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RADIATIVE FORCING DUE TO OZONE IN THE 1980S: DEPENDENCE ON ALTITUDE OF OZONE CHANGE

M. D. Schwarzkopf
GFDL/NOAA

V. Ramaswamy
AOS Program, Princeton University

Abstract. The radiative forcing of the surface-troposphere system caused by the changes in ozone in the 1980s is sensitive to the altitude profile of these changes. In the tropics, inclusion of lower stratospheric ozone depletions observed by SAGE results in a substantial negative radiative ozone forcing. In mid-latitudes, the magnitude of the negative stratospheric ozone forcing diminishes as the altitude of ozone depletion is raised above the tropopause. By contrast, the radiative forcing corresponding to the decadal tropospheric ozone increases observed at certain Northern Hemisphere mid-latitude locations is strongly positive. The magnitude and sign of the total (tropospheric + stratospheric) ozone forcing in Northern Hemisphere mid-latitudes is critically dependent on the vertical profile of the tropospheric ozone increases and the lower stratospheric losses near the tropopause.

Introduction

Observations from satellite and ground-based instruments indicate that significant changes in atmospheric ozone concentrations have taken place during the 1980s [WMO, 1992]. Decreases in total column ozone in middle and high latitudes have been measured by the TOMS instrument [Stolarski et al., 1991]. SAGE observations indicate that ozone depletion in the lower stratosphere has been occurring at all latitudes, including the tropics [McCormick et al., 1992]. Ground-based measurements at various latitudes also show losses in lower stratospheric ozone [WMO, 1992]. Additionally, several locations in the midlatitudes of the Northern Hemisphere have reported significant decadal increases in tropospheric ozone [WMO, 1990, 1992].

Calculations show that the decadal changes in lower stratospheric ozone produce a substantial negative radiative forcing of the surface-troposphere system at middle and high latitudes [Ramaswamy et al.,1992, hereafter RSS]. The magnitude of the ozone forcing is sensitive to both the amount of column ozone loss and the altitude profile of the ozone depletion [RSS; WMO, 1986, 1992; Lacis et al.,1990]. The greatest uncertainty in the reports of stratospheric ozone change is between 17 km and the tropopause, a region in which SAGE observations are limited in scope, due to the presence of clouds. Since this region is important in determining the radiative forcing of the surface-troposphere system [WMO, 1986], radiative calculations must incorporate assumptions for the ozone changes at these altitudes.

This study investigates the sensitivity of the stratospheric ozone radiative forcing computed for the 1980s to changes in the specification of the decadal ozone depletion profile. The calculations employ SAGE profiles of ozone changes above 17 km [McCormick et al., 1992], together with several assumed profiles of ozone depletion between 17 km and the tropopause. These computations have been performed at two representative latitudes: 4.5N (tropics) and 40.5N (mid-latitudes).

Tropospheric ozone increases may exert a significant radiative effect on the surface-troposphere system [Ramanathan and Dickinson, 1979; Lacis et al.,1990]. We therefore examine the sensitivity of the ozone radiative forcing to a combined stratospheric ozone decrease and a tropospheric ozone increase at Northern Hemisphere mid-latitudes.

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Model and data

The radiative transfer model used for these calculations is the GFDL (Geophysical Fluid Dynamics Laboratory) model described in RSS. The decadal ozone radiative forcing of the surface-troposphere system is defined [WMO, 1992] as the difference in the net flux at the tropopause obtained by the model when the ozone concentration is changed from the initial (1980) values to the 1990 values. This computation is performed under the conditions that: 1) tropospheric temperatures, water vapor and clouds, and surface temperatures and albedos, remain fixed; 2) stratospheric temperatures are those appropriate for an atmosphere in radiative-dynamical equilibrium, using the assumption of fixed dynamical heating (FDH) for the stratosphere [Ramanathan and Dickinson, 1979; Fels et al., 1980].

The baseline (1980) ozone concentrations, together with temperature, water vapor, cloud and surface parameters are obtained from zonally-averaged January values employed in the GFDL "SKYHI" general circulation model [Fels et al., 1980]. Concentrations of the non-ozone trace gases for 1980 and 1990 are those specified in WMO [1992, Chap.8]. The specification of the tropopause at a given latitude is the same as in RSS.

