities using relatively short (several years) data records. Although measurements of the ozone mixing ratio response amplitude (or "sensitivity") on this timescale have been extensive [e.g., *Gille et al.,* 1984; *Hood,* 1984, 1986; *Chandra,* 1986; *Keating et al.,* 1987; *Fleming et al.,* 1995; *Zhou et al.,* 1997; *Hood and Zhou,* 1998], several basic issues remain unresolved. These include the following: (1) the observed sensitivity and phase lag of column ozone,

Paper number 1999JD900466.
0148-0227/99/1999JD900466$09.00

(2) the difference (if any) between the ozone mixing ratio response in the upper stratosphere measured during the maxima of solar cycles 21 (around 1980) and 22 (around 1990), and (3) the origin of an observed latitude dependence of the upper stratospheric response that is not consistent with photochemical and radiative effects alone (for a recent review, see *Hood* [1999]). In this paper, we shall investigate the first two of these issues. In section 2, daily Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) data for two separate 4-year time intervals are analyzed to obtain independent estimates for the column ozone sensitivity and phase lag. In section 3, daily Nimbus 7 solar backscattered ultraviolet (SBUV) and NOAA 11 SBUV/2 ozone profile data for the same two 4-year intervals are analyzed to investigate possible response differences between solar cycles 21 and 22.

2. Column Ozone Response

There are significant differences between published measurements of the column ozone response to 27-day solar forcing and between these measurements and the predictions of stratospheric models (Table 1). According to a two-dimensional model calculation by *Brasseur* [1993, Figure 6] the column ozone response at the equator to a realistic solar spectral irradiance change (corresponding to a 3.3% increase at 205 nm) is ~0.25% at a lag of ~3 days. The theoretical sensitivity factor is therefore $\simeq$ 0.076. A later calculation by *Fleming et al.* [1995], using an independent two-dimensional (2-D) model, yielded a similar theoretical sensitivity near the equator of 0.077, also at a lag of ~3 days. These sensitivities and phase lags are expected to be in reasonable agreement with observations since the same models predict ozone profile sensitivities and phase lags that agree approximately with observations at most pressure levels down to 10 hPa (see, e.g., Figure 2 of the review by *Hood* [1999]). However, as shown in Table 1, although observed phase lags agree well with theoretical expectations, sensitivity estimates derived from observations are larger than those predicted by 2-D models and range from 0.11 to 0.19. The estimates by *Chandra* [1991] and *Fleming et al.* [1995] were based on standard regression analyses of high-pass-filtered, daily Nimbus 7 TOMS data averaged over the tropics (40°S to 40°N in the case of Chandra's study). Several different time intervals were analyzed separately (1979-1982, 1989-1991, and 1989-1990) with consistent results. The estimate by *Bjarnason and Rögnvaldsson* [1997] was based on multiple-taper spectral analysis of daily TOMS data at the equator for a 2-year period beginning in March 1989. Bjarnason and Rögnvaldsson suggested that the lower sensitivities obtained earlier by *Chandra* [1991] may have been caused by the increased data length and wider latitudinal averaging used in the study by Chandra since the mean sensitivity decreases with distance from the equator. It should also be noted that the standard deviation of the Bjarnason and Rögnvaldsson result is much larger and attempts to more realistically consider uncertainties associated with data gaps, data length, and smoothing. Because of the large standard deviation, the result of Bjarnason and Rögnvaldsson is formally consistent with the model results.

To carry out an independent analysis of daily TOMS data, we consider several time intervals and several latitude ranges of measurements. Analysis of multiple time intervals is intended to provide an empirical measure of uncertainties in addition to that given by statistical methods alone. To represent solar UV variations during the TOMS instrument lifetime, we follow earlier analysts by adopting the Mg II core-to-wing ratio (Mg II index), a satellite-based proxy for UV variations near 200 nm [*Heath and Schlesinger*, 1986; *Cebula and DeLand*, 1998]. The analytic procedure follows that developed originally for application to Nimbus 7 SBUV

Table 1. Models and Previous Measurements of the Tropical Total Ozone Response to 27-Day Solar UV Variations

Sensitivity*	Phase Lag, days	Latitude Range	Reference
		Two-Dimensional Models	
0.076	3	0°S - 10°N	*Brasseur* [1993]
0.077	3	10°S - 10°N	*Fleming et al.* [1995]
		Previous Measurements	
0.11 ± 0.007	3	40°S - 40°N	*Chandra* [1991]
0.11 ± 0.007	3–4	30°S - 20°N	*Fleming et al.* [1995]
0.19 ± 0.12	2	equator	*Bjarnason and Rögnvaldsson* [1997]

*Defined as percent change for a 1% change in solar 205 nm flux.

