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Response of Middle Atmosphere to Short-Term Solar Ultraviolet Variations: 1. Observations

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A series of studies were performed concerning the response of low-latitude ozone and temperature in the stratosphere and mesosphere to short-term solar ultraviolet variability associated with the rotation of the sun. The studies are based on Nimbus 7 Limb Infrared Monitor of the Stratosphere (LIMS) stratospheric ozone and temperature data, Nimbus 7 solar backscattered ultraviolet (SBUV) stratospheric ozone and 205-nm solar ultraviolet data, Solar Mesosphere Explorer (SME) 1.27-μm mesospheric O_3 data, SME 121.6-nm solar ultraviolet data, and Nimbus 7 Stratosphere and Mesosphere Sounder (SAMS) stratospheric and mesospheric temperature data. Using a longer temperature time series than has been used in the past for such studies, response times of temperature to solar UV variability in the stratosphere are found to be unexpectedly long (6 days at 2 mbar) and to become much shorter in the mesosphere (1 day at 0.01 mbar). Maximum sensitivity of temperature to solar variability (0.3 K/percent 205-nm radiation) is found to occur near 70 km. The coupling of the temperature and ozone response to solar UV variability has been isolated by studying ozone responses with and without temperature effects. Temperature effects tend to increase rather than decrease the amplitude and to shift the response time of stratospheric ozone to solar variability to an earlier time. Using a longer ozone time series than has been used in the past for such studies, the stratospheric ozone response with no correction for temperature effects is found to be approximately a 0.4% increase at 3 mbar for a 1.0% increase in 205-nm solar radiation. In the mesosphere a major systematic ozone decrease has been detected near 0.05 mbar ($\sim$70 km), with increased solar Lyman α (121.6 nm) radiation (-0.14% ozone decrease for a 1% increase in solar Lyman α). This may be caused by solar Lyman α photodissociating H_2O vapor producing HO_x, with subsequent destruction of O_x. Higher in the mesosphere, where H_2O mixing ratios should be much lower, ozone is found to increase with increasing solar UV. Observed responses of HNO_3 and NO_2 to solar UV variability are also briefly discussed. The theoretical response of middle atmosphere species and temperature to solar UV variability is discussed in detail in a companion paper (Brasseur et al., this issue).

1. INTRODUCTION

The study of the possible response of the middle atmosphere to solar activity variations has been pursued now for over 50 years. Most of this work has been concentrated on possible atmospheric variations associated with the 11-year solar cycle, including variations in ozone (see *Keating* [1981] for review) and temperature [*Quiroz*, 1979; *Angell and Korshover*, 1983]. In order to obtain convincing statistics on the existence of a cyclic oscillation, about 10 cycles generally need to be studied. A good discussion of the statistical significance of such oscillations as a function of degrees of freedom and data record length is given by *Jenkins and Watts* [1968]. For the 11-year cycle, 10 cycles would represent over 100 years of observations. Clearly, some other approach needs to be undertaken to detect the atmospheric response to solar variability if we hope to accurately separate these natural variations from anthropogenic effects in the near future. Recently, it has been shown that the response of ozone to short-term solar UV variability associated with the 27-day solar rotation can be detected using precise satellite data. Thus using data over a period of less than 1 year, as opposed to a 100-year time series, a significant statistical relation can be determined between ozone and solar UV variability. This allows photochemical relationships to be studied which are critical to fully understanding the photochemical behavior of the middle atmosphere. Once these relationships are understood, the long-term variations of ozone associated with long-term solar variability may be calculated and compared with the limited observations of long-term variability.

Figure 1 shows a number of measurements (including 1-σ errors, when available) of the response of ozone to 1% increases in 205-nm solar radiation. As may be seen, there appears to be substantial scatter in the results. This scatter may be due to various reasons, including temporal variations in the data; differences in the precision of different satellite data; in some cases, no correction for the effects of temperature variations in the ozone data; in some cases, determination of sensitivities using a proxy index as opposed, for example, to the 205-nm solar index; and differences in analytical techniques. A study by *Hood* [1984] used Nimbus 4 backscattered ultraviolet (BUV) measurements between 1.5 and 3 mbar from the early 1970s, when solar activity was lower than during the Nimbus 7 measurements, and direct measurements of 205-nm radiation were not available for comparison with the ozone data. *Chandra* [1985], performing a study on the same data, did not detect a statistically significant relationship between the BUV ozone data and solar variability, but he did not correct for temperature effects in the ozone data. The Nimbus 7 Limb Infrared Monitor of the Stratosphere (LIMS) ozone data have been compared with Nimbus 7 solar backscattered ultraviolet (SBUV) 205-nm solar data, and evidence of an ozone/UV response has been detected using cross-spectral analysis [*Gille et al.*, 1984], but temperature effects on ozone were not removed. Correction for these temperature effects in the LIMS data gave the strongest evidence to date for the O_3/UV relation, with very high correlation between the two detrended parameters [*Keating et al.*, 1985]. It has been found

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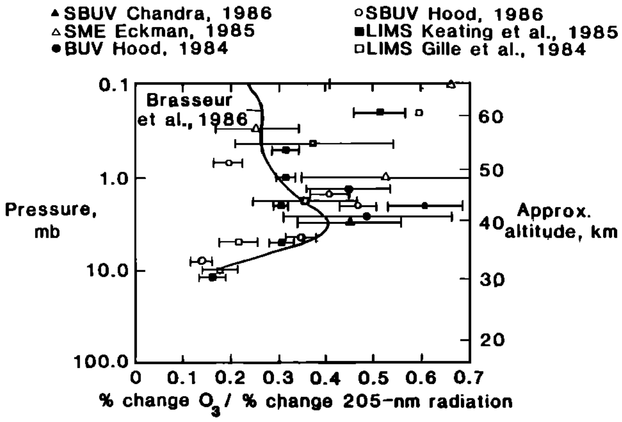

Fig. 1. Ozone response to change in 205-nm solar radiation derived by various investigations. One sigma error bars are provided when reported. The theoretical response without temperature effects for a 27-day solar oscillation given in *Brasseur et al.* [this issue] (labeled Brasseur et al. (1986)) is shown for comparison.

that data for the days December 2–4, 1979, should be removed from this early LIMS retrieval (E. E. Remsberg, private communication, 1986). However, removal of the data on these days does not significantly affect the high O_3/UV correlations. Also, the theoretical response of ozone to short-term solar UV variability was calculated and was found to agree well with the LIMS ozone observations [*Keating et al.*, 1985] when temperature effects were removed. In addition, the early Nimbus 7 SBUV ozone data have been compared directly with 205-nm solar radiation, and evidence of an O_3/UV relation has been detected by *Chandra* [1986], correcting for temperature effects, and by *Heath and Schlesinger* [1985] and *Hood* [1986], not correcting for temperature effects. The Solar Mesosphere Explorer (SME) UV ozone/UV sensitivities [*Eckman*, 1986] were obtained between 0.1 and 1 mbar. Ozone peaked many days before the solar UV maximized, and although a small negative lag can occur if temperatures are rising at the time of the solar UV peak, the magnitude of the lags that Eckman notes are in some cases inconsistent with theory as well as with other measurements. *Aikin and Smith* [1986] have attempted to use SME 1.27-μm data to study mesospheric ozone and see some evidence of a 27-day signal, but two independent data sets give inconsistent results, probably due to the noise in the limited data sets.

In this paper we use essentially the approach we developed for the LIMS data to study the Nimbus 7 SBUV and SME 1.27-μm ozone data, in an effort to obtain a self-consistent picture of the response of ozone to solar UV variability. As opposed to the approximate 2-year interval used previously for SBUV data, 4 years are analyzed here to check for consistency of the ozone/UV relation.

Since the solar UV variability should also affect temperature with subsequent "temperature feedback" on the ozone/UV response, the possible effects on temperature are investigated using the Nimbus 7 Stratospheric and Mesospheric Sounder (SAMS) temperature data. Recent studies by *Hood* [1986] have shown indications of a stratospheric temperature/UV relation. Four years of SAMS data are studied here, a much longer period than in the studies of *Hood* [1986]. In addition, the temperature data are broken into two independent data sets which give very similar results which are contrary to theoretical predictions. The changes in phase and amplitude of the O_3/UV response due to "temperature feedback" are then isolated for the first time by empirically determining the response, both with and without "temperature feedback." Previous investigators have studied the O_3/UV relation either with or without temperature effects. Also, differences in the atmospheric response to 27-day and 13-day solar oscillations are identified. Next, the ozone and temperature response in the mesosphere are determined. The ozone response is clearly isolated by using a much larger mesospheric ozone data base than has been used in the past. The ozone is found to respond strongly to solar Lyman α variations, probably through the photodissociation of water vapor, with subsequent destruction of ozone. The mesospheric temperature response to short-term solar variability is traced for the first time into the upper mesosphere. Thus the atmospheric response to short-term solar UV variability is isolated here for almost the entire low-latitude middle atmosphere.

This paper focuses on the observed response of ozone and temperature in the middle atmosphere to solar UV variations. A companion paper [*Brasseur et al.*, this issue] focuses on the corresponding theoretical response of ozone and temperature to solar UV variability.

2. DATA DESCRIPTION

In the present study, ozone, temperature, and solar flux measurements from several different satellite experiments have been utilized to detect the response of the middle atmosphere to short-term solar ultraviolet variations. In particular, ozone data from the Nimbus 7 LIMS, Nimbus 7 SBUV, and the SME 1.27-μm instrument, as well as temperature data from the Nimbus 7 SAMS and LIMS, have been correlated with SBUV 205-nm solar flux data and, in one case, with SME 121.6-nm solar flux data.

The 205-nm solar flux measurements were chosen as the solar index for stratospheric studies. The 205-nm wavelength has been shown to be much more strongly correlated with ozone variations than a classical solar index such as the 10.7-cm solar flux [*Keating et al.*, 1985]. Stronger correlations should be expected, since 205-nm radiation actually photodissociates O_2, with subsequent production of O_3, while proxy indices like 10.7-cm solar flux play no direct role in photochemistry. Also, a sharp drop occurs in solar variability at 208 nm (aluminum edge), so that the 205-nm flux is essentially the strongest solar signal with substantial variability. *Donnelly et al.* [1983] have shown that 205-nm solar radiation displays a much stronger 14-day component than the 10.7-cm solar flux because its solar emission is more directional. For mesospheric studies the solar Lyman α flux, obtained from daily measurements of the full solar disc by the SME satellite, has also been used [*Rottman*, 1982].