Altitude profiles of ozone change

Vertical profiles of stratospheric ozone change during the 1980s have been obtained from SAGE I and II measurements [McCormick et al., 1992]. Due to sampling problems, the available data consists of annually-averaged profiles for decadal ozone losses in tropical and middle latitudes. The profile shape is similar in each latitude belt. Ozone depletion occurs primarily below 25 km; the largest percentage loss is found at the altitudes nearest to the tropopause. In this paper, we use decadal percentage ozone changes measured by SAGE at 1 km vertical resolution from 17 to 50 km, at 4.5N (tropical case) and 40.5N (midlatitude case). We assume that these annually-averaged profiles are applicable to January atmospheric conditions.

Three scenarios have been devised to represent the range in possible stratospheric ozone depletion between the tropopause and 17 km. The first scenario assumes no ozone depletion below 17 km. The second presumes a linear decrease with altitude of the percentage of ozone depletion between 17 km (where the SAGE depletion is assumed) and the tropopause, where the depletion becomes zero. The third assumes that the depletion percentage between the tropopause and 17 km is equal to the SAGE depletion percentage at 17 km. The "standard" profiles for stratospheric ozone depletion used here combine the SAGE depletion profile for altitudes above 17 km with the profile shapes obtained using each of the scenarios defined above; they are termed profiles S1, S2 and S3, respectively.

An alternate scenario for stratospheric ozone change assumes a constant percentage of ozone depletion between the local tropopause and 7 km above the tropopause, as in RSS. The "standard" profile (profile S4), employs a percentage ozone depletion adjusted so that the total column ozone change is equal to that obtained using profile S1. Additional "normalized" profiles for ozone change have been constructed in which the shape of the "standard" ozone depletion profiles (S1, S2, S3 and S4) is maintained but the amount of column ozone change is varied.

Figure 1a illustrates the "standard" stratospheric ozone depletion profiles at January 4.5N in the 10-25 km altitude range. The range of stratospheric column ozone depletions is from ~7.3 to ~8.8 Dobson units (DU), depending on the scenario adopted (Table 1). This rather narrow variation results from the proximity of the model tropopause altitude (~15.1 km) to 17 km. Calculations using "normalized" profiles have stratospheric column ozone depletions ranging from 0 to ~9 DU. This range includes the observed SAGE depletions in the tropics.

Figure 1b displays the "standard" stratospheric ozone depletion profiles at January 40.5N, from 0 to 50 km. At this latitude, the model January tropopause altitude is ~11.4 km. Since the tropopause altitude is rather distant from 17 km, the column ozone depletion for each profile varies greatly, ranging from ~10.4 to ~20.7 DU (Table 2). Calculations using "normalized" profiles include a range of column ozone depletions from 0 to 30 DU; this range encompasses the TOMS monthly measurements of column ozone loss at 40.5N.

