TWO-D MODEL SIMULATION OF OZONE CLIMATOLOGY AND YEAR-TO-YEAR VARIATIONS

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ABSTRACT

Using a coupled 2-D model where all transport parameters are determined interactively from radiative transfer calculations using the observed NMC temperature input for the individual years in the period 1979–1986, we simulated the seasonal and year-to-year changes in the column ozone. Comparing the result with the zonally averaged data from TOMS, we find that the earlier climatology based on the first four years of TOMS data is well simulated, including the timing, magnitude and location of the spring maxima, and also the weak ozone hole that appeared. The year-to-year changes in column ozone at high latitudes follow the Quasi-Biennial Oscillation (QBO), as pointed out by several authors. This feature is also reproduced by the model.

1. INTRODUCTION

It has been well known since 1930s (Dobson, 1930) that the observed latitudinal and seasonal distributions of ozone abundance are almost opposite to that predicted by photochemical theory of ozone. "This gave rise to what has been known as the *ozone problem*, which is still not entirely resolved today and which represents a problem of considerable scientific interest" (Hunt, 1969). Considerable progress has been made towards the resolution of the ozone problem during the last two decades including a number of three-dimensional model studies (e.g. Hunt and Manabe, 1968; Hunt, 1969; London and Park, 1973; Newson, 1974; Cunnold *et al.*, 1975; Schlesinger and Mintz, 1979; Mahlman *et al.*, 1980). With the maturing of the 2-D models (see WMO, 1986), longer-term runs with coupled radiation, dynamics and chemistry are becoming feasible.

Today, we are interested not only in explaining the *sign* of the latitudinal and seasonal gradients, but also in quantitatively accounting for the drastic differences between the climatological ozone distribution between the Northern and Southern Hemispheres and in accounting for their year-to-year variations. The present work presents our first attempt in using a coupled third generation model with radiative feedbacks incorporated to study the ozone problem.

2. MODEL DESCRIPTION

Our 2-D model with coupled dynamics, radiation and chemistry has been documented in Yang (1988). The dynamical equations can also be found in Tung and Yang (1988b). The difference between the earlier version of the model (Tung and Yang, 1988b) and the present version lies mainly in the "comprehensive" radiative transfer code used in the present version and the additional modes of radiative-dynamical coupling that are now incorporated.

3. OZONE CLIMATOLOGY

The climatology of zonal mean column ozone, based on Nimbus 7 satellite data for a period of four years (from October, 1978 to September, 1982), can be found in Bowman and Krueger (1985). Model simulated ozone climatology is plotted in Fig. 1, which is an average of ozone values for model years from 1979 to 1982 when we have temperature data.

Important features present in both observed and simulated ozone climatology include the following: (1) the persistent minimum in the tropics, where the photochemical ozone production is most efficient with plenty of sunshine; (2) the spring maximum and fall minimum in high latitudes in NH; (3) the spring maximum in *mid*-latitudes in SH; (4) the springtime minimum in southern high latitudes (or the Antarctic ozone "hole"); (5) And the "filling up" of the ozone hole in November. We note that these features are robust, and can be found in observational data sets made in the early 1970s (see Hilsenrath *et al.*, 1979; Hilsenrath and Schlesinger, 1981; Prabhakara *et al.*, 1976). In particular, we suspect that the springtime high latitude minimum is a feature that persists every year, although the level in earlier years is higher (above or about 300 Dobson units). If this is true even for the pre-CFC era, then the *formation* of the ozone minimum is probably

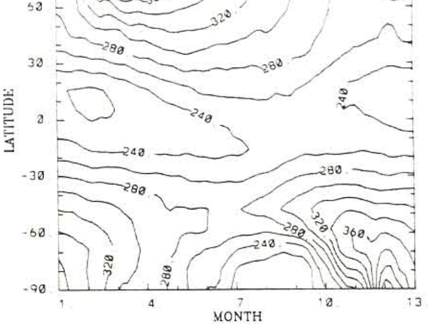

Fig. 1. Calculated time-latitude cross-section of the zonal mean total ozone (DU) averaged over model years 1979—1982.

