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Tropospheric Radiative Forcing of CH₄

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April 1994

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TROPOSPHERIC RADIATIVE FORCING OF CH₄

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January 12, 1994

ABSTRACT

We have evaluated the tropospheric radiative forcing of CH₄ in the 0–3000 cm⁻¹ wavenumber range and compared this with prior published calculations. The atmospheric test cases involved perturbed methane scenarios in both a McClatchey mid latitude, summer, clear sky approximation, model atmosphere, as well as a globally and seasonally averaged model atmosphere containing a representative cloud distribution. The scenarios involved pure CH₄ radiative forcing and CH₄ plus a mixture of H₂O, CO₂, O₃, and N₂O radiative forcing. The IR radiative forcing was calculated using a correlated k-distribution transmission model. The tropospheric radiative forcing values are compared to the IPCC formulae for methane tropospheric forcing as well as other published and unpublished values to determine the validity of the correlated k-distribution approach to the radiative forcing calculations. The results for the McClatchey models show agreement with previous calculations to the order of 10–15 percent. The results for the global average atmosphere show agreement with previous calculations to the order of 4 percent.

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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 must be large enough to produce a numerically significant flux change at the tropopause, without being so large as to produce unnecessary nonlinearities. Parametrized experiments for the calculation of radiative forcing for CH₄ 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 CH₄ in terms of the joint abundances of CH₄ and N₂O. Assuming a N₂O mixing ratio of 310 ppbv, and a CH₄ mixing ratio change from 1.72 to 3.44 ppmv, the IPCC formula predicts a tropospheric radiative forcing of 0.53 W/m². For a CH₄ mixing ratio change from 0 to 1.72 ppmv and a N₂O mixing ratio of 310 ppbv, the IPCC formula predicts a radiative forcing of 1.33 W/m². IPCC claims that the omission of cloud effects in the radiative transfer calculation results in a radiative forcing value which is approximately 20 percent too large. Ramanathan et al. (1987) presents CH₄ radiative forcing results for the case of CH₄, as the only radiatively active gas, for a clear-sky, mid-latitude, summer, model atmosphere, MLS, (McClatchey et al., 1972). For a CH₄ mixing ratio change from 1.75 to 3.5 ppmv, Ramanathan et al. (1987) gives a range of radiative forcing values of 1.78–1.83 W/m², with 1.78 W/m² being the result of a line-by-line calculation. For a “climatologically correct” model atmosphere, Ramanathan et al. (1987) give a surface temperature increase, due to a CH₄ mixing ratio change from 1.75 to 3.5 ppmv, of ~0.29 K. Using a climate feedback factor of 1.9 W/m²/K (Ramanathan et al., 1985), a tropospheric radiative forcing result of 0.55 W/m² is obtained, which is in excellent agreement with the IPCC (1990) result. In addition to these values, line-by-line calculations for CH₄ radiative forcing in a MLS atmosphere model were done by Ramaswamy (1993). For the case of CH₄, as the only radiatively active gas, an

abundance change from 0 to 1.75 ppmv produced a tropospheric radiative forcing value of 4.434 W/m². For a mixture of H₂O, CO₂, O₃, N₂O, and CH₄, with a CH₄ abundance change from 0 to 1.75 ppmv, a tropospheric radiative forcing value of 2.02 W/m² was obtained. The IPCC (1990) formula gives a value of 1.33 W/m² for this case. Most of the difference is probably due to the ignoring the radiative effects of clouds, which, according to IPCC (1990), should result in a value of the forcing that is approximately 20 percent higher than would be predicted by the IPCC formula. Additional CH₄ radiative forcing calculations have been made by Shine (1993) for a MLS atmosphere model. For the case of CH₄, as the only radiatively active gas, a tropospheric radiative forcing value of 1.89 W/m² was obtained, which is in reasonable agreement with Ramanathan et al. (1987). For the mixture of H₂O, CO₂, O₃, N₂O and CH₄, with a CH₄ abundance change from 1.72 to 3.44 ppmv, a tropospheric radiative forcing value of 0.852 W/m² was obtained. Considering the clear sky and constant CH₄ mixing ratio with altitude approximations used in the calculation, this is in reasonable agreement with the radiative forcing of 0.53 W/m² predicted by the IPCC (1990) formula.