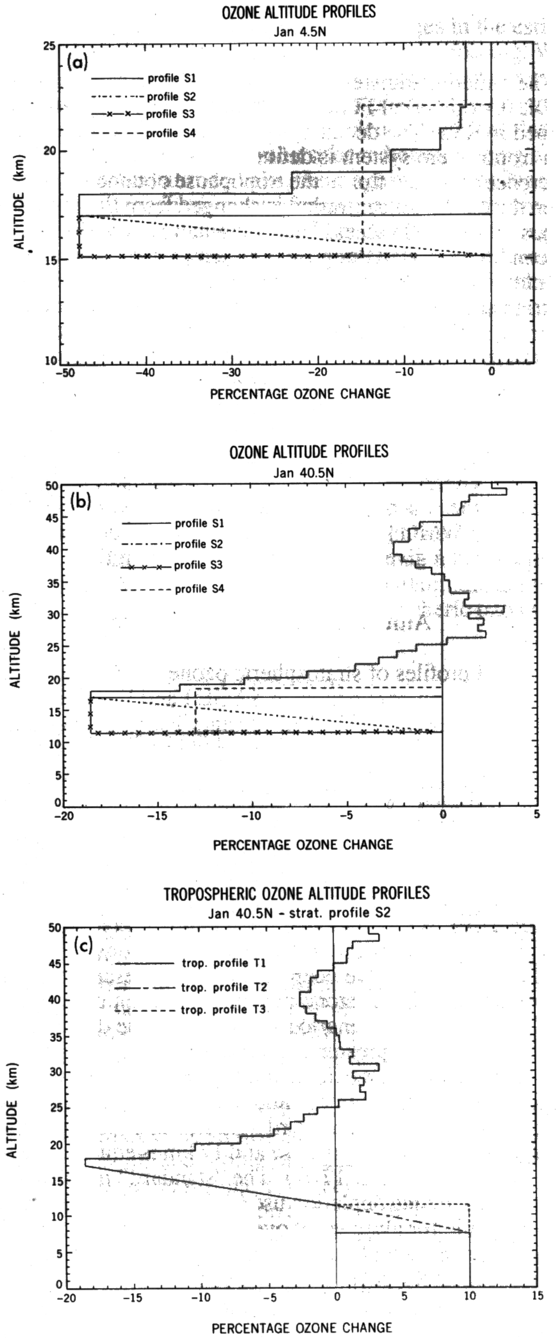

Fig. 1. "Standard" altitude profiles of stratospheric ozone depletion for (a) tropical and (b) mid-latitude cases; (c) mid-latitude ozone change profiles with a fixed stratospheric decrease and different tropospheric increases.

The scenario for decadal tropospheric ozone change adopted here assumes a constant percentage ozone increase from the surface to the tropopause. The "standard" tropospheric ozone profile (T3) uses a 10 percent tropospheric column ozone increase; other profiles employ relative ozone changes varying from 5 to 25 percent (~1.6 to ~7.8 DU). This range includes the decadal increases reported for several stations in the Northern Hemisphere mid-latitudes. These profiles have been combined with each of the "standard" mid-latitude stratospheric profiles S1, S2 or S3 to produce a set of atmospheric ozone change profiles.

Two additional tropospheric ozone change profiles are used to show the relative importance of upper tropospheric ozone change. Each employs the "standard" T3 profile below 7.5 km. The first profile (T1) then assumes no change from this altitude to the tropopause; the second (T2) adopts a linear decrease with altitude in percentage ozone change between 7.5 km and the tropopause. Figure 1c displays ozone altitude profiles combining the T1, T2 and T3 tropospheric profiles with the "standard" S2 mid-latitude ozone profile.The use of a constant percentage increase below 7.5 km is consistent with observed mid-latitude tropospheric ozone change profiles [WMO, 1992].

Results

Stratospheric ozone forcing computed using "standard" and "normalized" altitude profiles of ozone change are displayed in

