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DETECTION OF THE RESPONSE OF OZONE IN THE MIDDLE ATMOSPHERE TO SHORT-TERM SOLAR ULTRAVIOLET VARIATIONS

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Abstract. The response of ozone to solar UV variation is determined in the middle atmosphere between the heights of 10 and 0.2 mb. The definitive isolation of the smaller variations associated with short-term solar variability is accomplished only after removal of the larger changes of ozone related to temperature variations. Using this approach the correlation coefficients between detrended ozone (Nimbus 7 LIMS) and short-term 205 nm solar variation (Nimbus 7 SBUV) are found to be much higher (0.9) than achieved in previous studies. The theoretical response time and amplitude of response of ozone in the middle atmosphere to observed short-term solar UV variations is found to be in good agreement with observations, except near 0.2 mb. The corresponding long-term response over the solar cycle is also estimated.

Introduction

Efforts toward detecting the response of ozone in the middle atmosphere to variations in solar ultraviolet (UV) radiation have been pursued for over 50 years (see e.g., review of Keating, 1981). Detection of such a relationship is crucial for fully understanding the photochemical behavior of the middle atmosphere. Strong evidence of short-term solar UV variations come from solar measurements from the Nimbus 7 SBUV experiment (Heath et al., 1983) and a solar UV experiment aboard the Solar Mesosphere Explorer (SME) (London et al., 1984). Variations over 27 days are found to be as large as 7% and generally of the order of 3% from maximum to minimum from 170 to 208 nm (Aℓ I edge) with variations generally less than 2% at longer wavelengths.

Studies of the response of ozone to short-term solar UV variations have been recently reported for example by Gille et al., (1984b) and Hood (1984). Most of these previous studies however have not corrected for large temperature effects and were not compared with the theoretical response of ozone to short-term solar UV variations.

To perform the analysis of the response of ozone to short-term solar UV variations, Nimbus 7 ozone and temperature data from the Limb Infrared Monitor of the Stratosphere (LIMS) (provided in November 1983 by J.M. Russell, III) and simultaneous solar spectral irradiance measurements from the NIMBUS 7 Solar Backscatter Ultraviolet (SBUV) Experiment (provided in August 1984 by D.F. Heath) were employed. The LIMS instrument, a six-channel cryogenically-cooled radiometer, measured ozone and temperature in the stratosphere and mesosphere from 84°N to 64°S latitude from October 1978 to May 1979 (Russell, 1984; Gille and Russell, 1984; Remsberg et al., 1984; Gille et al., 1984a). The SBUV instrument employs a diffuser plate to make solar irradiance measurements from 160 to 400 nm (Heath et al., 1983) with a spectrometer bandpass of 1.0 nm.

Ozone-Temperature Relation

Temperature increases in the upper stratosphere lead to increased rates of ozone destruction by atomic oxygen (Chapman reaction) and by catalytic species. The net effect is a negative correlation between ozone and temperature variations (Barnett et al., 1975; Haigh and Pyle, 1982; Keating et al., 1983). Shown in Figure 1 is a 5-day running zonal mean of ozone volume mixing ratio and temperature at 2 mb as measured by Nimbus 7 LIMS averaged between 0° ± 20° latitude. The ozone clearly follows the temperature variations with a correlation coefficient before detrending of - 0.94 and a response time of ozone to temperature variations of less than a day. In order to detect clearly the response of ozone to solar UV variations, these large temperature effects, which are thought to stem from dynamical processes, need to be removed. Thus, ozone concentrations were normalized to the ozone value for mean temperature taking into account the regression coefficient between the two parameters. The regression coefficient was determined between the detrended parameters $(O_3 - \bar{O}_3)/\bar{O}_3$ and $T-\bar{T}$ where O_3 is the 5-day running mean of the ozone volume mixing ratio, $\bar{O}_3$ is a 27-day running mean of O_3, T is the 5-day running mean of stratospheric temperature, and $\bar{T}$ is the 27-day running mean of T. The corresponding observed value of $d\ell n O_3/d(1/T)$ at 2 mb is 1128K which is close to theoretical estimates (Barnett et al., 1975; Keating et al., 1983).

