Tropospheric Radiative Forcing of O₃ for the 1994 IPCC Report

Allen S. Grossman
Keith E. Grant
Donald J. Wuebbles

Global Climate Research Division, L-262
Lawrence Livermore National Laboratory
Livermore, California, 94550

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ABSTRACT

We have determined the tropospheric radiative forcing of O₃ in the 175–735 nm (UV-Visible) wavelength range plus the 500–1650 cm⁻¹ (Infrared) wavenumber range in accordance with a set of IPCC test cases provided to all interested modeling groups. The atmospheric test cases involved perturbed ozone scenarios in a McClatchey mid-latitude summer, clear sky, model atmosphere. A new short wave radiative transfer code has been developed to calculate the radiative forcing in the 175–735 nm wavelength range. The IR radiative forcing was calculated using a correlated k-distribution transmission model. The tropospheric radiative forcing values obtained for the IR spectral region and the UV-Visible spectral region lie in the middle of the range of preliminary values submitted from all of the models used in the IPCC test calculations.

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I. INTRODUCTION

The Intergovernmental Panel On Climate Change (IPCC) has issued an ozone radiative forcing test case for its 1994 report and has invited all interested modeling groups to perform radiative forcing calculations as part of a model intercomparison study. In a recent publication (Grossman and Grant, 1992), a correlated k-distribution model for atmospheric transmission was used to calculate the fluxes and heating rates for pure O₃ in the atmosphere between 0 and 60 km altitude, at wave numbers between 500 and 1200 cm⁻¹. Comparison of the heating rate results with the line-by-line calculations published by Lacis and Oinas (1991) showed agreement to approximately 10 percent over the spectral range 500–1200 cm⁻¹. This model was also used to calculate the fluxes and heating rates for mixtures of H₂O, CO₂, O₃, CH₄, and N₂O in the altitude range 0–60 km, and spectral range 0–2500 cm⁻¹ (Grossman and Grant, 1992). Comparison of the heating rate results with the GFDL line by line calculations (Ridgway et al., 1991) show agreement to the order of 10 percent. Both sets of calculations were done for a McClatchey mid-latitude summer, clear sky, model atmosphere. In addition to the longwave calculation described above, Grossman et al. (1993), and Grant and Grossman (1993) developed a short wave radiation model for the wavelength region 175–735 nm in which O₃ and Rayleigh scattering were the major sources of atmospheric extinction. UV-B surface radiation calculations made with this model compared very well with those of Madronich (1993).

The tropospheric radiative forcing is defined (IPCC, 1990) as the radiative flux change at the tropopause produced by a change in the column density of molecules of a particular gas with all other abundances held constant. Usually the amount of abundance change used in a radiative forcing calculation is chosen such that the change is just enough to produce a numerically significant flux change at the tropopause. Parametrized experiments for the calculation of radiative forcing have been published, for example, in IPCC (1990, 1992), and by Ramanathan et al. (1987). Radiative forcing calculations for SF₆ have been published by Grossman et al. (1993), and for O₃ and CH₄ by Wuebbles et al. (1993).

The main purpose of this paper is to calculate the tropospheric radiative forcing for O₃ for the three IPCC 1994 Report scenarios (Shine, 1993) and to compare the results to those produced by other workers for the same scenarios.

II. PARAMETERS OF THE CALCULATIONS

Tables 1 and 2 give the details of the IPCC 1994 ozone test scenario. The ambient model atmosphere is the McClatchey mid-latitude summer, clear sky approximation temperature, pressure, H₂O, and O₃ distribution. This is given in Table 1. The perturbed ozone distribution is given in Table 2 as a function of temperature and pressure. According to Shine (1993), the features of the perturbed ozone profile (shown in Table 2) are a uniform ten percent increase in the ozone below 8 km, a linear decrease, from +10 percent to 0, with altitude, between 8 km and the tropopause, and a scaled stratospheric

shape function similar to the S2 profile (Schwarzkopf and Ramaswamy, 1993) such that the total loss of stratospheric ozone is ~15.6 DU.

The other major trace gas concentrations are $\text{CO}_2 = 337$ ppmv, $\text{CH}_4 = 1.57$ ppmv, and $\text{N}_2\text{O} = 302$ ppbv. The other important parameters of the IR calculation are a ground temperature of 294 K, and a wave number range of $500\text{--}1650\text{ cm}^{-1}$ with 25 cm^{-1} sub intervals. The HITRAN 91 data base (Rothman et al., 1991) was used to provide the absorption line list.

The parameters of the short wave calculation were;

1. Solar constant = 1370 W/m^2 ,
2. Clear sky conditions,
3. Surface albedo = 0.1,
4. Cosine of the mean zenith angle = 0.515486,
5. Fraction of a day with the sun up = 0.557024,
6. Wavelength range of 175–735 nm.