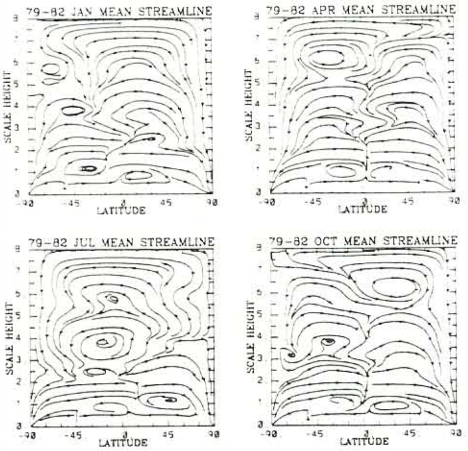

Fig. 2. Monthly mean streamlines of diabatic circulation for January, April, July and September averaged over model years 1979-1982.

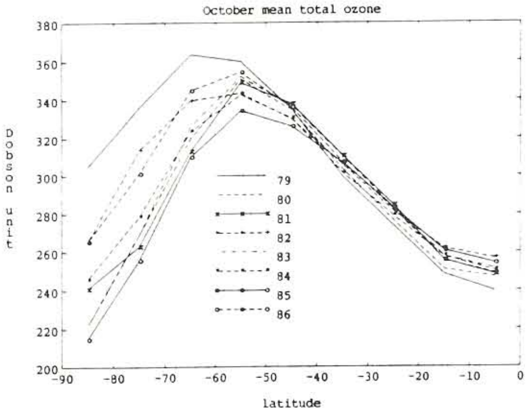

Fig. 3. Calculated monthly mean column ozone amount as a function of southern latitude for October of 1979—1986.

attributable to dynamics, although the *intensification* of the ozone hole in recent years may have an important chemically-induced component. Major departures of the simulated ozone climatology from observations include: (a) an underprediction of the column ozone amount during the southern polar night; and (b) values near the south pole after the final warming are too high and last too long.

The climatological column ozone distribution can be understood by examining the diabatic circulation calculated using our model. In Fig. 2, we plot the streamlines of diabatic circulation for January, April, July and October averaged for model years from 1979 to 1982. The upward motion near the tropics throughout the year constantly lifts ozone-poor air from the troposphere to replace ozone-rich air in the lower stratosphere, where ozone is produced by photochemistry, creating a minimum in the equatorial region. When the air rises, it cools through adiabatic expansion, resulting in the very cold equatorial tropopause, a region with abundant sunshine. This cold region traps most of the moisture reaching it and prevents it from entering the stratosphere, which explains the dryness of the stratosphere (WMO, 1986). In fact, the same kind of circulation, now known as the Brewer-Dobson circulation, has been inferred before from observed tracer distributions including water-vapor and ozone (Brewer, 1949; Dobson, 1956).

Higher values of ozone column amount are generally found in high latitudes due to poleward transport. During the northern winter when the photochemical time scale is very long in the polar night region, the ozone transported from lower latitudes accumulates in the polar region, leading to a maximum in spring. However, the situation during the southern polar night is quite different. The strong polar vortex prevents the transported ozone from reaching the polar region. The transport largely stops at the edge of the polar vortex so that a maximum is reached in mid-latitudes in the southern spring, while low values of column ozone amount are maintained during the polar night in the polar region. After spring in both hemispheres, the seasonal reversal in the upper circulation takes place and the lower circulation cell weakens, which together with enhanced photochemical destruction leads to the ozone column amount decreasing and later reaching a minimum in the fall. In our simulated ozone distribution, the fall minimum is not present in SH due to the lack of the increase phase in late fall and winter, which also leads to underprediction of ozone column amount in August and September.

In SH, the strong polar vortex also prevents effective heat transport into the polar night region, so that this region is very close to radiative equilibrium, especially in late winter. After the sun returns, increased heating due to solar absorption by ozone (and/or PSC which we have not included in the model) leads in our model to a net positive heating so that a reverse circulation develops in the lower stratosphere. This reverse circulation, as first suggested by Tung *et al.* (1986), will reduce the column ozone amount by replacing relatively ozone-rich air with ozone-poor air from below, just as in the tropics, thus helping to "deepen" the Antarctic ozone hole. After the final warming, the hole is "filled in" by ozone transported into the polar region when the polar vortex breaks down.