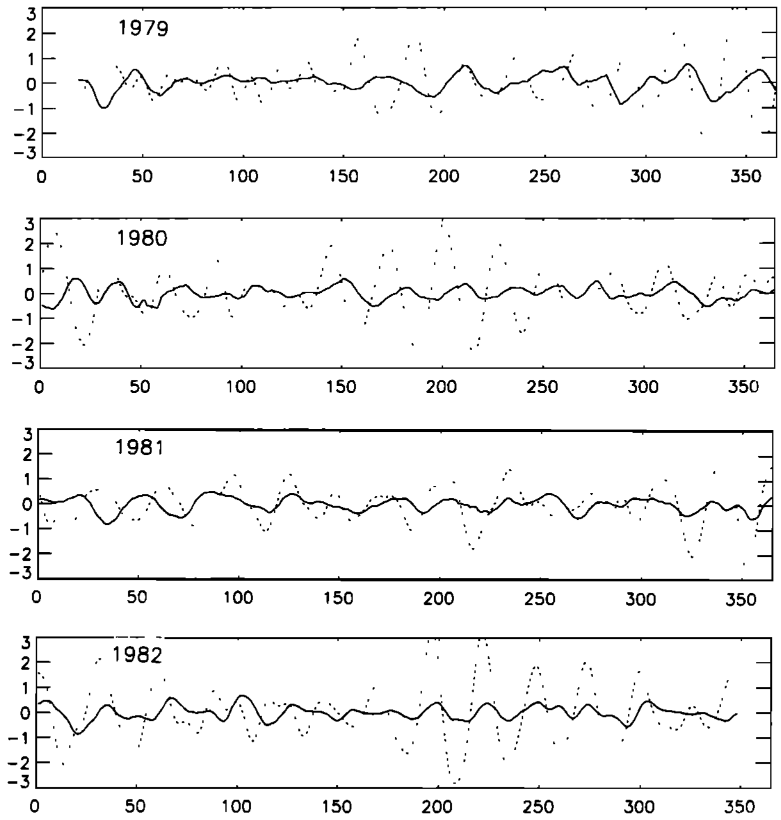


Figure 1. Comparison of 35-day running mean deviations of Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) column ozone (solid lines) and the Mg II core-to-wing ratio, a satellite-based proxy for solar UV variations (dashed lines) for four consecutive years near the maximum of solar cycle 21. The deviations are expressed in percent of the annual mean.

ozone profile data [*Hood*, 1986; *Chandra*, 1986; *Keating et al.*, 1987]. To prepare the data for analysis, both the TOMS and Mg II daily measurements are first interpolated and smoothed to eliminate missing days using a 7-day running average algorithm. A 35-day running average is then removed from both time series to minimize longer-period variations.

Figures 1 and 2 compare the resulting smoothed and filtered time series after averaging the TOMS data over tropical latitudes (30°S to 30°N). The two selected time intervals, 1979-1982 (Figure 1) and 1989-1992 (Figure 2), are centered approximately on solar activity maxima when 27-day UV variations typically have their largest amplitudes ($\leq$6%, peak to peak). A positive correlation between the two series is visually evident with a phase lag of ozone relative to UV of roughly +5 days. A formal cross correlation and linear regression analysis of each 4-year time interval yields the results listed in Table 2 for the 30°S - 30°N tropical average TOMS data. Error estimates on the sensitivities are standard deviations from the regression fits and may not account entirely for uncertainties associated with data gaps and smoothing of the data prior to analysis. However, the smoothing filter length (7 days) is much less than the solar rotation period, and data gaps were usually very short (1–2 days). Therefore we believe these error estimates to be representative of true statistical uncertainties at the 90% confidence level.

