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The Radiative Forcing Model Intercomparison Project (RFMIP): Experimental Protocol for CMIP6

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Abstract. The phrasing of the first of three questions motivating CMIP6 – "How does the Earth system respond to forcing?" – suggests that forcing is always well-known, but in fact forcing has historically been uncertain even in coordinated experiments such as CMIP. The Radiative Forcing Model Intercomparison Project endorsed by CMIP6 seeks to provide a foundation for answering the question for forcing and response through three related activities: (i) accurate characterization of the effective radiative forcing relative to a near pre-industrial baseline, and careful diagnosis of the components of this forcing; (ii) assessment of the absolute accuracy of clear-sky radiative transfer parameterizations against reference models on the global scales relevant for climate modeling; and (iii) identification of robust model responses to a tightly-specified aerosol radiative forcing from 1850 to present.

Complete characterization of effective radiative forcing can be accomplished with 180 years (Tier 1) of atmosphere-only simulation using a sea-surface temperature and sea ice concentration climatology derived from the host model's pre-industrial control simulation. Assessment of parameterization error requires trivial amounts of computation but the development of small amounts of infrastructure: new, spectrally-detailed diagnostic output requested as two snapshots at present-day and preindustrial conditions, and results from the model's radiation code applied to specified atmospheric conditions. The search for robust responses to aerosol changes rely on the CMIP6 specification of anthropogenic aerosol properties; models using this specification can contribute to RFMIP with no additional simulation, while those using a full aerosol model are requested to perform at least one, and up to four, 165-year coupled ocean-atmosphere simulations at Tier 1.

1 Evolving understanding of radiative forcing

Perturbations to the chemical or physical state of the climate system, including those caused by anthropogenic activities, can induce a *radiative forcing*: roughly, a change in the net radiation balance at the top of the atmosphere. Projections of future changes involve estimating the magnitude of future forcing and the strength of climate system's response to that forcing. If the system's response can be adequately described by a single temperature T (normally the global-mean surface temperature) then radiative forcing F is related to the top-of-atmosphere energy imbalance N (or equivalently, global ocean heat uptake) and the temperature change ΔT as

$$F = N + \alpha \Delta T \tag{1}$$

where the constant of proportionality between temperature and radiative response α is the climate feedback parameter.

Much attention has been paid to the diversity of responses to applied forcings across climate models, especially those participating in coordinated experiments such as including previous phases of the Coupled Model Intercomparison Project (CMIP, see e.g. Taylor et al., 2012). This diversity is normally interpreted as variability in climate feedback arising from different model formulations. Indeed such thinking underlies the question "How does the Earth system respond to forcing?," one of the central questions motivating the sixth phase of the CMIP (CMIP6; see Eyring et al., 2015). The formulation of this question presumes that the forcing to which the earth system, or a model representation of the system, is subject is well-known and/or precisely determined by the experimental protocol. But this is not true in practice: models participating in exercises like CMIP are subject to surprisingly large differences in forcing (Andrews et al., 2012; Forster et al., 2013) even when the perturbations applied to the physical system are the same. Observational estimates of the forcing to which the Earth itself has been subject (e.g. Skeie et al., 2011) are also relatively uncertain. Even the concept of radiative forcing continues to evolve (Sherwood et al., 2015) in a search for informative measures and precise methods for diagnosis. To answer questions about how the earth system responds to forcing it is first necessary both to understand the nature of forcing and to quantify the forcing experienced by different models.

Some diversity in forcing arises because individual models can produce a range of radiative changes for the same physical perturbation. Specifying atmospheric composition changes, as has been common in previous phases of CMIP, does not uniquely determine even the instantaneous change in radiative fluxes at the top of the atmosphere (the so-called "instantaneous radiative forcing" or IRF, in the langague of Myhre et al. (2013), but more precisely a flux perturbation IRP). This is partly because extinction by gases depends on the distributions of temperature and humidity, which vary across models, partly because computationally-efficient parameterizations for radiative transfer will differ to varying degrees with respect to reference models. This non-uniqueness is most relevant to forcing by greenhouse gases, changes in which are responsible for the largest radiative forcing since pre-industrial times (Myhre et al., 2013).

Diversity also arises because models may make different choices with respect to important but uncertain or loosely-specified physical perturbations, especially aerosols (Shindell et al., 2013) which, after greenhouse gases, are thought to be responsible for the second largest source of anthropogenic radiative perturbations. In the previous phase of CMIP diversity in aerosol IRP was larger than that due to greenhouses gases even as the signal is $\sim$3 times smaller (e.g. Myhre et al., 2013, Fig. 8.16).