In a recent publication (Grant et al., 1992) the infrared vertical fluxes and heating rates due to CH₄ and N₂O 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 1100–1340 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 5 percent. Fluxes and heating rates for a mixture of H₂O, CO₂, O₃, CH₄, and N₂O in the wavenumber range 0–2500 cm⁻¹, were also calculated using the correlated k-distribution model (Grossman and Grant, 1992). The agreement of the heating rates with the line by line calculations of Lacis and Oinas (1991) was of the order of 10 percent.

The major purposes of this paper are to first, use the correlated k-distribution model to calculate the tropospheric radiative forcing for CH_4 , as the only radiatively active gas, and in a mixture with H_2O , CO_2 , O_3 , and N_2O , for a McClatchey mid-latitude summer, clear-sky model atmosphere, and to compare the results to those obtained in the studies mentioned above. Second, we will calculate the tropospheric methane forcing in a globally and annually averaged atmosphere with and without a representative cloud distribution in order to validate the conjecture given in IPCC (1990) that the inclusion of clouds in the forcing calculations results in forcing values which are approximately 20 percent less than those obtained using clear sky approximations.

II. PARAMETERS OF THE CALCULATIONS

Flux calculations were made for the following model atmosphere parameters:

- A. McClatchey mid latitude, summer, temperature-pressure vertical profiles (MLS).
 1. Altitude resolution;
 - a. 1 km, 0–20 km altitude,
 - b. 2 km, 20–60 km altitude.
 2. A ground temperature of 294 K.
 3. CH_4 mixing ratios of 0.0, 1.72, and 3.44 ppmv, constant with altitude.
 4. An N_2O mixing ratio of 0.31 ppmv, constant with altitude.
 5. A CO_2 mixing ratio of 354 ppmv, constant with altitude.
 6. Vertical profiles of H_2O and O_3 mixing ratios as specified in the MLS atmosphere.
 7. A wavenumber range of 900 to 1650 cm^{-1} , in 25 cm^{-1} subintervals.
- B. Globally and seasonally averaged model atmosphere, GLAV, (Wuebbles et al., 1993):
 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 Table 1.
- 3. A ground temperature of 291 K.
- 4. 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/m².
- 6. A wavenumber range of 900 to 1650 cm⁻¹, in 25 cm⁻¹ subintervals.

III. RADIATIVE TRANSFER MODEL WITH A CLOUD DISTRIBUTION

The clear sky radiative transfer model outlined in Grant et al. (1992) was modified to accept a cloud distribution model using an algorithm based on Harshvardhan et al. (1987). In this algorithm the transmission between atmospheric layers is multiplied by the probability of a clear line of sight between the layers. The clouds are considered to be radiatively black at the thermal wavelengths. The fractional cloud cover is given as a number between 0.0 and 1.0. For the case of random overlap of the cloud layers, which is the case adopted in this paper, the probability of a clear line of sight between two layers i and j is given as,

$$C_{ij} = (1 - N_{j-1})(1 - N_{j-2}) \dots (1 - N_i) , \quad (1)$$

where the N 's represent the fractional cloud cover of the particular layers. The transmission is then given as,

$$T_{ij} = T_{\text{clr}} C_{ij} , \quad (2)$$

where T_{clr} is the clear sky transmission. The thermal upward flux was calculated for the model atmosphere given in Table 1 over the wavenumber range 0–3000 cm⁻¹ in 25 cm⁻¹ subintervals for both the clear sky and the cloudy sky conditions. For the clear sky case an upward flux of 266 W/m² was obtained. For the cloudy sky case an upward

flux of 239 W/m^2 was obtained, which is comparable to the climatological solar input (Peixoto and Oort, 1992).