As seen in Figure 3, correlation coefficients are a maximum of 0.3 - 0.4 at phase lags of ~6 days (1979 - 1982) and ~4 days (1989 - 1992). The similarity of the lags and correlation coefficients for these two separate time intervals demonstrates the reproducibility of the correlation. (Approximate reproducibility for separate time intervals is necessary to demonstrate physical significance since a positive correlation at some lag will always be obtained for time series filtered to a sufficiently narrow passband [cf. *Hood and Cantrell*, 1988].) The regression-derived sensitivity values are also nearly identical with a mean amplitude of 0.09 ± 0.01. This amplitude is slightly less than that estimated by *Chandra* [1991] and *Fleming et al.* [1995] for a different latitude range. It is also much less than that reported by *Bjarnason and Rögnvaldsson* [1997] for the equator. To test whether averaging over tropical latitudes (± 30°) could explain the lower sensitivities obtained here as compared to the equatorial estimate by Bjarnason and Rögnvaldsson the analysis was repeated using

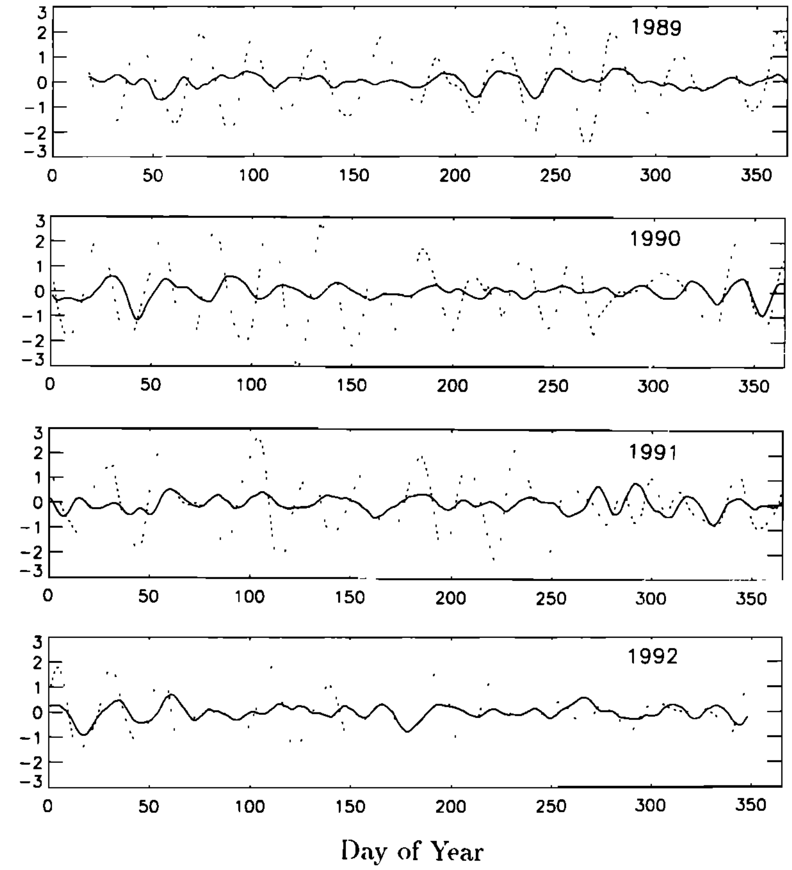


Figure 2. Same as Figure 1 but for the 1989 - 1992 time period.

equatorial TOMS data only with results shown in Table 2. In this case, the derived sensitivity ranges from 0.07 to 0.09, and the lags remain unchanged. Thus it appears that the shorter (2-year) interval selected for analysis and/or the analytic (multiple-taper and periodogram spectral) method is in some manner responsible for the larger sensitivity estimated by Bjarnason and Rögnvaldsson. The sensitivity and phase lag estimates shown in Table 2 are in approximate agreement with (or slightly larger than) the theoretical estimates shown in Table 1. Although the 1989-1992 equatorial sensitivity estimate (0.07) is somewhat lower than the other measurements, this single measurement does not clearly imply a disagreement with the latitude dependence (maximizing at the equator) predicted by models [see, e.g., *Brasseur,* 1993, Figure 6]. This is because ozone measurements at a single latitude (in this case, the equator) are more subject to errors associated with dynamically forced contributions that are normally reduced by averaging over latitude.