The LIMS instrument, which flew aboard the Nimbus 7 satellite, was a cryogenically cooled, limb-scanning radiometer with six channels centered at wavelengths between 6.2 and 15 μm. Radiance measurements from these channels are inverted to obtain profiles of temperature, ozone, H_2O, HNO_3, and NO_2 [*Russell*, 1984; *Russell and Gille*, 1978; *Gille and Russell*, 1984]. Ozone profiles are obtained from radiances measured by the 9.6-μm channel and temperature profiles from radiances measured by two channels centered at 15 μm. The vertical resolution of the ozone and temperature measurements is better than 3 km (J. M. Russell III, private communication, 1986). The resulting LIMS ozone and temperature data sets consist of 7 months (October 25, 1978 to May 28, 1979) of profiles at pressure levels between 100 and 0.1 mbar, from 84°N to 64°S in latitude.

Validation studies have been performed on the LIMS ozone data using balloon and rocket underflights, Umkehr soundings, and Dobson measurements [*Remsberg et al.*, 1984]. Correlative comparisons show mean differences with balloon data of less than 10% at mid-latitudes and less than 16% mean differences (up to pressure levels of 0.3 mbar) with rocket data. The precision of individual ozone measurements is estimated to be approximately 0.15 parts per million by volume (ppmv) ($\sim$2% at 2 mbar). For a 5-day zonal mean between $\pm 20°$ latitude, about 700 scans are averaged, increasing precision to $\sim$0.1%.

Validation studies performed on LIMS temperature data using radiosonde-rocketsonde data indicate mean differences of approximately 2 K or less below the altitude corresponding to 1 mbar [*Gille et al.*, 1984]. At altitudes above 1 mbar the rocketsonde comparison measurements probably contain significant errors, which further bias the data. Recent comparisons with ground-based lidar data indicate essentially the same agreement up to the 0.1-mbar level [*Remsberg*, 1986]. The precision of the individual temperature measurements is estimated to range from less than 0.2 K, at 50 mbar, to approximately 0.6 K, at 0.4 and 0.1 mbar.

The SBUV instrument, which is also aboard the Nimbus 7 satellite, is a nadir-viewing double monochromator which measures backscattered radiances at 12 discrete wavelengths from 255 to 340 nm, with a 1-nm band pass [*Heath et al.*, 1975]. Ozone profiles are obtained on a daily basis by inverting radiances between 255 and 340 nm. The vertical resolution of the ozone measurements is estimated to be approximately 8 km [*McPeters et al.*, 1984]. The SBUV ozone data set analyzed in this study consists of nearly 4 years of mixing ratio profiles (December 1978 to October 1982) at pressure levels ranging from 1 to 10 mbar, between 20°N–20°S in latitude.

Comparisons of SBUV ozone profiles with balloon and Umkehr data show constant biases of generally less than 10%, which may be due largely to inconsistencies in ozone absorption cross sections used for various measuring systems [*Bhartia et al.*, 1984]. The precision of individual ozone measurements is estimated to be better than 8% between 1 and 63 mbar.

The Nimbus 7 SBUV instrument also makes daily measurements of solar flux at 0.2-nm intervals, with a band pass of 1 nm in the 160- to 400-nm range of the solar UV spectrum, by deploying an aluminum diffusor plate [*Fleig et al.*, 1982]. The 205-nm radiation measurements were made available for the entire period from October 1978 until October 1982.

The SAMS instrument aboard the Nimbus 7 spacecraft is a multichannel, infrared limb-scanning radiometer which employs conventional chopping and pressure modulation techniques to measure temperature and minor constituents by thermal emissions [*Drummond et al.*, 1980; *Wate and Peskett*, 1984]. The temperature profiles as a function of pressure are determined by inverting radiances measured by two pairs of narrow band and wideband 15-μm carbon dioxide channels [*Rodgers et al.*, 1984]. One pair of channels obtains radiances from a higher altitude than the other pair. The vertical resolution of the temperature measurements is 8–10 km. Occasionally, only radiances from the low-altitude pair of 15-μm channels were used to determine temperature profiles, which reduced the signal-to-noise ratio of the measurements [*Barnett and Corney*, 1984, J. J. Barnett, private communication, 1986]. In the present study, only temperature measurements obtained from both pairs of channels have been included. The SAMS data set analyzed in this study consists of nearly 4 years of temperature profiles (December 1978 to October 1982) at pressure levels ranging from 0.002 to 30 mbar, from latitudes of 20°N to 20°S.

Validation studies performed on the SAMS temperature data show good agreement with rocket, radiosonde, and NOAA 6 stratospheric sounding unit (SSU) data [*Barnett and Corney*, 1984]. Also, SAMS agrees well with LIMS data [*Rodgers*, 1984]. These comparisons show differences of up to 2 K in the lower stratosphere and up to 1 K in the upper stratosphere. The precision of the individual temperature measurements is estimated to be typically 1 K.

The SME satellite, which was launched into a sun-synchronous orbit on October 6, 1981, consists of four limb-scanning instruments to measure ozone density and other minor constituents [*Barth et al.*, 1983]. Ozone densities are obtained by two methods. An ultraviolet spectrometer measures solar radiation at two wavelengths (265 nm and 297 nm), which are then inverted to yield ozone densities between 0.1 and 1 mbar [*Rusch et al.*, 1983]. Ozone densities between 0.002 and 1 mbar are determined from measurements of 1.27-μm airglow by a near-infrared spectrometer with a vertical resolution of approximately 3.5 km [*Thomas et al.*, 1983]. In the present study, approximately 2 years of SME IR ozone profiles (December 1981 to September 1983) at pressure levels ranging from 1 to 0.005 mbar, from 40°N to 40°S in latitude, have been analyzed.

The SME IR ozone profiles exhibit good agreement with the rocket model of *Krueger and Minzner* [1976]. *Thomas et al.* [1984] performed an error analysis on this experiment. Random errors are estimated to be less than 15%. Most of the measurements were obtained on the orbits that cover the longitude range from 40° to 100°W each day during local afternoon (1500 LT). This biased longitudinal coverage could cause spurious results when attempting to estimate zonal means.

The SME satellite also contains a two-channel spectrometer to measure full disc solar irradiance over a spectral interval of 120–305 nm, with a spectral resolution of approximately 0.75 nm [*Rottman et al.*, 1982]. Solar Lyman α fluxes (121.6 nm) measured by this instrument are used in this study.

Table 1 shows the individual data sets which were analyzed in these studies. Tabulated are the data which were correlated, the time interval of measurement, latitude bands over which the data were zonally averaged, and the pressure range over which the studies were performed.

3. SATELLITE DATA ANALYSIS

The predicted amplitudes of the response of middle atmosphere ozone and temperature to short-term variations in solar ultraviolet flux are relatively small (approximately 0.4% for ozone and 0.1 K for temperature for a 1% change in 205-nm solar flux). In order to detect these small variations it is advantageous to average large quantities of precise satellite data. For example, the average precision of individual ozone measurements from Nimbus 7 LIMS is approximately 0.15 ppmv [*Remsberg et al.*, 1984], which corresponds to about 2% precision at 2 mbar. The variations we are searching for are less than 2%, and therefore we must average hundreds of data points to obtain a clear signature. For example, if we average data over all longitudes and latitudes between $\pm 20°$ over a

TABLE 1. Data Sets Analyzed in These Studies

Data Correlated	Time Interval	Latitude Band	Pressure Range
O_3(LIMS)/205-nm(SBUV) (corrected for LIMS T)	Nov. 1, 1978–May 28, 1979	±20° and ±40°, zonal	10–0.5 mbar
O_3(SBUV)/205-nm(SBUV)	Dec. 24, 1978–Sept. 30, 1982	±20°, zonal	10–1 mbar
O_3(SBUV)/205-nm(SBUV) (corrected for SAMS T)	Dec. 24, 1978–Sept. 30, 1982	±20°, zonal	10–1 mbar
O_3(SBUV)/205-nm(SBUV)	~13.5 days (Jan. 25, 1979–June 8, 1979; Nov. 9, 1980–Jan. 26, 1981; July 15, 1981–Dec. 4, 1981; March 22, 1982–May 31, 1982)	±20°, zonal	10–1 mbar
	~27 days (Oct. 20, 1979–Feb. 3, 1980; May 27, 1980–Oct. 2, 1980; June 26, 1982–Sept. 28, 1982)	±20°, zonal	10–1 mbar
T(SAMS)/205-nm(SBUV)	Dec. 24, 1978–Oct. 13, 1980	±20°, zonal	10–0.02 mbar
	Oct. 14, 1980–Sept. 30, 1982	±20°, zonal	10–0.02 mbar
	Dec. 24, 1978–Sept. 30, 1982	±20°, zonal	10–0.002 mbar
O_3(SME)/205-nm(SBUV)	Dec. 15, 1981–Sept. 30, 1983	±40°	0.5–0.005 mbar
O_3(SME)/121.6-nm(SME)	Dec. 15, 1981–Sept. 30, 1983	±40°	0.5–0.005 mbar

In each case, two parameter ratios $(X - \bar{X})/\bar{X}$ are correlated, where X equals the 5-day running mean, and $\bar{X}$ is 27-day running mean of X. T equals temperature.

5-day period, about 700 scans are averaged. The standard error of the means obtained for such a data set is about 0.1%. The sun has a rotation period of approximately 27 days, and if active regions form on opposite sides of the sun, 13.5-day solar oscillations can occur (as is often the case). Therefore averaging data for periods much longer than 5 days can filter out important solar variations. Of course, the longer the time series, the less averaging is required to clearly detect a signal. However, when comparing a number of satellite data sets with different characteristics, it is advantageous to fix the averaging procedure. Test cases indicated that essentially the same statistics were obtained whether a straight 5-day running mean or, for example, a 5-day weighted moving average was used.

In order to detrend the data to reduce the effect on statistics of long-term trends and/or instrument drift, fractional variations relative to a 27-day running mean were determined. Thus ozone, solar flux, and temperature were analyzed in terms of "ratios,"

$$R(X) = \frac{X - \bar{X}}{\bar{X}}$$

where X is the 5-day running mean of the parameter and $\bar{X}$ is the 27-day running mean of X. It is then the ozone or temperature "ratios" which are correlated with the solar index "ratio" to determine the amplitude and phase of the atmospheric response. It should be noted that we have performed studies where $\bar{X}$ was averaged over time periods varying between 19 and 35 days and that we obtain correlation and regression coefficients very similar to the results we obtain for the $\bar{X}$ over 27 days. Increasing the width of the latitude band tends to increase precision up to a point, but higher-latitude data are more influenced by dynamics, which disguise the photochemical signal. Also, the sensitivity of the atmosphere to solar UV variability is latitude dependent. Generally, the clearest responses to solar UV variability result from averaging zonal means between ±20° and ±40° in latitude.

This method of improving the precision and detrending the data is the same approach used by *Keating et al.* [1985]. Somewhat similar approaches are being used by *Hood* [1986] and *Chandra* [1986].

Another approach is to perform cross-spectral analysis [*Gille et al.*, 1984; *Hood*, 1986; *Eckman*, 1985; *Aikin and Smith*, 1986] of two of the data sets. However, this approach requires long time series for good spectral resolutions and is much more affected by the methods by which data gaps are filled. Also, the longitude of active regions on the sun tends to shift with time, which tends to flatten out spectral peaks. *Eckman* [1986] points out that correlation analyses are not as limited by the length of the time series or its stationarity as are cross-spectral analyses.

