3034/2

# THE RESPONSE OF MIDDLE ATMOSPHERIC OZONE TO SOLAR UV IRRADIANCE VARIATIONS WITH A PERIOD OF 27 DAYS

*Li Chen*
Department of Physics, University of Colorado, Boulder, Colorado 80309-0391

*Guy Brasseur*
National Center for Atmospheric Research, Boulder, Colorado 80303-3000

*Julius London*
Department of Astrophysical, Planetary, and Atmospheric Sciences,
University of Colorado, Boulder, Colorado 80309-0391

## ABSTRACT

A one-dimensional photochemical-dynamical-radiative time-dependent model was used to study the response of middle atmospheric temperature and ozone to solar UV irradiance variations with a period of 27 days. The model incorporated the $O_x$, $HO_x$, $NO_x$, and $ClO_x$ families and modeled solar UV variations. The amplitude of the primary temperature response to the solar UV variation is +0.4 K at 85–90 km with a phase lag of about 6 days. A secondary maximum response of +0.3 K at 45–50 km appears with a phase lag of 1 day. There is a maximum positive ozone response to the 27-day solar UV oscillation of 2.5% at 80–90 km with a phase lag of about 10 days after the solar irradiance maximum. At 70 km the ozone response is about 1.2% and is out of phase with the solar variation. In the upper stratosphere (40–50 km) the relative ozone variation is small, about 0.2% to 0.3%, and there is a negative phase of about 4 days between the ozone and solar oscillations. These oscillations are in phase in the middle stratosphere (35–40 km) where there is again a maximum relative response of about 0.6%. The reasons for these ozone amplitude and phase variations are discussed.

## INTRODUCTION

Efforts toward detecting the responses of the middle atmosphere to the solar irradiance variations have been pursued for over 50 years. Understanding of such a response is crucial for (1) fully understanding the photochemical behavior of the middle atmosphere and the coupling between temperature and ozone and (2) detecting possible changes in the atmospheric composition due to anthropogenic effects. Satellite results are now available that show the ozone and temperature responses to solar irradiance variations with a period of 27 days (Keating et al., 1987; Hood, 1986, 1991). The purpose of this paper is to identify, through comparing theoretical results with satellite results, the main processes that control the ozone and temperature

responses to solar irradiance variation. A one-dimensional photochemical-dynamical-radiative time-dependent model extending from 10 to 100 km with a vertical resolution of 0.5 km was used to investigate the responses of ozone and temperature in the middle atmosphere to solar irradiance variations with a period of 27 days.

## MODEL DESCRIPTION

The model involves a total of 27 chemical species and 43 chemical reactions. The model uses the following families in order to avoid the mathematically stiff systems that are due to the large dispersion in the chemical lifetimes of the several species:

$$O_x = O_3 + O(^1D) + O(^3P),$$
$$HO_x = H + OH + HO_2,$$
$$NO_x = NO + NO_2,$$
$$Cl_x = Cl + ClO + HCl.$$
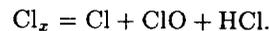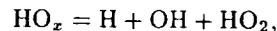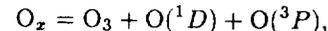
We used fixed profiles for $NO_x$ and $Cl_x$ (Brasseur and Solomon, 1985) in the model.

The dynamical (vertical diffusion) time constant varies with altitude from $10^5$ s at 100 km to $10^7$ s at 30 km (Brasseur and Solomon, 1985). For short-lived chemical species with lifetimes shorter than the dynamical time constant, concentrations were derived from photochemical equilibrium:

$$P_i - L_i = 0,$$

where $P_i$ is the production term (cm$^{-3}$ s$^{-1}$) for a given constituent $i$ and $L_i$ is the destruction term (cm$^{-3}$ s$^{-1}$) of the chemical species $i$. The species O, O($^1D$), NO, $NO_2$, ClO, Cl, H, OH, and $HO_2$ were assumed to be short lived in the model.

For $O_x$, $H_2$, and $H_2O$, which have long chemical lifetimes and are therefore sensitive to dynamics and chemistry, the following continuity equation was solved:

$$\frac{\partial n_i}{\partial t} = \frac{\partial}{\partial z}\left[K_z n \frac{\partial}{\partial z}\left(\frac{n_i}{n}\right)\right] + P_i - L_i,$$

where $n$ = air density (cm$^{-3}$), $n_i$ = the number density of a given constituent $i$, and $K_z$ = the vertical diffusion coefficient (cm$^2$ s$^{-1}$).