Solar Indices and Temperature Correction

In the present study, we compare correlations for the period November 1978 through May 1979 between $(O'_3 - \bar{O}'_3)/\bar{O}'_3$ and $(I - \bar{I})/\bar{I}$ where O_3' is the 5 day running mean of ozone normalized to a fixed temperature, $\bar{O}_3'$ is the 27-day running mean of O_3', I is the 5-day running mean of the solar index, and $\bar{I}$ is the 27-day

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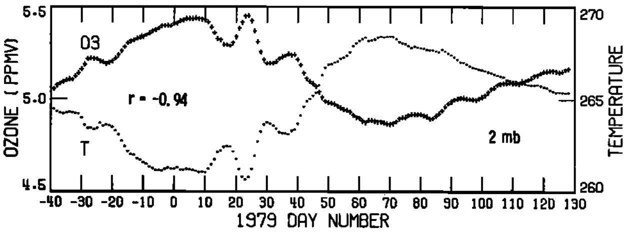

Fig. 1 Comparison between 5 day running means of O_3 (ppmv) and temperature (K) at 2 mb as measured by Nimbus 7 LIMS.

running mean of I. Since the 205 nm radiation is directly responsible for O_2 photodissociation and subsequent ozone production, the relation between ozone and solar output was studied using the irradiance at 205 nm as the solar index. As indicated by table 1, this parameter gives much higher correlation coefficients than the classical 10.7 cm index.

Also shown in Table 1 are the correlation coefficients between the parameter $(I_{205}-\bar{I}_{205})/\bar{I}_{205}$, where the subscript 205 indicates the 205 nm index, and the ozone parameter $(O_3 - \bar{O}_3)/\bar{O}_3$ for the ozone uncorrected for temperature variations. It is seen that the correlation coefficients between ozone and solar variability are much higher when the effects of temperature variations on ozone are removed. The temperature variations are mostly related to dynamical effects which make it more difficult to resolve the effects of solar variability. Even if small temperature increases occur, because of increased solar activity, they will only tend to diminish the net increase of ozone. Thus, removing the effects of these temperature variations will tend to improve resolution of a solar terrestrial relation. The temperature variations with solar activity during the period studied here are apparently not more than a small fraction of a degree Kelvin since correlations between detrended temperature and 205 nm flux were found to be statistically insignificant.

Ozone-205 nm Relation at 2 mbar

After correcting for temperature effects and using the appropriate solar index, the relation between detrended ozone and solar variability is found to be extraordinarily clear as shown in Figure 2. The ozone ratio $(O'_3-\bar{O}'_3)/\bar{O}'_3$ at 2 mb averaged between ± 40° latitude and the UV ratio $(I_{205}-\bar{I}_{205})/\bar{I}_{205}$ are given as functions of time from 40 days before until 130 days after December 31, 1978. Initially, the period of solar variability is of the order of 27 days in accord with the rotation period of the sun. Then, in early 1979, a 13-day periodicity occured in accord with two active regions on opposite sides of the sun. The ozone variations are observed to make the transition from the longer to shorter period oscillations in accord with the sun. Even the gradual decrease in the amplitude of oscillation of the solar UV until day 90 of 1979 is mirrored in the ozone oscillations. Referring back to Figure 1, the low amplitude response to solar UV variability may be seen especially between days 70 and 110 of 1979.

TABLE 1. Correlation between variation of O_3 and solar index.