In order to utilize as continuous a time series as possible, data gaps in the ozone, temperature, and solar UV indices were filled in through linear interpolation. Data gaps encountered were generally no longer than 1 or 2 days; in the case of the SAMS temperature data, gaps of up to 10 days occurred, but they were generally less than 5 days.

Generally, the ozone/UV relation can be detected more clearly by removing the effects of dynamically induced temperature variations on ozone. The method by which this can be accomplished is included in section 4.1.

4. STRATOSPHERIC RESPONSE

4.1. *O_3/UV Relation Without Temperature Feedback*

Increases in temperature in the upper stratosphere lead to increased rates of ozone destruction by atomic oxygen (Chapman reactions) and by catalytic species. *Keating et al.* [1985, Figure 1] show 5-day running means of LIMS ozone volume mixing ratio and temperature at 2 mbar, zonally averaged over the latitude band 0 ± 20°. The ozone variations clearly follow the temperature variations (in the opposite sense), with response times of less than 1 day. These large temperature variations are thought to be principally dynamical in nature [*Chandra*, 1985], although, as we shall show later, there is a small but significant signal associated with

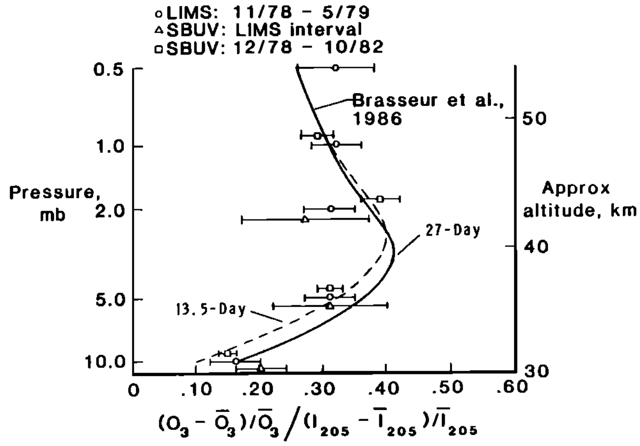

Fig. 2. Ozone response corrected for temperature effects to change in 205-nm solar radiation derived from Nimbus 7 LIMS (November 1978 to May 1979), Nimbus 7 SBUV over the same data interval as LIMS, and Nimbus 7 SBUV over the longer period from December 1978 to October 1982. The SBUV ozone data is corrected for temperature effects, using Nimbus 7 SAMS temperatures. The sensitivities are all obtained at 10, 5, 2, 1, and 0.5 mbar and are displaced on the figure for clarity. The "ratios" for ozone and 205-nm solar flux are defined as $(X - \bar{X})/\bar{X}$, where X is the 5-day running mean of the parameter and $\bar{X}$ is the 27-day running mean of X. The theoretical response without temperature effects for 27-day and 13.5-day solar oscillations given in *Brasseur et al.*, [this issue] (labeled Brasseur et al. (1986)) are shown for comparison.

solar variability imbedded in them. The small response of the temperature to solar UV variability leads to a "temperature feedback" effect on the O_3/UV relation, which is discussed in section 4.3. The direct response of ozone to solar UV variations can be isolated by removing the ozone variations associated with temperature variations.

There are also other advantages to studying the response of ozone after removing temperature effects. Temperature errors in the LIMS algorithm can create inversely related ozone errors. Thus removal of temperature effects would tend to minimize extraneous ozone errors associated with these small errors in temperature. Furthermore, comparisons of observed variations in the ozone/UV relation with theoretical calculations are more staightforward when temperature effects are removed because the theoretical calculations are less complex (theoretical calculations of the responses of ozone to UV variability need not take into account the response of temperature to solar UV variability). The temperature/UV relation is treated as a separate topic in section 4.2.

The method chosen to remove the temperature effects on ozone variations is to normalize the ozone mixing ratio to the ozone value for the mean temperature over the entire data set, taking into account the regression coefficient between ozone and temperature. The regression coefficient was determined between the detrended parameters $(O_3 - \bar{O}_3)/\bar{O}_3$ and $T - \bar{T}$ where, as previously defined, O_3 and T are 5-day running means and $\bar{O}_3$ and $\bar{T}$ are 27-day running means of O_3 and T, respectively. The corresponding observed value of $d \ln (O_3)/d(T^{-1})$ at 2 mbar is 1128 K for the LIMS data, which is close to theoretical estimates based on photochemistry [*Barnett et al.*, 1975; *Keating et al.*, 1983; *Brasseur et al.*, this issue]. However, even in the upper stratosphere, where the photochemical lifetime of ozone is short, the effect of dynamics can not be totally ignored. Indeed, as shown by *Rood and Douglas* [1985] and *Douglas et al.* [1985], in certain occasions, dynamics can mimic the relationship between ozone and temperature expected from photochemistry.

It was shown by *Keating et al.* [1985] that removal of the effects of temperature resulted in substantial improvement in the correlation between the ozone "ratio" and the solar index "ratio." For example, O_3/UV correlations of LIMS data between $\pm 20°$ latitude at 2 mbar increased from 0.43 to 0.82. In a number of studies, temperature corrections have not been made to ozone data. This includes studies of ozone data from Nimbus 7 LIMS [*Gille et al.*, 1984], Nimbus 7 SBUV [*Hood*, 1986], Nimbus 4 BUV [*Chandra*, 1985], SME UV [*Eckman*, 1986], and SME IR [*Aikin and Smith*, 1986].

The response of ozone to 205-nm solar variability during the LIMS data interval was clearly detected when temperature effects were removed from the ozone data (see Figure 2 of *Keating et al.* [1985]). Early in the LIMS experiment 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 in solar variability occurred when two active regions developed on opposite sides of the sun. The ozone variations follow the short-term solar variations remarkably well.

The response time of ozone to solar UV variability can be established by determining the time lag which gives the best correlation between the ozone ratio and the 205-nm solar flux ratio. Accordingly, *Keating et al.* [1985] showed that phase lags of $+0.5 \pm 1$ days occurred in the upper stratosphere (2 mbar and above), while phase lags of $+2 \pm 1$ days occurred deeper in the atmosphere (5 and 10 mbar). The theoretical response times were also found to be less than 1 day at 2 mbar and above, and 2 days or greater at 5 mbar and below [*Keating et al.*, 1985; *Brasseur et al.*, this issue].

TABLE 2. T(SAMS)/205-nm(SBUV) Relation Over Two Time Periods

		December 1978 to October 1980, ±20° Latitude				October 1980 to September 1982, ±20° Latitude			
P, mbar	~z, km	Lag, ±1 day	Corr.	S, %	σ	Lag, ±1 day	Corr.	S, %	σ
0.02	76	1	0.20	0.074	0.014	0	0.15	0.073	0.019
0.03	74	0	0.20	0.109	0.021	1	0.16	0.105	0.025
0.04	72	0	0.21	0.130	0.025	2	0.18	0.122	0.025
0.05	70	0	0.20	0.128	0.025	2	0.21	0.126	0.023
0.07	69	0	0.21	0.120	0.022	3	0.29	0.125	0.016
0.1	66	1	0.22	0.087	0.016	4	0.40	0.107	0.009
0.15	63	2	0.19	0.058	0.012	5	0.31	0.079	0.009
0.2	61	3	0.17	0.047	0.011	5	0.25	0.058	0.009
0.3	58	4	0.20	0.040	0.008	4	0.21	0.035	0.006
0.4	55	4	0.27	0.041	0.006	3	0.21	0.030	0.005
0.5	54	5	0.30	0.042	0.005	3	0.22	0.033	0.006
0.7	51	6	0.31	0.047	0.006	4	0.27	0.040	0.006
1.0	48	6	0.33	0.050	0.006	5.5	0.32	0.051	0.006
1.5	45	6	0.33	0.047	0.005	6	0.31	0.060	0.007
2.0	43	7	0.31	0.042	0.005	6.5	0.30	0.057	0.007
3.0	40	8	0.24	0.029	0.005	8	0.25	0.039	0.006
4.0	38	10	0.21	0.025	0.005	14	0.19	0.035	0.007
5.0	36	11.5	0.20	0.027	0.005	15	0.19	0.046	0.009
7.0	34	12	0.20	0.033	0.006	16	0.19	0.056	0.011
10.0	31	12	0.23	0.037	0.006	16	0.20	0.047	0.009

$S = [(T - \bar{T})/\bar{T}]/[(I_{205} - \bar{I}_{205})/\bar{I}_{205}]$; Corr. equals correlation coefficient.

TABLE 3. T(SAMS)/205-nm (SBUV) Relation Over 4 Years

		Dec. 24, 1978 to Sept. 30, 1982 ±20° Latitude			
P, mbar	~z, km	Lag, ±1 day	Corr.	S, %	σ
0.002	90	0.5	0.04	0.014	0.011
0.005	84	0.5	0.07	0.024	0.010
0.007	82	1.0	0.09	0.029	0.009
0.01	80	1.0	0.12	0.036	0.008
0.015	78	1.0	0.15	0.054	0.009
0.02	76	1.0	0.17	0.072	0.012
0.03	74	0.7	0.18	0.106	0.016
0.04	72	1.0	0.19	0.122	0.017
0.05	70	1.5	0.19	0.121	0.017
0.07	69	1.5	0.22	0.109	0.014
0.10	66	2.5	0.25	0.087	0.009
0.15	63	3.5	0.22	0.062	0.007
0.20	61	3.5	0.19	0.048	0.007
0.30	58	3.5	0.20	0.037	0.005
0.40	55	4.0	0.24	0.035	0.004
0.50	54	4.5	0.25	0.034	0.004
0.70	51	5.0	0.29	0.043	0.004
1.0	48	6.0	0.33	0.051	0.004
1.5	45	6.0	0.32	0.054	0.004
2.0	43	6.5	0.30	0.048	0.004
3.0	40	8.0	0.24	0.033	0.004
4.0	38	12.0	0.18	0.027	0.004
5.0	36	13.5	0.17	0.032	0.005
7.0	34	14.0	0.17	0.039	0.006
10.0	31	14.5	0.18	0.036	0.005

$S = [(T - \bar{T})/\bar{T}]/[(I_{205} - \bar{I}_{205})/\bar{I}_{205}]$; Corr. equals correlation coefficient.