IV. RESULTS AND DISCUSSION

The correlated k-distribution radiative transfer model was used to calculate the tropospheric radiative forcing for the following cases;

1. CH_4 only, 1.72–3.44 ppmv, McClatchey MLS-CS,
2. $\text{CH}_4 + \text{H}_2\text{O}$, CO_2 , O_3 , N_2O , CH_4 –1.72–3.44 ppmv, MLS-CS,
3. $\text{CH}_4 + \text{H}_2\text{O}$, CO_2 , O_3 , N_2O , CH_4 –0.0–1.72 ppmv, MLS-CS,
4. $\text{CH}_4 + \text{H}_2\text{O}$, CO_2 , O_3 , N_2O , CH_4 –amb.–2 x amb.,
Global Average-clear sky, GLAV-CS,
5. $\text{CH}_4 + \text{H}_2\text{O}$, CO_2 , O_3 , N_2O , CH_4 –amb.–2 x amb.,
Global Average-cloudy sky, GLAV-CLD,

For Cases 1–3 above, the troposphere was taken at a pressure of 179 mb. For the global average atmosphere (Cases 4–5), the troposphere was taken at a pressure of 118 mb. The troposphere in the model atmospheres were determined by the pressure level at which the troposphere temperature profile reached a minimum value. Table 2 gives a comparison of the results for Case 1 above (CH_4 only, MLS-CS). The calculations done in this study agree with the line by line calculations of Ramanathan et al. (1987) to about 6 percent. The comparison of our result to that of Shine (1993) shows agreement to about 13 percent. Table 3 gives a comparison of the results for Case 2 above (CH_4 + others, MLS-CS). The comparison of our result to the IPCC (1990) value indicates a difference of about 36 percent. Approximately 20 percent of this difference is probably due to the clear sky approximation and the rest is probably due to the differences between the McClatchey atmosphere and the global average atmosphere plus differences in the methodology. Comparison of our result to that of Shine (1993) shows agreement to the order of about 18 percent. This is of the same order as the agreement for the pure CH_4 case and probably reflects differences in the calculation methodology. Table 4 gives a

comparison of the results for Case 3 above (CH_4 + others, MLS-CS). The comparison of our result to the IPCC (1990) value indicates a difference of about 27 percent. Again approximately 20 percent of this difference is probably due to the clear sky approximation and the rest is probably due to the differences between the McClatchey atmosphere and the global average atmosphere plus differences in the methodology. Comparison of our result to that of Ramaswamy (1993) shows agreement to the order of about 20 percent but the Ramaswamy calculations are of the order of 50 percent larger than the IPCC (1990) value. Some of this difference may be due to a wavenumber range of $0\text{--}3000\text{ cm}^{-1}$ used by Ramaswamy as opposed to the wavenumber range of $900\text{--}1650\text{ cm}^{-1}$ used in this paper. We do not calculate any substantial increase in radiative forcing when we increase the wavenumber range beyond $900\text{--}1650\text{ cm}^{-1}$. Table 5 gives a comparison of the results of the radiative forcing calculations for the global average atmosphere, Case 4 (CH_4 + others, clear sky) and Case 5 (CH_4 + others, cloudy sky) above. Also shown is the value calculated by the formula given in IPCC (1990) as well as the value calculated by Ramanathan et al. (1987) for a "climatologically correct" atmosphere. The results show that for the cloudy sky case, the agreement between our calculation of the tropospheric radiative forcing and the IPCC (1990) value is better than 1 percent. The agreement between our calculation and that of Ramanathan et. al. is about 4 percent. The difference in tropospheric radiative forcing between the clear sky calculation and the cloudy sky calculation is a 24 percent increase for the clear sky case. This is in good agreement with the IPCC (1990) conjecture that the neglect of clouds results in a radiative forcing value approximately 20 percent higher than that which would be obtained if clouds were included in the calculation.

V. ACKNOWLEDGMENT

Work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 and was supported in part by the Department of Energy Environmental Sciences Division and the

Gas Research Institute under contract No. 5091-254-2167. The authors would like to acknowledge the assistance of Raymond Gentry with the numerical calculations.

