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New estimates of radiative forcing due to well mixed greenhouse gases

Gunnar Myhre

Department of Geophysics, University of Oslo, Norway

Eleanor J. Highwood and Keith P. Shine

Department of Meteorology, University of Reading, UK

Frode Stordal

Norwegian Institute for Air Research (NILU), Norway

Abstract. We have performed new calculations of the radiative forcing due to changes in the concentrations of the most important well mixed greenhouse gases (WMGG) since pre-industrial time. Three radiative transfer models are used. The radiative forcing due to CO_2, including shortwave absorption, is 15% lower than the previous IPCC estimate. The radiative forcing due to all the WMGG is calculated to 2.25 Wm^{-2}, which we estimate to be accurate to within about 5%. The importance of the CFCs is increased by about 20% relative to the total effect of all WMGG compared to previous estimates. We present updates to simple forcing-concentration relationships previously used by IPCC.

1. Introduction

The radiative forcing due to changes in the well-mixed greenhouse gases (WMGG) from pre-industrial times to the present day has been estimated to be 2.45 Wm^{-2}, carbon dioxide being the major contributor (64% of total) [*IPCC*, 1995]. However, several studies have since shown a lower radiative forcing due to CO_2 than the *IPCC* [1995] estimate [*Cess et al.*, 1993; *Pinnock et al.*, 1995; *Myhre and Stordal*, 1997; *Mitchell and Johns*, 1997]. Recent calculations also show a higher radiative forcing due to most of the halocarbons compared to *IPCC* [1995][*Pinnock et al.*, 1995; *Hansen et al.*, 1997a; *Myhre and Stordal*, 1997; *Christidis et al.*, 1997]. *IPCC* [1994] commented that some recent studies [e.g. *Shi and Fan*, 1992; *Lelieveld et al.*, 1993] indicated that the radiative forcing due to CH_4 could be as much as 20% higher than the *IPCC* [1990; 1995] estimate.

Radiative forcing is a valuable first order estimate for comparing the influence of different radiatively active components on the Earths' radiation balance, assuming that the stratospheric temperatures are allowed to adjust to the radiative perturbation [*Hansen et al.*, 1997a]. Previous estimates of radiative forcing [*IPCC*, 1995] have not necessarily been based on consistent model conditions.

This work presents new calculations of radiative forcing due to the most important WMGG, using a consistent set of models and assumptions. Three radiative transfer schemes are used, a line-by-line (LBL) model, a narrow-band model (NBM) and a broad band model (BBM). *IPCC* [1990] presented simplified expressions relating the radiative forcing to the change in concentration and initial concentration of the WMGG. The coefficients of the simplified expressions must also be reviewed when discrepancies arise between the IPCC estimates of radiative forcing and more recent calculations. New coefficients are suggested based on the new model results. Only the direct forcing due to a change in WMGG concentration is considered here.

2. Models and Methods

The LBL model [*Edwards*, 1992] is used to calculate optical depths and radiative fluxes are calculated as in the work of *Myhre and Stordal* [1997]. The NBM is the $10cm^{-1}$ narrow band radiative transfer scheme of *Shine* [1991]. In this study, the scheme is used with spectral band data from HITRAN-1996 except for CFC-11, which uses the average cross-section from *Christidis et al.* [1997] and CFC-12, which is from HITRAN-92. The BBM includes about 50 bands among all the trace gases of importance for modelling of the terrestrial radiation. This model is also described in *Myhre and Stordal* [1997]. The LBL model and the BBM use spectroscopic data for the halocarbons from the HITRAN-96 database, and for the other WMGG as in *Myhre and Stordal* [1997].

In this study, radiative forcing is calculated as the difference between irradiances in the pre-industrial and present day atmosphere due to change in the concentrations of WMGG as described in *IPCC* [1995]. The full definition of radiative forcing includes stratospheric temperature adjustment [*IPCC*, 1995]. However, radiative forcing prior to this adjustment is often used in

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the intercomparison of radiation schemes since it is less computationally expensive. We refer to these forcings as "adjusted" and "instantaneous" respectively.

Myhre and Stordal [1997] and *Freckleton et al.* [1998] have shown that for global radiative forcing calculations, it is not sufficient to use a single vertical profile. *Freckleton et al.* [1998] have shown that three vertical profiles (a tropical profile and northern and southern hemisphere extratropical profiles) can represent global calculations sufficiently. These profiles are used for all calculations in this study, except for the adjusted BBM forcing calculations where a horizontal resolution of 10° in longitudinal and latitudinal directions and the same meteorological input data as in *Myhre and Stordal* [1997] are used.

