Final report for DE-SC0012549
Collaborative Research: Centralized Activities in Support of the Radiative Forcing Model Intercomparison Project

Developing a protocol for understanding effective radiative forcing in CMIP6

The sixth iteration of the Coupled Model Intercomparison Project (CMIP6), now underway, will collect simulations from global modeling centers around the world to address a wide range of questions related to climate variability, extremes, and change. CMIP6 is organized around three questions. The first questions if "How does the Earth system respond to forcing?," suggests that forcing is always well-known but this is not the case: radiative forcing has historically been uncertain in coordinated experiments even as understanding of how best to infer radiative forcing has evolved. The Radiative Forcing Model Intercomparison Project (RFMIP) endorsed by CMIP6 provides a foundation for answering the question. RFMIP consists of three related activities:

(i) Integrations with specified sea-surface temperatures to provide accurate characterization of the effective radiative forcing (ERF, meaning the instantaneous radiative perturbation and any adjustments in atmospheric state not related to global-mean warming) relative to a near-preindustrial baseline. This includes CMIP6 experiments in the RFMIP-ERF group.
(ii) Assessment of the absolute accuracy of clear-sky radiative transfer parameterizations against reference models on the global scales relevant for climate modeling, including distinct efforts to assess errors in treatments of greenhouse gases and aerosols. In CMIP6 parlance these are the RFMIP-IRF-GHG and RFMIP-IRF-Aer experiments.
(iii) Detection-and-attribution experiments using tightly specified anthropogenic aerosol radiative forcing from 1850 to present to identify robust model responses to time-evolving aerosol forcing: the RFMIP-SpAer experiments.

The US Department of Energy's Regional and Global Climate Modeling program supported much of the initial development of the RFMIP protocol. Funding from 2015-2017, extended at no cost through 2018, supported the following activities.

Project-wide:

- Coordination with modeling centers. This included encouraging participation in RFMIP by modeling centers, establishing points of contact, and setting up mailing lists for news dissemination and sharing of experiences and concerns. As centers begin simulations we are beginning to see interactions and shared problem-solving.
- Coordination with CMIP. This involved identifying links between specific sets of CMIP and RFMIP experiments, ensuring compatible protocols, advocating for CMIP panel endorsement of RFMIP, communicating RFMIP progress to the CMIP panel, and providing feedback as forcing datasets were constructed
- Coordination with other satellite MIPs associated with CMIP6. RFMIP is closely linked to the Cloud Feedbacks MIP through a shared concern with adjustments, especially of clouds to aerosol; to AerChemMIP with which we share diagnostic protocols and an interest in quantifying the effective radiative forcing for a range of agents; and to the Detection and Attribution MIP, with whom we have carefully matched protocols and experiments in order to leverage D+A methodologies to identify the robust singles of aerosols on circulation and temperature changes.

- Coordination with the non-CMIP Precipitation Driver and Response MIP. Results from PDRMIP informed the specification of RFMIP experiments, particularly the use of “fixed-SST” experiments for diagnosing effective radiative forcing.
- Participation in workshops. RFMIP coordinators have participated in most annual CFMIP meetings where we have ben able to inform analyses of cloud adjustments and feedbacks. In June 2018 RFMIP held its first post-initiation workshop together with AerChemMIP and PDRMIP. This joint workshop was quite useful in highlighting how analyses, techniques, and perspectives from past activities might inform analysis of RFMIP simulations, and in coordinating community plans for analysis.
- Community engagement. The coordinators of RFMIP speak frequently in public venues and use these opportunities to introduce issues related to radiative forcing.

RFMIP-ERF:

- Experimental specification. The careful diagnosis of ERF for each model and each experiment is potentially the most broadly useful element of RFMIP. The final choice of experiments (180 years of atmosphere-only simulations for Tier 1 experiments to determine present-day ERF for a range of agents, plus 1800 years of atmosphere-only for diagnosing time-evolving ERF for a narrower range of agents at Tier 2) represents a careful balance between relatively light requests to encourage participation and a comprehensive enough request to inform analyses of model response.
- Protocol development. Results from PDRMIP along with custom integrations provided a basis for deciding how many years of simulation were required to establish representative sea-surface temperature fields and to estimate regional-mean ERF to 5% accuracy from integrations using these fields. The protocol also had to be clarified to work equally well regardless of whether models predict ozone interactively.

