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RADIATIVE FORCING FOR CHANGES IN TROPOSPHERIC O_3

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ABSTRACT

We have evaluated the radiative forcing for assumed changes in tropospheric O_3 in the 500–1650 cm^{-1} wavenumber range. The radiative forcing calculations were performed as a function of latitude as well as for a globally and seasonally averaged model atmosphere, both in a clear sky approximation and in a model containing a representative cloud distribution. The scenarios involved radiative forcing calculations for O_3 at normal atmospheric abundance and at a tropospheric abundance depleted by 25 ppbv, at each altitude, for all northern hemisphere latitudes. Normal abundances of H_2O, CO_2, CH_4, and N_2O were included in the calculations. The IR radiative forcing was calculated using a correlated k-distribution radiative transfer model. The tropospheric radiative forcing values are compared to the IPCC formulae for ozone tropospheric forcing as well as other published values to determine the validity of the correlated k-distribution approach to the radiative forcing calculations. The results for the global average atmosphere show agreement with previous results to the order of 10 percent. We conclude that the O_3 forcing is linear in the background abundance and that the radiative forcing for ozone for the globally averaged atmosphere and the latitude averaged radiative forcing in the clear sky approximation are in agreement to within 10 percent. For the case of an atmosphere in which the tropospheric ozone has been depleted by 25 ppbv at all altitudes in the northern hemisphere, the mid latitude zone contributes ~50 percent of the forcing, the tropic zone contributes ~37 percent of the forcing and the polar zone contributes ~13 percent of the total forcing.

I. INTRODUCTION

The tropospheric radiative forcing is defined (IPCC, 1990) as the decrease in the net upward radiative flux at the tropopause produced, per molecule change of a particular gas, with all other abundances held constant. For an actual radiative forcing calculation, the abundance change must be large enough to produce a numerically significant flux change at the tropopause, without being so large as to produce unnecessary nonlinearities. Parameterized experiments for the calculation of radiative forcing for O_3 have been published, for example, in IPCC (1990, 1992), and by Ramanathan et al. (1987). IPCC (1990) provides a formula for the radiative forcing of O_3. The IPCC formula predicts a tropospheric radiative forcing of 0.02 $W/m^2/ppbv$, linear in the O_3 change. IPCC claims that the above value is tentative. For a "climatalogically correct" model atmosphere, Ramanathan et al. (1987) give a surface temperature increase, due to an O_3 mixing ratio change of 1.15 times ambient at all altitudes less than 12 km, of ~0.1 K. Using a climate feedback factor of 1.9 $W/m^2/K$ (Ramanathan et al., 1985), a tropospheric radiative forcing result of 0.19 W/m^2 is obtained.

In a recent publication (Grossman and Grant, 1992a) the infrared vertical fluxes and heating rates due to O_3 in the atmosphere between 0 and 60 km were calculated. A radiative transfer model based on a correlated k-distribution algorithm for the transmission between atmospheric layers was used. Wavenumbers ranged between 500–2500 cm^{-1}, with 25 cm^{-1} subintervals. The agreement of the heating rates with the line-by-line calculations of Lacis and Oinas (1991) was of the order of 10 percent. Fluxes and heating rates for a mixture of H_2O, CO_2, O_3, CH_4, and N_2O in the wavenumber range 0–2500 cm^{-1}, were also calculated using the correlated k-distribution model (Grossman and Grant, 1992b). The agreement of the heating rates with the line by line calculations of Lacis and Oinas (1991) was of the order of 10 percent. Wuebbles et al. (1994) performed a radiative forcing calculation for a 1.15 x O_3 tropospheric perturbation, using the correlated k-distribution radiation model. They used a globally and seasonally averaged model atmosphere, in a clear sky approximation, and obtained a forcing value of 0.266 W/m^2 at 12 km. Allowing for a 20 percent decrease in the radiative forcing due to clouds (IPCC, 1990) agreement with the Ramanathan et. al. (1985) result is of the order of 10 percent. Grossman et al. (1993) used the correlated k-distribution model to calculate the tropospheric radiative forcing for O_3 in accordance with a set of test cases (Shine et al., 1994). The results were in very good agreement with other calculations performed for the same test scenarios.

The major purposes of this paper are to first, use the correlated k-distribution model to calculate the tropospheric radiative forcing for O_3 in a globally and annually averaged atmosphere both with and without a representative cloud distribution in order to determine the cloud correction factor for O_3. Second, the tropospheric radiative forcing will be calculated at five different latitudes in order to compare the latitude-averaged radiative forcing with the radiative forcing calculated for the globally averaged atmosphere. Third, the globally averaged radiative forcing will be calculated for scenarios in which various northern hemisphere zones have been depleted by 25 ppbv, in the O_3 mixing ratio, at all tropospheric altitudes. This depletion is representative of the average change in tropospheric O_3 content experienced in the northern hemisphere over the last 150 years (IPCC, 1990).