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TABLE 1. LLNL GLOBAL ANNUAL AVERAGE REFERENCE ATMOSPHERE

Layer Edge Press. (mb)	Layer Mean Press. (mb)	Layer Mean Temp. (K)	Layer Mean Density (molec/cm ³)	Layer Mean H ₂ O (ppv)	Layer Mean O ₃ (ppmv)	Layer Mean CO ₂ (ppmv)	Layer Mean CH ₄ (ppmv)	Layer Mean N ₂ O (ppmv)
2.4356e-01								
3.2154e-01	2.8255e-01	248.44	8.2373e+15	6.711e-06	9.808e-01	3.500e+02	1.548e-01	1.215e-03
4.2450e-01	3.7302e-01	253.12	1.0674e+16	6.684e-06	1.189e+00	3.500e+02	1.683e-01	1.771e-03
5.6042e-01	4.9246e-01	258.47	1.3800e+16	6.655e-06	1.448e+00	3.500e+02	1.853e-01	2.547e-03
7.3986e-01	6.5014e-01	262.73	1.7923e+16	6.638e-06	1.735e+00	3.500e+02	2.052e-01	3.716e-03
9.7676e-01	8.5831e-01	265.08	2.3452e+16	6.583e-06	2.073e+00	3.500e+02	2.339e-01	5.547e-03
1.2895e+00	1.1331e+00	266.15	3.0837e+16	6.498e-06	2.481e+00	3.500e+02	2.705e-01	8.048e-03
1.7024e+00	1.4959e+00	264.76	4.0924e+16	6.391e-06	2.949e+00	3.500e+02	3.112e-01	1.126e-02
2.2475e+00	1.9749e+00	261.71	5.4657e+16	6.286e-06	3.477e+00	3.500e+02	3.533e-01	1.506e-02
2.9671e+00	2.6073e+00	257.33	7.3386e+16	6.172e-06	4.110e+00	3.500e+02	4.023e-01	1.995e-02
3.9172e+00	3.4422e+00	251.99	9.8937e+16	6.061e-06	4.849e+00	3.500e+02	4.591e-01	2.661e-02
5.1714e+00	4.5443e+00	246.67	1.3343e+17	5.905e-06	5.625e+00	3.500e+02	5.373e-01	3.764e-02
6.8273e+00	5.9994e+00	240.92	1.8036e+17	5.702e-06	6.477e+00	3.500e+02	6.371e-01	5.357e-02
9.0133e+00	7.9203e+00	235.44	2.4365e+17	5.454e-06	7.276e+00	3.500e+02	7.534e-01	7.640e-02
1.1899e+01	1.0456e+01	230.68	3.2830e+17	5.199e-06	7.768e+00	3.500e+02	8.648e-01	1.022e-01
1.5709e+01	1.3804e+01	226.16	4.4208e+17	4.938e-06	7.931e+00	3.500e+02	9.787e-01	1.311e-01
2.0739e+01	1.8224e+01	223.03	5.9182e+17	4.753e-06	7.208e+00	3.500e+02	1.071e+00	1.570e-01
2.7380e+01	2.4059e+01	220.52	7.9023e+17	4.567e-06	6.060e+00	3.500e+02	1.148e+00	1.791e-01
3.6147e+01	3.1764e+01	218.05	1.0551e+18	4.380e-06	4.655e+00	3.500e+02	1.227e+00	2.012e-01
4.7721e+01	4.1934e+01	215.49	1.4095e+18	4.252e-06	3.431e+00	3.500e+02	1.308e+00	2.225e-01
6.3001e+01	5.5361e+01	212.86	1.8837e+18	4.002e-06	2.413e+00	3.500e+02	1.397e+00	2.452e-01
8.3173e+01	7.3087e+01	210.08	2.5198e+18	3.863e-06	1.460e+00	3.500e+02	1.494e+00	2.697e-01
9.5566e+01	8.9369e+01	208.47	3.1050e+18	4.281e-06	9.616e-01	3.500e+02	1.558e+00	2.852e-01
1.0981e+02	1.0269e+02	207.19	3.5897e+18	4.613e-06	5.663e-01	3.500e+02	1.609e+00	2.974e-01
1.2617e+02	1.1799e+02	208.58	4.0972e+18	9.726e-06	4.570e-01	3.500e+02	1.614e+00	2.992e-01
1.4496e+02	1.3557e+02	210.18	4.6716e+18	1.560e-05	3.315e-01	3.500e+02	1.619e+00	3.011e-01
1.6656e+02	1.5576e+02	212.01	5.3212e+18	2.235e-05	1.872e-01	3.500e+02	1.626e+00	3.034e-01
1.9138e+02	1.7897e+02	215.51	6.0149e+18	4.976e-05	1.627e-01	3.500e+02	1.630e+00	3.040e-01
2.1990e+02	2.0564e+02	219.53	6.7846e+18	8.125e-05	1.346e-01	3.500e+02	1.634e+00	3.047e-01
2.5266e+02	2.3628e+02	224.15	7.6349e+18	1.174e-04	1.022e-01	3.500e+02	1.638e+00	3.054e-01
2.9030e+02	2.7148e+02	229.15	8.5809e+18	2.668e-04	9.072e-02	3.500e+02	1.642e+00	3.058e-01
3.3356e+02	3.1193e+02	234.89	9.6185e+18	4.385e-04	7.750e-02	3.500e+02	1.647e+00	3.062e-01
3.8326e+02	3.5841e+02	241.49	1.0750e+19	6.358e-04	6.231e-02	3.500e+02	1.652e+00	3.066e-01
4.4036e+02	4.1181e+02	247.78	1.2038e+19	1.161e-03	5.429e-02	3.500e+02	1.657e+00	3.069e-01
5.0597e+02	4.7316e+02	255.01	1.3439e+19	1.765e-03	4.508e-02	3.500e+02	1.662e+00	3.072e-01
5.8136e+02	5.4366e+02	261.64	1.5050e+19	2.744e-03	3.788e-02	3.500e+02	1.668e+00	3.074e-01
6.6798e+02	6.2467e+02	268.10	1.6876e+19	4.148e-03	3.174e-02	3.500e+02	1.675e+00	3.076e-01
7.6751e+02	7.1774e+02	273.74	1.8991e+19	6.332e-03	2.767e-02	3.500e+02	1.682e+00	3.077e-01
8.8187e+02	8.2469e+02	279.58	2.1365e+19	8.931e-03	2.435e-02	3.500e+02	1.690e+00	3.079e-01
1.0133e+03	9.4758e+02	286.06	2.3992e+19	1.195e-02	2.102e-02	3.500e+02	1.698e+00	3.080e-01