III. RESULTS AND DISCUSSION

The zero-atmosphere solar flux in each wavelength bin of the short wavelength model was taken from Connell and Wuebbles (1983) and is similar to WMO-16 (1985). Using data from Allen (1985) for the zero-atmosphere solar flux at wavelengths longer than 735 nm, the calculated solar constant was 1368 W/m^2 . The IPCC value given above is 1370 W/m^2 and we conclude that the agreement is very good.

The quantities given in Tables 1 and 2 were interpolated on to an altitude grid with 1 km resolution in the altitude range 0–20 km (no interpolation required in this altitude range) and 2 km resolution in the altitude range 20–70 km using piecewise, Hermite cubic spline interpolation. By convention, the tropopause was set at a pressure level of 179 mb.

The radiative forcing calculation was considered in three scenarios. The first scenario was the forcing between the ambient atmosphere (Table 1) and the perturbed ozone atmosphere given in Table 2. The second scenario was the forcing between the ambient atmosphere and a perturbed atmosphere consisting of the tropospheric ozone profile from Table 2 and the ambient atmosphere above the tropopause. The third scenario was the forcing between the ambient atmosphere and a perturbed atmosphere consisting of the stratospheric ozone profile from Table 2 and the ambient atmosphere below the tropopause. Table 3 gives a comparison of the IR, O_3 tropospheric radiative forcing (179 mb), in the $500\text{--}1650\text{ cm}^{-1}$ wave number range, between the LLNL correlated k-distribution radiative transfer model (Grossman and Grant, 1992) results and the preliminary IPCC 1994 results (Shine, 1993). Table 4 gives a comparison of the short wave O_3 radiative forcing, in the 175–735 nm wavelength range, between the LLNL short wave model (Grossman et. al., 1993) results and the preliminary IPCC 1994 results (Shine, 1993). Table 5 gives the net (IR + SW) O_3 radiative forcing comparison between the LLNL and the IPCC results. Tables 3, 4, and 5 show that the LLNL results are

situated right in the middle of the range of the reported O₃ tropospheric forcing results. These results provide excellent validations of the LLNL IR correlated k-distribution radiative transfer model as well as the LLNL short wave radiative transfer model. A future study will address the effects of allowing equilibration of the stratospheric temperature distribution following the ozone perturbation.

IV. ACKNOWLEDGEMENT

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Table 1.
McClatchey Mid-Latitude Summer Atmosphere

height	temperature	pressure	mmr(H ₂ O)	mmr(O ₃)
(km)	(K)	(mb)	(mass mixing ratios)	
0.00000	294.000000	0.101300E+04	0.116631E-01	0.499863E-07
	292.035828	0.957500E+03	0.101166E-01	0.525824E-07
0.991953	289.971863	0.902000E+03	0.858391E-02	0.553685E-07
	287.687012	0.852000E+03	0.725535E-02	0.582131E-07
1.981609	285.043579	0.802000E+03	0.596628E-02	0.612139E-07
	282.124634	0.756000E+03	0.488384E-02	0.654296E-07
2.988222	279.070404	0.710000E+03	0.386576E-02	0.699535E-07
	276.143005	0.669000E+03	0.308229E-02	0.747439E-07
3.980928	273.114044	0.628000E+03	0.236288E-02	0.798963E-07
	270.184265	0.591000E+03	0.183195E-02	0.854145E-07
4.973490	267.148773	0.554000E+03	0.139021E-02	0.913586E-07
	264.185028	0.520500E+03	0.115206E-02	0.984958E-07
5.971597	261.097076	0.487000E+03	0.937971E-03	0.106190E-06
	258.014099	0.456500E+03	0.780093E-03	0.117046E-06
6.983919	254.775269	0.426000E+03	0.637592E-03	0.128757E-06
	251.626678	0.399000E+03	0.514204E-03	0.139631E-06
7.984175	248.341568	0.372000E+03	0.403320E-03	0.151390E-06
	245.179321	0.348000E+03	0.323970E-03	0.167195E-06
8.977831	241.893585	0.324000E+03	0.252832E-03	0.184306E-06
	238.715179	0.302500E+03	0.201681E-03	0.199702E-06
9.975264	235.411789	0.281000E+03	0.154626E-03	0.216435E-06
	232.255890	0.262000E+03	0.101276E-03	0.255326E-06
10.965798	228.973999	0.243000E+03	0.591365E-04	0.297533E-06
	225.798080	0.226000E+03	0.366875E-04	0.330613E-06
11.965093	222.503830	0.209000E+03	0.197273E-04	0.366720E-06
	219.580872	0.194000E+03	0.116118E-04	0.440405E-06
12.964431	216.997314	0.179000E+03	0.575907E-05	0.521981E-06
	216.133667	0.166000E+03	0.448005E-05	0.619327E-06
13.961350	215.785629	0.153000E+03	0.402773E-05	0.728729E-06
	215.759888	0.141500E+03	0.400231E-05	0.812129E-06
14.994699	215.751816	0.130000E+03	0.400000E-05	0.905163E-06
	215.751404	0.120500E+03	0.400000E-05	0.103141E-05