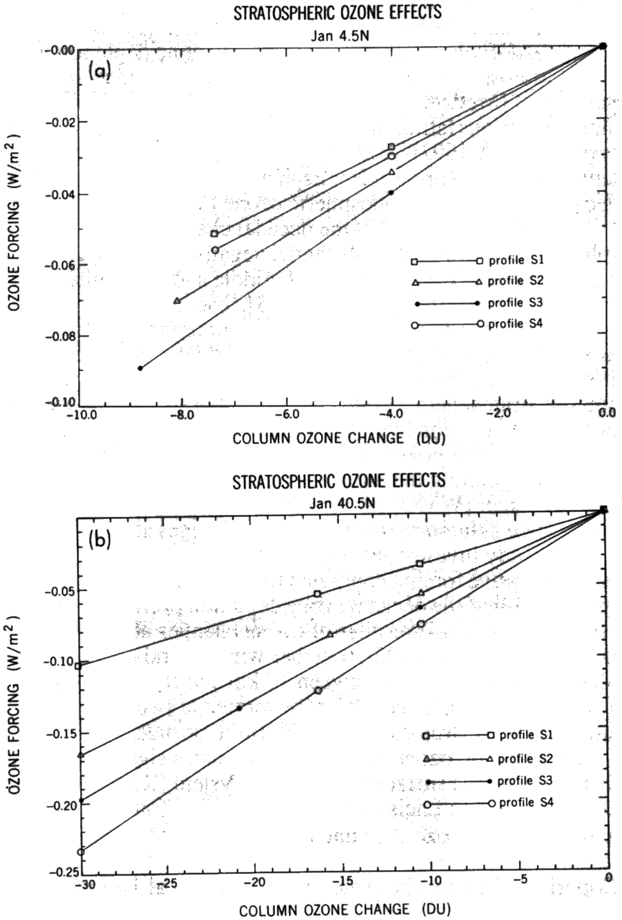

Fig. 2. Stratospheric ozone forcing using "standard" and "normalized" profiles for (a) tropical and (b) mid-latitude cases.

TABLE 1. Decadal stratospheric column ozone change in DU, stratospheric ozone forcing in W/m^2, and stratospheric radiative forcing gradient (SRFG) in W/m^2/DU for "standard" tropical (January 4.5N) profiles. The SRFG derived here is valid over a stratospheric column ozone decrease of 0 - 10 DU.

profile	S1	S2	S3	S4
column change	-7.34	-8.07	-8.79	-7.34
forcing	-0.052	-0.071	-0.090	-0.052
SRFG	.0071	.0087	.0102	.0071

Figures 2a (for January 4.5N) and 2b (for January 40.5N). The radiative forcing is seen to vary almost linearly with column ozone change, over the range of ozone depletions (0 to ~10 DU for the tropical case; 0 to 30 DU for the mid-latitude case) considered in this study. This permits definition of a stratospheric radiative forcing gradient (SRFG) as the change in the radiative forcing associated with a 1 DU change in total stratospheric column ozone. Table 1 lists stratospheric ozone forcings for the four "standard" tropical profiles and the corresponding SRFGs; values for the mid-latitude cases are given in Table 2.

In the tropics, SRFG values range from ~.007 to ~.01 W/m^2/DU, with profile S3 having the largest gradient. This is consistent with the fact that profile S3 has the largest percentage ozone depletions near the tropopause (Figure 1a). In general, we expect that the net stratospheric ozone forcing will become more positive (or less negative) as the altitude of the stratospheric ozone depletion is increased while the change in total column ozone is held constant [WMO, 1992].

The mid-latitude results (Figure 2b and Table 2) demonstrate that the sensitivity of the stratospheric ozone forcing depends strongly on the altitude of the ozone depletion layer. Thus, the SRFG for the S4 profile, where ozone depletion begins at the tropopause, is more than double that of the S1 profile, for which ozone depletion begins more than 5 km above the tropopause. The SRFGs, ranging from ~.003 to.007 W/m^2/DU, are somewhat smaller than their tropical counterparts, except for the S4 profile. This is largely due to the fact that a relatively smaller fraction of the ozone depletion occurs near the tropopause in the mid-latitude S1, S2 and S3 profiles (Figures 1a and 1b).

Figure 3 displays the total ozone forcing in mid-latitudes as a function of tropospheric column ozone change. In this case, the radiative forcing varies almost linearly with tropospheric column ozone change, in the range of ozone increases used here. We therefore define the tropospheric radiative forcing gradient (TRFG) as the change in the ozone forcing due to a 1 DU change in tropospheric column ozone, with the stratospheric ozone profile held fixed. Table 3 lists the TRFGs for five atmospheric profiles; three combine the T3 profile with the S1, S2 or S3 profiles; two others combine the S2 profile with the T1 or T2 profiles. The TRFG is ~.028 W/m^2 /DU when the T3 profile is used, regardless of which stratospheric profile is employed; this value is considerably larger than the corresponding SRFG. About 25 percent of the TRFG appears to result from upper tropospheric ozone change (compare S2-T1 with S2-T3). Both the TRFG and the SRFG are positive, since increases in either tropospheric or lower stratospheric ozone result in a positive ozone radiative forcing. It is clear that the magnitude and even the sign of the total ozone forcing in mid-latitudes depend strongly on the assumptions for both the stratospheric ozone loss between the tropopause and 17 km and the amount of tropospheric ozone increase.

