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Interactive comment on "AerChemMIP: Quantifying the effects of chemistry and aerosols in CMIP6" *by* William J. Collins et al.

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This manuscript describes the Aerosol Chemistry Model Intercomparison Project (AerChemMIP) - a CMIP6 endorsed MIP. The motivation for this MIP is to quantify the climate forcing and response due to near term climate forcers including tropospheric ozone, aerosols and methane, and N2O in a coordinated manner within the Coupled Model Intercomparison Project (CMIP). Although the contribution of tropospheric aerosols and ozone to climate forcing was recognized since the early 1990s, attribution of climate forcing due to these species within the CMIP framework was not performed until CMIP5. And even within the CMIP5, the radiative forcing due to tropospheric aerosols and ozone was calculated by a combination of methods (offline, double calls) partly because not all models included chemistry-aerosols and partly because all the required diagnostics were not available from CMIP. AerChemMIP represents the

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first coordinated effort towards quantifying climate forcing and response, and air quality impacts from tropospheric aerosols and ozone within the mainstream physical climate model intercomparison project, the CMIP, a major step forward. The manuscript is generally well-written, provides motivation for why modeling centers should participate in this computationally expensive (over 3000 simulation years) MIP, and provides examples of scientific studies that can be conducted beyond the goals of the MIP. However, I note some issues that should be addressed to improve the manuscript.

We wish to thank reviewer 1 for taking the time to make valuable comments on the AerChemMIP description.

Given that the multi-model output will be made publicly available for the wider community and users, and the complexity of chemistry-climate models, I suggest indicating that a model documentation/evaluation paper is required for participation in this MIP. This will address two issues - 1) often errors in the submitted data are not revealed until the data is compared against observations; model evaluation and documentation will ensure that the data (or at least the key atmospheric chemistry and aerosol fields) has been looked at before being submitted to the CMIP6 database, 2) each model is unique and data users are not in a position to know the details of all the parameters/processes/chemical schemes that are included in a model; a model documentation paper would be a source of this information.

We agree that model documentation and evaluation is extremely important. CMIP does not request individual model evaluation papers in advance of submission of the model output to ESGF since this would cause a substantial delay in making the model output available to the community. We therefore will not require this for AerChemMIP either. However, model documentation will occur through the ES-DOC component of CMIP6, see https://www.earthsystemcog.org/projects/es-doc-models/ and the models will be centrally evaluated with the ESMValTool and PCMDI metrics package as soon as the output is submitted to the ESGF (see Eyring et al. 2016). This will include the evaluation of chemistry and aerosols

with diagnostics implemented into the ESMValTool. We have added this to the text.

Some thought needs to be given to the third scientific question that AerChemMIP aims to answer - Can the uncertainties associated with anthropogenic emissions be quantified? Based on section 2.3, it is not clear to me how perturbing emissions by 10% will inform us about the dependence of radiative forcing on anthropogenic emissions. Also, it is not clear why a 10% perturbation is chosen.

We realise that the 10% perturbations would have imposed extra work on the modelling groups. We have instead added extra single species simulations to SO2, NH3 and OC in section 3.3 in order to cover the main NTCFs. These simulations are also necessary to characterise the individual ERFs fully. This will generate sufficient data to answer the question whilst limiting the computational requests. This section will now read: "The primary focus of this question is to understand the sensitivity of present-day ERF to uncertainties in estimates of the historical NTCF emissions. Indeed, while all proposed simulations rely on the usage of a central estimate, it is clear that there is a range of emission estimates (as discussed in Granier et al., 2011; Smith et al., 2011; Bond et al., 2013) that needs to be considered. While this uncertainty will clearly be region, sector and species dependent, it would be unrealistic to explore the full spectrum of variations. For that purpose, we will make use of the perturbations (pre-industrial to present-day) simulations. This is likely to provide an upper bound on the impact of uncertainties. Results from the simulations can be directly compared to the simulations in section 3.1 and analysed for differences in radiative forcing as well as air quality and overall atmospheric composition. Inter-model differences will document their varying sensitivities to emissions."

Specific and Minor Comments:

P1, L3-4: According to Myhre et al (2013), NTCFs are defined as species "whose

impact on climate occurs primarily within the first decade after their emissions" and includes methane in addition to ozone, aerosols and their precursors. Suggest revising this sentence to avoid confusion.

