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STRATOSPHERIC EFFECTS OF SOLAR ULTRAVIOLET VARIATIONS ON THE SOLAR ROTATION TIME SCALE

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The purpose of this paper is to present a summary of some current work on measurement and interpretation of stratospheric ozone and temperature responses to observed short-term solar ultraviolet variations. Although some studies have yielded provisional evidence for a nearly in-phase ozone-solar cycle relationship, they extend at most over only one or two eleven-year cycles so the statistical significance of the correlations is not large. Similarly, the relatively short lengths of individual satellite data sets combined with the problem of estimating the effect of changes in instrument sensitivity (drift) during the observing period have complicated attempts to infer long-term or solar cycle ozone trends. The solar rotation and active region development time scale provides an alternate time scale for which detailed studies of middle atmospheric ozone and temperature responses to solar ultraviolet variability are currently possible using available satellite data sets. At tropical latitudes where planetary wave amplitudes are relatively small, clear correlative evidence for the existence of middle atmospheric ozone and temperature responses to short-term solar ultraviolet variations has been obtained in recent years [GILLE et al., 1984; HEATH and SCHLESINGER, 1985; HOOD, 1984; 1986; KEATING et al., 1985; 1987; CHANDRA, 1986; ECKMAN, 1986; AIKIN and SMITH, 1986; HOOD and CANTRELL, 1988]. These measurements will ultimately allow improved empirical and theoretical calculations of longer-term solar induced ozone and temperature variations at low and middle latitudes.

The satellite remote sensing measurements that are utilized here consist of the Nimbus 7 solar backscattered ultraviolet (SBUV) daily zonal mean profiles and stratosphere and mesosphere sounder (SAMS) gridded retrieved temperature data available from the U.S. National Space Science Data Center. In order to characterize variations in solar spectral irradiance at wavelengths where photodissociation of molecular oxygen is important, the flux at 205 nm as measured with the SBUV instrument is chosen to be consistent with earlier studies. The flux at this wavelength has been found from analyses of SBUV solar flux data to be representative of short-term variations throughout the 170–260 nm range that is of importance for ozone photochemistry [DONNELLY et al., 1987].

Figure 1 compares the 205 nm solar irradiance time series with zonally averaged SBUV ozone mixing ratios and SAMS temperatures for the equator at 1.5 mbar (approximately 45 km altitude). This altitude is chosen because it is intermediate between the locations of the ozone response maximum (about 40 km) and the temperature response maximum (about 50 km). A low latitude is selected because of the increasing seasonal and planetary wave amplitudes with increasing latitude which increase the difficulty of detecting changes caused by solar ultraviolet variations. Day-to-day variations and short gaps between daily zonal mean temperature, ozone, and solar ultraviolet time series were minimized using a 7-day running mean and linear interpolation algorithm.

The 205 nm flux time series is characterized by a broad maximum corresponding to the solar activity maximum of 1980–1981 and short-term variations associated with active region development and solar rotation. The originally measured 205 nm flux data set also contains a long-term trend ascribable to instrument drift. We have therefore employed the Mg II core ratio of HEATH and SCHLESINGER (1986) to represent changes in the 205 nm flux on time scales greater than 35 days. The resulting scaled 205 nm flux time series (normalized to a value of 10.22 W cm^{-3} as measured on November 7, 1978) decreases by approximately 6% between solar maximum in 1980–1981 and late 1984. For comparison, the Solar Mesosphere Explorer satellite has measured a change in monthly mean 200-205 nm flux of approximately 5.5% between early 1982 and early 1985 although instrument error sources are still being evaluated (G. ROTTMAN, private communication).

The 1.5 mbar equatorial SAMS temperature time series (bottom panel) is characterized by semiannual and annual components with superposed shorter-term fluctuations. Because of the strong temperature dependences of the reaction rates that determine the ozone concentration, these semiannual and annual temperature variations produce negatively correlated ozone variations as shown in the center panel. This characteristic emphasizes the need to consider simultaneous temperature measurements when interpreting ozone temporal behavior at altitudes and latitudes where photochemical equilibrium is a reasonable first approximation. Finally, it should be noted that small interannual trends present in both the SBUV and SAMS measurements could be due in part to instrument drift and are not necessarily real.