P(mb)	$F_{10.7}$ index T correction	205 nm index T correction	 no T corr.
0.5	.46	.66	.31
1.0	.41	.77	.38
2.0	.48	.82	.43

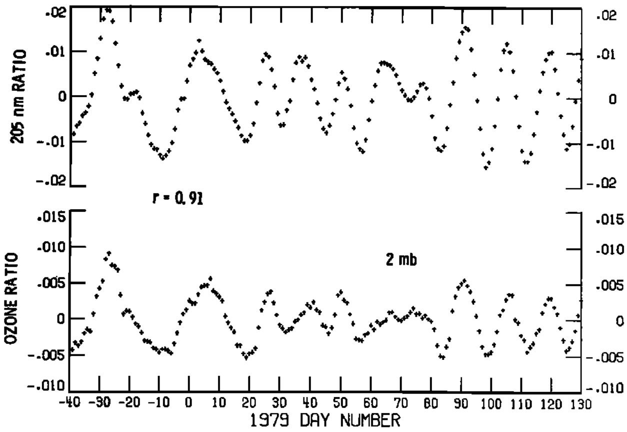

Fig. 2 Relation between ozone ratio $(O'_3-\bar{O}'_3)/\bar{O}'_3$ (lower curve) and 205 nm solar UV variability $(I_{205}-\bar{I}_{205})/\bar{I}_{205}$ (upper curve) at 2 mb after correcting for temperature effect.

Comparison with Theory

The model which is used in the present study (Brasseur et al., 1982) is a one-dimensional chemical/radiative time-dependent model that extends from the Earth's surface to 100 km altitude. It simulates the behavior of about 35 species belonging to the oxygen, hydrogen, nitrogen, chlorine, and carbon families. The long-lived species and the families such as O_x, NO_x or $C\ell_x$ are transported in the vertical by an "eddy diffusion" type exchange. Fast reacting species such as HO_x radicals are assumed to be in photochemical equilibrium.

Relative spectral variations as a function of wavelength were assumed to be in accord with the relative variability averaged over 15 solar

TABLE 2. Short-term spectral variability.

Wavelength nm	$\frac{\Delta I}{I_{av}} / \frac{\Delta I_{205}}{I_{av,205}}$
Lyα	10.15
170.0 - 188.7	1.30
188.7 - 198.0	1.09
198.0 - 208.3	1.00
208.3 - 250.0	0.42
250.0 - 270.3	0.23
270.3 - 317.5	0.09
> 317.5	0.00

TABLE 3. Correlation and lag of short-term O_3 response to 205 nm variation.

Observed (LIMS)			Theory	
P(mb)	Corr.	Lag, Days	(T Feedback) Lag, days	(No T Feedback) Lag, days
10	.42	2(±1)	4(± 0.25)	3.75(±0.25)
5	.71	2	1	2.25
2	.82	0.5	0	0.25
1	.77	0.5	0	0.25
0.5	.66	0.5	0	0
0.2	.59	0.5	0	0

variations, as measured by the Nimbus 7 SBUV instrument (Heath et al., 1983). The corresponding assumed solar variability relative to 205 nm variability is given in Table 2, where I_{AV} and $I_{AV,205}$ are based on Brasseur and Simon (1981).

Tabulated on the right of Table 3 is the predicted response time of the middle atmosphere ozone to the 27-day sinusoïdal solar variations associated with solar rotation. The response time is shown with and without temperature feedback. Shown on the left of Table 3 is a summary of the correlation coefficients and lag times of the observed ozone response to the 205 nm index of solar variability at various pressure levels. The lag times tabulated give the best correlation between $(O'_3 - \bar{O}'_3/\bar{O}'_3$ averaged between ± 20° and $(I_{205}-\bar{I}_{205})/\bar{I}_{205}$ and have an accuracy of about ± 1 day. Lag times between 0 and 1 day are designated 0.5 ± 1 day. The lag times are short in the upper stratosphere and become longer in the middle stratosphere in general accord with theory. As can be seen, the correlation coefficients are extremely high. The correlation coefficients at the upper levels are even higher when the data are averaged between ± 40° latitude. For example, the correlation coefficient between the two parameters in Figure 2 is 0.91 but at lower levels dynamical effects become larger when the data are evaluated between ± 40° latitude as opposed to ± 20°.

Although some studies have shown evidence of temperature decreases resulting from longer-term solar activity decreases (Quiroz, 1979), no statistically significant short-term variation was detected in the LIMS data. This is consistent with our theoretical estimates of a very small temperature change. The calculated short-term increase in temperature at 2 mb for a 1% increase in 205 nm radiation (and corresponding 0.09% increase from 270.3 nm to 317.5 nm) was only 0.05 K.