Equation 1 is a diagnostic framework, and experience in using (1) to interpret the response of comprehensive models of the climate system suggests that instantaneous radiative perturbation is not, in practice, related very closely to changes in surface temperature, a point highlighted by Hansen et al. (1997) but well-known for even longer. Far more useful in Eq. 1 is the *effective radiative forcing* (ERF) that accounts for the model's base climate state, including factors such as the masking of the clear atmosphere by clouds, as well as *adjustments*, the component of climate response that does not depend on surface temperature (Sherwood et al., 2015). Many such adjustments, for example the reduction in oceanic subtropical boundary layer cloudiness due to increased downwelling longwave from increased CO_2, occur much more rapidly than the time scale for warming (e.g. Kamae and Watanabe, 2013) leading to the terminology "rapid adjustments." The accurate diagnosis of ERF requires custom model integrations, either using linear regression to diagnose F and α (assumed constant) in Equation 1 from temporal variations in N and ΔT following abruptly-applied forcing (Gregory et al., 2004), or by approximately suppressing ΔT by fixing sea surface temperatures and inferring forcing from N following Hansen et al. (2005). Unlike the instantaneous radiative perturbation arising from a composition change ERF depends on the fullness of the model response so its calculation is no longer an exercise in pure radiative transfer.

Better estimates of effective radiative forcing will refine understanding of how the earth system responds to forcing, but the potentially knotty relationships between forcing and response suggest value in subjecting models to ERFs that are as similar as possible. In signal processing it is common, when looking for a signal amidst a noisy background, to reduce the noise as close to the source as possible. In the context of ERF the largest source of variability is the treatment of atmospheric aerosol. RFMIP therefore includes coupled atmosphere-ocean simulations in which aerosol radiative forcing over the historical period is prescribed as much as possible, by analogy to protocols in which greenhouse gas concentrations over time are similarly specified. This is not to diminish the true uncertainty in historical concentration of anthropogenic aerosols but to ascertain what model responses robustly arise from a plausible historical aerosol forcing.

The Radiative Forcing Model Intercomparision Project, RFMIP, seeks to provide a foundation for answering one of the guiding question of CMIP6, namely "how does the earth system respond to forcing?" This will be accomplished by

1. accurately characterizing the effective radiative forcing relative to a near pre-industrial baseline, and understanding the components of this forcing,

2. assessing the absolute accuracy of clear-sky radiative transfer parameterizations on the global scales relevant for climate modeling, and

3. identifying robust responses of comprehensive models to a specified aerosol radiative forcing over the period of instrumental measurements, i.e., 1850 to present.

This paper describes each of these efforts in greater detail, including the contributions requested from participating modeling centers, reference calculations to be undertaken as part of RFMIP, and planned analyses. The simulations are summarized in tables in Appendix A.

2 Diagnosing effective radiative forcing

The concept of radiative forcing has evolved over time, as can be seen by comparing the discussions in Hansen et al. (1997) with those in Sherwood et al. (2015), which we follow here. Partly for this reason, and partly because the climate system response was considered the largest unknown, previous iterations of CMIP have emphasized model response without careful characterization of effective radiative forcing. This omission has made it challenging to understand how much diversity in model response arises purely from different feedbacks. In the previous phase of CMIP, for example, models exhibited a wide

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range of global-mean temperature changes over the Historical period (1860-2005 for CMIP5). These models were driven by the same concentration changes, but for the reasons described above the same concentration time-series applied to different models led to different temporal evolutions of ERF including rapid adjustments (Forster et al., 2013). It remains largely unknown how much of the diversity in CMIP3 and CMIP5 Historical simulations was due to forcing differences among models, and how much due to feedback differences.

Limited understanding of ERF has severely hampered progress in key areas of physical climate science, including: understanding historical temporal and spatial variations in climate feedbacks (Armour et al., 2013; Rose et al., 2014; Andrews et al., 2015); attribution of aerosol and greenhouse gas signals from the historic record (Bindoff et al., 2013); diagnosis of equilibrium climate sensitivity from observed energy budget changes (Masters, 2013; Otto et al., 2013); diagnosing transient climate response from historic trends (Gregory and Forster, 2008; Storelvmo et al., 2016); understanding the causes of global and regional precipitation trends (Richardson et al., 2016); and our understanding of decadal variations in surface temperature, including the recent "hiatus" in surface warming (Marotzke and Forster, 2015; Fyfe et al., 2016).

RFMIP will diagnose model ERF by suppressing response, i.e. specifying sea surface temperatures and sea ice concentrations (Hansen et al., 2005). The "fixed-SST" method has important advantages compared to regressions of top-of-atmosphere imbalance against surface temperature change (Gregory et al., 2004). The first is better error characteristics (Forster et al.): thirty years of simulation using only the atmospheric and land components of an earth system model can diagnose global ERF to better than 0.1 $\mathrm{W/m^2}$ standard error, such that a $2\times CO_2$ forcing of 3.7 $\mathrm{W/m^2}$ is larger than its standard error over 70% of the globe. Achieving similarly small errors from regression requires ensembles of coupled model integrations and therefore many centuries of simulation. Using fixed SSTs also allows model groups to diagnose transient ERF while regressions are suitable only for diagnosing forcing from abrupt changes. Transient forcings are of particular interest in Historical simulations.