Table 1 continued

height	temperature	pressure	mmr(H ₂ O)	mmr(O ₃)
(km)	(K)	(mb)	(mass mixing ratios)	
15.997259	215.751343	0.111000E+03	0.400000E-05	0.117169E-05
	215.752487	0.103000E+03	0.400000E-05	0.135797E-05
16.985218	215.756378	0.950000E+02	0.400000E-05	0.156464E-05
	215.806000	0.881000E+02	0.400000E-05	0.183567E-05
17.982046	215.948593	0.812000E+02	0.400000E-05	0.213754E-05
	216.375580	0.753500E+02	0.400000E-05	0.248246E-05
18.973122	216.925034	0.695000E+02	0.400000E-05	0.286706E-05
	217.501572	0.645000E+02	0.400000E-05	0.320357E-05
19.968149	218.113144	0.595000E+02	0.400000E-05	0.357772E-05
	218.693039	0.552500E+02	0.400000E-05	0.398797E-05
20.961210	219.304703	0.510000E+02	0.400000E-05	0.444368E-05
	219.889328	0.473500E+02	0.400000E-05	0.480886E-05
21.962135	220.505951	0.437000E+02	0.400000E-05	0.521439E-05
	221.078857	0.406500E+02	0.400000E-05	0.547068E-05
22.941849	221.682541	0.376000E+02	0.400000E-05	0.575420E-05
	222.278305	0.349000E+02	0.400000E-05	0.604081E-05
23.957947	222.909119	0.322000E+02	0.400000E-05	0.635893E-05
	223.505844	0.299500E+02	0.400000E-05	0.664815E-05
24.950291	224.149384	0.277000E+02	0.400000E-05	0.696853E-05
	228.071411	0.204500E+02	0.400000E-05	0.817253E-05
29.951078	234.043777	0.132000E+02	0.400000E-05	0.101792E-04
	238.854309	0.986000E+01	0.400000E-05	0.101113E-04
34.942440	245.041580	0.652000E+01	0.400000E-05	0.992527E-05
	250.272507	0.492500E+01	0.400000E-05	0.962846E-05
39.932396	257.177368	0.333000E+01	0.400000E-05	0.908939E-05
	262.644836	0.254500E+01	0.400000E-05	0.780061E-05
44.908684	269.369965	0.176000E+01	0.400000E-05	0.571139E-05
	273.466858	0.135550E+01	0.400000E-05	0.489649E-05
49.913174	276.338104	0.951000E+00	0.400000E-05	0.358667E-05
	258.619476	0.509050E+00	0.400000E-05	0.300527E-05
69.400307	219.512512	0.671000E-01	0.400000E-05	0.807602E-06
	219.512512	0.335500E-01	0.400000E-05	0.807602E-06

Table 1 continued

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22.941849	221.682541	0.376000E+02	0.400000E-05	0.575420E-05
	222.278305	0.349000E+02	0.400000E-05	0.604081E-05
23.957947	222.909119	0.322000E+02	0.400000E-05	0.635893E-05
	223.505844	0.299500E+02	0.400000E-05	0.664815E-05
24.950291	224.149384	0.277000E+02	0.400000E-05	0.696853E-05
	228.071411	0.204500E+02	0.400000E-05	0.817253E-05
29.951078	234.043777	0.132000E+02	0.400000E-05	0.101792E-04
	238.854309	0.986000E+01	0.400000E-05	0.101113E-04
34.942440	245.041580	0.652000E+01	0.400000E-05	0.992527E-05
	250.272507	0.492500E+01	0.400000E-05	0.962846E-05
39.932396	257.177368	0.333000E+01	0.400000E-05	0.908939E-05
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69.400307	219.512512	0.671000E-01	0.400000E-05	0.807602E-06
	219.512512	0.335500E-01	0.400000E-05	0.807602E-06

Table 3.

O ₃ IR RADIATIVE FORCING COMPARISON 500–1650 cm ⁻¹ (W/m ²)			
	Scenario 1 Tropo. + Strat	Scenario 2 Tropo. only	Scenario 3 Strat. only
LLNL	0.096	0.159	-0.067
IPCC	0.077–0.108	0.148–0.163	-0.073– -0.050

Table 4.

O ₃ RADIATIVE FORCING COMPARISON 175–735 nm (W/m ²)			
	Scenerio 1 Tropo. + Strat	Scenario 2 Tropo. only	Scenario 3 Strat. only
LLNL	0.2779	0.0227	0.2549
IPCC	0.241–0.392	0.015–0.031	0.226–0.361

Table 5.

O ₃ NET RADIATIVE FORCING COMPARISON (W/m ²)			
	Scenerio 1 Tropo. + Strat	Scenario 2 Tropo. only	Scenario 3 Strat. only
LLNL	0.374	0.182	0.188
IPCC	0.323–0.492	0.165–0.187	0.153–0.311

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