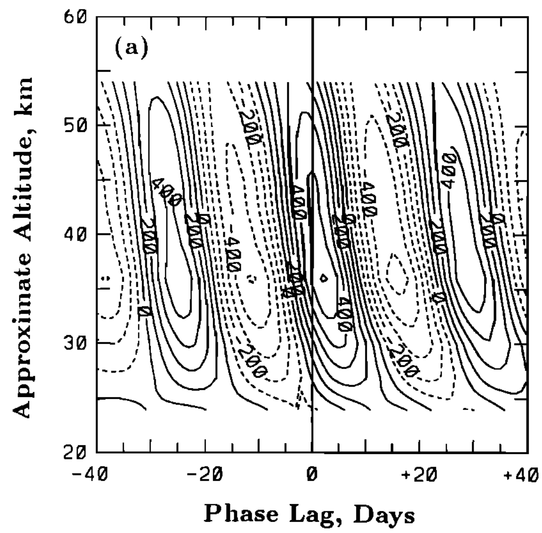
3. Ozone Profile Response

In principle, long-term trends in stratospheric composition and/or mean thermal structure could lead to detectable changes in the sensitivity of ozone to 27-day solar UV variations. For example, increased chlorine loading would decrease the ozone photochemical life-

Table 2. Measurements of the Tropical Total Ozone Response to 27-Day Solar UV Variations

Period	Latitude Range	Sensitivity*	Phase Lag, days	Correlation Coefficient
1979–1982	30°S - 30°N	0.095 ± 0.007	6	0.33
1989–1992	30°S - 30°N	0.093 ± 0.006	4	0.36
1979–1982	equator	0.092 ± 0.008	6	0.30
1989–1992	equator	0.071 ± 0.008	4	0.23

*Error estimates represent standard deviations from the regression fit.



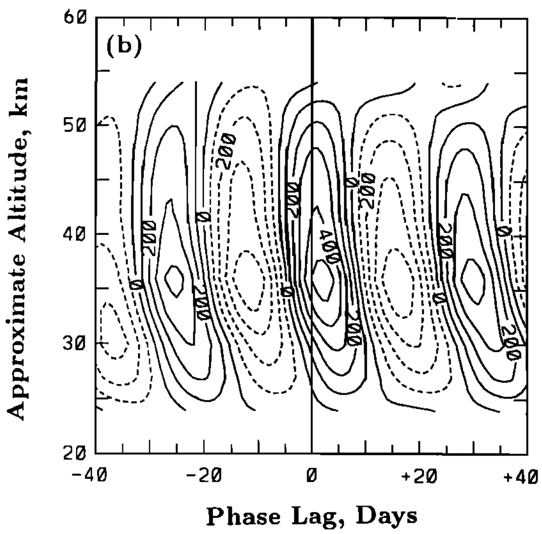


Figure 3. Comparison of tropical ozone mixing ratio - Mg II index cross correlation functions for the 1979 - 1982 and 1989 - 1992 time periods. (a) Tropical mean (30°S to 30°N Nimbus 7 solar backscattered ultraviolet (SBUV) data were used for the 1979 - 1982 period while (b) tropical mean NOAA 11 SBUV/2 data (version 6.0) were used for the 1989 - 1992 period.

time and reduce the equilibrium chemical sensitivity of ozone to temperature [e.g., *Stolarski and Douglass*, 1985]. These modifications of ozone photochemistry could then lead to an enhanced ozone response to solar UV change [see, e.g., *Hood*, 1986]. Alternatively, decreased mean ozone concentrations and associated temperature trends in the upper stratosphere could modify the ozone response to solar UV variations.

Several previous analyses of NOAA 11 SBUV/2 data for 1989-1990 have suggested significant differences between the 27-day upper stratospheric ozone response during solar cycle 22 (around 1990 maximum) and that during cycle 21 (around 1980 maximum) [*Chandra et al.*, 1994; *Fleming et al.*, 1995]. For example, *Fleming et al.* (see their Figure 6), using an earlier version of the SBUV/2 data set, estimated reduced ozone sensitivities at several levels, including a 25–40% lower sensitivity at 1–2 hPa for 1989–1990 as compared with 1979–1983. If real, such a large change in sensitivity would imply corresponding large changes in ozone photochemical parameters [*Hood and Douglass*, 1988].