2.1 Protocol: Effective radiative forcing

The protocol for RFMIP fixed-SST integrations is to use a monthly-averaged model-specific climatology of SST and sea-ice based on the model's preindustrial DECK integration (Eyring et al., 2015). Applying a climatology limits variability and improves the diagnoses of small ERF differences; because ERF is weakly dependent on background state (Forster et al.) this choice has little impact on the forcing estimate. We also hope that a simple approach will encourage model centers to participate without compromising accuracy.

Time-slice simulations (Table 1), in which forcing agents are held constant at present-day or $4\times CO_2$ values, provide estimates of present-day and $4\times CO_2$ ERF. Present-day estimates provide a direct comparison between the estimates of ERF in the model with other estimates e.g. in assessment reports (Myhre et al., 2013). Estimate of ERF will also let us understand basic aspects of each model's temperature and other climate responses in the Historical and $4\times CO_2$ DECK simulations.

Transient simulations (Table 2) in which forcing agent concentrations evolve over time are designed to give a complete picture of the CMIP6 Historical transient ERF and possible future radiative forcing. The future scenario (SSP2.4.5) matches experimental protocols requested by the Decadal Climate Prediction Project (DCPP; see manuscript under discussion at https://dx.doi.org/10.5194/gmd-2016-78) and the Detection and Attribution Model Intercomparison Project (DAMIP; see manuscript

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under discussion at https://dx.doi.org/10.5194/gmd-2016-74). The full forcing history from these simulations will give a much better understanding of decadal variability in the models and will aid attribution studies.

We urge all centers to participate in "RFMIP-light" by performing the Tier 1 simulations in Table 1 even if they participate in no other aspect of RFMIP. Knowing the present-day and 4×CO_2 ERF will enable modeling centers to understand why their DECK and Historical simulations differ from those performed by other models. Having all modeling centers perform these is important to understand outliers in the multi-model ensemble, allowing us to probe if outliers are caused by forcing-related or feedback-related processes. Further, the transient simulations in Table 2 are important for understanding model decadal variability and transient variations in climate feedbacks. This will benefit both decadal projections and attribution.

2.2 Planned analyses: Effective radiative forcing

Global and regional effective radiative forcing will be diagnosed for each model participating in RFMIP by differencing top-of-atmosphere radiative fluxes from the experiment with those from the preindustrial control simulation. RFMIP will characterize present day, historical and future ERF for the main radiative forcing groups (all anthropogenic changes; greenhouse gas changes, and aerosol and ozone changes, see Tables 1 and 2). Aerosol and ozone changes are investigated together to allow participation from both concentration-driven and emission-driven models, as emissions of NOx, for example, can drive both ozone and aerosol changes. The complimentary Aerosols Chemistry Model Intercomparison Project (AerChemMIP, reference to come) ERF simulations adopt the same methodology as RFMIP and allow us to further decompose present day forcing into a larger set of individual components.

Regional patterns of ERF will be compared across the models. This will aid the understanding of regional differences in climate response including an investigation of spatial variation in climate feedbacks.

The rapid adjustment component of effective radiative forcing will also be investigated. Rapid adjustments associated with aerosol-cloud-interaction are the major contributor to the negative aerosol ERF, and quantifying these effects has been a focus of much previous work (Boucher et al., 2013). Rapid adjustments are also likely important for many forcings including CO_2 (Sherwood et al., 2015). RFMIP requests joint histograms of cloud optical thickness and cloud top pressure from the "ISCCP simulator" (Klein and Jakob, 1999; Webb et al., 2001), part of the CFMIP Observation Simulator Package (Bodas-Salcedo et al., 2011) providing specialized diagnostics for the Cloud Feedback Model Intercomparison Project (CFMIP, see manuscript under discussion at https://dx.doi.org/10.5194/gmd-2016-70). These will be used to estimate rapid adjustments by clouds using radiative kernels (Zelinka et al., 2012, 2014) that map changes in cloud properties into top-of-atmosphere radiative flux perturbations. Where these diagnostics are not available the approximate partial radiative perturbation methodology of Taylor et al. (2007) will be applied to clear and all-sky components of shortwave (SW) radiative fluxes, to estimate the rapid adjustments due to cloud changes. Non-cloud radiative kernels (Soden et al., 2008) will also be applied to standard diagnostics of water vapor and temperature to estimate instantaneous radiative perturbations as well as stratospheric and tropospheric adjustments (Zhang and Huang, 2014; Chung and Soden, 2015).

