ACCELERATION OF UPPER STRATOSPHERIC RADIATIVE DAMPING: OBSERVATIONAL EVIDENCE

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Abstract. Satellite observations of southern hemisphere stratospheric ozone and temperature near the stratopause during October 1970 show these fields to have undergone large longitudinal variations, negatively correlated with each other. Radiative transfer model calculations of the corresponding variations in ozone solar heating rates, show that the observed negative correlation between temperature and ozone nearly doubles the rate of radiative damping of temperature perturbations in the upper stratosphere from that due to infrared radiation alone.

Introduction

Radiative heating and cooling in the stratosphere play an important role in the general circulation of the stratosphere. The main radiative energy source in this region is the absorption of solar ultraviolet and visible radiation by ozone and the main radiative sink is the flux divergence of infrared radiation by 15 μm bands of CO_2, the 9.6 μm band of O_3 and the rotational bands of H_2O. The problem of feedback between photochemically produced atmospheric ozone and temperature in the stratosphere was first raised by Craig and Ohring [1958] (see also (Leovy [1964]). Blake and Lindzen [1973] using a detailed (but now rather obsolete) photochemical model, which includes the hydrogen and nitrogen reactions, reexamined the coupling between ozone heating and temperature. Their results indicated that this coupling almost doubles the rate of relaxation of temperature perturbations in the upper stratosphere over that due to infrared radiative transfer alone. Recently, Strobel [1978] and Hartmann [1978] have pointed out that the radiative-photochemical relaxation rate may be substantially reduced in the stratosphere at any particular level as a consequence of absorption by the varying ozone column density above that level--the so-called opacity effect.

The availability of satellite observations of ozone and temperature within the stratosphere provides a unique opportunity to test the theories concerning interactions between photochemistry and radiation. In this paper, we utilize the ozone observations by a backscatter ultraviolet (BUV) instrument, and temperature measurements by a selective chopper radiometer (SCR) on board the Nimbus IV satellite to examine the effect of longitudinal variations in ozone solar heating and infrared cooling on the relaxation rates near the stratopause. The radiative heating and cooling rates are calculated using the radiative transfer model described in Ramanathan [1976]. The emphasis is on a short period during October 1970 in the southern hemisphere when large longitudinal variations in temperature (≈20 K) and in ozone (≈50%) were present in the observations (perhaps due to a minor spring warming during this period).

The results reveal a strong negative correlation between variations in temperature and variations in ozone heating. A simplified analysis is presented which supports the suggestion that the negative correlation between variations in ozone heating and temperature may substantially accelerate the rate of damping of temperature perturbations within the upper stratosphere. Such strong damping is important for the structure of vertically propagating planetary waves and the zonal mean circulation in the stratosphere.

Computational procedure and observations

The radiative transfer model described in Ramanathan [1976] is used for computing radiative heating rates. The interest here is primarily on O_3 solar heating and hence we will briefly describe those aspects of the model which concern O_3 heating computations. The model accounts for surface and cloud reflection and Rayleigh scattering effects. The cloud and Rayleigh scattering albedo are a function of solar zenith angle. Solar absorption by ozone is treated by the method given in Lacis and Hansen [1974]. The model extends from the ground to 55 km in altitude.

The radiation model utilized the vertical distributions of ozone density at 10 pressure levels between 30-0.5 mb level retrieved from the BUV experiment. The BUV-double monochromater instrument measures the backscattered ultraviolet radiation from the terrestrial atmosphere and by inversion, the ozone density profiles. The inversion procedures are described in Heath et al. [1970], who also discuss the BUV experiment.

The temperature values used in this study are those obtained from the SCR [see, e.g., Barnett, 1974]. The SCR measures the infrared emission of the 15 μm CO_2 band in different spectral regions. Temperatures are thereby deduced for about 10 km thick atmospheric layers in the lower and upper stratosphere.