The net heat was transported as a tracer with an altitude-dependent vertical-exchange coefficient. The potential temperature was derived from the following energy equation:

$$n\frac{\partial\theta}{\partial t} - \frac{\partial}{\partial z}\left(K_z n\frac{\partial\theta}{\partial z}\right) = n(H - C)\left(\frac{p_0}{p}\right)^\kappa,$$

where $\theta$ = potential temperature (K), $H$ = the solar heating rate (K s$^{-1}$), $C$ = the IR cooling rate (K s$^{-1}$), $p_0$ = pressure at the ground (1013 mb), $p$ = pressure (mb), and $\kappa = R/C_p$ (0.286 for dry air).

The solar heating rate based on absorption by molecular oxygen and ozone was modeled after Schoeberl and Strobel (1978). A small contribution from water vapor was prescribed. The cooling rate below 30 km was parameterized from a model developed by Morcrette (Brasseur et al., 1987) after taking into account the emission and absorption of atmospheric radiation by $O_3$, $CO_2$, and $H_2O$. Above 40 km, an algorithm to compute the radiative cooling due to carbon dioxide, which has been developed by W. Wehrbein et al. (in preparation), was adopted. This method explicitly includes non-LTE and multiple bands and utilizes the method known as lambda iteration to calculate the populations for each of the energy levels in each atmospheric layer. A wideband model of ozone absorption in the 9.6-$\mu$m region (Rosenfield, 1991) was used in the model. A transition between the two models was used for the layer between 30 and 40 km.

The absorption cross sections of $O_2$ (SRC + Hertzberg bands) and $O_3$ (Hartley + Huggins + Chappuis + Hertzberg bands) (from WMO, 1985) and the absorption cross sections of $H_2O_2$ (190–350 nm) and $NO_2$ (185–410 nm) (from DeMore et al., 1987) were used in the model. The absorption cross section of $O_2$ over the Schumann-Runge band was calculated according to Allen and Frederick (1982). Values for the photodissociation rates for water vapor (SRB + Lyman-$\alpha$) and $O_2$ (Lyman-$\alpha$) used in the model were taken from Brasseur and Solomon (1985). The solar irradiance at different altitudes was approximated by using Beer's law, and the solar irradiance at the top of the atmosphere was from WMO (1985). The chemical reaction rates given in NASA Reference Publication 1242 (Watson et al., 1990) were used. All of the initial profiles and the vertical diffusion coefficient used to develop the vertical transport for chemical species were taken from Brasseur and Solomon (1985). Boundary conditions used in the model are listed in Table 1.

## RESULTS AND DISCUSSION

A 27-day sinusoidal oscillation of the daily average solar irradiance was applied to the model as the external forcing. The amplitude of the solar flux relative variation over a period of 27 days is a strong function of

TABLE 1.

| | 10 km | 100 km |
|---|---|---|
| $O_x$ | $\Phi = 0$ | $\Phi = 0^*$ |
| $H_2$ | $n = 4.2E + 12$ | $\Phi = 5.E + 7$ |
| $H_2O$ | $n = 3.06E + 14$ | $\Phi = 0$ |
| $\theta$ | $\theta = 288$ K (0 km) | $\theta = 12359$ K |

*Note:* $n$ is the number density (cm$^{-3}$) and $\Phi$ is the flux (cm$^{-2}$ s$^{-1}$).

* $\Phi = 0$ at 100 km is not a realistic boundary condition for $O_x$. We found, however, that the sponge layer is about 7 km below the upper boundary after using different boundary conditions. Therefore, we only show the results below 90 km.

wavelength. A 23% relative variation of Lyman-$\alpha$ with a period of 27 days was taken in the model. The wavelength dependence of 27-day relative amplitudes for the period of maximum solar irradiance observed by SME (8 July 1982 to 4 August 1982) was taken from London and Rottman (1990). The variation of solar irradiance ($\lambda > 300$ nm) was considered to be zero.