From the amplitudes of seasonal ozone and temperature variations as well as the possibility of instrument related long-term drifts, it is clear from Figure 1 that detection of solar ultraviolet induced ozone or temperature responses on seasonal and longer time scales from the currently available Nimbus 7 data sets would be very difficult. On the other hand, as can be seen in the top panel, 27-day 205 nm flux variations are as large as 6–7% (peak-to-peak) and are therefore comparable to the probable change in the monthly-mean flux over a solar cycle. Consequently, most recent efforts to detect and characterize middle atmospheric ozone and temperature responses to solar ultraviolet variations have concentrated on the solar rotation time scale.

In order to isolate temporal variations on time scales comparable to the solar rotation period, all time series may be detrended by subtracting the 35-day running mean in each case. In order to allow a direct visual comparison of the resulting short-term 205 nm flux deviations with the ozone and temperature deviations, Figure 2 superposes the UV time series onto the atmospheric time series. Positive correlations between equatorial 1.5 mbar ozone variations on this time scale and solar 205 nm flux variations are evident; this is particularly true during intervals of relatively strong and continuous 27-day solar UV variations such as those occurring in October 1979–February 1980, May–August 1980, and June–August 1982. It is apparent from the lower panel of Figure 2 that 1.5 mbar temperature deviations are not positively correlated with UV deviations at zero lag. However, a tendency for temperature maxima to occur after UV maxima by 5–10 days can be discerned visually in some time intervals, particularly October 1979–February 1980 and June–August 1982.

In order to derive the average low-latitude ozone or temperature response sensitivity to observed changes in the 205 nm solar flux, cross-correlation and linear regression methods have been applied. This sensitivity is defined as the percent change in either ozone mixing ratio or temperature for a 1% change in the 205 nm flux. Also determined is the phase lag in days of either ozone or temperature relative to the 205 nm flux. In order to test the reproducibility of the previous results of HOOD [1986], HOOD and CANTRELL (1988) analyzed separately the two independent time intervals 'A' and 'B' of Figure 2. Figures 3

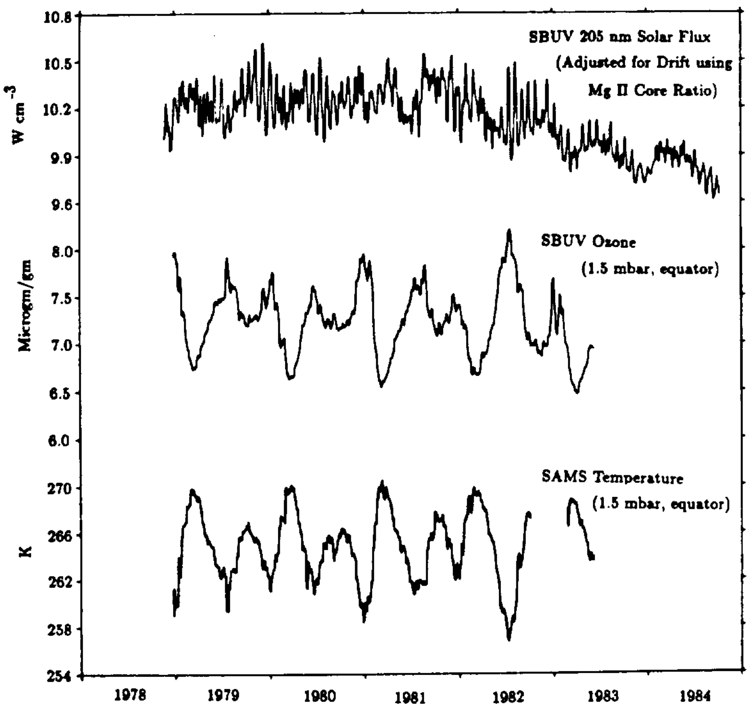


Figure 1. Comparison between the SBUV 205 nm solar flux (adjusted for long-term trends using the Mg II core ratio of HEATH and SCHLESINGER, 1986) and zonal mean equatorial ozone mixing ratio and temperature at the 1.5 mbar level.