4. YEAR-TO-YEAR VARIATION

It is observed that the level of ozone in the Antarctic region has decreased dramatically in recent years. The observed zonal mean, monthly mean column ozone amount as a function of latitude for October of 1979 to 1985 is reported by Schoeberl *et al.* (1986). The October mean column ozone amount near the south pole in 1985 is more than 40% lower than that in 1979. The 1986 level is a little higher, but the 1987 level is more than 50% lower than that of 1979 (Schoeberl, personal communication).

In Fig. 3, the calculated column ozone amount is plotted as a function of latitude for October of 1979 to 1986. The simulated October mean column ozone amount compares favorably with the observations. In high latitudes, the column amount is well simulated by the model for the early four years, while for the later four years, the calculated values are higher than the observations. At 85S, the simulated ozone decline from 1979 to 1985 by the model is about 90 DU, 72% of the observed decrease, which is about 125 DU. This result should be compared with the 100 DU reported by Tung and Yang (1988b) using the Newtonian cooling approximation without the feedback between ozone and the radiative heating rates. At 65S, the model produced about a 50 DU decline from 1979 to 1985, same as in Tung and Yang (1988b), while the observed change in the maximum region is about 80 DU.

The non-monotonic nature of ozone year-to-year variation is evident from Fig. 4. Note that the up-and-down pattern of year-to-year column ozone variation produced by the model matches that of observations almost perfectly. This is because

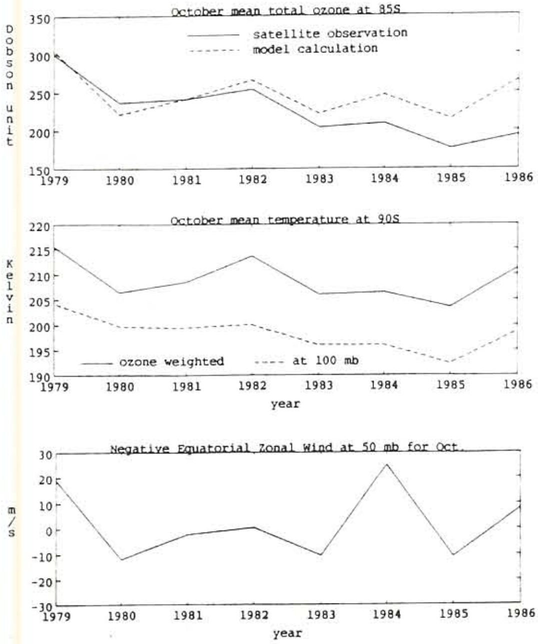

Fig. 4. Correlation between column ozone amount, temperature and equatorial zonal wind for October of 1979—1986. Top: the observed and calculated monthly mean ozone at 85S; middle: the ozone partial pressure weighted and 100 mb monthly mean temperatures at 90S; bottom: equatorial zonal wind (data taken from Garcia and Solomon, 1987).

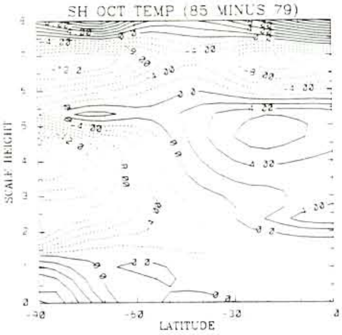

Fig. 5. Difference in Southern Hemisphere October mean temperatures between 1985 and 1979.

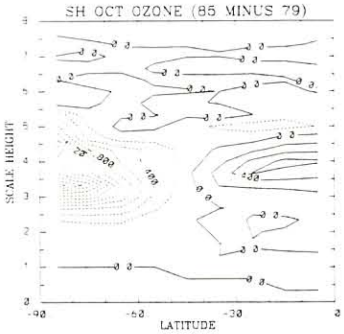

Fig. 6. The difference of the simulated October mean ozone mixing ratio between 1985 and 1979.

both the model simulated ozone and the ozone in the real atmosphere are correlated with the observed temperature. In the middle panel of Fig. 4, the ozone partial pressure weighted and 100 mb temperatures are plotted for October. One can see that the temperature variations in October match those of ozone changes.