Satellite ozone and temperature (radiances) data were available for October 1970. The period of present study is for 16-20 October

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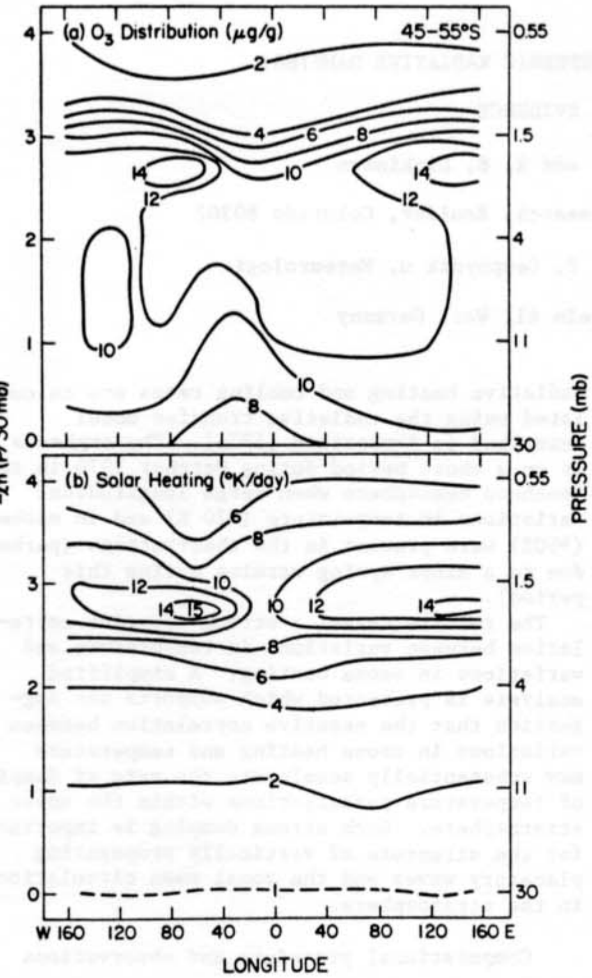

Figure 1(a). Longitude-height cross section of observed ozone mass mixing ratio distribution for the latitude zone 45-55°S averaged for October 16-20, 1970. Figure 1(b). Same as Fig. 1(a) but for ozone solar heating rates computed from the ozone distributions shown in Fig. 1(a).

when large zonal variations of ozone and temperature near the stratopause were detected. The zonal mean distribution of BUV ozone values and temperature at 2 mb have been previously discussed by Chazi et al. [1976] for October 1970. Ghazi [1977] has also described the characteristics of thermal planetary wave and ozone variations in the upper stratosphere for this springtime in the southern hemisphere. Eddy activity was observed to be at a maximum at about 55°S at this time together with total ozone reaching its seasonal maximum at 60°S. Therefore, emphasis in this paper is on the 45°S-55°S region where large longitudinal variations in temperature and ozone density were observed.

For each 10° of latitude in the southern hemisphere about 50 observations were available each day corresponding to an average of 11 sunlit orbits/day. Hence, in particular for the five days considered here, for the 10° of latitude between 50°S and 70°S a sum of about 250 observations were obtained or about 7 for each 10° of longitudes.

The BUV data are now being reevaluated and there may be some changes in the winter ozone profiles, especially at high and polar latitudes, due to corrections in algorithm and instrument positioning. However, the selected days of data consist mainly of observations made for relatively low zenith angles (<60°) and the total ozone observations for this period are not changing significantly after the evaluation (Hilsenrath, NASA, private communication). Below 30 mb we have used the ozone values from the midlatitude vertical ozone distribution given in U.S. Standard Atmosphere [1976].

Results

Figure 1a shows the longitude-height cross section of ozone distribution for a 10° latitude zone centered at 50°S for 16-20 October 1970. Correspondingly, Figure 1b is presented to show the heating rates (K/day) calculated for the same zone and same period. The significant features are the maximum rates of heating (≃15 K/day) at 2 mb level (≃45 km) around 60°W and 140°E, which correspond to ozone maxima at the same location in Figure 1a.