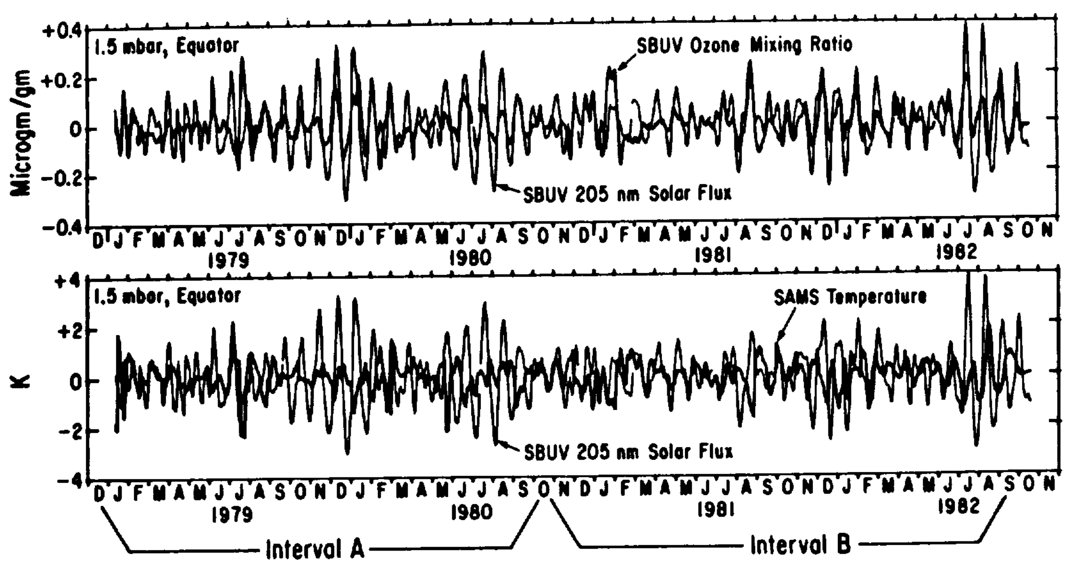


Figure 2. Superposition of the detrended (35-day running mean removed) solar 205 nm flux onto the detrended equatorial ozone and temperature time series at the 1.5 mbar level (from HOOD and CANTRELL, 1988).

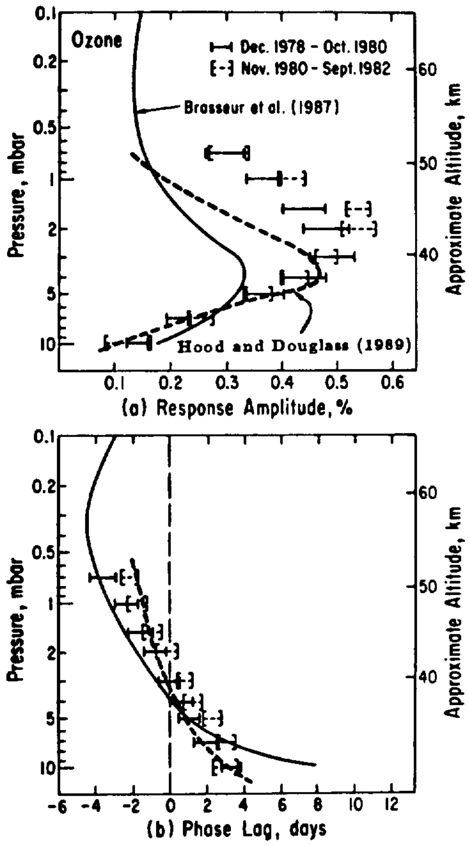
and 4 summarize their results. The ozone response is seen to reach a maximum of about 0.5% near the 2 mbar level for a 1% change in the 205 nm flux. Actual peak-to-peak ozone mixing ratio changes were as large as 3% corresponding to maximum 205 nm flux changes of 6–7% on the 27-day time scale. The temperature response maximizes near the stratopause and amounts to 0.06% (about 0.17 K) for a 1% change in the 205 nm flux. Actual peak-to-peak temperature changes were as large as 1 K. Formal error limits for each time interval represent standard deviations from the mean of separate estimates for the five 10° latitude zones between 25°S and 25°N. As shown in Figure 3, ozone response amplitudes and phase lags derived in these separate analyses are generally in agreement. Formal error limits overlap in all cases except for the response amplitude at 2 mbar which is somewhat larger during interval 'B' than during interval 'A'. As shown in Figure 4, temperature response amplitudes and phase lags are also in approximate agreement although formal error limits are significantly larger for the response amplitudes. Temperature phase lags below 2 mbar also appear to be somewhat larger during interval 'B' than during interval 'A'. These response measurements agree well with an independent analysis by KEATING et al. (1987) of the same 4-year time interval.