Figure 2 shows the sensitivity of ozone, after temperature effects have been removed, to variations in the 205-nm solar UV irradiance (as measured by SBUV) as a function of pressure level. Three different data sets are represented in Figure 2. Sensitivities calculated from the LIMS ozone data set are depicted by circles, triangles represent sensitivities calculated using only SBUV ozone measurements from the time interval of the LIMS experiment, and sensitivities using 4 years of the SBUV data are indicated by rectangles. Error bars represent the 2-σ error in a least mean squares fit for each sensitivity. For clarity the error bars are displaced somewhat from the actual pressure levels indicated on the left of Figure 2. The SBUV ozone data were corrected for temperature effects, using simultaneous Nimbus 7 SAMS temperature data in the same way the LIMS ozone data were corrected. As may be seen, the SBUV data over the LIMS period gave much larger error bars than the LIMS data and only gave statistically significant solutions up to 2 mbar. The large errors associated with sensitivities from the SBUV data over the LIMS time interval may partially result from SBUV being a nadir-viewing instrument with less vertical resolution than LIMS, which makes it difficult to accurately correct for temperature effects using the temperature measurements from the limb-viewing SAMS instrument. As can be seen, however, when 4 years of SBUV ozone data are used, precision increases and ozone sensitivities have accuracies comparable to those determined by LIMS. The increased precision of sensitivities, as determined from 4 years of SBUV ozone data, is partially because of the longer period of measurement and partially because of greater solar variability after the period of the LIMS measurements. Figure 2 shows good agreement between the sensitivities derived from the LIMS and SBUV data.

The theoretical response of ozone to solar ultraviolet variability has been calculated using the Brasseur et al. one-dimensional time-dependent, radiative photochemical model described in some detail in a companion paper [*Brasseur et al.*, this issue]. A sinusoidal variation in the solar ultraviolet radiation is assumed with periods of 27 and 13.5 days. The short-term solar spectral variability relative to the variability at 205 nm is assumed to be that given by *Keating et al.* [1985, Table 2]. This variability is consistent with the relative variability averaged over 15 solar oscillations, as measured by the Nimbus 7 SBUV instrument [*Heath et al.*, 1983]. The essentially sinusoidal response of ozone to the sinusoidal variations in solar ultraviolet radiation is used to determine the amplitude and phase lag of the ozone variation relative to the solar UV variation. Shown also in Figure 4, then, is the theoretical response of ozone to 13.5-day and 27-day oscillations of the sun before correcting ozone for the response of temperature to solar UV variability.

As may be seen, the theoretical calculations with no temperature effects are in fair agreement with observations. The drop in sensitivity near 10 mbar is predicted by theory and is detected in both the LIMS and SBUV measurements.

4.2. *Temperature/UV Relation*

In order to study the response of ozone to variations of temperature brought about by solar UV variability, an effort has been made to isolate the temperature response to solar UV variability. Theoretically, the upper stratospheric temperature response should only be approximately 0.1 K for a 1% increase in 205-nm radiation [*Brasseur et al.*, this issue; *Eckman*, 1986]. In order to detect such a small variation, it was considered important to investigate a data set which includes large short-term variations in solar UV variability as well as a long time interval so that the effects of noise could be reduced. As a result, the approximately 4 years of temperature data from the Nimbus 7 SAMS experiment as well as the 7 months of Nimbus 7 LIMS temperature data have been investigated.

In order to establish the reality and persistence of the temperature response to solar UV variability, the SAMS temperature data were divided into two intervals of approximately 2 years each (see Table 1). The results at various pressure levels are shown on the left-hand side of Table 2 for the period December 1978 through October 1980 and on the right-hand side of Table 2 for the period October 1980 through September 1982. At each pressure level the approximate altitude,

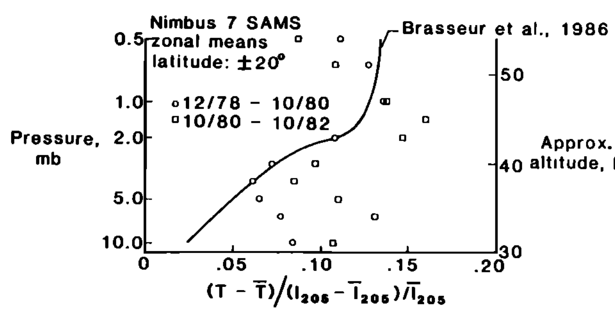

Fig. 3. Response of stratospheric temperatures, zonally averaged between ±20° latitude, to solar UV variability as a function of pressure and approximate altitude. The term T is the 5-day running mean of temperature and $\bar{T}$ is the 27-day running mean of T. Sensitivities are provided for two intervals of the Nimbus 7 SAMS data. For comparison the theoretical response given by *Brasseur et al.* [this issue] for a 27-day solar oscillation (labeled Brasseur et al. (1986)) is also provided.

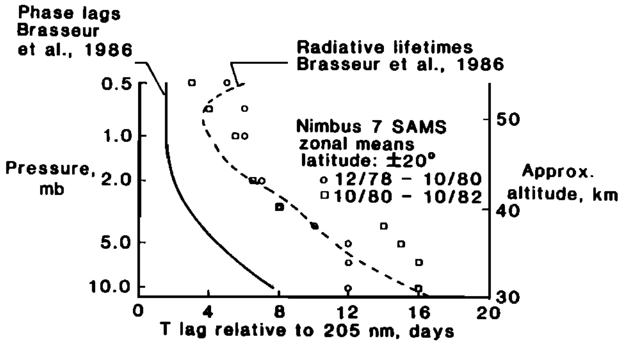

Fig. 4. Observed phase lags after the 205-nm solar UV peak of the corresponding temperature peak corresponding to the temperature sensitivities in Figure 3 derived from two sets of Nimbus 7 SAMS data. Shown for comparison are the corresponding calculated phase lags for a 27-day solar oscillation as well as radiative lifetimes derived by *Brasseur et al.* [this issue], labeled Brasseur et al. (1986).

phase lag (±1 day), correlation between the temperature "ratio" and 205-nm "ratio", temperature sensitivity (T ratio/205-nm ratio), and standard deviation in temperature sensitivity from a least mean squares fit to the data are tabulated. In Table 3, similar results are shown when the entire data set from December 1978 to September 1982 are combined. The correlation between the temperature "ratio," zonally averaged between ±20° latitude, and the 205-nm "ratio" generally maximized a number of days after the peak at 205 nm. Although the correlations were generally not strong, both the correlations and regression coefficients were statistically significant at the two standard deviation level. Dynamical effects are clearly the major cause of the short-term temperature variations, but the secondary solar response is indeed observable. Depicted in Figure 3 are the corresponding stratospheric temperature/UV sensitivities in degrees Kelvin per percent for the two 2-year data sets. Note that the units here are different than in Tables 2 and 3. Also shown is the theoretical response from *Brasseur et al.* [this issue] for 27-day solar oscillations. As may be detected, both data sets give sensitivities of approximately 0.1 K per percent variation in 205-nm radiation. A comparable study over a shorter interval of SAMS data (December 1978 to October 1980) by *Hood* [1986] gives similar results (see *Brasseur et al.*, [this issue]).

Figure 4 shows the corresponding phase lags in peak stratospheric temperature with respect to the solar UV peak. Comparisons with the solid theoretical curve from *Brasseur et al.* [this issue] show that the observed phase lags exceed the theoretical phase lags in every case. For example, at 2 mbar the theoretical lag is 1.5 days, while the observed lag based on SAMS data is ~7 days for the first 2 years and 6.5 days for the second 2 years. A similar study of the 7 months of LIMS data yields, at 2 mbar, a phase lag of 7.3 days and a temperaure sensitivity of 0.13 K per percent increase of 205-nm solar radiation. The study by *Hood* [1986] gives a lag of 7 days. Other theoretical calculations yield phase lags ranging from 1 day [*Wuebbles*, 1985] to approximately 3 days [*Eckman*, 1986; *Hood*, 1986; *Chandra*, 1986]. Therefore the observed phase lags clearly exceed the theoretical estimates. Also shown in Figure 4 by the dashed line is the calculated radiative lifetime as a function of altitude. It may be seen that the radiative lifetimes exceed the calculated phase lags for a sinusoidal oscillation in solar UV radiation but are closer to the observed phase lags. Figure 5 shows phase lags determined using all 4 years of the SAMS data. As may be detected, phase lags become considerably shorter in the mesosphere (i.e., 1 day at 0.02 mbar, or ~76 km). One possible explanation for the long lag times in the stratosphere could be related to wave propagation. Of course, theories on vertically propagating disturbances must take into consideration the effects of variations in the zonal wind fields. Pilot studies on the possible downward propagation of solar disturbances are currently being performed [*Dameris et al.*, 1986; *Ebel et al.*, 1986].

4.3. *Effect of "Temperature Feedback" on O_3/UV Relation*

It is now of interest to investigate the effect on ozone of the response of temperature to solar variability, including the effect of long phase lags in the temperature/UV response. The effects of temperature on the ozone response (principally, changing reaction rates) is referred to here as "temperature feedback."

Some insight into the effects on ozone of the long phase lags in T/UV response can be gained by referring to the schematic diagrams in Figure 6. Shown on the top of Figure 6 is case A, where no phase lag is assumed between the solar UV peak and the temperature peak. The curve corresponding to the ozone response for no temperature feedback in case A is essentially in phase with solar ultraviolet. This corresponds to the

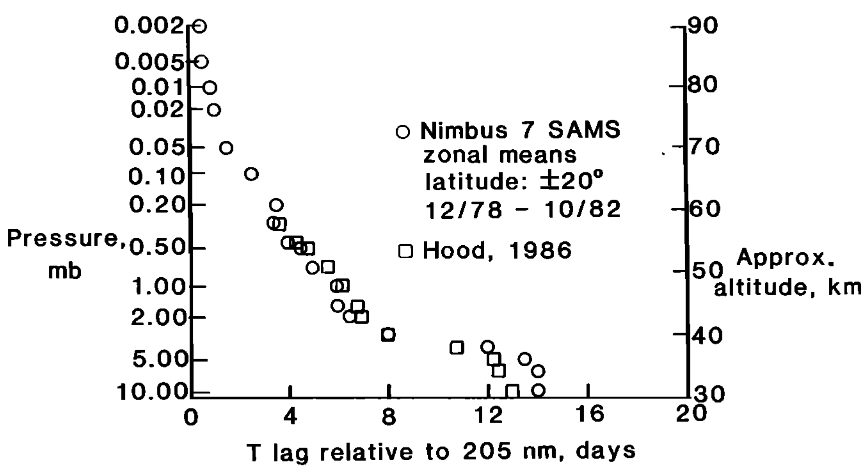

Fig. 5. Observed phase lags after the 205-nm solar UV peak of the corresponding stratospheric and mesospheric temperature peak using 4 years of Nimbus 7 SAMS data, where zonal means are averaged between ±20° latitude. For comparison the stratospheric results of *Hood* [1986], based on less than 2 years of the SAMS data are also shown.