RFMIP-IRF-GHG:

- Experimental specification. Developing the RFMIP protocol required balancing the desires of the radiative transfer communities, which seek detailed information about the causes of parameterization error, with the needs of the climate community represented by CMIP. The final protocol contains 17 perturbations focused on assessing errors in a focused set of circumstances (aggregate forcing at present-day, in future, and at the Last Glacial Maximum; carbon dioxide forcing over a wide range; sensitivities to temperature and water vapor amount).
- Protocol specification. RFMIP-IRF-GHG seeks to assess the accuracy of radiative parameterizations in reproducing annual-mean, global-mean radiative forcing but brute-force benchmark calculations are prohibitively expensive. RFMIP adopted a novel sampling approach in which a small number of optimally-chosen columns (100 in the final protocol) are used to represent the global, annual mean with very small sampling error.
- Community engagement. RFMIP has successfully solicited reference clear-sky calculations from four groups with independent line-by-line models. The reference models agree quite well, strengthening the argument that deviations from benchmarks represent true error. This activity also requires the most custom effort on the part of modeling centers who have had to be encouraged to participate.
- Engagement with technical community. The Earth System Grid which distributes results for CMIP and related activities has strict standards for data formats and metadata. These standards aid interoperability but are not designed for data which does not arise directly from simulations by global models. Developing formats for forcing data sets and results

and establishing identities for radiative transfer models independent of climate models has consumed an enormous amount of time.

RFMIP-IRF-Aer:

- Experimental specification, particularly the choice of a small number of days throughout the historical period chosen to expose errors over a wide range of condition.
- Protocol specification. This included the compact specification of the new variables required to characterize spectrally-dependent aerosol optical properties completely enough to enable benchmark calculations of clear-sky aerosol radiative effect.
- Community engagement. Variables requested for CMIP follow the “CF” conventions so introducing new variables required negotiating extensive metadata for most of these variables.

The work took place at five institutions:

- The University of Colorado provided overall coordination with the broader CMIP community and developed the RFMIP-IRF-GHG protocol
- The University of Leeds, in consultation with a wide community of modelers and diagnosticians, developed the protocol for RFMIP-ERF
- Atmospheric and Environmental Research, Inc. supported the development of the RFMIP-IRF-GHG protocol and provided a set of reference line-by-line calculations that will enable assessment of parameterization accuracy
- Lawerence Berkeley Lab helped develop the RFMIP-IRF-Aer protocol and provided tools and calculations to support this activity along with RFMIP-IRF-GHG
- NOAA’s Geophysical Fluid Dynamics Lab, using DOE funds to leverage substantial internal investments, contributed to the development of the RFMIP-IRF-Aer protocol and the tool chains required to assess each model. They also provided line-by-line model results for RFMIP-IRF-GHG.

The results of these efforts were published in four papers:

Jones, A. L. et al., 2017: A new paradigm for diagnosing contributions to model aerosol forcing error. *Geophys. Res. Lett*. **44**, 12004–12012, doi:10.1002/2017GL075933

Forster, P. M. et al., 2016: Recommendations for diagnosing effective radiative forcing from climate models for CMIP6. *J. Geophys. Res. - Atmos*., **121**, 12460-12475, doi: 10.1002/2016JD025320.

Pincus, R., P. M. Forster, and B. Stevens, 2016: The Radiative Forcing Model Intercomparison Project (RFMIP): experimental protocol for CMIP6. *Geosci. Model Dev.,* **9**, 3447-3460, doi: 10.5194/gmd-9-3447-2016.

Pincus, R. et al., 2015: Radiative flux and forcing parameterization error in clear, clean skies. *Geophys. Res. Lett*., **42**, 5485–5492, doi:10.1002/2015GL064291.

The RFMIP-SpAer is coordinated by Bjorn Stevens and Stephanie Fiedler at the Max Planck Institute for Meteorology in Hamburg. These efforts and the resulting publications are supported by the MPI and so not discussed here beyond efforts needed to coordinate those experiments with CMIP and DAMIP.

Funding to the University of Colorado also resulted in three publications not directly related to the specification of RFMIP:

Marvel, K., R. Pincus, G. Schmidt, and R. L Miller, 2018: Internal variability and disequilibrium confound estimates of climate sensitivity from observations. *Geophys. Res. Lett*. **45**, 1595–1601, doi:10.1002/2017GL076468

Mauritsen, T. and R. Pincus, 2017: Committed warming inferred from observations. *Nature Clim. Change*, **7**, 652-655, doi:10.1038/nclimate3357.

Voigt, A. et al., 2017: Fast and slow shifts of the zonal-mean intertropical convergence zone in response to an idealized anthropogenic aerosol. *J. Adv. Modeling Earth Sys*., **9**, 870-892, doi:10.1002/2016MS000902.