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Global warming, caused by an increase in the concentrations of greenhouse gases, is the direct result of greenhouse gas–induced radiative forcing. When a doubling of atmospheric carbon dioxide is considered, this forcing differed substantially among 15 atmospheric general circulation models. Although there are several potential causes, the largest contributor was the carbon dioxide radiation parameterizations of the models.

The most comprehensive way to estimate climate change caused by increasing concentrations of greenhouse gases is to use three-dimensional general circulation models (GCMs). But even for the most straightforward climate-change simulation, a change in equilibrium climate that results from a doubling of atmospheric CO_2, there is a roughly threefold variation in the predicted increase in global mean surface temperature (*1*, *2*) (Fig. 1). Global climate change caused by a CO_2 doubling may be conceptually interpreted as a two-stage process: forcing and response. The forcing is the direct radiative perturbation caused by the CO_2 increase, whereas the response is the climate change associated with restoring the global-mean radiation balance. Climate feedback mechanisms that govern the response differ substantially among GCMs (*3–7*), but it is not known to what extent differences in Fig. 1 are attributable to variations in forcing among models. In an earlier comparison (*8*), significant differences were found in CO_2 radiative forcing from radiation codes used in several GCMs.

Potential forcing differences attributable to other facets of the GCMs were not, however, addressed. These included:

1) Forcing is dependent on lapse rate, which is the decrease of atmospheric temperature with height. Because CO_2 forcing is a change in the greenhouse effect, it could be affected by differences in lapse rate among models (*9*).

2) The forcing is substantially reduced through radiative overlap of the CO_2 absorption bands by the absorption of water vapor (*8*), so differences in atmospheric water vapor distributions among models could likewise affect CO_2 forcing, as well as differences in the parameterization of radiative overlap in the radiation codes.

3) Clouds also reduce the forcing (*10*), so the substantial differences among different GCMs' cloud fields (*6*) could cause forcing differences.

In this study we specifically address these

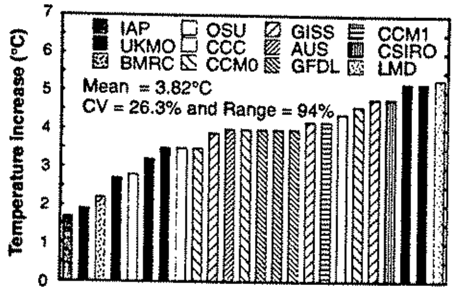

Fig. 1. Summary of the increase in global mean equilibrium surface temperature caused by a doubling of atmospheric CO_2 concentrations. These results are from simulations with atmospheric GCMs with a seasonal cycle, a mixed layer ocean, and interactive clouds. Multiple simulations were performed for several models in the context of sensitivity studies related to specific processes. Changes in cloud parameterizations for the United Kingdom Meteorological Office GCM produced the greatest differences (*3, 4*). This figure is taken from table 3.2(a) of (*1*) and table B2 of (*2*), and the model acronyms are those used in these two references. The coefficient of variation (CV) is the standard deviation divided by the mean.

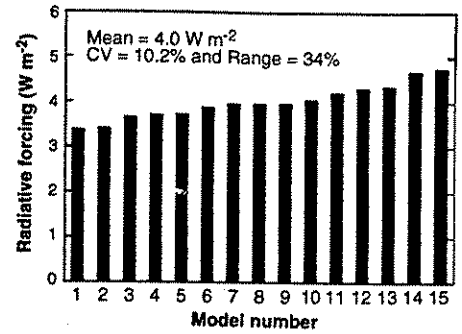

Fig. 2. Summary of global mean CO_2 radiative forcing for the 15 GCMs used in the current study.

issues so as to better understand the differences shown in Fig. 1.

We can define CO_2 forcing as the reduction in net upward radiative flux at the tropopause (top of the troposphere) caused by the CO_2 increase, with all other climate parameters held fixed. It is thus the direct radiative heating of the surface-troposphere system, which acts as a single thermodynamic system because the surface and troposphere are convectively coupled (*10*). We have adopted a global mean tropopause at 200 mbar. The CO_2 mixing ratio was increased from 330 to 660 parts per million (ppm) by volume, and we evaluated the forcing by performing a second radiation computation, for 660 ppm of CO_2, during the control climate (330 ppm of CO_2) averaging period. The 660-ppm radiation calculation was performed at the same times as the 330-ppm calculation, with the forcing comprising the 200-mbar radiative flux difference between the two calculations (*11, 12*). To evaluate the impact of clouds, clear-sky forcing was evaluated by Method II (*13*), by which clear-sky fluxes are computed at each grid point.

The GCM results (identified by number, Table 1) are from two perpetual July runs similar to those used earlier (*5, 6*). In the first, the sea-surface temperature was set 2°C below the typical 15 July values and in the second 2°C above; we report only the cold run results. The results show that the range and coefficient of variation (CV) of net forcing, the sum of the LW (longwave; terrestrial thermal radiation) and SW (shortwave; solar radiation) contributions, are substantial (Fig. 2) and could account for more than one-third of the differences among the models (Fig. 1), although Figs. 1 and 2 refer to different sets of GCMs.