These analyses will comprehensively characterize ERF in the each model participating in RFMIP. Radiative kernel diagnostics will enable us to go beyond a simple forcing estimate towards understand rapid adjustment processes. We will test

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the kernel approach by comparing IRP estimated from the kernel method with the best estimate of IRP from the line-by-line radiative transfer modes according to the experimental design outlined in Section 3.

3 Assessing parameterization error in clear-sky radiative forcing

One of the causes for model diversity in effective radiative forcing for the same physical perturbation is error in radiative transfer parameterizations. This is somewhat surprising: radiative transfer is unique among the processes parameterized in atmospheric models because there is so little fundamental uncertainty. Line-by-line models can map atmospheric conditions and gas concentrations to extinction with very high accuracy and at very high spectral resolution. Transport algorithms, given enough computing resources, can compute fluxes to a precision limited primarily by uncertainty in inputs. But this deep knowledge is not completely represented in climate models. Parameterizations strike a practical compromise between accuracy and computational cost and might be expected to have some error even under the best of circumstances. More subtly, parameterizations require so much effort to develop and maintain that they can lag behind current spectroscopic knowledge. These errors have been apparent in previous assessments of radiative transfer parameterizations for both gaseous absorption (Ellingson and Fouquart, 1991; Collins et al., 2006; Oreopoulos et al., 2012; Pincus et al., 2015) and aerosols (Randles et al., 2013).

RFMIP will assess parameterization error in instantaneous radiative perturbations due to both greenhouse gases and due to aerosols. The assessments are independent and take somewhat different approaches but will both highlight global- and regional-mean errors.

Despite the important roles of clouds in modulating effective radiative forcing RFMIP focuses on parameterization error in cloud-free skies. This is partly because errors in clear skies are always present and may affect e.g. surface fluxes even when the top-of-atmosphere impact is masked by clouds, and partly because inter-model differences in the spatial and temporal distribution of cloud optical properties are likely to have a much larger impact on estimates of radiative forcing than are parameterization errors.

3.1 Protocol: Parameterization error

Assessments of radiative transfer parameterizations rely on computationally-expensive reference models. This has historically meant that only a few atmospheric conditions are considered, making it difficult to infer the error in global-mean forcing (Pincus et al., 2015) or the flux pairs which underlie forcing. The narrow range of conditions has also obscured important differences between parameterizations including the widely-varying sensitivity of shortwave absorption to water vapor that underlies much of the diversity in hydrologic sensitivity among climate models (Fildier and Collins, 2015; DeAngelis et al., 2015).

RFMIP is developing a compact sample of atmospheric conditions (profiles of pressure, temperature, humidity and other trace gas concentrations, surface properties, etc.) and perturbations around those conditions that, when weighted appropriately, can be used to estimate global-mean fluxes or the change in those fluxes from one of the perturbations. (Sampling approaches are common in remote sensing problems; see for example Garand et al., 2001). Present-day conditions are sampled from

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reanalysis. Some perturbed states (see Table 3) represent changes in conditions tied to CMIP DECK or Historical simulations. The more idealized perturbations described in Table 4 are aimed at exposing model errors with global impacts, especially in present-day forcing by specific greenhouse gases.

The sample is optimized to minimize the sampling error in present-day clear-sky, aerosol-free forcing by greenhouse gases (i.e. the difference in fluxes using present-day and pre-industrial gas concentrations). The sampling error, even with as few as 50 distinct conditions, is several orders of magnitude smaller than the forcing; forcing errors for other composition changes are larger but still small relative to the change in flux.

When finalized this set of conditions will be distributed on the Earth System Grid as a single file. Modeling centers are asked to compute fluxes using off-line versions of their radiative transfer parameterizations (or using any work flow that computes fluxes as the host model does using precisely the specified conditions). Results from one or more reference models will also be made available on the ESG, as discussed in the next section.

The assessment of aerosol instantaneous clear-sky (direct) radiative perturbations seeks to determine parameterization error "in the wild", i.e. under climatological conditions specific to each model. The effort is diagnostic: we request from modeling centers climate model estimates of clear-sky instantaneous radiative perturbations and the detailed optical properties necessary to reconstruct this estimate, including instantaneous four-dimensional fields of spectrally-resolved surface albedo aerosol extinction, single-scattering albedo, and asymmetry parameter on the models native atmospheric grid and using the native spectral discretization. The request is limited to solar radiation, and to a single day in the pre-industrial and present-day epoch taken from the model's CMIP6 Historical simulations. Participation involves no additional simulation but does require producing outputs new to CMIP that include a spectral dimension.

3.2 Planned analyses and supporting calculations: Parameterization error

For each calculation requested from modeling centers RFMIP will obtain matching calculations from one or more line-by-line reference radiative transfer models, allowing the accuracy of parameterization estimates of flux and forcing to be assessed. One set of such calculations will be performed with a version of the LBLRTM radiative transfer model (Clough et al., 2005) updated to reflect recent changes to the HITRAN spectroscopic database (Rothman et al., 2013). Many of the reference models participating in the intercomparison exercise described by Pincus et al. (2015) have indicated that they will also provide analogous results. Reference results will be provided for the specified atmospheric conditions used to characterize instantaneous radiative perturbations by greenhouse gases – of order 10000 profiles for all perturbations, depending on the final number of columns in the optimized sampling.