II. PARAMETERS OF THE CALCULATIONS

Flux and radiative forcing calculations were made for the following model atmosphere parameters.

A. Globally and seasonally averaged model atmosphere, (Wuebbles et al., 1994):

1. Altitude resolution;
    a. 1 km, 0–20 km altitude,
    b. 2 km, 20–60 km altitude.

2. Temperature–pressure–mixing ratio vertical profiles given in Figures 1 and 2.
3. A ground temperature of 291 K.
4. Tropopause at 166 mb.
5. Cloud Distribution;
   a. Cloud thickness of 1 km.
   b. Cloud bases at 2 km, 4 km, and 10 km altitudes.
   c. Fractional cloud cover amounts of 0.31 (low), 0.09 (middle), 0.17 (high).
5. Outgoing terrestrial radiation of 239 W/m^2.
6. A wavenumber range of 500 to 1650 cm^{-1}, in 25 cm^{-1} subintervals

B. Latitude Model Parameters

1. Latitudes 30, 60N, Eq., 30, 60S.
2. Tropopause pressures;
   60N–278 mb,
   30N–135 mb,
   Eq–123 mb,
   30S–139 mb,
   60S–278 mb.
3. Averaging weights,
   60N,S–0.212,
   30N,S–0.496,
   EqN,S–0.292.
4. Model atmosphere temperature-pressure-abundance distributions at each latitude from Wuebbles et al. (1994).

III. MODEL ATMOSPHERES

The model atmospheres used for the radiative forcing calculations were taken from Wuebbles et al. (1994). The current version of the LLNL zonally-averaged two-dimensional chemical-radiative-transport model determines the atmospheric distributions of 44 chemically active atmospheric trace constituents in the troposphere and stratosphere. The model domain extends from pole to pole, and from the ground to 60 km. The sine of latitude is used as the horizontal coordinate, with uneven increments corresponding to approximately 10 degrees in latitude. The vertical coordinate corresponds to the natural logarithm of pressure; the scale height is 7.2 km and the surface pressure is 1013 mb. The vertical resolution is 1.5 km in the troposphere and 3 km in the stratosphere. The 2-dimensional model-derived ambient atmosphere used for these calculations is based on 1990 emissions of the source gases. The two-dimensional (i.e. latitude, altitude) distributions of the radiatively important trace gases—water vapor, carbon dioxide, ozone, nitrous oxide, and methane—are averaged over the annual cycle and from pole to pole. The resulting globally- and annually-averaged altitude profiles for water vapor, ozone, and methane are depicted in Figure 1. Carbon dioxide is constant at 350 ppmv throughout the model atmosphere. Nitrous oxide decreases monotonically from 308 ppbv near the surface to 1.2 ppbv at 59 km. The pressure-temperature profile for the model atmosphere is shown in Figure 2. The tropopause in the globally-averaged atmosphere, based on the temperature gradient in the troposphere decreasing to a value of 2K/km, indicated in Figure 2, occurs at 166 mb (~13.2 km). The Tropospheric distributions of the ozone mixing ratio with altitude, for latitudes 30N and 60N are given in Figure 3 for the month of January, in Figure 4 for the month of April, in Figure 5 for the month of June, and in Figure 6 for the month of October. Comparison of these distributions with the observational ozone distributions given by Komhyr et al. (1989) indicates that the model distributions are in reasonable agreement with the observations.

IV. RESULTS AND DISCUSSION

Table I shows the results of tropospheric radiative forcing calculations for O_3 in the globally and annually averaged atmosphere. Three cases were considered in terms of the amount of forcing, 10 ppbv, 20, ppbv, and 25 ppbv, at each altitude. Both the clear sky approximation and the model with clouds are shown.