Although near-infrared bands of CO_2 absorb SW radiation and thus heat the atmospheric column, this heating occurs mostly in the stratosphere; thus, less SW radiation reaches the tropopause, and the SW forcing is negative. On average, this reduced the forcing by 4.7%, whereas, if the models that do not include SW forcing were deleted (models 9, 11, and 15), the reduction would be 6.0%. Because of this small magnitude, SW forcing is a minor contributor to model-to-model differences in net forcing (Table 2).

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Table 1. List of GCMs used in the present study.

Model	Investigator
1. European Centre for Medium-Range Weather Forecasts (ECMWF)	Potter, Morcrette, Gates
2. Laboratoire de Météorologie Dynamique (LMD)	Le Treut and Li
3. National Center for Atmospheric Research (NCAR) Community Climate Model, Version 2 (CCM2)	Zhang, Cess, Kiehl, Hack
4. ECMWF, Max Planck Institute for Meteorology, Hamburg (ECHAM)	Roeckner and Esch
5. Main Geophysical Observatory (MGO)	Meleshko, Sokolov, Sporyshev
6. State University of New York; Institute for Atmospheric Physics, Beijing (SUNY/IAP)	Liang and Wang
7. Canadian Climate Centre (CCC)	Barker
8. United Kingdom Meteorological Office (UKMO)	Ingram
9. NCAR Community Climate Model, Version 1; Lawrence Livermore National Laboratory (CCM/LLNL)	Taylor
10. Bureau of Meteorology Research Centre (BMRC)	McAvaney, Fraser, Colman
11. Colorado State University (CSU)	Randall and Dazlich
12. NASA Goddard Institute for Space Studies (GISS)	Lacis and Del Genio
13. Geophysical Fluid Dynamics Laboratory (GFDL)	Wetherald
14. Centre National de Recherches Météorologiques (CNRM)	Mahfouf and Royer
15. Department of Numerical Mathematics of the Russian Academy of Sciences (DNM)	Galin

Radiative overlap by water vapor is often regarded as a major source of uncertainty (8). To isolate differences caused by this factor, we modified the radiation codes for all GCMs except model 14 so as to remove overlap. The LW clear (with clouds removed) forcings with and without overlap are correlated (Fig. 3A) and show that variations about the linear fit are the actual contributions by water vapor overlap to forcing differences; the standard deviation (SD) of this residual is only 0.12 W m^{-2}. This small SD includes model-to-model differences in both humidity profiles and the way overlap is parameterized in the radiation codes.

To further isolate differences caused by model-to-model variations in humidity profiles and lapse rates, we inserted humidity profiles and lapse rates for a standard mid-latitude summer atmosphere (8) into column (one-dimensional) versions of the GCM radiation codes. As shown in Fig. 3B, these were not significant sources of differences because the column model calculations adopt a single humidity profile and lapse rate. We confirmed this result by inserting global mean humidity profiles and lapse rates for the GCMs into the CCM2 column radiation code. The LW clear forcings computed in this manner were in remarkable agreement; SD = 0.03 W m^{-2} without overlap and 0.06 W m^{-2} with overlap. The implied invariance with vertical resolution is consistent with the results of a related sensitivity study in which vertical resolution was varied in the CCM2 column radiation code while the humidity profile and lapse rate were kept fixed. Although inclusion of clouds reduced the LW forcing by an average 14% and there are substantial differences among the GCMs' cloud fields (6), clouds were not a major cause of LW forcing differences (Fig. 3C).

The largest single cause of forcing differences was model-to-model differences in the LW radiation codes for CO_2 (Table 2). Earlier GCM comparisons (5–7) considered climate change feedback mechanisms for which there are no standards for comparison. For CO_2 forcing, however, line-by-line (LBL) calculations of LW clear forcing are available as standards of comparison (8). Deviations of the GCM column model forcings from the LBL results, both with and without water-vapor overlap, are large for many models (Fig. 4A), particularly those that predict low forcings. Although results for model 14 (which was not included in Fig. 3A because "without water vapor overlap" GCM forcing was not available) agreed well with the LBL results when water vapor overlap was included, there was substantial disagreement in the forcing without water vapor overlap. Here, overly strong overlap compensated for a positive forcing bias produced by this model's CO_2 radiation code.

The tendency for models to underestimate LW clear forcing (Fig. 4A) is partly a result of the neglect of certain CO_2 absorption bands. This gas has a dominant 15-μm band complex, but also has absorption bands at 10.4, 9.4, and 4.3 μm. None of the models incorporated the 4.3-μm band; the 10.4- and 9.4-μm bands are included in models 1, 2, 5, 7, 11, and 13 but not in the other models. A fairer test (although not a test of reality) of the radiation codes is to delete those bands in the LBL calculation that are not included in the respective GCM radiation codes. This did reduce the tendency of the models to underestimate the forcing (Fig. 4B). Models 1 and 2 share the same LW radiation code.