In order to investigate further whether the upper stratospheric ozone sensitivity to 27-day solar UV variations changed significantly between cycles 21 and 22, more recent reprocessed versions (6.0, 6.1.2) of NOAA 11 SBUV/2 data [e.g., *Lienesch et al.*, 1996] were analyzed for the 1989 - 1992 time period. For comparison an identical analysis was conducted of SBUV data for the 1979 - 1982 period. The method of analysis was identical to that applied to TOMS data in section 2. Cross-correlation functions for the two 4-year intervals are plotted versus approximate altitude in Figure 3. Figure 3a was calculated using tropical average (30°S - 30°N) SBUV data for 1979 - 1982, and Figure 3b was calculated using SBUV/2 data (version 6.0) for 1989 - 1992. These functions are similar to one another and to those derived previously from SBUV data [e.g., *Hood*, 1986]. The maximum correlation (0.5 - 0.6) occurs near the 4 hPa level (~38 km), and the phase lag increases with decreasing altitude. No significant evidence for a difference in 27-day response characteristics between cycles 21 and 22 is apparent in Figure 3. This result agrees with an earlier preliminary analysis of 4 months of SBUV/2 data reported by *Chandra and McPeters* [1994].

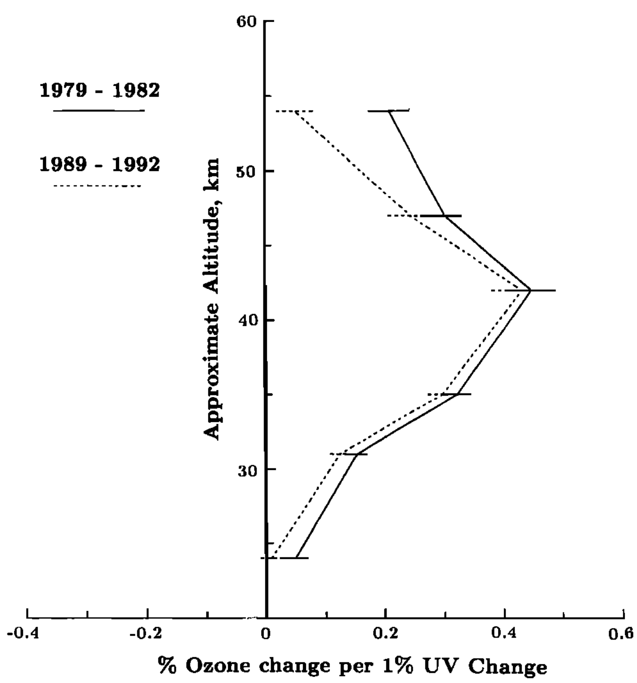


Figure 4. Sensitivities versus approximate height obtained from regression analyses of mean tropical SBUV data for the 1979 - 1982 period (solid line) and from SBUV/2 data (version 6.0) for the 1989 - 1992 period (dashed line).