The lower part of Figure 2 shows the plot of SCR Channel A radiance, expressed as equivalent temperature, versus longitude for zone 45-55°S and compared to the plot of ozone concentration (μg/g) at 2 mb. The radiances of Channel A of the SCR peak at 2 mb and are nearly equivalent to 2 mb temperatures [Barnett et al., 1975]. Barnett et al. [1975] have discussed high negative correlations between temperatures and ozone around the stratopause, such as seen in Figure 2. They suggest that the magnitude of the observed variations in T and O_3 is consistent with photochemical theories of ozone (e.g., see their Table 1). We extend the analysis of this correlation by considering the connection between ozone solar heating and the temperature.

The longitudinal variation of the O_3 solar heating rates shown in Figure 2 is likewise negatively correlated with temperature variations and implies that O_3 solar heating perturbations would tend to damp temperature perturbations. The magnitude of this damping is estimated by assuming the rate of longitudinal temperature change in the stratosphere is given by

$$\partial T'/\partial t = F_D + Q'_S + Q'_{IR} \tag{1}$$

where T' is the perturbation temperature (in the present case T' is the departure from zonal mean), t the time, F_D the dynamical source term for the temperature change (e.g., planetary waves) and Q' is the perturbation radiative heating (or cooling) with the subscripts S and IR denoting respectively solar and infrared terms. These latter two terms, in turn, can be approximated by

$$\begin{aligned} Q'_{IR} &= -aT' \\ Q'_S &= -bT' \end{aligned} \tag{2}$$

The Newtonian cooling coefficient may be estimated from Dickinson [1973]. The photochemical relaxation coefficient "b" is estimated from the data shown in Figure 2. The upper stratosphere is perhaps the best level to assume Q'_S is approximated by equation (2), since O_3 and hence Q'_S variations adjust on a time scale less than a day to whatever T' is present. From Dickinson [1973], the value of a at 2 mb is approximately 0.18 day^{-1}. To obtain a zonal mean value of b, we let

$$b = -\overline{Q'_S T'} / \overline{T'^2} \qquad (3)$$

where the overbar indicates an average over a latitude zone. Equation (3) is obtained by multiplying both sides of equation (2) by T' and then averaging over longitudes. By inserting the computed Q'_S and T' values (shown in Figure 2) into equation (3) we obtain b = 0.17 day^{-1} which is essentially equal to the 2 mb value of a. Thus it is seen that the total rate of damping of temperature perturbations at 2 mb is estimated to be 0.35 day^{-1}, as compared to the value of 0.18 day^{-1} based on infrared cooling alone. This result is in good agreement with the results of Blake and Lindzen [1973] who report that the rate of damping of temperature perturbations in the upper stratosphere is enhanced by factors ranging from 2 to 3 due to the coupling between ozone photochemistry and radiation. However, this good agreement is perhaps fortuitous because Blake and Lindzen's [1973] calculations are performed for 0° latitude at equinox and furthermore they ignore variations in the overlying ozone column which, as we will now discuss, strongly influence the value of b.

The importance of such an "opacity" effect on the damping rates has been suggested by Hartmann [1978] and Strobel [1978] and is confirmed by analysis of the present results. The top of Figure 2 shows that the ratio of the ozone mixing ratio between the 1 mb and 2 mb levels for the latitude and time considered is negatively correlated with the O_3 solar heating rates. An increase in this ratio would cause a decrease in the solar heating at 2 mb because more solar radiation is absorbed at the 1 mb level. Consequently, the negative correlation between this ratio and O_3 heating at 2 mb level contributes partly to the previously estimated value of b.