The ozone response measurements of Figure 3 are compared to two simulations of the expected response calculated using radiative-photochemical models. The solid lines show the response amplitude and phase lag calculated by BRASSEUR et al. (1987) using a one-dimensional time dependent radiative photochemical code. This simulation is in qualitative agreement with the measurements but the amplitude of the calculated ozone response is noticeably less than the observed response above about 5 mbar. It has been suggested that a part of the difference between the model result and the observed ozone response is due to the use of diurnally averaged photodissociation rates in the model calculations. HOOD and DOUGLASS (1989) have reported calculations using a parameterized perturbation-order radiative photochemical model but using a variable solar zenith range in the photodissociation calculations that is more appropriate for comparison with the SBUV measurements. The resulting ozone response amplitude and phase lag are shown in Figure 3 as dashed lines. The increased photodissociation rate changes result in a higher amplitude for the ozone response that is more nearly in agreement with the observed amplitude at levels below about 3 mbar.

As noted earlier, the monthly mean solar 205 nm flux (scaled using the Mg II core ratio) decreases by approximately 6% between solar maximum in 1980–1981 and late 1984 (Figure 1). Adopting this flux variation, the same radiative photochemical code used to produce the dashed line model of Figure 3 for the 27-day time scale may be applied in order to estimate the expected solar cycle variation of ozone mixing ratio at levels between 3 and 10 mbar and at equatorial latitudes. Results show predicted mean ozone mixing ratio decreases of 2.0% at 3 mbar, 2.3% at 4.5 mbar, and 0.8% at 10 mbar for the interval between solar maximum in 1980 and solar minimum in 1985. Such decreases would be small in comparison to seasonal variations and would be difficult to detect relative to other natural sources of variability such as the El Chichon volcanic eruption. The net change in the ozone column at low latitudes resulting directly from these upper stratospheric mixing ratio decreases would be less than 1%.

Although radiative-photochemical models can yield an approximate agreement with the observed ozone responses and phase lags below 3 mbar, it is unlikely that the large discrepancy between observed and theoretically calculated temperature phase lags (Figure 6) can be simulated by such models. As previously argued by HOOD (1986; 1987) and by BRASSEUR et al. (1987), the shortfall of the calculated temperature phase lags results

Figure 3. SBUV ozone response amplitudes (sensitivities) and phase lags determined by linear regression for the indicated time intervals. Error bars are standard deviations from the mean for separate regression estimates for five 10° latitude bands centered on the equator. Also shown for comparison are two theoretical profiles (see the text). (after HOOD and DOUGLASS, 1989)



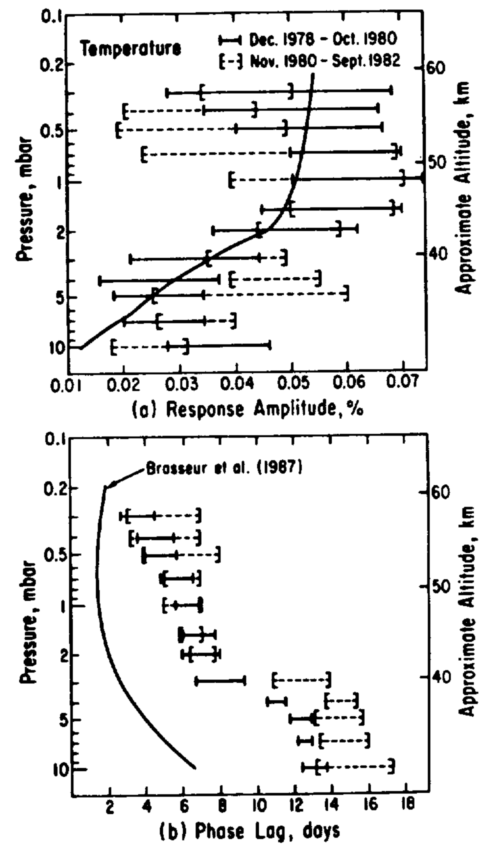


Figure 4. Same as Figure 3 but for SAMS temperature.

from the fact that Newtonian cooling lifetimes in the upper stratosphere are relatively short (e.g. about 5 days near 1.5 mbar; SCHOEBERL and STROBEL, 1978). Consequently, calculated temperature phase lags for 27-day solar ultraviolet forcing are no more than 3-4 days when only radiative heating is considered. It therefore appears that more than a one-dimensional model that considers only photochemistry and radiative heating is needed to provide a complete description of the observed responses. At a minimum, a two-dimensional model with coupled dynamics may be required.

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