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RADIATIVE FORCING BY WELL-MIXED GREENHOUSE GASES: ESTIMATES FROM GCMS IN THE IPCC AR4

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1. INTRODUCTION

The radiative effect of well-mixed greenhouse gases (WMGHGs) is probably the most significant anthropogenic forcing of the climate system. The most comprehensive tools for simulating past and future climates influenced by WMGHGs are fully coupled atmosphere-ocean general circulation models (GCMs). Because of the importance of WMGHGs as forcing agents, it is essential that GCMs compute the radiative forcing by these gases as accurately as possible. We present the results of an intercomparison between the forcings computed by GCMs and by benchmark line-by-line (LBL) radiative transfer codes. The comparison is focused on forcing by CO_2, CH_4, N_2O, CFC-11, CFC-12, and the increased H_2O expected in warmer climates. The models participating in the intercomparison include representatives from many of the modeling groups participating in the IPCC 4th Assessment Report (AR4) and from a number of the principal groups developing LBL codes. The results indicate that there are still substantial discrepancies between GCMs and LBL models for forcings by CH_4, N_2O, and CO_2. We quantify these differences and discuss the implications for interpreting variations in forcing and response across the multi-model ensemble of GCM simulations assembled for the IPCC AR4.

2. DESCRIPTION

We have asked modeling groups to participate in an intercomparison of the radiative forcings due to specified changes in radiatively active species. The goals of this exercise are to facilitate the comparison of GCMs included in the IPCC AR4 and to establish new benchmark calculations for this purpose. The chief objective is to determine the differences in forcing caused by the use of different radiation codes in the GCMs used for IPCC climate change simulations.

For this first exercise, we are primarily concerned with quantifying the differences in forcing calculated among various codes. Based upon the experience from previous intercomparisons, we recognize that our list of experiments is not sufficient for detailed causal attribution of the differences.

The types of species to be evaluated are well-mixed gases. We have collected calculations from two types of radiative transfer models: the parameterizations used in GCMs, and line-by-line (LBL) models. We have solicited participation from the global modeling groups in WGCM participating in IPCC and from a number of LBL modelers.

For the purposes of this initial intercomparison, we are examining just the instantaneous changes in clear-sky fluxes. While the relevant quantity for climate change is all-sky forcing, the introduction of clouds would greatly complicate the initial intercomparison exercise. In addition, we have requested that the calculations omit the effects of stratospheric thermal adjustment to forcing using Fixed Dynamical Heating (FDH). This omission will facilitate comparison of fluxes from LBL codes and GCM parameterizations, and it will exclude discrepancies arising from differences in dynamical heating rates from various GCMs. Therefore, for the purposes of this exercise we have defined “flux” to mean “flux for clear-sky conditions” and “forcing” to mean “instantaneous changes in fluxes without stratospheric adjustment”.

In order to establish a common baseline, we have specified the background atmospheric state for all the experiments using a thermodynamic profile for present-day conditions. The AFGL midlatitude summer atmospheric profile (MLS) has been used in all the calculations. We have provided versions of the MLS profile at low and high vertical resolution for the GCM and LBL calculations, respectively. Unless otherwise specified, all experiments use the same vertical profiles of temperature T and ozone mass-mixing ratio. The specific humidity is also the same for all but one experiment.

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2.1 *Fields calculated for the intercomparison*

The sets of calculations we collected cover several scenarios:

1. Forcing for CO_2 change (experiments 1 and 2);
    a. Present – preindustrial
    b. 2xCO_2 - 1xCO_2
2. Forcing for changes in major well-mixed GHGs (present – preindustrial; experiment 3); and
3. The effect of water vapor changes on the forcing by CO_2 (experiment 4).

The calculations from each participating group include:

1. Net shortwave and longwave clear-sky flux at the top of the model;
2. Net shortwave and longwave clear-sky flux at 200 mb (a surrogate for the tropopause);
3. Net shortwave and longwave clear-sky flux at the surface; and (optionally)
4. Net shortwave and longwave clear-sky fluxes at each layer interface in the MLS profile.

In addition, we have asked each GCM group to document their radiative transfer codes using a standard protocol. We have used Q. Fu's survey of radiation schemes used in GCMs for this purpose. Results from this survey were presented at the IAMAS meeting and the Gordon Conference on "Shortwave Radiation and Climate" in 2003.

The LBL groups have been invited to submit their calculations of spectrally resolved fluxes corresponding to the basic products. The LBL groups have been asked to use spectral ranges of 100 to 2500 cm^{-1} for the longwave and 2000 to 57600 cm^{-1} for the shortwave. The GCM groups have been asked to use the standard spectral ranges for their respective radiative parameterizations.

For all the shortwave calculations, the boundary conditions are:

1. A Lambertian surface with a spectrally flat albedo = 0.1
2. Solar zenith angle = 53 degrees
3. Total input insolation = 1360 Wm^{-2}

For all the longwave calculations, the surface is assumed to have a spectrally flat emissivity equal to 1.

2.2 *Specification for the experiments*

1. Pre-industrial for CO_2:
    a. Constant volume mixing ratio for CO_2 = 287 ppmv (1860 value)
    Note: Please do not include effects from other radiatively active species, except for molecular Rayleigh scattering and absorption by the default H_2O and O_3.
2. Present-day and doubled CO_2
    a. Repeat (1a), except CO_2 = 369 ppmv (2000 value).
    b. Repeat (1a), except CO_2 = 574 ppmv (2xCO_2, i.e., 2x preindustrial value).
3. Well-mixed GHGs
    a. Repeat (1a), but with additional well-mixed gases at pre-industrial values:
        i. CH_4 = 806 ppbv
        ii. N_2O = 275 ppbv
        iii. CFC11 = 0 pptv
        iv. CFC12 = 0 pptv
    b. Repeat (2a), but with additional well-mixed gases at Year 2000 values:
        i. CH_4 = 1760 ppbv
        ii. N_2O = 316 ppbv
        iii. CFC11 = 267 pptv
        iv. CFC12 = 535 pptv
    c. Repeat (2a), but with CH_4 at Year 2000 values:
        i. CH_4 = 1760 ppbv
        ii. N_2O = 275 ppbv
        iii. CFC11 = 0 pptv
        iv. CFC12 = 0 pptv
    d. Repeat (2a), but with N_2O at Year 2000 values:
        i. CH_4 = 806ppbv
        ii. N_2O = 316 ppbv
        iii. CFC11 = 0 pptv
        iv. CFC12 = 0 pptv

4. CO_2 feedback experiment
    a. Repeat (2b), but increase the water vapor mixing ratios by 20%. This is a rough approximation to the expected increase in H_2O under higher atmospheric CO_2 conditions.

3. RESULTS

None of the GCMs exhibit sign errors in forcings for the WMGHGs. A few of the participating GCMs still omit the effects of CFCs on the longwave, and the majority omit the effect of CH_4 in the shortwave. Perhaps the most surprising finding is a substantial systematic bias in GCM estimates of CO_2 forcing at the surface. In the mean, GCMs underestimate the CO_2 longwave surface forcing relative to LBL calculations by approximately 40% (relative). The RMS spread in the GCM forcings is 66% (relative). The spread in the corresponding GCM estimates of CO_2 shortwave surface forcing is close to 90% (relative). These findings indicate a substantial divergence in forcings for the most important anthropogenic greenhouse gas.

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