3. Comparison of the radiative transfer schemes

Table 1 shows the instantaneous clear sky radiative forcing due to changes in the concentrations of several WMGG calculated using the three models. For CO_2 the agreement between all three models is very good. For the other WMGG, the BBM and the LBL model differ by at most 7.7%, which is the deviation for CF_4. The agreement between the NBM and LBL schemes is also good, to within about 6%, except for CH_4, where the disagreement is 12%. The NBM is most accurate for the weak-line limit and the strong-line limit; however for the present atmospheric abundance of CH_4 the absorption lies between these two limits. As mentioned earlier, several other models report a higher forcing for CH_4, consistent with the NBM; we suggest that this cluster of high forcings may be due to the problem of narrow band models in this absorption regime as identified by *Ramanathan et al.* [1987]. There is similar problem for N_2O, but the overestimation is smaller as the abundance of N_2O is closer to the weak-line limit. The integrated band strength of CFC-12 used in the NBM (HITRAN-92) is 8% lower than in the LBL and the BBM. This is also reflected in the forcing because of the almost linear relationship between radiative forcing and band strength for the halocarbons. In total, the agreement between the three models is well within 10%, except for CH_4.

Table 1. Global-Mean Instantaneous Clear Sky Radiative Forcing (in Wm^{-2}) Due to Changes in the Mixing Ratios of Several Greenhouse Gases from Pre-Industrial to Present Conditions

	LBL	NBM	BBM
CO_2	1.759	1.790 (1.8)	1.800 (2.3)
CH_4	0.625	0.702 (12.4)	0.651 (4.2)
N_2O	0.150	0.160 (6.1)	0.154 (2.6)
CFC-11	0.0886	0.0911 (2.8)	0.0871 (-1.7)
CFC-12	0.204	0.196 (-3.7)	0.211 (3.6)
CFC-13	0.0014		0.0014 (-1.6)
CFC-113	0.0338		0.0328 (-3.0)
CFC-114	0.0078		0.0082 (5.1)
CFC-115	0.0023		0.0024 (4.6)
HCFC-22	0.0230		0.0241 (4.8)
CCl_4	0.0223		0.0235 (5.4)
CF_4	0.0071		0.0077 (7.7)
SF_6	0.0021		0.0022 (1.4)

Relative differences, in %, for the NBM and BBM results relative to the LBL results. The mixing ratios of the WMGG are taken from *IPCC* [1995] and are assumed to be constant throughout the atmosphere.

Table 2. Global-Mean Adjusted Cloudy Sky Radiative Forcing (in Wm^{-2})

	NBM	NBM altered	BBM
CO_2	1.370	1.313 (-4.2)	1.322 (0.7)
CH_4	0.578	0.578 (-0.1)	0.500 (-13.5)
N_2O	0.134	0.130 (-2.5)	0.119 (-8.7)
CFC-11	0.0757	0.0692 (-8.6)	0.0646 (-6.6)
CFC-12	0.164	0.171 (4.3)	0.162 (-5.3)
CFC-13			0.0011
CFC-113			0.0249
CFC-114			0.0063
CFC-115			0.0018
HCFC-22			0.0186
CCl_4			0.0173
CH_3CCl_3			0.0070
CF_4			0.0067
C_2F_6			0.0008
SF_6			0.0016
TOT			2.247

Changes in the concentrations of the WMGG are as in Table 1. NBM altered and BBM results include stratospheric decay of the WMGG.

The 'altered NBM' has been adjusted for the effects of solar absorption by CO_2, decay of the gases in the stratosphere, CFC-12 absorption band strength from HITRAN-96, based on results from the BBM. Relative differences, in %, are given for the altered NBM results relative to the NBM results and for the BBM results relative to the NBM altered results.

4. Updated radiative forcings

Table 2 shows the adjusted cloudy radiative forcing calculated for the NBM and the BBM. The BBM takes into account the decay in concentration of some of these gases with height in the stratosphere, while the NBM considers constant profiles of the WMGG. The BBM also includes solar absorption by CO_2, yielding 4% lower forcing than the NBM. The longwave components for both models are almost identical. The absorption of solar radiation in the troposphere yields a positive radiative forcing at the tropopause. This effect is however weak due to overlap with water vapour and a high reference concentration of CO_2. The absorption in the stratosphere therefore dominates, leading to a shortwave forcing of -0.11 Wm^{-2}, about the same or somewhat larger than the average of GCM calculations in *Cess et al.* [1993]. However the shortwave absorption due to CO_2 reduces the longwave cooling of the strato-

sphere significantly, and therefore increases the longwave radiative flux from the stratosphere to the troposphere, contributing a positive forcing of 0.05 Wm^{-2}. The net forcing due to inclusion of solar absorption by CO_2 is -0.06 Wm^{-2}.

