Reducing uncertainties in climate models

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Radiative forcing is a fundamental quantity for understanding both anthropogenic and natural changes in climate. It measures the extent to which human activities [such as the emission of carbon dioxide (CO_2), see the image] and natural events (such as volcanic eruptions) perturb the flow of energy into and out of the climate system. This perturbation initiates all other changes of the climate in response to external forcings. Inconsistencies in the calculation of radiative forcing by CO_2 introduce uncertainties in model projections of climate change, a problem that has persisted for more than two decades. The explicit calculation of radiative forcing and a careful vetting of radiative transfer parameterizations provide a straightforward means to substantially reduce these uncertainties and improve the projections.

CO_2 is the main forcing agent in both 20th- and 21st-century emission scenarios (*1*). Twenty-five years ago, Cess *et al.* provided the first comprehensive assessment of the calculation of radiative forcing by CO_2 in global climate models (GCMs) (*2*). They found that when CO_2 was doubled, the radiative forcing differed substantially among 15 different GCMs, ranging from ~3.3 to 4.7 W/m_2(see the graph; see the supplementary materials for further details). This spread mainly arose from intermodel differences in the parameterization of infrared absorption by CO_2. Other sources of differences, such as the parameterization of overlapping absorption by water vapor or differences in the cloud distributions, were shown to be small.

Thirteen years later, Collins *et al.* conducted a more extensive intercomparison of radiative forcing, using a newer generation of more than 20 different GCMs (*3*). They found a similar range in radiative forcing at the top of the atmosphere for a doubling of CO_2 (see the graph), which again was largely due to spread in the infrared component of CO_2 absorption. The authors also compared the radiative forcing computed using line-by-line (LBL) calculations; the latter solve the equation of radiative transfer for each absorption line individually, rather than parameterizing their absorption over spectrally integrated bands. The forcing calculations between several different LBL models were in much better agreement (see the graph). The LBL calculations have also been extensively validated by using both laboratory and field measurements (*4*), and the spectroscopic foundation for this radiative forcing is quite robust (*5*). The agreement among LBL models forms the basis for the narrow uncertainty range for CO_2 forcing noted in the

Intergovernmental Panel on Climate Change (IPCC) reports (*1*). However, LBL calculations are computationally expensive, and parameterized models of radiative transfer must be used in GCMs. Unfortunately, substantial differences still exist in these parameterizations. Chung and Soden found that the spread in CO_2forcing from the most recent generation of GCMs remains largely unchanged compared with that documented in previous generations (see the graph) (*6*).

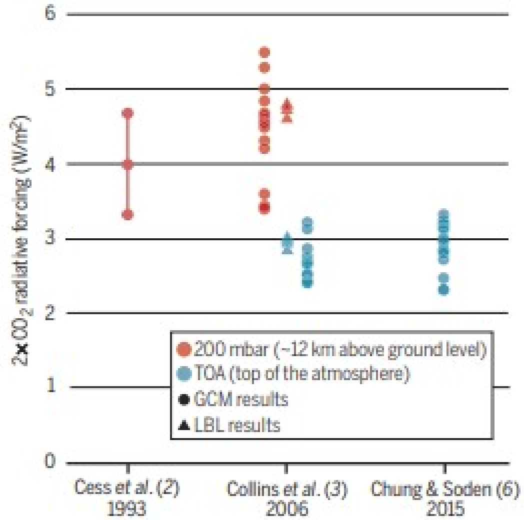
The precise measure of radiative forcing differs slightly between these three studies (*7*). As a result, their absolute values of radiative forcing are not directly comparable. However, the relative spread in radiative forcing between models is meaningful and has shown little change compared with the true uncertainty in radiative transfer, as represented by the spread in the LBL calculations.

This lack of progress over the past 25 years is disconcerting. The spread in model calculations of CO_2 forcing does not represent an uncertainty in radiative transfer theory, but rather the failure to implement that theory consistently in radiative transfer parameterizations. This introduces unnecessary noise into the model experiments that is difficult to remove. Although the users of these models are largely unaware of this ongoing problem, the unsatisfactory implementation of CO_2 forcing propagates needlessly onto efforts to reduce uncertainty in projections of future climate change.

As noted by Cess *et al.*, the impact of this inconsistency in the calculations of radiative forcing on estimates of climate sensitivity “is nearly half of the often quoted range of uncertainty of 1.5° to 4.5°C.” Thus, even if we could make all other aspects of the models perfect, the spread in projections of CO_2-induced climate change would only be reduced by 50% because of the remaining differences in radiative forcing.

Reducing the uncertainty

Radiative forcing uncertainty in GCMs has remained high over the past 25 years. LBL calculations show that this uncertainty can be substantially reduced.



The contributions of erroneous CO_2 forcing to the persistent spread in climate projections undermines the utility of these models to answer fundamental questions of central societal importance. These errors add unnecessary confusion to the development of scientifically rigorous targets for atmospheric CO_2 concentrations—and therefore, emissions reductions—that are required to limit global temperature change. Constraining global warming to less than 2°C, as set by the Paris Climate Agreement, requires a limit to be set on the maximum globally averaged CO_2concentration compatible with that constraint. This limit should be established by a multimodel ensemble, but the corresponding range of allowable CO_2 concentrations is unnecessarily large because the ensemble does not consistently incorporate known and established physics that relate rising CO_2 concentrations to radiative forcing.

Although some efforts are under way to better document these differences (*8*), there are two immediate solutions that could help. First, it is essential that radiative forcing be routinely computed and reported for models that participate in Coupled Model Intercomparison Projects (CMIP), a series of coordinated experiments performed in support of the IPCC assessments. For each experiment, model simulations are performed by using matching emission scenarios, with the intent of imposing identical forcings. However, radiative forcing is rarely reported explicitly by these models. Requiring models to do so for all emission scenarios would help to ensure transparency between the radiative forcing experienced by the models and the climate response that results. Cess *et al.* made a similar recommendation 25 years ago (*2*). The adoption of this recommendation is long overdue.

Second, the diversity of radiative transfer parameterizations used in GCMs should be reduced. Maintaining diversity in models is valuable for areas where there is substantial uncertainty in the underlying physics. For most aspects of radiative transfer of relevance to climate change, this is not the case. An effort to consolidate the number of radiative transfer parameterizations used and to implement only those that have been thoroughly vetted against LBL calculations would significantly reduce the spread in model projections. It would also reduce discrepancies in the parameterization of other key absorbers, such as water vapor, that also affect model calculations of climate sensitivity. Last, it would enable those researchers who focus on less well-known forcing agents and their radiative interactions to have a readily available, radiometrically accurate understanding of the direct radiative influence of the quantities they are measuring, and the processes they are studying, on Earth's climate system.

References and Notes

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