TABLE 2. Same as Table 1, except for mid-latitude (January 40.5N) profiles. The SRFG derived here is valid over a stratospheric column ozone decrease of 0 - 30 DU.

profile	S1	S2	S3	S4
column change	-10.38	-15.55	-20.72	-10.38
forcing	-.035	-.084	-.134	-.078
SRFG	.0034	.0054	.0065	.0075

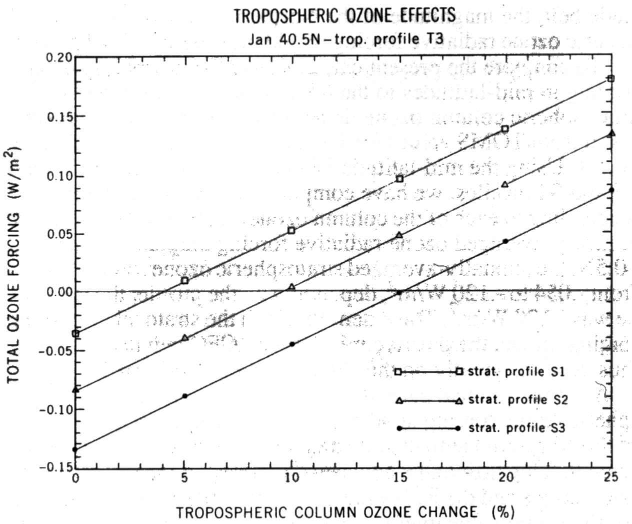

Fig. 3. Total ozone forcing using "standard" stratospheric ozone change profiles and tropospheric profiles that assume a constant percentage ozone increase from the surface to the tropopause.

Implications

The existence of a linear relationship between column ozone loss and radiative forcing in the tropics and mid-latitudes, obtained using January data, makes it possible to estimate ozone radiative forcings at other seasons. We first presume that the shape of the ozone depletion profile (not necessarily the amount of ozone change) is invariant with season. If the SRFG for a particular ozone depletion profile is also insensitive to seasonal changes in the baseline atmospheric profiles, we may apply the SRFGs computed for January to obtain ozone forcings for other seasons, and thus for annually-averaged conditions. Calculations using the S4 mid-latitude ozone profiles indicate that the seasonal variation of the SRFG is, in fact, only ~10 percent.This result justifies the use of January conditions instead of annually-averaged profiles in the present work, and permits a discussion of the implications of these calculations on the evaluation of the decadal hemispheric ozone forcing. In RSS, the area-weighted Northern Hemisphere stratospheric ozone radiative forcing was reported as -.08 W/m^2; below, we examine the changes to this value brought about separately by the results of each sensitivity study.

SAGE measurements at 4.5N suggest a decadal decrease of ~ 8 DU in stratospheric column ozone (Table 1). Using the SRFG for the tropics, we obtain annually-averaged stratospheric ozone forcings ranging from -.056 to -.081 W/m ^{2}. Such forcings represent a significant offset of the positive CFC radiative forcing in the tropics obtained in RSS. These calculations suggest an increase in the negative Northern Hemisphere stratospheric ozone forcing over the value calculated in RSS, since that paper included no contribution to the ozone forcing from the tropics. Thus, if the present results represent the annual forcing for the 0-10N lat-

TABLE 3. Tropospheric radiative forcing gradient (TRFG) in W/m^2/DU for five atmospheric ozone change profiles with tropospheric increases and stratospheric decreases. The TRFG is valid over a tropospheric column ozone increase of 0 - 8 DU.

profile	S1-T3	S2-T1	S2-T2	S2-T3	S3-T3
TRFG	.0280	.0216	.0262	.0282	.0284

itude belt, the magnitude of the Northern Hemisphere stratospheric ozone radiative forcing would increase by 12-18 percent.

To compare the present calculations of stratospheric ozone forcing in mid-latitudes to the RSS values, we assume that stratospheric column ozone depletions in each season may be taken from TOMS values for January, April, July and October at 40.5N. Using the mid-latitude SRFGs obtained from the S1, S2, S3 and S4 profiles, we have computed the radiative forcing corresponding to each of the column ozone changes; from these, the annually-averaged ozone radiative forcing may be obtained. At 40.5N, the annually-averaged stratospheric ozone forcing ranges from -.054 to -.120 W/m^2, depending on the profile; the RSS value was -.120 W/m^2. The extent to which the stratospheric ozone forcing offsets the positive mid-latitude CFC radiative forcing thus depends greatly on the choice of the altitude profile.