TABLE 2. COMPARISON OF PURE CH₄ FORCING IN MLSCS MODEL

Author	Radiative Forcing (W/m ²) ($\Delta\text{CH}_4 = 1.72\text{--}3.44$ ppmv)
Ramanathan et al. (1987)	1.78
Shine (1993)	1.89
This Paper	1.67

TABLE 3. COMPARISON OF CH₄ + OTHERS FORCING IN MLSCS MODEL

Author	Radiative Forcing (W/m ²) ($\Delta\text{CH}_4 = 1.72\text{--}3.44$ ppmv)
IPCC (1990)	0.529
Shine (1993)	0.852
This Paper	0.718

TABLE 4. COMPARISON OF CH₄ + OTHERS FORCING IN MLSCS MODEL

Author	Radiative Forcing (W/m ²) ($\Delta\text{CH}_4 = 0.00\text{--}1.72$ ppmv)
IPCC (1990)	1.33
Ramaswamy (1993)	2.02
This Paper	1.69

TABLE 5. COMPARISON OF CH₄ + OTHERS FORCING IN GLAV MODEL

Author	Radiative Forcing (W/m ²) (Δ CH ₄ = 1.65–3.30 ppmv)
IPCC (1990)	0.519
This paper (with clouds)	0.521
This paper (clear sky)	0.647
Ramanathan et. al. (1987)	0.550

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