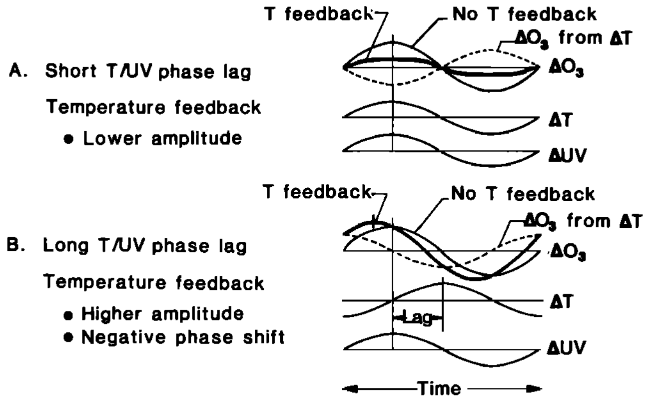

Fig. 6. Schematic diagram showing ozone response when response of temperature to UV variability is (*a*) rapid and (*b*) slow as observed.

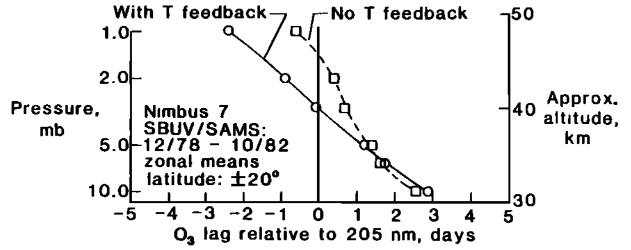

Fig. 7. Observed lag times of the ozone peak after (positive) or before (negative) the 205-nm solar UV peak, as a function of pressure and approximate altitude. The results are based on 4 years of Nimbus 7 SBUV zonal mean ozone data, averaged between ±20° latitude. The effects of temperature on ozone are removed in the "No *T* Feedback" case, employing 4 years of Nimbus 7 SAMS temperature data.

cases in section 4.1, where temperature effects were removed (thereby removing "temperature feedback"). The ozone perturbation produced by the temperature variation is shown by the dashed line in case A and is, of course, negatively correlated with temperature. When the "no temperature feedback" wave is combined with the ozone perturbation produced by the temperature variation, the resultant wave represents the ozone variation with temperature feedback. As may be seen, the net effect of temperature feedback in this case is to reduce the amplitude of the ozone variation.

When there is a substantial positive lag in the temperature response (i.e., the temperature peak is substantially later than the UV peak), we obtain an entirely different scenario, shown as case B. In case B a phase lag of approximately one quarter of a revolution is assumed between the temperature peak and the solar UV peak. This would correspond to the temperature peak occurring about 7 days after the peak of the 27-day solar oscillation, which is approximately the situation near 2 mbar. When the corresponding ozone perturbation resulting from the temperature wave, indicated by the dashed line in case B, is combined with the "no temperature feedback" wave, the resulting ozone variation "with temperature feedback" appears entirely different than in case A. In case B the amplitude of the ozone wave with temperature feedback is actually greater than the amplitude of the ozone wave with no temperature feedback. Furthermore, with temperature feedback the ozone peak actually occurs before the solar UV peak (negative lag). The ozone peak shifts to an earlier time because at the time of the UV peak the temperature wave exhibits a positive slope. If the scenario in case B is correct, then temperature feedback would be expected to increase the ozone/UV sensitivity and shift the ozone/UV phase lag to earlier times.

This hypothesis has been tested using approximately 4 years of Nimbus 7 SBUV ozone data, which covers intervals when there is strong solar UV variability. Such a data set allows detection of the ozone response to solar UV with and without temperature feedback. Shown on the left side of Table 4 is the response of SBUV ozone, not corrected for temperature effects ("temperature feedback" case), zonally averaged between ±20° latitude for the period October 1978 through November 1982. Tabulated are the pressure, lag times ±1 day (where positive lags mean ozone peaks occur after the solar UV peak), correlation between ozone ratio and 205-nm ratio, O_3 sensitivity (ozone ratio/205-nm ratio), and standard deviation in O_3 sensitivity from a least mean squares fit to the data. Similarly, shown on the right-hand side of Table 4 is the response of SBUV ozone over the same interval but corrected for temperature effects (i.e., "no temperature feedback"). In this case the SBUV ozone data were corrected for temperature effects employing simultaneous Nimbus 7 SAMS temperature measurements, using the same approach as was used on the LIMS data. It should be noted that correction for temperature effects improved the correlation and reduced the standard deviation in every case. This improvement was also realized with

TABLE 4. O_3(SBUV, ±20° Latitude) Sensitivity to 205-nm (SBUV) Solar Radiation With and Without Temperature Correction (SAMS) for the Period December 24, 1978, through September 30, 1982

		T Feedback (No *T* Correction)				Without *T* Feedback (*T* Correction)			
P, mbar	~*z*, km	Lag, ±1 day	Corr.	*S*	σ	Lag, ±1 day	Corr.	*S*	σ
1.0	48	−2.4	0.477	0.332	0.017	−0.6	0.524	0.280	0.013
2.0	43	−0.9	0.568	0.435	0.017	+0.4	0.603	0.389	0.014
3.0	40	−0.1	0.588	0.436	0.016	+0.7	0.669	0.387	0.012
5.0	36	+1.2	0.615	0.332	0.012	+1.4	0.653	0.309	0.010
7.0	34	+1.8	0.605	0.244	0.009	+1.7	0.613	0.232	0.008
10.0	31	+2.9	0.530	0.162	0.007	+2.6	0.550	0.150	0.006

$S = [(O_3 - \bar{O}_3)/\bar{O}_3]/[(I_{205} - \bar{I}_{205})/\bar{I}_{205}]$; Corr. equals correlation coefficient.

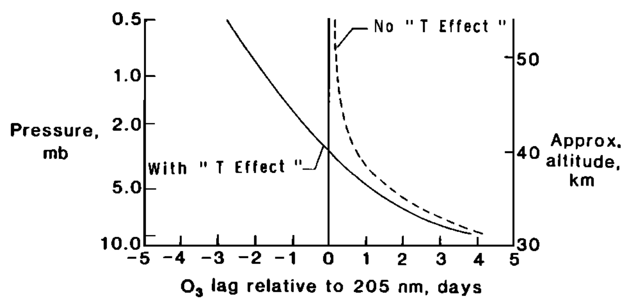

Fig. 8. Theoretical lag times of the ozone peak after (positive) or before (negative) the 205-nm solar UV peak as a function of pressure and approximate altitude based on *Brasseur et al.* [this issue]. The "No *T* Effect" case shows lag times before correcting ozone chemistry for temperature changes. The "With *T* Effect" results are calculated specifying long lag times in the temperature response to solar UV variations, similar to what is observed. The theoretical shift to negative lags for the "With *T* Effect" case is also observed (see Figure 7).

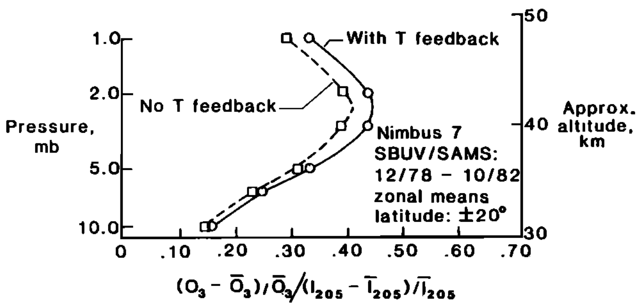

Fig. 9. Observed response of ozone to 205-nm solar UV variation, as a function of pressure and approximate altitude. The terms are defined as in Figure 2. The results are based on 4 years of Nimbus 7 SBUV zonal mean ozone data, averaged between ±20° latitude. The effects of temperature on ozone are removed in the "No T Feedback" case, employing 4 years of Nimbus 7 SAMS temperature data.

the LIMS data. This is the first published study where ozone sensitivities are determined with and without temperature variations. Previous studies have analyzed the ozone response with either temperature effect included or the temperature effect removed. Looking at both cases allows the effect of temperature on the O_3/UV relation to be clearly isolated.

Figure 7 shows the phase of the Nimbus 7 SBUV ozone response relative to the solar UV variation. As may be seen, when "temperature feedback" is allowed, the phase shifts to earlier times, which is consistent with the second scenario in Figure 6.

When the long temperature response times are specified, as described in our companion paper [*Brasseur et al.*, this issue], results similar to the observations are obtained. Figure 8 shows the theoretical ozone phase lag relative to the UV peak for a 27-day solar oscillation. The negative phase shift occurs when the effect of the temperature variation is taken into account.

Shown in Figure 9 is the observed amplitude of the SBUV ozone/UV response. When "temperature feedback" is allowed, an increase in the amplitude of the ozone response occurs, which is also in accord with the second scenario in Figure 6. Thus the long phase lags of the temperature response to solar UV variability are in accord with the observed shifts in the phase and amplitude of the ozone response related to temperature.

Figure 10 shows the corresponding theoretical amplitude of the O_3/UV response with and without the "temperature effect." As may be seen, the amplitude increases when the temperature effect is included. If the long temperature lag times are not specified, the amplitude sharply decreases (rather than increases) relative to the "no temperature effect" case [*Brasseur et al.*, this issue].

SBUV ozone data, obtained during periods when solar oscillations where approximately 13.5 days (see Table 1), have been compared with SBUV ozone data obtained during periods when solar oscillations were approximately 27 days (see Table 1). The phase lags for the 13.5-day cases are found to be generally shorter (closer to zero days) than the phase lags for the 27-day cases. The LIMS ozone data with no temperature correction (temperature feedback), which were obtained during a period when oscillations were approximately 13.5 days, also exhibited phase lags closer to zero days [*Gille et al.*, 1984]. Shown in Figure 11 are the phase lags for the Nimbus 7 SBUV data when solar oscillations were approximately 13.5 days and 27 days. Shown in Figure 9*b* of *Brasseur*

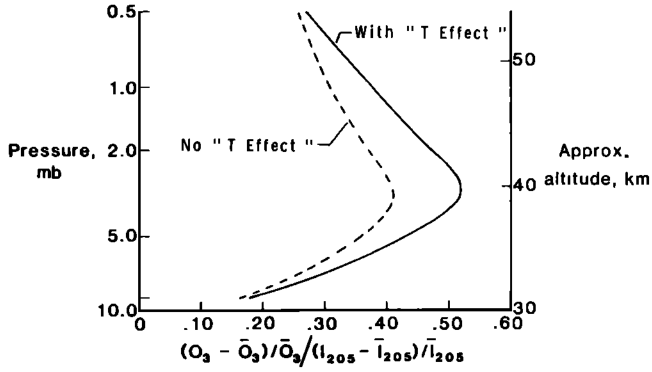

Fig. 10. Theoretical response of ozone to 205-nm solar UV variation, as a function of pressure and approximate altitude, based on *Brasseur et al.* [this issue]. The terms are defined as in Figure 2. The "No T Effect" case shows sensitivities before correcting ozone chemistry for temperature changes. The "With T Effect" case results are calculated specifying long lag times in the temperature response to solar UV variations, similar to what is observed. An increase in sensitivity for the "With T Feedback" case is also observed (see Figure 9).

et al. [this issue] are the theoretical phase lags of O_3/UV response (with the temperature effect) for 13.5- and 27-day solar oscillations. The differences in phase lag for the two cases are in fair accord with observations. The large differences in phase lag between the 13.5- and 27-day solar oscillation cases apparently occurs because a 7-day shift in the temperature peak relative to the solar UV peak gives twice the angular phase shift for a 13.5-day compared to a 27-day solar oscillation.