Table 1. O_3 Radiative Forcing in Global Average Atmosphere

	CASE A(CLEAR SKY)	
	TOTAL FORCING (W/m^2)	FORCING(PPBV) (W/m^2/ppbv)
Ambient-10 ppbv	0.306	0.0306
Ambient-20 ppbv	0.624	0.0312
Ambient-25 ppbv	0.793	0.0317

	CASE B(CLOUDS)	
	TOTAL FORCING (W/m^2)	FORCING(PPBV) (W/m^2/ppbv)
Ambient-10 ppbv	0.208	0.0208
Ambient-20 ppbv	0.438	0.0219
Ambient-25 ppbv	0.555	0.0222
IPCC (1990)		0.0200

The results of Table 1, for the case with clouds, agree to within 10 percent of the radiative forcing formula result given in IPCC (1990) which predicts a radiative forcing of 0.02. For the clear sky models the present calculations predict a tropospheric radiative forcing which is about 50 percent larger than the IPCC (1990) value. IPCC (1990) states that the clear sky radiative forcing should be approximately 20 percent larger than the cloud model radiative forcing. Grossman and Grant (1994) found that this factor was 25 percent for the case of CH_4. Since the cloudy sky model results are in good agreement for O_3, the interpretation is that the clear sky-cloudy sky multiplication factors may be species dependent, particularly when there is an altitude profile variation as is the case for

O_3. Table 2 shows the clear sky radiative forcing results as a function of latitude. The depleted

Table 2. O_3 Radiative Forcing Variation with Latitude ($W/m^2/ppbv$)

	60S	30S	EQ	30N	60N
Ambient-10 ppbv	0.0215	0.0341	0.0421		
Ambient-20 ppbv			0.0436	0.0319	0.0217
Ambient-25 ppbv			0.0429	0.0325	0.0218
Depleted Atmosphere (Ambient-25 ppbv)			0.0398	0.0346	0.0220

atmosphere result is calculated by taking the difference between the (Ambient-20 ppbv) total radiative forcing and the (Ambient-25 ppbv) total radiative forcing and dividing the result by 5 ppbv. Table 2 shows that the depleted atmosphere radiative forcing is within 10 percent of the normal atmosphere radiative forcing on a ppbv basis, for the northern latitude model atmospheres. The results in Tables 1 and 2 are used to calculate the radiative forcing for ozone for the globally averaged atmosphere and the latitude averaged radiative forcing in the clear sky approximation. The value obtained for the globally averaged atmosphere is 0.031 W/m2/ppbv. The latitude averaged radiative forcing is 0.034 W/m2/ppbv. The latitude averaged radiative forcing obtained for an atmosphere in which the northern hemisphere O_3 has been depleted by 25 ppbv at all tropospheric altitudes is 0.033 W/m2/ppbv. We conclude that the O_3 forcing is linear in the background abundance and that the radiative forcing for ozone for the globally averaged atmosphere and the latitude averaged radiative forcing in the clear sky approximation are in agreement to within 10 percent. Table 3 shows the global average radiative forcing, for a cloudy sky approximation, resulting from a 25 ppbv O_3 depletion at all tropospheric altitudes within a particular latitude zone. The radiative forcing is calculated as the product of 1, the radiative forcing per ppbv in the particular latitude zone, 2, the 25 ppbv abundance change, 3, the zonal average weighting factor, and 4, a factor of 0.7 which approximates the correction applied to the clear sky results to obtain the cloudy sky results. The results indicate that the mid-latitude zone radiative forcing contributes approximately 50 percent of the total northern hemisphere radiative forcing, the tropic zone contributes approximately 37 percent of the total northern hemisphere radiative forcing, and the polar zone contributes approximately 13 percent of the total northern hemisphere radiative forcing.

Table 3. Global Average Radiative Forcing for Ozone Depleted Zones

LATITUDE ZONE	WEIGHTING FACTOR	RADIATIVE FORCING
Northern Hemisphere	0.5	0.28 (W/m^2)
Tropic Zone	0.146	0.11 (W/m^2)
Mid-Latitude Zone	0.248	0.15 (W/m^2)
Polar Zone	0.106	0.04 (W/m^2)

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Figure Captions

Figure 1. Globally and annually averaged profiles of water vapor, ozone, and methane as a function of altitude for the ambient atmosphere.

Figure 2. Pressure-temperature profile for the ambient atmosphere. The temperatures are globally and annually averaged.

Figure 3. Theoretical profile of the tropospheric ozone mixing ratio (ppbv) as a function of altitude (km) for the month of January at (a) 30N latitude, and (b) 60N latitude.

Figure 4. Theoretical profile of the tropospheric ozone mixing ratio (ppbv) as a function of altitude (km) for the month of April at (a) 30N latitude, and (b) 60N latitude.

Figure 5. Theoretical profile of the tropospheric ozone mixing ratio (ppbv) as a function of altitude (km) for the month of June at (a) 30N latitude, and (b) 60N latitude.

Figure 6. Theoretical profile of the tropospheric ozone mixing ratio (ppbv) as a function of altitude (km) for the month of October at (a) 30N latitude, and (b) 60N latitude.

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