The model ran for a time period of 81 days starting from the spring equinox (i.e., from calender day 80 today 161). The mean solar zenith angle at the equator was calculated each day. The model runs were performed for both constant solar irradiance and a sinusoidal solar irradiance variation with a period of 27 days. The response of the chemical species to the solar irradiance variation was defined as the percent change in species concentration between the two cases:

$$\% \text{ response } = \frac{n_{\text{sinu}} - n_{\text{const}}}{n_{\text{const}}} \times 100\%.$$

where $n_{\text{const}}$ = chemical species density for the constant solar irradiance and $n_{\text{sinu}}$ = chemical species density for the solar irradiance with sinusoidal variation.

The temperature response to solar irradiance variations, which is defined as the difference between the temperature with a 27-day solar irradiance variation and that with constant solar irradiance, is shown in Figure 1. The primary maximum of the temperature response, about 0.4 K, was found about 85–90 km about 5.8 days after the peak of the solar irradiance oscillation. This maximum results from the increasing absorption of solar irradiance over the Schumann-Runge continuum and the Schumann-Runge bands by molecular oxygen. The secondary maximum, about 0.3 K, occurs at about 45–50 km and is due to increased absorption of solar irradiance over the Hartley band by ozone. A positive phase lag, about 1 day, was observed at about 50 km, which is much shorter than that in the upper layer (above 70 km) and lower layer (below 40 km). This phenomenon occurs because the radiative lifetime of the middle atmosphere (about 3–5 days) is shorter than the
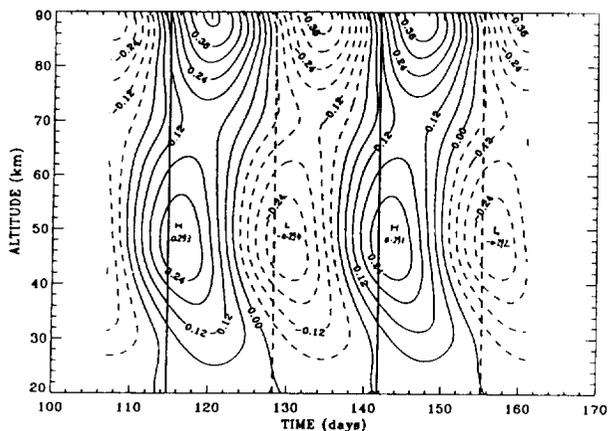
Fig. 1. The temperature difference (K) between the running model with solar irradiance variations and with constant solar irradiance. Only the results of the last 54 days are shown. Time is day of the year starting from 1 January. The solid vertical lines represent the times of solar oscillation maxima, located on days 114.75 and 141.75. The dashed vertical lines represent the times of solar oscillation minima, located on days 128.25 and 155.25. Solid contours represent positive values; dashed contours represent negative values.
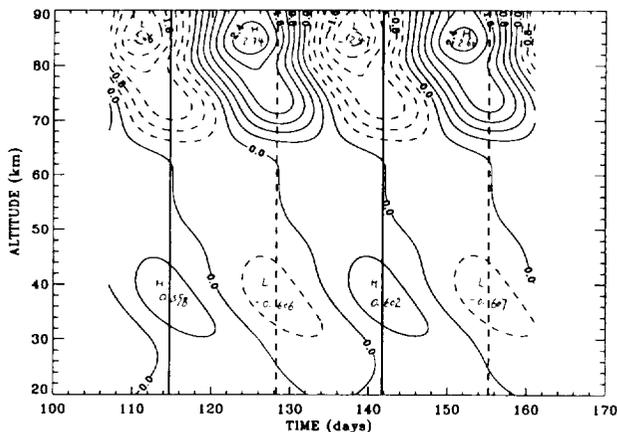


Fig. 2. The ozone response to solar irradiance variations. For complete explanation, see Figure 1.

dynamical time constant (a few weeks). The temperature field at this height, therefore, results largely from a trend toward a radiative equilibrium and is not strongly dependent on transport. Another reason is that the radiative lifetime of the middle and upper stratosphere is shorter than that of the upper mesosphere and the phase lag of the temperature response is dependent on the ratio of the radiative lifetime to the period of solar irradiance oscillation (Hood, 1986). The ozone response with temperature feedback, which is the effect of tem-
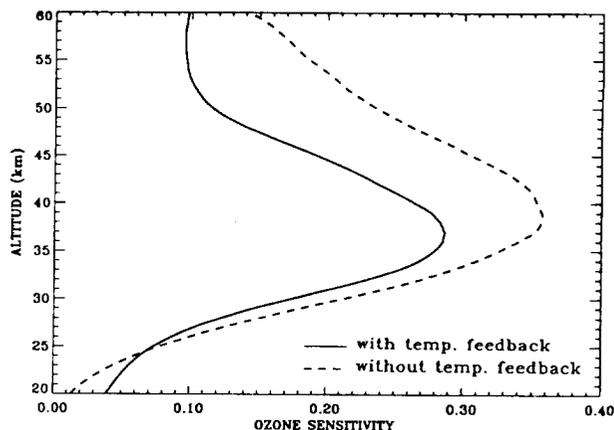