We will make this revision

P2, L25: Insert "tropospheric" in "...increases in ozone.." and insert "stratospheric in "...decreases in ozone. . ."

We will not make this change. While the impacts of ozone precursors will be mainly in the troposphere and those of ODSs mostly in the stratosphere, they are not restricted to these layers.

P2, L30: Ozone and O3 are used interchangeably in the text. Recommend sticking with one and specifically "ozone" throughout the manuscript. Same holds for methane.

We will use "ozone", "methane" and "nitrous oxide" throughout instead of the chemical formulae.

P3, L3: Please reference a chapter in the IPCC (2014).

The reference is to the SPM.

P3, L5-7: I am not sure what the authors are trying to convey in this sentence. Is it that the "regional/local" air pollution policies should informed by the projections of air pollutants from CMIP6 models? If so, I am not convinced that this would be possible given the large model diversity in projected atmospheric composition (e.g, Young et al., 2013).

This will be rephrased: "CMIP6 will provide comprehensive information on the future large-scale evolution of atmospheric composition thus updating the knowledge base used to manage air pollution."

P3. L7-9: This sentence appears to represent an incomplete thought. Please elaborate or cut.

This sentence will be moved up where it fits better.

P3, L30: Define the acronym ACCENT here rather than on Page 4, since it is used here for the first time in the text.

This change will be made.

P3, L31: This sentence assumes that the relationship between IPCC and CMIP is commonly known. Please clarify how CMIP3 is related to the IPCC Fourth Assessment report.

This will be clarified

P4, L11: A few of the newer generation CCMs available now with coupled ocean-atmosphere-chemistry have been documented and can be cited here. For eg., John et al. (2012); Shindell et al. (2013).

These references will be added.

P4, L11-13: This sentence is giving short-shrift to the tremendous amount of work done under ACCMIP to assess the performance of CCMs with coupled strat-trop chemistry. The model shortcomings highlighted by ACCMIP studies is being addressed by more detailed analysis within CCMI as noted on http://blogs.reading.ac.uk/ccmi/. Suggest revising this sentence to recognize earlier work regarding the assessment of the performance of CCMs with coupled strat-trop chemistry.

This paragraph was focussing on stratospheric ozone. We are not aware of ACCMIP studies that addressed this.

P4, L15-16: I am not sure if the inclusion of time-varying ozone in the climate models has led to an improvement in the climate forcing by stratospheric ozone. What has really improved since AR4 is the representation of climate forcing by stratospheric ozone in the CMIP5 models. Please revise sentence.

We will revise the sentence as suggested.

P4, L28-32: Sentence is confusing. Please rephrase.

This sentence will be broken down into shorter ones.

P4, section 1.2: A key point missing in this section is that the radiative forcings due to short-lived species provided in Myhre et al. (2013) were decoupled from the CMIP5 climate model simulations that provided the basis for IPCC-AR5 chapters on climate change (historical - Bindoff et al., 2013; future - Kirtman et al., 2013; Collins et al. 2013). This made it difficult to relate the temperature responses to radiative forcing due to NTCFs and also to constrain the climate sensitivity. AerchemMIP is designed to fill in this information gap to inform the IPCC-AR6. Suggest adding a sentence to note this point.

We will add the suggested sentence to the text.

P5, L10: CO is the largest sink of OH followed closely by methane . Suggest rephrasing to "...is a dominant sink of the hydroxyl radical (OH), the primary tropospheric oxidizing agent. . ."

We will rephrase this as suggested.

P5, L11: References for methane's influence on aerosol oxidation and natural aerosol precursors would be helpful.

We will add a reference to Shindell et al. (2009).

P5, L12-13: Methane also influences stratospheric ozone directly by converting reactive chlorine into the reservoir hydrochloric acid HCl (e.g., Pawson et al., 2014).

We will add the suggested sentence.

P5, section 2.1: Diverging multi-model results lead to more questions than answers. An example of model diversity from the multimodel analysis in ACCMIP was the opposing changes in trends in hydroxyl radicals simulated by the models (Naik et al., 2013; Voulgarakis et al., 2013) which did little to alleviate the uncertainty in our understanding

of OH trends. Similarly, models that resolve stratospheric chemistry could produce diverging results on the impact of stratospheric ozone depletion on regional climate, reinforcing the uncertainty in our understanding. The issue of diversity in model results should be recognized in the text.