The diagnostic request for aerosol instantaneous radiative perturbation is substantially larger. Each model uses its own ambient atmospheric conditions, with order 65000 columns per times step for a 1 degree climate model. Eight 3-hourly time steps are requested for present-day and pre-industrial conditions. Reference calculations will be some combination of line-by-line modeling at reduced spectral resolution (though still much finer than in broad bands used in parameterizations) and subsets of columns sampled from each model to optimally represent present-day forcing by aerosols.

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4 Seeking robust signatures of aerosol radiative forcing

The simulations described in Section 3 are aimed at quantifying the degree to which parameterization error impacts estimates of effective radiative forcing – that is, the degree to which parameterization error increases model diversity when the physical perturbation is well-specified. Although RFMIP seeks to understand this error for anthropogenic aerosols it is clear that the vast majority of model diversity arises from different prescriptions of aerosol precursors and processes, the resulting distribution of anthropogenic aerosols. As a result the temporal and spatial distribution of ERF caused by anthropogenic aerosols varies widely, greatly hindering attempts to identify and explain robust responses to aerosol perturbations including how anthropogenic aerosols affected twentieth century climate.

While the 21st century is likely to be the century of carbon dioxide, the 20th century belonged to sulfate. Carslaw et al. (2013) estimate that the global optical depth of sulphate aerosols, the aerosol component thought to dominate the signal of ERF, increased three-fold through the first hundred years of industrialization. During the first three quarters of the twentieth century aerosol and precursor emissions were concentrated over the north Atlantic, stretching roughly from central Europe to central North America (Smith et al., 2011) – a region covering about a tenth of Earth's surface. Starting in the mid 1970's western European emissions of SO_2 reduced five-fold from their peak values around 1970 and North American emissions have been reduced by more than a factor of two (Smith et al., 2011), while emissions over South and East Asia increased four to five fold, so that anthropogenic SO_2 emissions remained roughly constant on the global scale. The short life-time of sulfate implies that regional changes in aerosol concentrations were commensurately larger.

One way to estimate the ERF from these changes to atmospheric composition is to calculate it directly from first principles i.e. from emissions information and chemical modeling. This approach is used increasingly frequently in earth system models but has so far led to wide disagreement in estimates of anthropogenic aerosol burden (Shindell et al., 2013) and aerosol ERF (cf Fig. 7.18 in Boucher et al., 2013). This diversity is unsurprising: understanding of aerosol chemistry and physics is far from complete, and the ability to implement existing understanding is limited both by poor understanding of past emissions of aerosol and their precursors (Carslaw et al., 2013) and by incomplete understanding of aerosol interactions with other components of the climate system, especially clouds and precipitation (Stevens and Feingold, 2009; Bony et al., 2015).

Thus, beyond agreement that temporal and spatial changes in aerosols have been large, there is little consensus as to how they influenced the twentieth century climate beyond reducing the temperature by some indeterminate amount. Yet the response of the climate system to historical emissions of aerosols might offer the best chance of bounding aerosol ERF (Stevens, 2015). The strong warming in the first half of the century, a period when CO_2 concentrations rose only modestly, is difficult to reconcile with understanding of natural variability and a purported large (less negative than $-1\ \mathrm{W/m^2}$) aerosol radiative forcing. This argument depends on the extent to which the climate response to a localized aerosol forcing is itself more localized than the response to a globally-distributed greenhouse gas forcing – if the northern hemisphere is subject to a net negative radiative forcing, but the global radiative forcing is slightly positive, is it reasonable to expect global warming that is northern-hemisphere amplified?

To answer these and similar questions it would be helpful to better understand how the climate system responds to a given aerosol perturbations in the presence of other physical perturbations. Tightly-constrained aerosol effective radiative forcing is far more likely to uncover robust relationships between aerosol perturbations and the climate repsonse when subjected to formal methods of detection and attribution (e.g., Stott et al., 2010) than the current tangle of widely variable physical perturbations and resulting responses.