For CH_4, N_2O, CFC-11, and CFC-12 clouds reduce the forcing by 5-7% more in the BBM than in the NBM. The high clouds in the BBM are more black than those in the NBM and therefore have a greater effect on the forcing. CO_2 is less affected by clouds than the other WMGG [*Myhre and Stordal*, 1997]. The effect of stratospheric temperature adjustment differs by less than 2% between the two models. Investigations using the BBM demonstrated that inclusion of decay in the stratosphere decreases the forcing for N_2O, CFC-11, and CFC-12 by 3%, 9%, and 4%, respectively. When this difference in profiles between the NBM and BBM and the difference in band strength for CFC-12 discussed previously is taken into account (the "altered" NBM column in Table 2), the two models agree to better than 10%, except for CH_4.

The radiative forcing for several WMGG now shows considerable differences from the previous *IPCC* [1995] estimates. For CO_2, the IPCC estimate is 18% higher than the BBM value and 14% higher than the NBM value. The IPCC estimate did not include solar absorption by CO_2 nor did it include the effect of stratospheric adjustment. In a recent GCM study, *Mitchell and Johns* [1997] have reported an adjusted forcing which is close to our value. In some studies, the non-CO_2 WMGG are represented by an amount of CO_2, estimated by scaling the ratio of the radiative forcing to the forcing by CO_2. The findings of this study imply that the impact of these gases have been underestimated if *IPCC* [1995] values of radiative forcing are used for the scaling. In the case of N_2O, the radiative forcing is 4% and 18% higher in IPCC compared to the NBM and BBM respectively. The BBM values for CH_4 are within 5% of the IPCC estimate while the NBM values are 18% higher. For most of the halocarbons a forcing higher than that in *IPCC* [1995] has been calculated, this effect being particularly pronounced for CFC-11 and CFC-12. As a result, the relative importance of the halocarbons compared to the other WMGG is increased here. The total radiative forcing due to WMGG calculated with the BBM is 2.25 Wm^{-2}, 0.2 Wm^{-2} and 0.2-0.3 Wm^{-2} lower than the IPCC estimate and *Hansen et al.* [1997b], respectively. We estimate an uncertainty in the forcing of about 5% based on the difference between the NBM and BBM adjusted forcings and the BBM and LBL instantaneous forcings. The uncertainty in the forcing due to individual gases is higher, of order 10%.