We will add the text: "As a multi-model exercise AerChemMIP will identify areas of consensus and disagreement in the answers."

P5, L40: Commas needed after NTCF emissions and CH4.

These will be added

P6, L5: Need references for SSP3-7.0 scenario. Does this scenario include land-use changes, and if so, do they influence air pollutant emissions?

Most of the SSP3-7.0 description is in section 3.2 where we will add a reference to Fujimori et al. (2016)

P6, L15: This in my opinion is the least framed question in the AerChemMIP proposal. It is not clear to me what perturbing emissions by 10% will tell us about the dependence of radiative forcing on uncertainties in anthropogenic emissions. Besides the uncertainty in radiative properties of NTCFs, the uncertainty in the NTCF radiative forcing comes from their spatial and temporal distributions which in turn are a function of their emission estimates. A wide variety of chemistry and physics parameterizations are implemented in CCMs which then lead to diversity in simulated atmospheric composition and therefore radiative forcing, despite implementing the same anthropogenic emissions (e.g., different tropospheric ozone, aerosols, methane lifetimes in ACCMIP). It would help to elaborate what inter-model differences in radiative forcings from 10% increase in anthropogenic emissions will tell us about the uncertainty in radiative forcing induced by emissions. Further, it is not clear from the tables 1-6 which experiments could be used to perform this analysis.

We realise that the 10% perturbations would have imposed extra work on the

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modelling groups. We have instead added extra single species simulations in section 3.3 in order to cover the main NTCFs. These simulations are also necessary to characterise the individual ERFs fully. This will generate sufficient data to answer the question whilst limiting the computational requests. This section will now read: "The primary focus of this question is to understand the sensitivity of present-day ERF to uncertainties in estimates of the historical NTCF emissions. Indeed, while all proposed simulations rely on the usage of a central estimate, it is clear that there is a range of emission estimates (as discussed in Granier et al., 2011; Smith et al., 2011; Bond et al., 2013) that needs to be considered. While this uncertainty will clearly be region, sector and species dependent, it would be unrealistic to explore the full spectrum of variations. For that purpose, we will make use of the perturbations (pre-industrial to present-day) simulations. This is likely to provide an upper bound on the impact of uncertainties. Results from the simulations can be directly compared to the simulations in section 3.1 and analysed for differences in radiative forcing as well as air quality and overall atmospheric composition. Inter-model differences will document their varying sensitivities to emissions."

P6, L24-25: Please complete this sentence.

This should have finished "... biogeochemical feedbacks."

P6, L29: Insert space before 5).

We will add a space.

P7, L9-10: Does the CMIP6-specified stratospheric ozone dataset use the CMIP specified forcings? If not, how will this impact results from tropospheric-only chemistry models. Will the stratospheric ozone dataset for future scenarios considered here also use future CMIP6 scenarios.

No, the new CMIP6 ozone forcing dataset will not follow CMIP6 scenarios, since

these were not ready in time for implementation in the models that had to be run to generate the ozone fields. Instead CMIP5 scenarios were used with different RCPs into the future. The changes in historical emissions are deemed to have only a small effect on atmospheric chemistry, while for the future differences will exist. The full effects will need to be quantified when suitable model simulations become available. However, the main advantage of the CMIP6 over the CMIP5 ozone forcing database is that it was produced using stratosphere-troposphere resolving chemistry-climate models (CCMs) instead of patching together fields from one stratospheric and one tropospheric chemistry climate model, so that the influence of the tropospheric chemistry on the stratospheric ozone (and vice-versa) is now included appropriately.

P8, section 3.1.1: Given that the natural precursor emissions are tied to model meteorology, the perturbed NTCF simulations (hist-piNTCF, hist-piAer, hist-1950HC) will likely simulate different natural emissions compared to that in the historical simulation. Some information on how this natural component will be separated from the anthropogenic component in the simulated climate response will be helpful here.

Perturbing NTCFs will change the climate, and a changed climate will affect the NTCFs through natural emissions, chemistry, transport etc. These feedbacks are included in the response and a sentence clarifying this will be added to the text.