In order to examine the contribution to b by this opacity effect, we repeated the calculations of Q'_S at 2 mb after fixing O_3 concentrations at and above 1 mb at all longitudes to its zonal mean value. The value of b computed from this Q'_S is smaller by about 40% than that computed including the 1 mb O_3 variations. The calculations which employ zonal mean O_3 concentrations at and above 1 mb is our baseline case, i.e., the zero opacity case. Hence, the present calculations indicate that, for the latitude and time considered here, the opacity effect amplifies the radiative relaxation rate by 40%. This result agrees with regard to the magnitude but not the sign of the opacity effect obtained by Hartmann [1978] which suggests the opacity effect may reduce the 2 mb value of b by about 50%. Hartmann's [1978] theoretical model considers a single planetary wave with vertical perturbation in O_3 and temperature. On the other hand, from a visual inspection of Figure 1a, longitudinal O_3 variations at and below 2 mb seem to be due to a superposition of wave number 2 and a

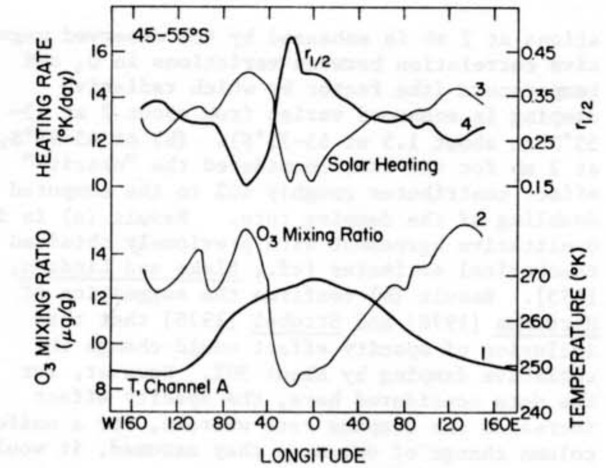

Figure 2. Curve 1: Temperature (K) equivalent to Channel A radiances of SCR (Nimbus IV) for the 10° latitude zone centered at 50°S. Curve 2: Ozone mass mixing ratio of 2 mb level for the same latitude zone. Curve 3: Ozone solar heating rates (K/day) computed for the distribution shown in Curve 2. Curve 4: Plot of the ratio between the observed ozone mixing ratio at 1 mb and 2 mb levels ($r_{1/2}$).

relatively weaker wave number 1 whereas above 1 mb, longitudinal O_3 variations have primarily a wave number 1 pattern. Consequently, the O_3 variations shown in Figures 1a and 2 have significantly vertical structure, with O_3 variations at 2 mb being negatively correlated with the overlying ozone column rather than positively correlated as assumed by Hartmann [1978]. It is likely that the out-of-phase column change above the level being considered occurs only at certain levels and perhaps only at certain times. If so, our results may represent an unusual occurrence, with the situation hypothesized by Hartmann [1978] occurring more often than not.

The calculations were also done for the latitude zones 55-65°S and 65-75°S and the value of b for these zones is respectively 0.14 and 0.09. The poleward decrease of b at 2 mb is caused by the following factors: (a) poleward decrease in solar insolation. (b) The 1 mb ozone density increases poleward and hence radiatively less solar radiation penetrates to the 2 mb level at high latitudes. This effect accounts for roughly 40% of the decrease in b. (c) The magnitude of the negative correlation between longitudinal variations in ozone and temperature decreases poleward. Other latitude zones ranging from 55°N to 35°S were also examined but the magnitude of longitudinal variations of both temperature and ozone at 2 mb relative to the observational noise level were not large enough to formally obtain statistical significance.

Conclusions

Springtime O_3 solar heating rates at 45-55°S, 55-65°S and 65-75°S, computed as a function of altitude and longitude from observed O_3 distributions, reveal the following features: (a) The rate of radiative damping of temperature variations at 2 mb is enhanced by the observed negative correlation between variations in O_3 and temperature (the factor by which radiative damping is enhanced varies from about 2 at 45-55°S to about 1.5 at 65-75°S). (b) At 45-55°S, at 2 mb for the time considered the "opacity" effect contributes roughly 40% to the computed doubling of the damping rate. Result (a) is in qualitative agreement with previously obtained theoretical estimates [cf., Blake and Lindzen, 1973]. Result (b) confirms the suggestion of Hartmann [1978] and Strobel [1978] that the inclusion of opacity effect would change the radiative damping by about 50%. However, for the data considered here, the opacity effect increased the damping rate whereas, for a uniform column change of ozone as they assumed, it would have decreased it.

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