As in the tropical case, these new evaluations of the stratospheric ozone forcing at 40.5N produce changes in the estimate of the Northern Hemisphere stratospheric ozone forcing. We assume that the difference between the present annually-averaged calculations and the RSS value for stratospheric ozone forcing at 40.5N is applicable over the Northern Hemisphere mid-latitude belt (30N - 60N). If the RSS values for radiative forcing are assumed for all other latitude belts, the magnitude of the Northern Hemisphere stratospheric ozone forcing is reduced, by amounts varying from 30 percent (using the S1 profile) to zero (using S4). If the S2 profile, which yields results intermediate between the S1 and S3 profiles, is assumed to represent the most representative case, the magnitude of the Northern Hemisphere stratospheric ozone forcing is reduced by 18 percent.

The present calculations of the mid-latitude tropospheric ozone radiative forcing reiterate that small increases in tropospheric column ozone amount exert a greater influence on the forcing of the surface-troposphere system than do equivalent decreases in stratospheric column ozone [WMO, 1986]. Thus, the specification of a tropospheric column ozone increase of 15 percent in the Northern Hemisphere mid-latitudes, which is less than the decadal increases reported at certain stations in this latitude belt, would produce a tropospheric ozone forcing of ~ 0.13 W/m^2. This positive forcing is similar, in magnitude, to the largest estimate of the annually-averaged stratospheric ozone forcing in this latitude belt.

Conclusions

The effect of decadal ozone change on the radiative forcing of the surface-troposphere system may be examined from two different perspectives. In the first, we note that stratospheric ozone decrease and tropospheric ozone increase arise from entirely different causes [WMO, 1992], and study the respective radiative forcings separately. In the second, we attempt to evaluate the forcing due to total ozone change, regardless of cause.

The amount of stratospheric ozone forcing during the 1980s depends principally on two factors: the amount of total column ozone depletion, and the altitude profile of the ozone change. In the tropics, where stratospheric ozone change profiles are available almost to the tropopause, the principal question is the quantity of lower stratospheric ozone loss. This study indicates that the magnitude of the decadal Northern Hemisphere stratospheric ozone forcing would increase significantly if ozone depletion has occurred in the tropics, as implied by SAGE observations.

In mid-latitudes, the stratospheric ozone forcing depends strongly on the altitude profile of decadal ozone change in the mid-latitude lower stratosphere, especially in the layers nearest the tropopause. This conclusion agrees with the results of Lacis et al. [1990] which was based on earlier data. In this study we have adopted four plausible representations for the mid-latitude ozone change profile. Other altitude profiles are conceivable. For instance, use of a profile with constant percentage depletion of ozone throughout the stratosphere yields an ozone radiative forcing far smaller than that obtained using any of the "standard" profiles (see RSS). On the other hand, a profile in which the ozone depletion percentage increases all the way to the tropopause would produce a radiative forcing larger than those calculated here. Accurate measurements of ozone change in the vicinity of the tropopause are therefore necessary to arrive at a precise estimate of the stratospheric ozone forcing and to estimate the extent of the offset of the CFC radiative forcing.

Tropospheric ozone increases have been reported in many regions of the Northern Hemisphere. If these increases are confirmed on a hemispheric scale, the results of this study indicate that a substantial positive tropospheric ozone forcing has also occurred in the past decade, of a magnitude possibly comparable to that produced by decadal stratospheric ozone decreases.

The present results suggest uncertainty in both the magnitude and the sign of the decadal total ozone forcing. It is emphasized that assumptions concerning the amount and the altitude profile of the lower stratospheric ozone losses, and the amount of the tropospheric ozone increases, are critical in determining the influence of ozone on climate.

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V. Ramaswamy and M.D. Schwarzkopf, P.O. Box 308, Princeton, NJ 08542

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