Fig. 3. Ozone sensitivity represents the amplitude of the ozone response corresponding to a change of 1% of the amplitude of the solar irradiance variation at 205 nm. *Without temperature feedback* means holding temperature constant in the model (i.e., using 1976 U.S. standard atmosphere).

perature on the ozone response to solar irradiance variations, is shown in Figure 2. The strong ozone increase at 85–90 km results from photodissociation of molecular oxygen by the Schumann-Runge continuum and Schumann-Runge bands and subsequent recombination of atomic oxygen with molecular oxygen. The phase delay, about 10 days after solar irradiance maximum, occurs because of the low concentrations of third bodies necessary for the three-body recombination process. The ozone decrease at 70–75 km at the time of solar irradiance maximum results from the photodissociation of $H_2O$ at that height by solar Lyman-$\alpha$. At lower levels (e.g., around 40–50 km), increased photodissociation of molecular oxygen leads to an ozone increase. The negative phase lags (i.e., the peak of the ozone oscillation before the peak of the solar irradiance oscillation) were found in the upper stratosphere and lower mesosphere. The peak of the ozone oscillation is about 7 days before the peak of the solar irradiance oscillation at about 50 km.

The ozone sensitivity, which is here defined as the ozone variation associated with a 1% solar irradiance variation at 205 nm, and the ozone phase lag with temperature feedback were compared with these two parameters without temperature feedback (the temperature profile in the model is not changed with time) in Figures 3 and 4. The value of the ozone response with temperature feedback is generally smaller than that without temperature feedback. An increasing solar irradiance will increase the solar heating rate and hence the temperature. An increasing temperature will cause a higher photochemical destruction rate of ozone and a lower rate of ozone production. The combination of these effects produces a smaller ozone response to
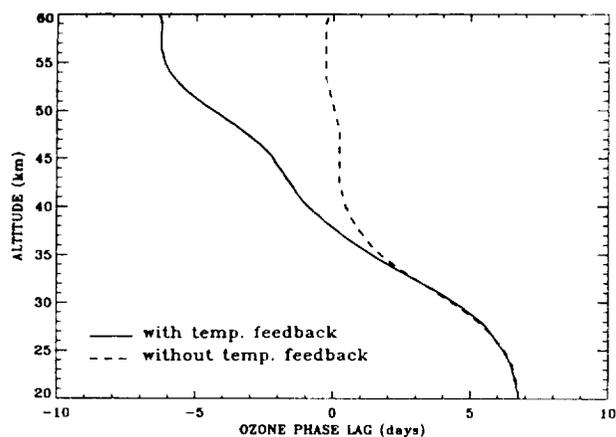
353

Fig. 4. The phase lag is the difference between the maxima (or minima) of the ozone response and the maxima (or minima) of the solar irradiance oscillation. Twenty-seven days were added to the phase lag above the inflection point. *Without temperature feedback* means holding temperature constant in the model (i.e., using 1976 U.S. standard atmosphere).

solar irradiance oscillations with temperature feedback, as compared to the ozone response without temperature feedback.

When compared with the previous results (Keating et al., 1987; Hood, 1986; Brasseur et al., 1987), the ozone sensitivity from our one-dimensional model agrees qualitatively with observed data (Keating et al., 1987; Hood, 1986) and quantitatively with theoretical values (Brasseur et al., 1987). The difference between the theoretical values and the observed data may be caused by the incomplete treatment of the temperature feedback in our model. We also ran our one-dimensional model with a suggested observed temperature variation associated with observed relative variations at 205 nm (Keating et al., 1987; Hood, 1986; Hood et al., 1991). The agreement between the calculated values and the observed data was improved greatly.

## ACKNOWLEDGMENTS

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