The desire for a uniform, easily controlled and implemented representation of anthropogenic aerosol perturbations motivated the development of a semi-analytic representation of the distribution of anthropogenic aerosol-radiative and cloud-active properties over the full historical record. MACv2-SP (Stevens et al., 2016) specifies only the anthropogenic perturbation to the atmospheric aerosol and describes this perturbation directly and so does not interfere with the model development processes or tuning of the controlled coupled climate. The climatology prescribes the four dimensional distribution of anthropogenic aerosol radiative properties needed in two-stream radiative transfer calculations, i.e., the wavelength dependent aerosol optical depth, single-scattering albedo, and asymmetry factor. The influence of anthropogenic aerosol on clouds is specified as a multiplicative factor applied to the cloud droplet number concentrations used to calculate cloud droplet effective radius and hence cloud optical properties. Some models have experimented with representing a variety of more speculative aerosol-cloud interactions, for example increased cloudiness caused by changes to precipitation (Albrecht, 1989) that arise from aerosol perturbations. Given an increasing body of evidence (cf Christensen and Stephens, 2011; Boucher et al., 2013; Seifert et al., 2015; Haywood et al., 2016) calling these descriptions into question, MACv2-SP does not incorporate such effects.

4.1 Protocol: Specified aerosol forcing

Simulations using MACv2-SP to describe the anthropogenic perturbation to the control background over the historical period (1850-2015) form the basis for the Specified Aerosol (SpAer) component of RFMIP. The simulations, described fully below, repeat either DECK or other RFMIP simulations.

The recommendation for CMIP6 is that models using prescribed aerosol for the Historical simulations use the MACv2-SP specification (Eyring et al., 2015). (Ideally modeling centers will only use their own prescription of anthropogenic aerosols for participation in AerChemMIP.) Models using MACv2-SP to describe anthropogenic aerosols can participate in RFMIP-SpAer without additional effort by submitting the corresponding DECK or RFMIP simulation as part of RFMIP. Additional simulations beyond those needed to participate in CMIP6 or other components of RFMIP are only necessary if a modeling center *does not* adopt the MACv2-SP as their default aerosol prescription.

4.1.1 Tier 1 Simulation: SpAer-All

For this component of RFMIP only a single Tier 1 simulation,***SpAer-All***, is requested. This simulation replicates the CMIP6-Historical simulation but using the MACv2-SP aerosol (Stevens et al., 2016) as the description of the anthropogenic aerosol forcing for models which use other representations for the CMIP6-Historical submission. A single ensemble member is required, but if it is intended to use this simulation also for DAMIP an ensemble size of four members is required.

4.1.2 Tier 2 Simulations

Tier 2 simulations are designed to augment the analysis of the Tier 1 simulations by making them useful for detection and attribution and to improve the diagnosis of radiative forcing. They either replicate simulations requested within DAMIP or within the ERF component of RFMIP. Again, they arise as an additional experimental request only for models that chose not to use MACv2-SP for their default description of the anthropogenic aerosol forcing.

SpAer-aer: This simulation is analogous to the Tier 1 simulation, *SpAer-All*, except that the only time-varying forcing that is to be specified is that associated with the anthropogenic aerosol through the prescription of MACv2-SP. Volcanoes, solar variability and other non-aerosol forcings (both natural and anthropogenic) are to be omitted. Like *SpAer-All* it should use the full coupled (ocean-atmosphere) model and simulate the period between 1850 through 2014. For those models that adopt MACv2-SP as their default aerosol prescription it can replace the DAMIP aerosol-only simulation to satisfy the DAMIP protocol. Hence this additional simulation should only be performed for models wishing to contribute to DAMIP, and in this case the Historical Natural Simulations must, through DAMIP, also be performed, i.e. historical simulations with only Natural Forcing.

SpAer-piClim-anthro: This atmosphere-only simulation mimics the RFMIP *piClim-anthro* simulation described in Table 2 but using the MACv2-SP prescription of the anthropogenic aerosol as the aerosol component of the anthropogenic forcing. For what *piClim-anthro* describes as the “present day" aerosol, MACv2-SP provides a special description which averages aerosol properties for the period between 1985 and 2005.

SpAer-piClim-AerO3: This atmosphere-only simulation mimics the RFMIP *piClim-AerO3* simulation but using the MACv2-SP prescription of the anthropogenic aerosol as the aerosol component of the anthropogenic forcing. For what *piClim-AerO3* describes as the “present day" aerosol, MACv2-SP provides a special description which averages aerosol properties for the period between 1985 and 2005.

SpAer-piClim-histall: This atmosphere-only simulation mimics the RFMIP *piClim-histall* simulation but using the MACv2-SP prescription of the anthropogenic aerosol as the aerosol component of the anthropogenic forcing.

SpAer-piClim-histaer: This atmosphere-only simulation mimics the RFMIP *piClim-histaer* simulation but using the MACv2-SP prescription of the anthropogenic aerosol as the aerosol component of the anthropogenic forcing.

4.2 Planned analyses: Aerosol forcing

Because the chosen experimental design mimics that of the ERF component of RFMIP as well as allows for participation in DAMIP through a prescribed aerosol forcing, the analysis is planned to follow identically what is proposed for these families of simulations. In particular the SpAer-All experiments are planned for incorporation in formal detection attribution studies to assess the magnitude of aerosol forcing.