Comparison between the predicted and observed magnitude of response of ozone to short term solar ultraviolet variations is also shown in Figure 3. Essentially the same theoretical results are determined for 27 day and 13.5 day variation except at the lowest levels. It may be observed that there is generally good agreement with the theoretical magnitude of sensitivity for the no temperature feedback case (case A). Since the observed sensitivities have been normalized to a fixed temperature, the observations should be consistent with the no temperature feedback case. The observed sensitivity sharply increases from 10 mb to 5 mb and then remains near 0.3 except at 0.2 mb where there is a substantial increase. By removing H_2O in the model, an increase in sensitivity at 0.2 mb can be forced to occur (case C). Thus, the high sensitivity of ozone to solar UV variability may indicate a relatively dry mesosphere. On the other hand, larger solar transmittance in the Schumann-Runge bands than is generally assumed would also enhance the ozone variability at these levels. Other discrepancies between observed and calculated parameters above 40 km such as the concentration of O_3 (∿ 20 percent below observations here and in other models), HNO_3 and other source gases may also be related to one of these causes.

Finally, it is of interest to determine the long-term response of O_3 to solar UV variability consistent with the spectral variability relative to 205 nm assumed here. This result has important implications concerning the response of ozone to 11-year solar variations. Figure 3 shows the steady state sensitivity with (case E) and without (case F) temperature feedback. As may be seen, the variations in the upper stratosphere, where time constants are short, are close to the ozone response to short-term solar UV variability. However, much higher sensitivities occur near 10 mb. Thus, if there were a 15% long-term variation of 205 nm radia-

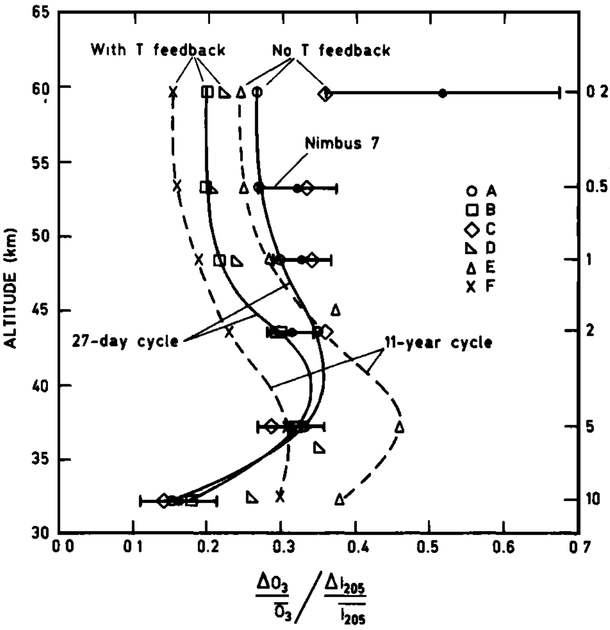

Fig. 3 Sensitivity of the ozone concentration to variations in the solar UV irradiance at 205 nm. Predicted ratios $[(O'_3-\bar{O}'_3)/\bar{O}'_3]/[(I_{205}-\bar{I}_{205})/\bar{I}_{205}]$ are represented at different altitude levels for several cases and are compared with values derived from Nimbus 7 data between ± 20° latitude. Cases A and B : 27 day solar variability (see table 3) without and with temperature feedback respectively. Cases C and D : same as A and B but assuming no water vapor in the middle atmosphere. Cases E and F : same as A and B but for steady state conditions (long-term solar variability).

tion corresponding to ∿ 20% at 180 nm estimated by Hinteregger (1981), Mount (1980), and Brasseur and Simon (1981), the long-term ozone variability at low latitudes from 1 to 10 mb would be 3 to 5% with temperature effects of ∿1 K. The corresponding sensitivity (with temperature feedback) of percent total column ozone to percent 205 nm variability would be 0.17 which would result in a change of total ozone of 2 to 3% over the solar cycle in accord with Keating et al. (1981).

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