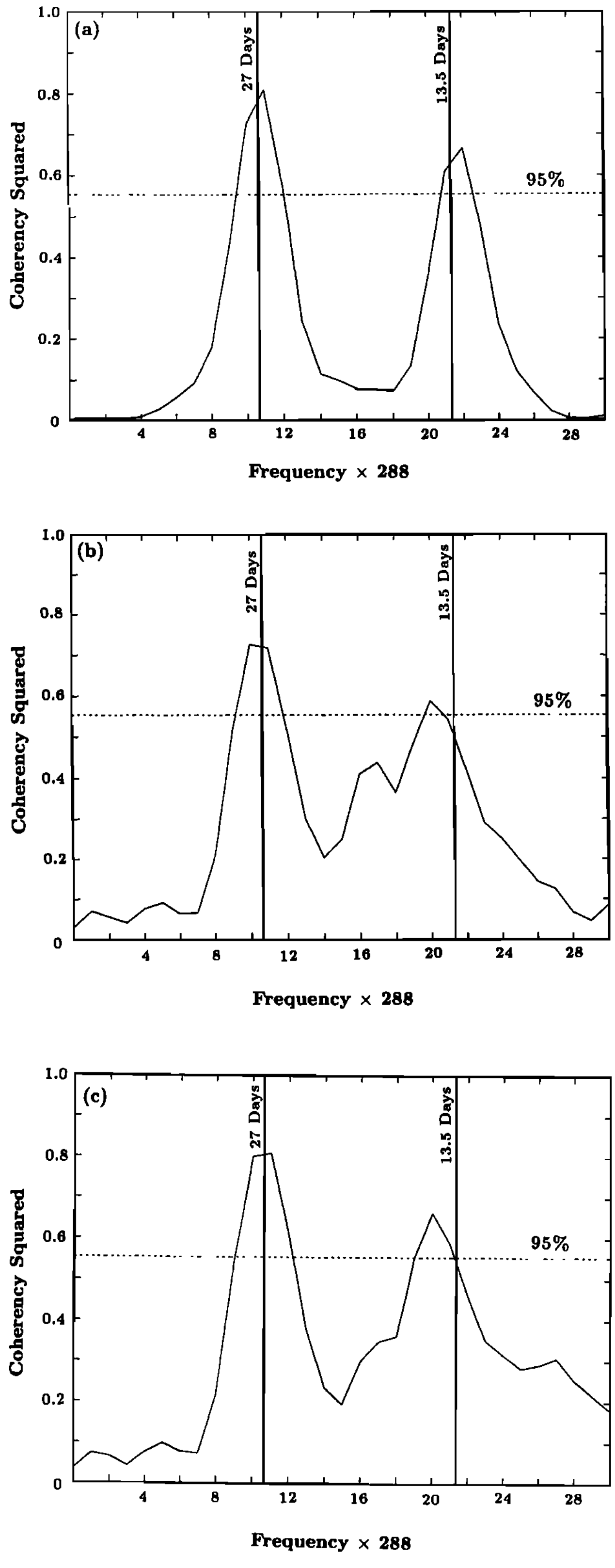


Figure 5. Tropical mean coherency spectra at the 5 hPa level for (a) the 1979 - 1980 period using Nimbus 7 SBUV data, (b) the 1989 - 1990 period using NOAA 11 SBUV/2 data (version 6.0), and (c) the 1989 - 1990 period using version 6.1.2 SBUV/2 data. Frequencies corresponding to periods of 27 days and 13.5 days and 95% confidence thresholds are also indicated.

Plots of mean tropical (30°S - 30°N) sensitivities for the two 4-year intervals are compared in Figure 4. Error bars represent standard deviations derived from the regression line fit. Sensitivities for the 1989 - 1992 interval were again calculated using version 6.0 SBUV/2 data. Although the 1989 - 1992 sensitivities (dashed line) are slightly less than the 1979 - 1982 sensitivities (solid line), the error bars are overlapped except at the uppermost level (0.5 hPa). However, the 0.5 hPa level is near the upper boundary of the region where the SBUV instrument can resolve the ozone profile [*McPeters et al.*, 1984]. To test whether the sensitivity difference at 0.5 hPa could be affected by processing algorithms, a separate analysis was conducted using the latest version (6.1.2) of the SBUV/2 data for a 2-year interval (1989 - 1990). It was found that the sensitivity is larger at 0.5 hPa when version 6.1.2 is employed such that the associated error limits overlap with those for the 1979 - 1982 sensitivities.

Finally, power spectra were calculated for selected intervals of Mg II index and tropical mean SBUV - SBUV/2 ozone data by harmonically analyzing autocorrelograms using a fundamental period of 432 days [*Hood and Zhou*, 1998]. The spectral coefficients were smoothed using a (1,2,1) filter. Resulting coherency spectra at the 5 hPa level are plotted in Figure 5 for (1) 1979 - 1980 (SBUV), (2) 1989 - 1990 (SBUV/2, version 6.0), and (3) 1989 - 1990 (SBUV/2, version 6.1.2). Ninety-five percent confidence thresholds are indicated. In all cases, ozone mixing ratio and the Mg II index are spectrally coherent near periods of 27 and 13.5 days. Coherency increases slightly when SBUV/2 version 6.1.2 (Figure 5c) is used in place of version 6.0 (Figure 5b).