Considering the fairly good agreement between observation and photochemical theory, the response of ozone to short-term solar ultraviolet variations appear to be principally photochemical in nature. However, dynamically driven oscillations at periods near 27 days [*Chandra*, 1986; *Ebel et al.*, 1986] may affect the solution somewhat, especially if they are driven by the sun.

4.4. *Other Stratospheric Species*

A study similar to this study of the short-term response of ozone and temperature has been performed on LIMS HNO_3 and NO_2 data [*Keating et al.*, 1986]. The observed response at 10 mbar of HNO_3 and NO_2 to short-term solar UV variability has now been detected and is found to be in fair agreement with model calculations. HNO_3, at 10 mbar is found to be more than twice as sensitive to short-term solar UV variability than O_3. However, HNO_3 decreases with increased solar

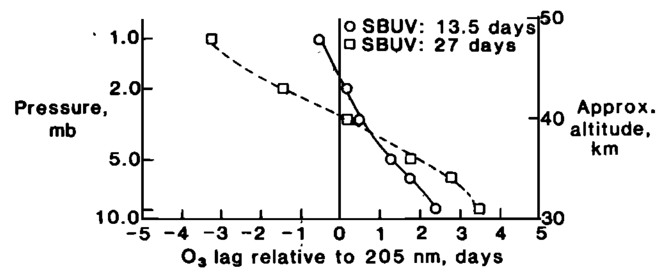

Fig. 11. Observed lag times of the ozone peak after (positive) or before (negative) the 205-nm solar UV peak for periods when solar oscillations were ~13.5 days and ~27 days (see Table 1). The results are based on zonal means of Nimbus 7 SBUV data, averaged between ±20° latitude, not corrected for temperature effects and are given as a function of pressure and approximate altitude.

TABLE 5. O_3 (SME, 1.27-μm, ±40° Latitude)/Sensitivity to Solar UV Radiation for the Period December 15, 1981, to September 30, 1983

P, mbar	~z, km	205 nm Corr.	205 nm S	205 nm σ	Lyman α Corr.	Lyman α S	Lyman α σ
0.005	84	0.167	0.497	0.122	0.145	0.083	0.024
0.007	82	0.217	0.489	0.091	0.226	0.098	0.018
0.01	80	0.215	0.476	0.090	0.239	0.102	0.017
0.015	78	0.146	0.296	0.084	0.099	0.039	0.016
0.02	76	0.008	0.014	0.078	−0.120	−0.044	0.015
0.03	74	−0.340	−0.519	0.060	−0.445	−0.131	0.011
0.04	72	−0.463	−0.619	0.049	−0.539	−0.139	0.009
0.05	70	−0.441	−0.578	0.049	−0.542	−0.137	0.009
0.07	69	−0.300	−0.406	0.054	−0.435	−0.114	0.010
0.10	66	−0.113	−0.145	0.054	−0.251	−0.063	0.010
0.15	63	0.102	0.112	0.046	0.009	0.002	0.009
0.2	61	0.201	0.203	0.041	0.149	0.029	0.008
0.3	58	0.302	0.291	0.038	0.277	0.051	0.007
0.5	54	0.301	0.302	0.040	0.302	0.058	0.008

$S = [(O_3 - \bar{O}_3)/\bar{O}_3]/[(I - \bar{I})/\bar{I}]$; Corr. equals correlation coefficient.

activity as a result of photodissociation, while O_3 increases. When HNO_3 decreases, NO_2 (a product of HNO_3 photodissociation) is observed to increase. Clearly, tests on photochemical response should be performed on a number of middle atmosphere species to validate photochemical models.

5. MESOSPHERIC RESPONSE

5.1. O_3/UV Relation

In the mesosphere the SME IR ozone data, which extend from 1 to 0.002 mbar (~48–90 km), were used in the present study. Previously, the SME UV data set, which only covers the altitude range from 1 to 0.1 mbar (~48–66 km), was investigated [*Eckman*, 1986]. Results from the *Eckman* [1986] study on the ozone/UV relation are somewhat inconsistent with the LIMS and SBUV results and show lag times as large as −7 days which were not explained by theory. Both SME ozone data sets give limited longitudinal coverage, and this can lead to misinterpretation of results if, for example, a transient wave passes through the band of longitudes where measurements are obtained. *Aikin and Smith* [1986] indicated inconsistencies between O_3/UV results they obtained over various time intervals of the SME IR data. This is probably an indication of substantial noise as well as extraneous effects brought about by the limited longitudinal coverage. Thus we chose to analyze as large a set of SME IR data as was available. *Aikin and Smith* [1986] analyzed bands ±2.5° in latitude for 110 and 244-day cases. On the other hand, we analyze here a band extending between ±40° in latitude for over 655 days, which corresponds to a factor of 95 more data than an Aikin and Smith 110-day case. This increase in the amount of data analyzed sharply reduces noise and allows an unambiguous detection of the solar signal in the ozone data. Since mesospheric temperatures were not measured by SME, monthly climatological temperatures were used by SME investigators to determine ozone from the 1.27-μm airglow measurements. Fortunately, the 1.27-μm airglow is apparently not too sensitive to temperature (R. J. Thomas, private communication, 1986). However, since climatological temperatures were already assumed in the data reduction, it did not seem productive to correct the SME IR ozone variations for short-term temperature effects using simultaneous Nimbus 7 SAMS temperatures. Thus we studied the response of SME IR ozone data to solar UV variability with temperature feedback included (since the data are not corrected for short-term temperature effects).

The response of the SME IR ozone data to solar UV variability is tabulated in Table 5. On the left-hand side of Table 5 is the relation between mesospheric ozone and 205-nm solar radiation index. Shown are pressure, approximate altitude, correlation coefficient between the ozone ratio (determined between ±40° latitude) and the 205-nm ratio, ozone sensitivity to solar UV variability, and the standard deviation in the least mean squares fit to ozone sensitivity. Shown on the right-hand side of Table 5 are the same tabulations relating mesospheric ozone to solar Lyman α radiation measured by the SME satellite. Unlike the SME UV ozone data, the SME IR data gave the best correlations between mesospheric ozone and solar UV variability, with essentially zero phase lag. Therefore the sensitivities shown are for zero-phase lag. The observed short time lags with the sun are another indication that a solar-terrestrial relation was detected Since the phase lags for temperature at these altitudes are also observed to be short (see Figure 5), substantial phase lags in ozone are not expected and are not observed.

Figure 12 presents the response of mesospheric ozone to the 205-nm solar index variations. The responses are determined using the SME IR data (±40° latitude). It is clear that ozone decreases with increased solar UV near 0.05 mbar (approximately 70 km). This observation might be explained by the photodissociation of water vapor by solar Lyman α (121.6 nm) radiation with subsequent destruction of O_x by HO_x. This hypothesis has been tested using solar Lyman α as the solar index in place of the 205-nm solar flux. Figure 13 shows the response of the ozone ratio to the solar Lyman α ratio. The negative response of ozone to solar UV variability again maximizes near 0.05 mbar (~70 km). Referring to Table 5, the correlation coefficient is considerably higher (−0.55) using solar Lyman α than the case when the 205-nm solar radiation was used (−0.44). This strong negative ozone/UV relationship was not found in the previous work of *Aikin and Smith* [1986].

It is interesting to note that some years ago *Frederick* [1977] predicted a sharp decrease in ozone near 70 km with short-term increases in solar Lyman α flux. Shown in Figure

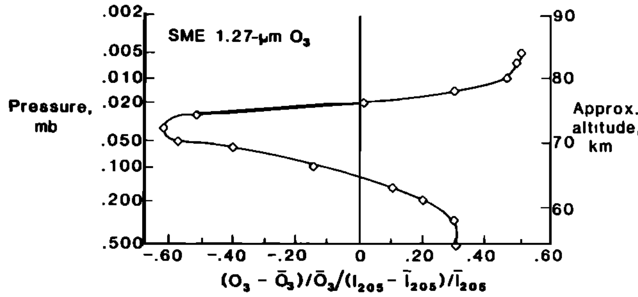

Fig. 12. Mesospheric ozone response to change in 205-nm solar radiation, as a function of pressure and approximate altitude in the mesosphere. The terms are defined as in Figure 2. The sensitivities are determined from SME 1.27-μm ozone data averaged between ±40° latitude (December 1981 to September 1983).

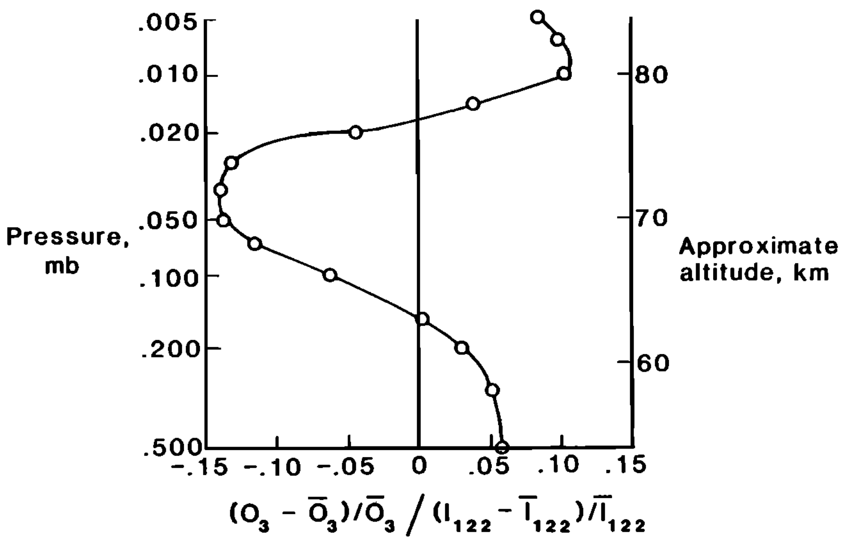

Fig. 13. Mesospheric ozone response to change in 121.6-nm (solar Lyman α) radiation, as a function of pressure and approximate altitude. The terms are defined as in Figure 2. The sensitivities are determined from SME 1.27-μm ozone data averaged between ±40° latitude and SME solar Lyman α data (December 1981–September 1983).