More specifically the degree of northern-hemispheric warming (and variability across the model ensemble) will be used to evaluate the hypothesis by Stevens (2015) that northern hemispheric warming between 1850 and 1950 is not consistent with an aerosol radiative forcing more negative than $-1\mathrm{W/m^2}$. The Tier 1 experiment SpAer-All will also be used to identify

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robust responses to an aerosol forcing. For example a multi-model ensemble will be crucial to advancing our understanding of the extent to which aerosol forcing underlies the warming hole in the east-central United States (Leibensperger et al., 2012), shifts in the tropical convergence zones (Bollasina et al., 2011), or phasing of Atlantic (Booth et al., 2012) and Pacific (Meehl et al., 2009) decadal variability. Tier 2 experiments are primarily concerned with allowing analysis already planned to also be performed for models with the MACv2-SP aerosol, for instance SPAer-piClim-anthro will be used to characterize how different the ERF is for an identical specification of aerosol optical and cloud active properties, and to what extent these differences arise from differences in the adjustments or in the instantaneous radiative perturbations being differently masked by atmospheric properties.

5 Summary

CMIP addressed three broad questions: (i) how does the Earth system respond to forcing?, (ii) what are the origins and consequences of systematic model biases?, and (iii) how can we assess future climate changes given climate variability, limited predictability, and uncertainties in scenarios? (Eyring et al., 2015). As we have noted, results from all phases of RFMIP will be central in addressing question (i) both by better charactering the ERF relevant to each model's Historical simulation (in RFMIP-ERF) and by examining the response of those same models to far more tightly-constrained ERF due to aerosols (RFMIP-SpAer). RFMIP will contribute valuable information on model biases (question ii) through the assessment of radiative transfer parameterizations on global scales (RFMIP-IRF) and help reduce, in a small way, the uncertainty in scenarios caused by error in the translation of gas concentrations to radiative flux perturbations.

RFMIP also supports elements of the World Climate Research Program's Grand Science Challenges. Links are especially strong to the effort on Clouds, Circulation, and Climate Sensitivity (Bony et al., 2015, with which BS and RP are involved) though a shared interest in cloud adjustments, for which the ISCCP simulator diagnostic information requested in section 2.2 will be quite useful. Many of the challenges have strong regional aspects that may benefit from the RFMIP-SpAer simulations in which the regional forcing is constrained to be more similar across models than has been true to date.

RFMIP also offers a chance to explore methods for model development and experimental protocols. The assessment of radiative transfer parameterizations has a 25+ year history but such assessments have often been performed on a narrow range of idealized conditions, obscuring their relevance to climate model response until underlying errors become evident in important aspects of model response (e.g. Fildier and Collins, 2015; DeAngelis et al., 2015). By identifying a tractably-sized but globally-representative set of conditions we hope to enable routine testing of parameterizations stringent enough to identify errors during model development; these will provide a useful complement to observationally-constrained conditions (Oreopoulos et al., 2012) useful for testing reference models.

Data availability

All data requested by RFMIP will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned, as will the inputs required for offline radiative transfer calculations described in Section 3 and results

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Table 1. Experiments for diagnosing radiative forcing at present-day and under 4×CO_2 conditions. These are atmosphere-only integrations with interactive vegetation using sea-surface temperatures and sea ice concentrations fixed at model-specific pre-industrial control climatology. All experiments are perturbations to RFMIP-ERF-PI-Cntrl.

Experiment Title	CMIP6 Label (experiment_id)	Experiment Description	Years	Major Purposes
Tier 1 experiments				
RFMIP-ERF-PI-Cntrl	piClim-control	Pre-industrial conditions	30	Baseline for model-specific effective radiative forcing (ERF) calculations
RFMIP-ERF-Anthro	piClim-anthro	Present-day anthropogenic forcing (greenhouse gases, aerosols and land-use)	30	Quantify present-day total anthropogenic ERF
RFMIP-ERF-GHG	piClim-ghg	Present-day greenhouse gases	30	Quantify present-day ERF by greenhouse gases
RFMIP-ERF-AerO3	piClim-AerO3	Present-day aerosols and ozone	30	Quantify present-day ERF by aerosols and ozone
RFMIP-ERF-LU	piClim-lu	Present-day greenhouse gases	30	Quantify present-day ERF by land use changes
RFMIP-ERF-4xCO2	piClim-4xCO2	CO_2 concentrations set to 4 times pre-industrial	30	Quantify ERF of 4×CO_2
Tier 2 experiments				
RFMIP-ERF-AerO3x01	piClim-aerO3x0p1	Changes in RFMIP-ERF-Aer scaled by 0.1	30	Explore forcing impacts of non-linearity of cloud-aerosol interactions
RFMIP-ERF-AerO3x2	piClim-aerO3x2	Changes in RFMIP-ERF-Aer scaled by 2	30	Explore forcing impacts of non-linearity of cloud-aerosol interactions

from reference models. It is the intent of RFMIP that this data be freely available; our expectation is that users of the data will give proper credit to the groups producing that data (i.e. by referencing the relevant DOIs) and generally comply with the recommendations of the WGCM Infrastructure Panel as described in their invited contribution to this Special Issue, including acknowledging CMIP6, the participating modelling groups, and the ESGF centres (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip).