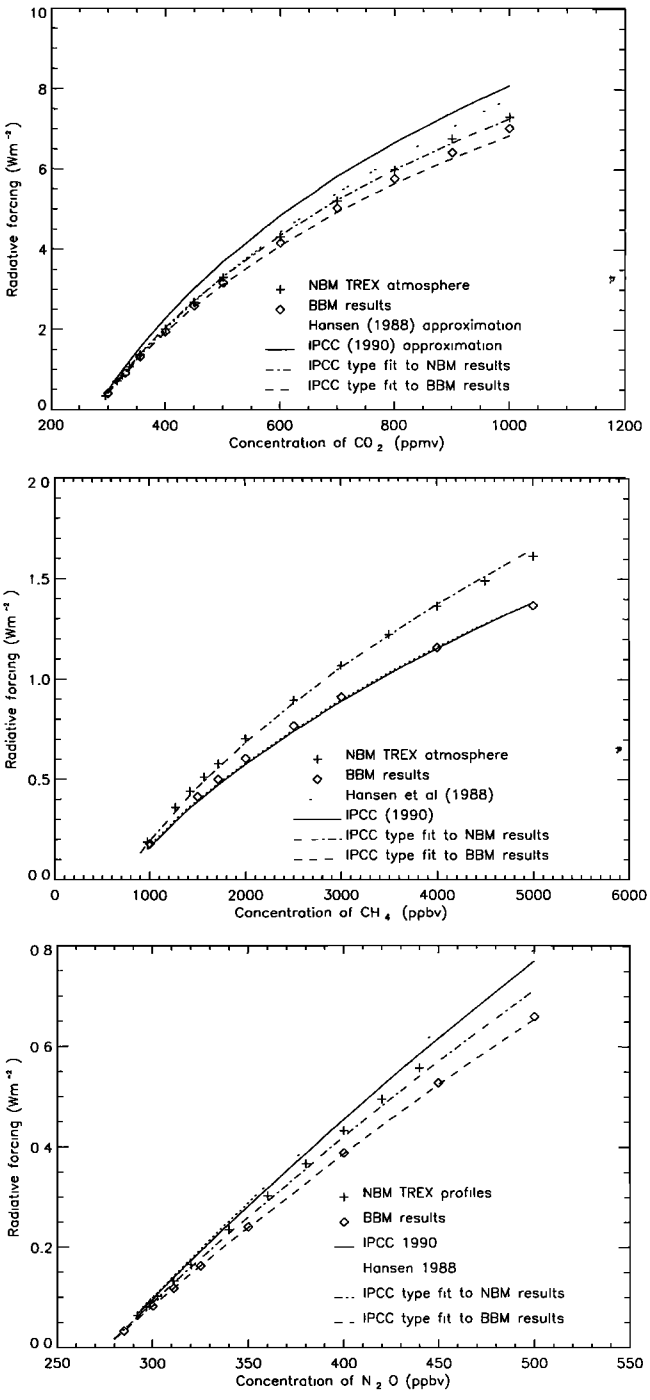

Figure 1. Radiative forcing as a function of concentration for CO_2, CH_4, and N_2O, from the NBM, BBM, *Hansen et al.* [1988], *IPCC* [1990], and using expression from *IPCC* [1990] and new constants derived from calculations for the NBM and BBM.

5. Simplified expressions

The differences between our model results and the expressions from IPCC and *Hansen et al.* [1988] for CO_2, N_2O, and CH_4 are illustrated for a wide range of concentrations in Figure 1. This figure also shows results based on the IPCC expressions calculated with new coefficients derived from the two models. The IPCC expressions and coefficients are shown in Table 3. It is an overall good agreement between the NBM and BBM calculations and the IPCC expressions with new coefficients for CO_2, CH_4, and N_2O, with poorest agreement for large concentrations of the three WMGG. Based on the NBM and BBM calculations as well as the LBL calculations our best estimates for new coefficients to the

Table 3. Simplified expressions used in *IPCC* [1990] (Table 2.2)

Trace gas	Simplied expression Radiative forcing, ΔF, Wm^{-2}	Constants α IPCC	Best estimate this work[a]
CO_2	$\Delta F=\alpha \ln(C/C_0)$	6.3	5.35
CH_4	$\Delta F=\alpha (\sqrt{M}-\sqrt{M_0})-(f(M,N_0)-f(M_0,N_0))$	0.036	0.036
N_2O	$\Delta F=\alpha (\sqrt{N}-\sqrt{N_0})-(f(M_0,N)-f(M_0,N_0))$	0.14	0.12
CFC-11[b]	$\Delta F=\alpha (X-X_0)$	0.22	0.25
CFC-12	$\Delta F=\alpha (X-X_0)$	0.28	0.33

$f(M,N)=0.47 \ln[1+2.01\times10^{-5}(MN)^{0.75}+5.31\times10^{-15}M(MN)^{1.52}]$
C is CO_2 in ppmv
M is CH_4 in ppbv
N is N_2O in ppbv
X is CFC in ppbv
The subscript 0 denotes the unperturbed concentration.
[a]Based on the NBM and BBM results the uncertainties associated with the constants are assumed to be 1% for CO_2, 10% for CH_4, 5% for N_2O and CFC-11, and 3% for CFC-12.
[b]The same expression is used for all CFCs, but with different values for α.

IPCC expressions are shown in Table 3. For CO_2 we have chosen the coefficients based on the BBM calculations, which is lower than the one derived from the NBM, due to inclusion of solar absorption by CO_2 only in the BBM.

6. Summary

Three radiative transfer models are used to estimate the radiative forcing due to the WMGG. The radiative forcing due to CO_2 is found to be about 15% lower than the IPCC estimate. On the other hand the radiative forcing due to the CFCs are higher than the IPCC estimates, especially for CFC-11 and CFC-12 (between 10% and 25% higher and somewhat model dependent). IPCC has used simplified expressions for the radiative forcing of the WMGG. We recommend new constants for these expressions resulting from our calculations which treat all the components in a consistent way. We suggest an explanation for the range of forcings found for CH_4 in other studies.

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G. Myhre, Department of Geophysics, University of Oslo, P.O. Box 1022 Blindern, 0315 Oslo, Norway. (e-mail: Gunnar.Myhre@geofysikk.uio.no)

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