14 (from *Frederick* [1977]) is the predicted response of ozone and other species to short-term solar Lyman α variability. The maximum response occurs near 70 km, as observed, which is approximately one optical depth for solar Lyman α. Theoretical studies which have predicted a long-term decrease of O_3 in the mesosphere as a result of increased photodissociation of H_2O by solar Lyman α include *DeBaets et al.* [1981], *Brasseur et al.* [1983], and *Garcia et al.* [1984]. *Garcia et al.* [1984] predict a 10% depletion in ozone to occur near 70 km over the 11-year solar cycle. On the other hand, *Allen et al.* [1984] do not predict such a long-term depletion and argue that a short-term effect of Lyman α on mesospheric ozone should be small because its amplitude will be dependent on the rate at which water vapor replenishes photodissociated water vapor in the mesosphere. In Frederick's simplified model the water vapor mixing ratio was held constant, and this may be why his predicted ozone response is greater than what is actually observed. Of course, the water mesospheric vapor concentration decreases with height and the photodissociation coefficient increases with height. The product of these two quantities apparently reaches a maximum in the middle mesosphere, causing increased HO_x and the observed substantial depletion of ozone when the solar UV irradiance is enhanced.

Referring again to Figure 13, there is evidence that ozone/UV sensitivities reach peak positive values near 80 km. Peak positive ozone/UV sensitivities are also predicted by *Garcia et al.* [1984] near 80 km. These increases are attributed to greater O_x production by photolysis of O_2 in the Schuman-Runge bands and continuum. At these higher mesospheric altitudes where HO_x plays less of a role, as might be expected, the Lyman α index does not give improved correlation over the 205-nm index.

5.2. *Temperature/UV Relation*

In order to study the response of mesospheric temperature to solar UV variations, the Nimbus 7 SAMS temperatures were evaluated at meosospheric altitudes. As with the stratospheric temperature/UV study, the temperature data were divided into two sets: December 1978 to October 1980 and October 1980 to September 1982. The temperature sensitivities were determined by correlating measured temperature "ratios" with 205-nm "ratios." Unfortunately, solar Lyman α measurements were not available over most of the SAMS data period, and therefore only the 205-nm measurements were used as a solar index.

Figure 15 presents the resulting temperature sensitivities as a function of pressure level and approximate altitude. As may be seen, the vertical signature of the temperature sensitivity is nearly identical for the two independent data sets. The statistics on these sensitivities are given in Tables 2 and 3. In both cases the sensitivity of temperature to solar UV variability peaks near 70 km. As noted by *Brasseur et al.* [this issue], a substantial fraction of the solar heating above 70 km results from the absorption of solar radiation by molecular oxygen (in addition to ozone). A significant contribution of this energy deposition is associated with the absorption of the Lyman α irradiance, whose variability over a solar period is much greater than in the 200-nm spectral region. The temperature variation resulting from the short-term changes in Lyman α maximizes at approximately one optical depth (i.e., at approxi-

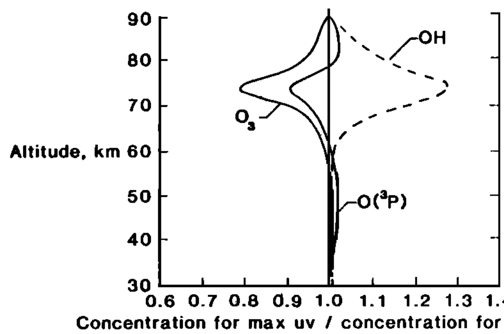

Fig. 14. Theoretical response of ozone and other species to a 27-day oscillation in solar Lyman α. The solar Lyman α photodissociates H_2O with production of HO_x and subsequent destruction of ozone [from *Frederick*, 1977].

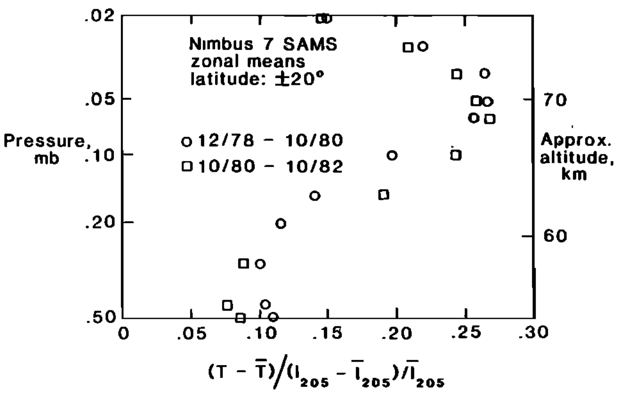

Fig. 15. Response of mesospheric temperature (zonally averaged between ±20° latitude) to solar UV variability, as a function of pressure and approximate altitude. The Nimbus 7 SAMS temperature parameters are defined in Figure 3. The two independent 2-year data sets are fairly consistent with one another.

mately the same altitude where the ozone sensitivity reaches its highest negative value as a result of the photodissociation of water vapor by *Lyman* α). There should be some decrease of SAMS instrument sensitivity in the upper mesosphere, which could shift the observed peak temperature/UV sensitivity to a somewhat lower altitude than the actual peak (J. Barnett, private communication, 1986). However, the decrease on the top side of the peak is so sharp that not much of an altitude shift is expected. A study of long-term variations in the vertical temperature structure in the mesosphere, measured by a series of rockets at four latitudinally separated stations, reveals a maximum amplitude of temperature sensitivity to solar variations (10.7-cm solar index) occurring between 65 and 70 km, with essentially zero phase lag [*Mohanakumar*, 1985]. Others have also detected long-term variability in middle mesospheric temperatures, which they attribute to 11-year solar variability [*Kokin et al.*, 1981; *von Cossant*, 1984].

In Figure 16 the response of temperature and ozone to short-term solar UV variability in essentially the entire middle atmosphere can be seen. The temperature sensitivity to solar UV variability (205 nm) is based on nearly 4 years of the Nimbus 7 SAMS data (December 24, 1978, to September 30, 1982) (Table 3), while the ozone sensitivities (without temperature feedback) are based on three satellite data sets. In Table 3 it is seen that above 70 km, response times to UV variability are 1.5 days or less, and they appear to decrease with increasing altitude. Near 70 km, where temperature sensitivity amplitudes maximize, the sharp increase in temperatures may increase somewhat the rates of ozone destruction; shifting the ozone sensitivity amplitudes further negative.

6. CONCLUSIONS

In this study of the middle atmosphere response to short-term solar UV variability measured by means of a number of satellite data sets (three for ozone, two for temperature, and two for solar ultraviolet radiation), a detailed description of the solar/terrestrial relation has emerged.

1. The response of low-latitude stratospheric temperature to solar variability has been clearly detected in two independent data sets, and response times are unexpectedly long. The response amplitude (about 0.1 K per percent change in 205-nm radiation) is in general accord with theory.

2. The response of low-latitude ozone to solar variability, when temperature effects are removed, has been studied over a much longer time interval (4 years) than previous studies and gives response amplitudes (about 0.35% increase in ozone per percent increase in 205-nm radiation at 2 mbar) and response times (less than 1 day at 2 mbar), which are in good agreement with photochemical theory when temperature effects were deleted in model calculations. There is also good agreement between the responses measured by the Nimbus 7 LIMS and SBUV ozone data sets.

3. The effects of coupling between the response of ozone to solar UV variability and the response of temperature to solar variability have been clearly isolated for the first time by looking empirically at both the effects with and without temperature perturbations. The changes in temperature alter the reaction rates for the ozone chemistry (and may also alter dynamics), producing what is referred to here as "temperature feedback." It has been predicted that these "temperature feedback" effects would reduce the response of ozone to short-term solar UV variability. On the contrary, "temperature feedback" enhances the short-term ozone variability as a result of

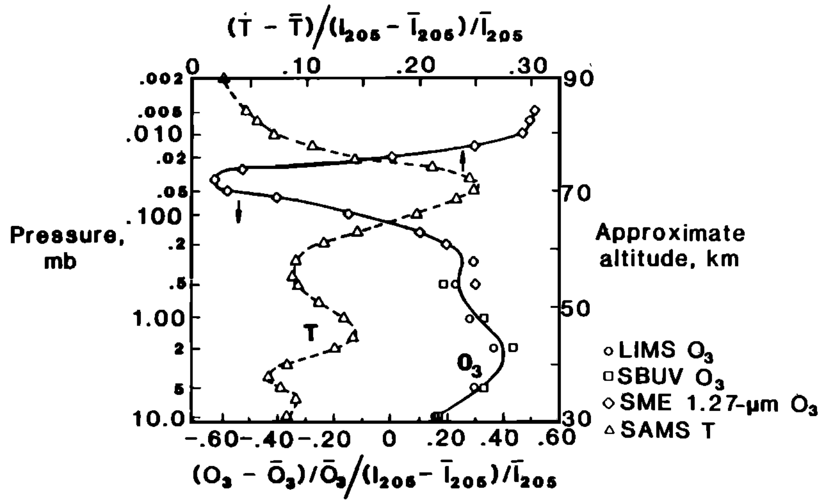

Fig. 16. Response of middle atmosphere ozone and temperature to 205-nm solar variability, as a function of pressure and approximate altitude. The parameters are defined in Figures 2 and 3. Note that the O_3 scale is on the bottom and the *T* scale is on the top of the figure.

the unexpectedly long response times of temperature to solar variability.

4. The shift in ozone response time due to "temperature feedback," has also been isolated. With "temperature feedback," ozone responds earlier to short-term solar variability (2 days earlier at 1 mbar). The shift is also found to be greater for 27-day solar variability than for 13-day solar variability. The nature of these phase shifts can be understood taking into account the response times of temperature.

5. The response of mesospheric ozone to solar UV variability has also been clearly identified by using much larger data sets than have been used previously. Near 70 km it has been discovered that ozone is immediately depleted by short-term increases in solar ultraviolet. When solar Lyman α radiation is chosen as the solar index, the negative correlation with ozone increases over that using the 205-nm solar index. This points toward a possible mechanism for the ozone depletion being increased HO_x resulting from photodissociation of H_2O vapor by solar Lyman α. Thus the magnitude of the depletion and its vertical structure could give a measure of the O_x-HO_x coupling in the mesosphere.

6. The response of mesospheric temperatures to short-term solar UV variability has also been isolated for the first time. The response times are found to be of the order of 1 day in the mesosphere as opposed to the order of 1 week in the stratosphere. Sensitivity of temperature to solar UV variability peaks near 70 km, and two independent 2-year data sets give almost the same peak sensitivites of 0.3 K increase for a 1% increase in 205-nm solar radiation. This temperature sensitivity peak may act to increase further the depletion of mesospheric ozone during short-term increases in solar ultraviolet radiation.

Thus the response of both ozone and temperature in the stratosphere and mesosphere to short-term variations in solar ultraviolet variability has been clearly detected. The determinations of response amplitude and response times, the coupling between the ozone and temperature responses, and the detection of O_x–HO_x coupling provide new tests of the validity of theoretical models of the middle atmosphere. Theoretical models which properly predict the observed short-term responses are more likely to predict long-term natural variations, allowing possible anthropogenic effects to be isolated.