Table 2. Experiments for diagnosing time-evolving effective radiative forcing. Three-member ensembles of atmosphere-only integrations interactive vegetation and using sea-surface temperatures and sea ice concentrations fixed at model-specific pre-industrial control climatology. Forcing post 2015 uses a scenario consistent with DCPP and DAMIP (SSP2-4.5)

Experiment Title	CMIP6 Label (experiment_id)	Experiment Description	Start	End	Major Purposes
RFMIP-ERF-HistAll	piClim-histall	Time-varying forcing from all agents.	1850	2100	Diagnose transient ERF from all agents
RFMIP-ERF-HistNat	piClim-histnat	Time-varying forcing from volcanoes, solar variability, etc.	1850	2100	Diagnose transient natural ERF
RFMIP-ERF-HistGHG	piClim-histghg	Time-varying forcing by greenhouse gases	1850	2100	Diagnose transient ERF from greenhouse gases
RFMIP-ERF-HistAer	piClim-histaerO3	Time-varying forcing by aerosols	1850	2100	Diagnose transient ERF from aerosols

Table 3. Sets of atmospheric conditions to be supplied by RFMIP for assessing parameterization error in forcing for . The entire set of conditions is described as CMIP Experiment RFMIP-IRF with CMIP6 Label (experiment_id) rad-irf

Atmospheric conditions	Gas concentrations	Major Purpose	Relevant Experiment
Present-day	Present-day	Baseline	
Present-day	Pre-industrial	Present-day forcing	Historical
Present-day	4× pre-industrial CO_2	Forcing from 4×CO_2	abrupt4xCO2
Present-day	“future”	Forcing in future conditions	RCP8.5 at 2100

Appendix A: Summary of requested simulations and other calculations

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Table 4. Sets of atmospheric conditions to be supplied by RFMIP for assessing forcing by specific agents and probing sources of parameterization error. The entire set of conditions is described as CMIP Experiment RFMIP-IRF with CMIP6 Label (experiment_id) rad-irf

Atmospheric conditions	Gas concentrations	Major purpose
Present-day	Pre-industrial $CO_2 \times 0.50$	Forcing dependence on CO_2
Present-day	Pre-industrial $CO_2 \times 2$	Forcing dependence on CO_2
Present-day	Pre-industrial $CO_2 \times 3$	Forcing dependence on CO_2
Present-day	Pre-industrial $CO_2 \times 8$	Forcing dependence on CO_2
Present-day	Pre-industrial CO_2	Present-day forcing by CO_2
Present-day	Pre-industrial CH_4	Present-day forcing by CH_4
Present-day	Pre-industrial N_2O	Present-day forcing by N_2O
Present-day	Pre-industrial O_2	Present-day forcing by O_3
Present-day	Pre-industrial HFC	Present-day forcing by hydroflourocarbons
Present-day +4K	Present-day	Assess error in temperature dependence
Present-day	Relative humidity increased 20%	Assess error in sensitivity to water vapor
Pre-industrial	Pre-industrial	Sensitivity of combined concentration/condition changes
"Future"	"Future"	Sensitivity of combined concentration/condition changes

Table 5. RFMIP simulations with specified anthropogenic aerosols (SpAer). All simulations are all based on the MACv2-SP prescription of anthropogenic aerosol optical and cloud active properties. They are only to be performed to replicate other simulations in the DECK, within the ERF component of RFMIP, or within the Detection and Attribution Model Intercomparison Project (DAMIP) in the case when MACv2-SP is not used as the default aerosol climatology in the parent simulation.

Experiment Title	Experiment_id	Tier	Period (or years)	Members	Parallel Experiment_id
RFMIP-SpAerO3-all	hist-all-spAerO3	1	1850-2014	1 (4)	CMIP6-Historical
RFMIP-SpAerO3-aer	hist-aer-spAerO3	2	1850-2014	4	Historical-Aer (DAMIP)
RFMIP-SpAerO3-anthro	piClim-spAerO3-anthro	2	30	1 (4)	piClim-anthro (RFMIP-ERF)
RFMIP-SpAerO3-aer	piClim-spAerO3-AerO3	2	30	1 (4)	piClim-AerO3 (RFMIP-ERF)
RFMIP-SpAerO3-piSST-histall	piClim-spAerO3-histall	2	1850-2014	1 (4)	piClim-histall (RFMIP-ERF)
RFMIP-SpAerO3-piSST-histaer	piClim-spAerO3-histaer	2	1850-2014	1 (4)	piClim-histaer (RFMIP-ERF)

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