The models in Fig. 1 produced an average global warming close to 4°C, whereas the models in our study produced an average CO_2 forcing of 4.0 W m^{-2}, so this amounts to an average climate sensitivity of 1°C of warming for each 1 W m^{-2} of forcing. Now imagine 15 GCMs, all with the same climate sensitivity, a 1°C warming per 1 W m^{-2} forcing, but CO_2 forcing varying like the 15 GCMs in this study. They would give global warming projections ranging from 3.4° to 4.7°C just because of their forcing differences (Fig. 2). This range is substantial and is nearly half of the often quoted range of uncertainty of 1.5° to 4.5°C (1, 14), which has been based on feedback uncertainties assuming no differences in the forcing.

Ideally one would like to use these results to isolate differences in Fig. 1 that are attributable to forcing differences. But the perpetual July forcings may not be representative of annual mean forcings. Nor is the present set of GCMs the same as in Fig. 1, for which the forcings would have to refer to the same averaging period as used for the doubled CO_2 climate simulations. The inclusion of forcing values would be reasonably straightforward to accomplish when the simulations are performed (12), and future studies should provide CO_2 forcing values as a routine diagnostic.

Table 2. Summary of standard deviation (SD) and range for individual processes contributing to differences in CO_2 radiative forcing.

Process	SD (W m^{-2})	Range (W m^{-2})
CO_2 SW radiation*	0.08	0.32
Water-vapor overlap†	0.12	0.41
Temperature and humidity profile differences†	0.11	0.37
Clouds (LW)†	0.16	0.58
CO_2 LW radiation	0.62	2.12

*Refers only to those models that include SW forcing. †Computed as the residual (see Fig. 3).

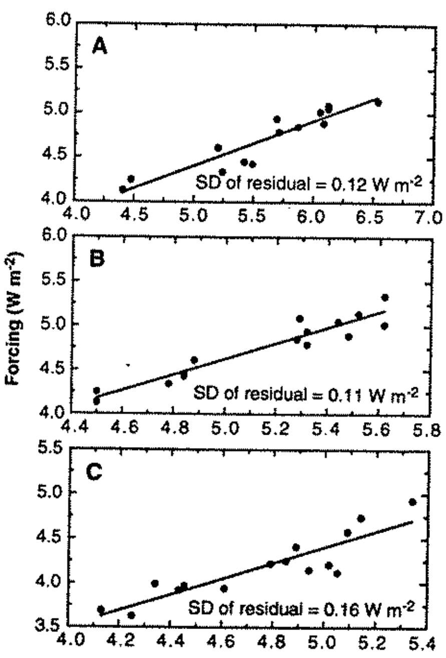

Fig. 3. **(A)** Scatter plot of LW clear (clear sky) radiative forcing, as generated by the GCMs, with and without overlap of the CO_2 absorption bands by water vapor absorption. **(B)** Scatter plot of LW clear forcing as generated by the GCMs versus those generated by their respective column models using the standard mid-latitude summer atmosphere. **(C)** Scatter plot of LW cloudy (all sky) forcing versus LW clear forcing as generated by the GCMs. In (A) through (C) the solid line represents a linear root-mean-square fit.

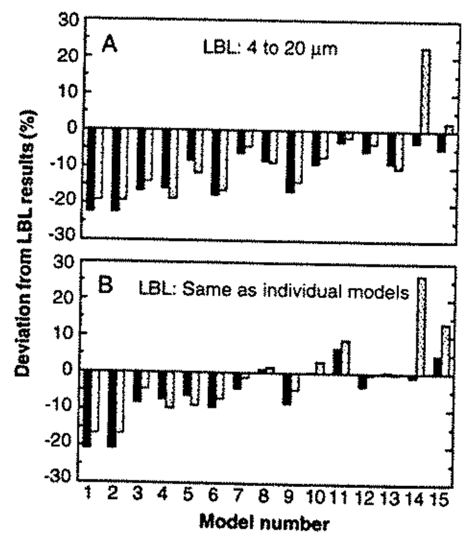

Fig. 4. **(A)** Percent deviation of the GCM LW column model tropopause forcings from reference LBL results for mid-latitude summer temperature and humidity profiles (8). The LBL values are 5.80 W m^{-2} with water vapor overlap (solid bars) and 6.90 W m^{-2} without (stippled bars). **(B)** The same as (A) but with CO_2 bands removed in the LBL calculation so as to represent those included in the GCMs (see text). With the 4.3-μm band removed, the LBL values are 5.68 W m^{-2} with water vapor overlap and 6.69 W m^{-2} without. With additional removal of the 9.4- and 10.4-μm bands, these respective values are 5.27 and 6.21 W m^{-2}.

Because the global mean temperature increase is linearly proportional to the CO_2 forcing, a figure similar to Fig. 1 but showing the ratio of the temperature increase to the CO_2 forcing would be far more informative because this normalized temperature increase would remove forcing differences and so isolate differences caused by feedback processes (*12*).

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