4. Summary and Discussion

In this brief report, we have reexamined several intervals of Nimbus 7 TOMS, Nimbus 7 SBUV, and NOAA 11 SBUV/2 data in an attempt to resolve several issues concerning the ozone response to 27-day solar UV variations. Analyses of daily tropical (30°S to 30°N) TOMS data for the 1979 - 1982 and 1989 - 1992 intervals yield mean column ozone sensitivities of 0.09 ± 0.01 and phase lags of 4–6 days. This derived sensitivity is significantly less than that estimated in a recent multiple-taper spectral study of TOMS data by *Bjarnason and Rögnvaldsson* [1997] and is more nearly in accord with theoretical sensitivities of ~0.08 [*Brasseur*, 1993; *Fleming et al.*, 1995]. This derived sensitivity is also slightly less than that estimated using similar analytic techniques by *Chandra* [1991] and *Fleming et al.* [1995], possibly because of the somewhat different time intervals and latitude ranges analyzed. Analysis of more recent versions (6.0 and 6.1.2) of SBUV/2 ozone profile data also appears to yield no significant evidence for a difference in ozone 27-day response characteristics between solar cycles 21 and 22. This result is consistent with an analysis of UARS Microwave Limb Sounder ozone profile data [*Hood and Zhou*, 1998] and indicates that any real trends in ozone photochemical lifetime and/or temperature sensitivity in the upper stratosphere are too small to detect using this observational technique.

Acknowledgments. We thank the Nimbus 7 TOMS, SBUV, and NOAA SBUV/2 processing teams for their work in producing the data sets utilized in this paper. Daily Mg II core-to-wing ratios were provided by L. Puga of NOAA in Boulder. Helpful discussions with J. Miller and support for S.Z. by J. Miller are appreciated. This research was supported at the University of Arizona by NASA grant NAG-1-2023 and at NOAA/NCEP by the NASA UARS program.

References

Bjarnason, G., and Ö. Rögnvaldsson, Coherency between solar UV radiation and equatorial total ozone, *J. Geophys. Res., 102*, 13,009-13,018, 1997.

Brasseur, G., The response of the middle atmosphere to long-term and short-term solar variability: A two dimensional model, *J. Geophys. Res., 98*, 23,079-23,090, 1993.

Cebula, R. P., and M. T. DeLand, Comparisons of the NOAA-11 SBUV/2, UARS SOLSTICE, and UARS SUSIM Mg II solar activity proxy indexes, *Sol. Phys., 177*, 117-132, 1998.

Chandra, S., The solar and dynamically induced oscillations in the stratosphere, *J. Geophys. Res., 91*, 2719-2734, 1986.

Chandra, S., The solar UV related changes in total ozone from a solar rotation to a solar cycle, *Geophys. Res. Lett., 18*, 837–840, 1991.

Chandra, S., and R. D. McPeters, The solar cycle variation of ozone in the stratosphere inferred from Nimbus 7 and NOAA 11 satellites, *J. Geophys. Res., 99*, 20,665-20,671, 1994.

Chandra, S., R. D. McPeters, W. Planet, and R. M. Nagatani, The 27-day solar UV response of stratospheric ozone: Solar cycle 21 versus solar cycle 22, *J. Atmos. Terr. Phys., 56*, 1057-1065, 1994.

Chen, L., J. London, and G. Brasseur, Middle atmospheric ozone and temperature responses to solar irradiance variations over 27-day periods, *J. Geophys. Res., 102*, 29,957-29,979, 1997.

Fleming, E. L., S. Chandra, C. H. Jackman, D. B. Considine, and A. R. Douglass, The middle atmospheric response to short and long term solar UV variations: Analysis of observations and 2D model results, *J. Atmos. Terr. Phys., 57*, 333-365, 1995.

Gille, J. C., C. M. Smythe, and D. F. Heath, Observed ozone response to variations in solar ultraviolet radiation, *Science, 225*, 315-317, 1984.

Heath, D.F., and B.M. Schlesinger, The Mg 280-nm doublet as a monitor of changes in solar ultraviolet irradiance, *J. Geophys. Res., 91*, 8672-8682, 1986.

Holton, J. R., The quasi-biennial oscillation in the Earth's atmosphere and its links to longer period variability, in *The Solar Engine and Its Influence on Terrestrial Atmosphere and Climate, NATO ASI Ser.*, vol. 125, edited by E. Nesme-Ribes, pp. 259-273, Springer-Verlag, New York 1994.