Clearly, a number of other studies along this line need to be conducted with existing data sets as well as future data sets, such as UARS. These should include studies of the latitudinal-seasonal variations in the photochemical response; studies in the mesosphere of H_2O climatology consistent with ozone depletions; studies tying together short-term, medium-term, and long-term variations; and studies identifying the cause for the long lag times for stratospheric temperature/UV variations. It is expected that these future statistical studies of large data sets will reveal other problem areas, leading ultimately to further improvements in our understanding of the middle atmosphere processes.

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REFERENCES

Aikin, A. C., and H. J. P. Smith, Mesospheric ozone changes associated with 27-day solar ultraviolet flux variations, *Geophys. Res. Lett. 13*, 427, 1986.

Allen, M., J. I. Lunine, and Y. L. Yung, The vertical distribution of ozone in the mesosphere and lower thermosphere, *J. Geophys. Res., 89*, 4841, 1984.

Angell, J. K., and J. Korshover, Global temperature variations in the troposphere and the stratosphere, 1958–1982, *Mon. Weather Rev., 111*, 901, 1983.

Barnett, J. J., and M. Corney, Temperature comparisons between the Nimbus 7 SAMS, rocket/radiosondes, and the NOAA 6 SSU, *J. Geophys. Res.., 89*, 5294, 1984.

Barnet., J. J., J. T. Houghton, and J. A. Pyle, The temperature dependence of ozone concentration near the stratopause, *Q. J. R. Meteorol. Soc., 101*, 245, 1975.

Barth, C. A., D. W. Rusch, R. J. Thomas, G. H. Mount, G. J. Rottman, G. E. Sanders, and G. M. Lawrence, Solar Mesosphere Explorer: Scientific objectives and results, *Geophys. Res. Lett., 10*, 237, 1983.

Bhartia, P. K., K. F. Klenk, A. J. Fleig, C. G. Wellemeyer, and D. Gordon, Intercomparison of Nimbus 7 Solar Backscattered Ultraviolet ozone profiles with rocket, balloon, and Umkehr profiles, *J. Geophys. Res., 89*, 5227, 1984.

Brasseur, G., P. DeBaets, and A. De Rudder, Solar variability and minor constituents in the lower thermosphere and in the mesosphere, *Space Sci. Rev., 34*, 377, 1983.

Brasseur, G., A. DeRudder, G. M. Keating, and M. C. Pitts, Response of middle atmosphere to short-term solar ultraviolet variations, 2, Theory, *J. Geophys. Res.*, this issue.

Chandra, S., Solar-induced oscillations in the stratosphere: A myth or reality? *J. Geophys. Res., 90*, 2331, 1985.

Chandra, S., Solar and dynamically induced oscillations in the stratosphere, *J. Geophys. Res. 91*, 2719, 1986.

Dameris, M., A. Ebel, and H. J. Jacobs, Three-dimensional simulation of quasiperiodic perturbations attributed to solar activity effects in the middle atmosphere, *Ann. Geophys. Gauthier-Villars, 4*(A), 287, 1986.

DeBaets, P., G. Brasseur, and P. C. Simon, Chemical response of the middle atmosphere to solar variations, *Sol. Phys., 74*, 349, 1981.

Donnelly, R. F., D. F. Heath, J. L. Lean, and G. J. Rottman, Differences in the temporal variations of solar UV flux, 10.7-cm solar radio flux and active region evolution, *J. Geophys. Res., 88*, 9883, 1983.

Douglas, A. R., R. B. Rood, and R. S. Stolarski, Interpretation of ozone temperature correlation, 2, Analysis of SBUV ozone data, *J. Geophys. Res., 90*, 10,693, 1985.

Drummond, J. R., J. T. Houghton, G. D. Peskett, C. D. Rodgers, M. J. Wale, J. Whitney, and E. J. Williamson, The Stratospheric and Mesospheric Sounder on Nimbus 7, *Philos. Trans. R. Soc. London, Ser. A, 296*, 219, 1980.

Ebel, A., A. Dameris, H. Hass, A. H. Manson, C. E. Meak, and K. Petzoldt, Vertical change of the response of solar activity oscillations with periods around 13 and 27 days in the middle atmosphere, *Ann. Geophys. Gauthier Villars, 4*(A), 271, 1986.

Eckman, R. S., Response of ozone to short-term variations in the solar ultraviolet irradiance, 2, Observations and interpretation, *J. Geophys. Res., 91*, 6705, 1986.

Fleig, A. J., K. F. Klenk, P. K. Bhartia, D. Gordon, and W. H.

Schneider, User's Guide for the solar backscattered ultraviolet (SBUV) instrument first-year ozone-*S* data set, *NASA Ref. Publ., RP-1095*, 1982.

Frederick, J. E., Chemical response of the middle atmosphere to changes in the ultraviolet solar flux, *Planet. Space Sci., 25*, 1, 1977.

Garcia, R. R., S. Soloman, R. C. Roble, and D. W. Rusch, A numerical response of the middle atmosphere to the 11-year solar cycle, *Planet. Space Sci., 32*, 411, 1984.

Gille, J. C., and J. M. Russell III, The Limb Infrared Monitor of the Stratosphere: Experiment description, performance, and results, *J. Geophys. Res., 89*, 5125, 1984.

Gille, J. C., J. M. Russell III, P. L. Bailey, L. L. Gordley, E. E. Remsberg, J. H. Liensch, W. G. Planet, F. B. House, L. V. Lujak, and S. A. Beck, Validation of temperature retrievals obtained by the Limb Infrared Monitor of the Stratosphere experiment on Nimbus 7, *J. Geophys. Res., 89*, 5147, 1984.

Heath, D. F., and B. M. Schlesinger, Global responses of stratospheric ozone to ultraviolet solar flux variations, in *Atmospheric Ozone, Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece*, edited by C. S. Zerefas and A. Ghazi, p. 666, D. Reidel, Hingham, Mass., 1985.

Heath, D. F., A. J. Krueger, H. A. Roeder, and B. D. Henderson, The solar backscatter ultraviolet and total ozone mapping spectrometer (SBUV/TOMS) for Nimbus G, *Opt. Eng., 14*, 323, 1975.

Heath, D. F., R. F. Donnelly, and R. G. Merrill, Nimbus 7 SBUV observations of solar UV spectral irradiance variations caused by solar rotation and active evolution for the period November 7, 1978–October 26, 1979, *NOAA Tech. Rep., ERL 424-ARL7*, August 1983.

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, 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, 1986.

Jenkins, G. M., and D. G. Watts, *Spectral Analysis And Its Applications*, Holden-Day, Oakland, Calif., 1968.

Keating, G. M., The response of ozone to solar activity variations: A review, *Sol. Phys., 74*, 321, 1981.

Keating, G. M., J. A. Pyle, M. C. Pitts, D. F. Young, J. Y. Nicholson III, and J. J. Barnett, Latitudinal-seasonal variations of ozone-temperature relations (abstract), *Eos Trans. AGU, 64*, 780, 1983.

Keating, G. M., G. P. Brasseur, J. Y. Nicholson III, and A. DeRudder, Detection of the response of ozone in the middle atmosphere to short-term solar ultraviolet variations, *Geophys. Res. Lett., 12*, 449, 1985.

Keating, G. M., J. Nicholson III, G. Brasseur, A. DeRudder, U. Schmailzl, and M. Pitts, Detection of stratospheric HNO_3 and NO_2 response to short-term solar ultraviolet variability, *Nature, 322*, 43, 1986.

Kokin, G. A., L. A. Ryazanova, and G. F. Tulinov, Effect of solar activity on atmospheric temperatures in the polar region, *Meteorol. Gidrol., 6*, 105, 1981.

Krueger, A. J., and R. A. Minzner, A mid-latitude model for the 1976 U.S. Standard Atmosphere, *J. Geophys. Res., 81*, 4477, 1976.

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, 1984.

Mohanakumar, K., An investigation on the influence of solar cycle on mesospheric temperature, *Planet. Space Sci., 33*, 795, 1985.

Quiroz, R. S., Stratospheric temperatures during solar cycle 20, *J. Geophys. Res., 84*, 2415, 1979.

Remsberg, E. E., The accuracy of Nimbus 7 LIMS temperatures in the mesosphere, *Geophys. Res. Lett., 13*, 311–314, 1986.

Remsberg, E. E., J. M. Russell III, J. C. Gille, L. Gordley, P. L. Bailey, W. G. Planet, and J. E. Harries, The validation of the Nimbus 7 LIMS measurements of ozone, *J. Geophys. Res., 89*, 5161, 1984.

Rodgers, C. D., R. L. Jones, and J. J. Barnett, Retrieval of temperature and composition from Nimbus 7 SAMS measurements, *J. Geophys. Res., 89*, 5280, 1984.

Rood, R. B., and A. R. Douglas, Interpretation of ozone temperature correlation, 1, Theory, *J. Geophys. Res., 90*, 5733, 1985.

Rottman, G. J., C. A. Barth, R. J. Thomas, G. H. Mount, G. M. Lawrence, D. W. Rusch, R. W. Sanders, G. E. Thomas, and J. London, Solar spectral irradiance, 120 to 190 nm, October 13, 1981–January 3, 1982, *Geophys. Res. Letts., 9*, 587, 1982.

Rusch, D. W., G. H. Mount, C. A. Barth, G. J. Rottman, R. J. Thomas, G. E. Thomas, R. W. Sanders, G. M. Lawrence, and R. S. Eckman, Ozone densities in the lower mesosphere measured by a limb-scanning ultraviolet spectrometer, *Geophys. Res. Lett., 10*, 241, 1983.

Russell, J., III, The global distribution and variability of stratospheric constituents measured by LIMS, *Adv. Space Res., 4*(4), 107, 1984.

Russell, J. M., III, and J. C. Gille, The Limb Infrared Monitor of the Stratosphere (LIMS) Experiment, *Nimbus 7 User's Guide*, p. 71, NASA Goddard Space Flight Center Greenbelt, Md., 1978.

Thomas, R. J., C. A. Barth, G. J. Rottman, D W Rusch, G. H. Mount, G. M. Lawrence, R. W. Sanders, G. E. Thomas, and L. E. Clemens, Ozone density distribution in the mesosphere (50–90 km) measured by the SME limb scanning near infrared spectrometer, *Geophys. Res. Lett., 10*, 245, 1983.

Thomas, R. J., C. A. Barth, D. W. Rusch, and R. W. Sanders, Solar Mesosphere Explorer near-infrared spectrometer: Measurements of 1.27-μm radiances and the inference of mesospheric ozone, *J. Geophys. Res., 89*, 9569, 1984.

von Cossant, G., Influence of the solar cycle upon the upper mesosphere, *Beitr. Geophysik, 93*, 329, 1984.

Wate, M. J., and G. D. Peskett, Some aspects of the design and behavior of the stratospheric and mesospheric sounder, *J. Geophys. Res., 89*, 5287, 1984.

Wuebbles, D. J., Effects of solar variability on stratospheric ozone and temperature, (abstract) *Eos Trans. AGU, 66*, 1010, 1985.

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