It has been pointed out by many authors (Sekiguchi, 1986; Newman and Schoeberl, 1986; Chubachi, 1986; Angell, 1986; Mahlman and Fels, 1986) that the total ozone column amount is well correlated with the temperature of the lower stratosphere, with low column ozone amount correlated with low temperature and high column ozone amount correlated with high temperature. The mechanism of this correlation was explored by Tung and Yang (1988a). Cooling of the lower stratosphere induces a transport taking ozone away from the cooled region and it was shown analytically that a 1% temperature change weighted by ozone partial pressure produces a 7% change in column ozone amount. One can see that 1985 is colder than 1979 at the south pole by 12°K when temperature is weighted by ozone partial pressure. For a 12°K (about 5.5%) temperature change from 1979 to 1985, the simple analytic solution appears to give an estimate of the right magnitude. If a second-order correction is added to the first-order solution, the ozone decrease should be 36% or 108 DU for a 5.5% temperature change from 1979 to 1985. This should be compared to the simulated 90 DU decrease, and the observed 125 DU decrease.

The correlation of column ozone amount and temperature does not tell which one is the cause. Temperature change due to dynamical variation can influence the ozone transport, while chemically induced ozone change would also affect the temperature due to altered ozone absorption. The present work seems to suggest that an October mean temperature change of the order of 12°K can induce as much as 72% of the observed ozone depletion. However the work of Kiehl *et al.* (1988) suggests that the radiative effect of ozone reduction on temperature can be a cooling of the October mean temperature of about 3°K (see Tung and Yang, 1988b). Even if one assumes that *all* of the ozone-induced temperature change is due to chemistry and subtracts it from the total temperature change, the temperature change left (presumably due to dynamics) can still account for about 54% of the observed ozone depletion, according to the present work. However, there are still large uncertainties in the model calculations (e.g., associated with radiative transfer codes).

As pointed out by Garcia and Solomon (1987), the phase of QBO may have important effects on the observed ozone and temperature variations. One can see from Fig. 4 that warm (cold) years and high (low) ozone are correlated with the easterly (westerly) phase of the QBO. If the link between QBO and temperature/ozone variation is established, then the temperature and ozone changes in October are likely to be strongly influenced by dynamical causes, since QBO is a tropical phenomenon.

In Fig. 5, the difference of October mean temperature between 1985 and 1979 is plotted. In Fig. 6, we plot the difference of October mean ozone concentration between 1985 and 1979. Comparing Fig. 6 with Fig. 5, one sees the striking *spatial* correlation between the temperature and ozone, except, of course, in the upper stratosphere where ozone is controlled by chemistry, which is fixed in our model for every year. The decrease in high latitudes is accompanied by an *increase* in low latitudes. The spatial correlation between the *total* ozone pattern and the distribution of temperature in the lower stratosphere has been pointed out by many authors before (Stolarski *et al.*, 1986; Newman and Schoeberl, 1986; Sekiguchi, 1986; Chubachi, 1986).

One of the important features of the Antarctic ozone hole is that the seasonal depletion occurs mainly in a layer from about 12 to 20 km (Chubachi, 1985; Hofmann *et al.*, 1987; Gernandt, 1987; Komhyr *et al.*, 1988). Examining Fig. 2 indicates that a reverse diabatic circulation (Tung *et al.*, 1986) exists in the same region where the ozone amount is observed to decrease. However, the reverse circulation based on the present study is quite weak, which suggests that in recent years (after 1983), the accelerated deepening of the Antarctic ozone hole cannot be explained by dynamics alone. When accelerated chemical depletion rates are added into our model to bring the model Antarctic values to the observed ones in 1986, we find that the heating rates are further reduced to close to radiative equilibrium values even in spring in the presence of increasing solar radiation (but not enough ozone to absorb it). The absence of upwelling in 1986 in our model and in the observed data (Hofmann *et al.*, 1987) does not imply that the dynamical mechanism is incorrect. One can argue that if the vertical velocity is close to zero for the 1986 condition, then in an earlier year when the ozone amount in the lower stratosphere is higher, and/or the temperature is lower, the vertical velocity may well be positive and play an important role in the ozone seasonal decline in those early years.

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