Hood, L. L., The temporal behavior of upper stratospheric ozone at low latitudes: Evidence from Nimbus 4 BUV data for short-term responses to solar ultraviolet variability, *J. Geophys. Res., 89*, 9557-9568, 1984.

Hood, L. L., Coupled stratospheric ozone and temperature responses to short-term changes in solar ultraviolet flux: An analysis of Nimbus 7 SBUV and SAMS data, *J. Geophys. Res., 91*, 5264-5276, 1986.

Hood, L. L., Effects of short-term solar UV variability on the stratosphere, *J. Atmos. Sol. Terr. Phys., 61*, 45-52, 1999.

Hood, L. L., and S. Cantrell, Stratospheric ozone and temperature responses to short-term solar ultraviolet variations: Reproducibility of low-latitude response measurements, *Ann. Geophys., 6*, 525-530, 1988.

Hood, L. L., and A. Douglass, Stratospheric responses to solar ultraviolet variations: Comparisons with photochemical models, *J. Geophys. Res., 93*, 3905-3911, 1988.

Hood, L. L., and S. Zhou, Stratospheric effects of 27-day solar ultraviolet variations: An analysis of UARS MLS ozone and temperature data, *J. Geophys. Res., 103*, 3629-3638, 1998.

Huang, T. Y. W., and G. P. Brasseur, Effect of long-term solar variability in a two-dimensional interactive model of the middle atmosphere, *J. Geophys. Res., 98*, 20,413-20,427, 1993.

Intergovern. Panel on Climate Change, *Climate Change 1995*, edited by J. Houghton et al., Cambridge Univ. Press, New York, 1996.

Keating, G., J. Nicholson III, D. F. Young, G. Brasseur, and A. De Rudder, Response of middle atmosphere to short-term solar ultraviolet variations, 1, Observations, *J. Geophys. Res., 92*, 889-902, 1987.

Kodera, K., On the origin and nature of the interannual variability of the winter stratospheric circulation in the Northern Hemisphere, *J. Geophys. Res., 100*, 14,077-14,087, 1995.

Kodera, K., and K. Yamazaki, Long-term variation of upper stratospheric circulation in the Northern Hemisphere in December, *J. Meteorol. Soc. Jpn., 68*, 101-105, 1990.

Lienesch, J. H., W.G. Planet, M. T. DeLand, K. Laaman, R. P. Cebula, E. Hilsenrath, and K. Horvath, Validation of NOAA-9 SBUV/2 total ozone measurements during the 1994 Antarctic ozone hole, *Geophys. Res. Lett., 23*, 2593-2596, 1996.

McPeters, R. D., D. F. Heath, and P. K. Bhartia, Average ozone profiles for 1979 from the Nimbus 7 SBUV instrument, *J. Geophys. Res., 89*, 5199-5214, 1984.

Stolarski, R. S., and A. R. Douglass, Parameterization of the photochemistry of stratospheric ozone including catalytic loss processes, *J. Geophys. Res., 90*, 10,709-10,718, 1985.

van Loon, H., and K. Labitzke, The global range of the stratospheric decadal wave, I, Its association with the sunspot cycle in summer and in the annual mean, and with the troposphere, *J. Clim., 11*, 1529-1537, 1998.

World Meteorological Organization, 1994 assessment of ozone depletion, *Rep. 37*, World Meteorol. Organ. Ozone Secr., Geneva, 1995.

Zhou, S., G. Rottman, and A. Miller, Stratospheric ozone response to short- and intermediate-term variations of solar UV flux, *J. Geophys. Res., 102*, 9003-9011, 1997.

L. L. Hood, Lunar and Planetary Laboratory, University of Arizona, Kuiper Space Sciences Building, 1629 E. University Boulevard, Tucson, AZ 85721-0092. (lon@lpl.arizona.edu)

S. Zhou, NOAA/NCEP, 5200 Auth Road, W/NP53 Room 808, Camp Springs, MD 20233. (wd53sz@sun1.wwb.noao.gov)

(Received December 2, 1998; revised June 11, 1999; accepted June 17, 1999.)