P8, L33-34: Some justification for why observed SSTs and sea ice from 1870 to 2014 (available as a forcing from CMIP) could not be used for these forcing calculations, similar to the work of Andrews (2014), should be provided here.

The DECK AMIP experiment (and Andrews et al. 2014) only starts in 1979 and we wish to categorise forcings from the start of the historical (1850).

P8,L37-39: Without a reference to RFMIP simulation, this sentence is confusing. Either cut this discussion (as it is being discussed in section 5.1) or provide a reference to

RFMIP here.

We will clarify this: "Use of historical SSTs rather than pre-industrial will eliminate any effects of using an inconsistent background climate state (such as different cloud cover and natural emissions) which could affect concentrations of aerosols and reactive species, and the ERFs. The impact of background state on the diagnosis of ERFs is likely to be small (Forster et al., submitted)."

P9, section 3.2.1: Some discussion of how natural emissions will be impacted in these simulations is needed here.

A sentence will be added to explain this: "Where natural emissions are modelled interactively, these will vary with the evolving climate and will differ between ssp370 and ssp370-lowNTCF as the climate diverges."

P10, L10: I probably misunderstand this experiment (ssp370SST-lowLu). The chemistry impacts of land-use changes can only be diagnosed if the precursor emissions (biogenic VOCs, fire emissions, dust) in the model are tied to model land-surface characteristics. If a model does not include land-surface and emission coupling then it is not clear to me how the chemical impacts of land-use changes can be simulated. It would be helpful to clarify this point.

A sentence will be added to clarify this: " . . . **for models which include interactive schemes for emission and deposition. Not all models will model all these processes interactively."**

P10, L20-21: How different would the pre-industrial to present-day ERFs be if they were calculated using results (10 year means for PI and PD) from the transient simulations described in section 3.1.2? If the results are similar then this would avoid having to run additional time-slice simulations and considerably pare down the number of requested AerChemMIP simulations.

A sentence will be added to clarify this: "These simulations differ from those in

3.1.2 in that they use pre-industrial SSTs and maintain the same emissions (or concentrations) for 30 years. They therefore give a more accurate representation of pre-industrial conditions to present ERF than would be obtained from portions of the transient historical ERF simulations."

P12, section 4.2: This section appears to be primarily focused on diagnostics to document aerosol forcing. There is no mention of diagnostics for gaseous NTCF forcings (e.g., ozone). Suggest adding a short paragraph on diagnostics needed to better quantify ozone, methane forcings.

We will explicitly mention gases in the discussion of ERF. We will also add the sentence: "For gaseous pollutants ozone molar mixing ratios and methane lifetime are requested in order to diagnose forcing offline."

P13, L31: Suggest revising this sentence to: A thorough documentation of natural emissions and 3D fields of reactive gases and aerosols is needed.

The sentence will be revised as suggested

P13, L35-36: Need a reference here.

A reference to Collins et al. (2011) will be added.

P14, section 4.6: Which simulations will be used to evaluate the skill of models in simulating chemical composition and aerosol radiative parameters? Since modelers are encouraged to increase model output during the AMIP period, would the DECK AMIP simulations be the cornerstone for model evaluation? If so, then it would be helpful to recommend (or even make it a requirement) that each model group evaluate and document chemistry and aerosols in their AMIP simulations, to ensure data quality.

We agree that model documentation and evaluation is extremely important. CMIP does not request individual model evaluation papers in advance of submission of the model output to ESGF since this would cause a substantial delay in making the model output available to the community. We therefore will not require this

for AerChemMIP either. However, model documentation will occur through the ES-DOC component of CMIP6, see https://www.earthsystemcog.org/projects/es-doc-models/ and the models will be centrally evaluated with the ESMValTool and PCMDI metrics package as soon as the output is submitted to the ESGF (see Eyring et al. 2016b). This will include the evaluation of chemistry and aerosols with diagnostics implemented into the ESMValTool. We have added this to the text.

P14, L28-29: The ability of models to simulate climate is measured in terms of how well they simulate global temperature and precipitation. Are there equivalent metrics for the simulation of chemistry and aerosols in the face of large uncertainties and data gaps in observations of short-lived chemicals? Suggest adding examples of robust metrics that could be used to measure the skill of CCMs.

We will add a reference to the SPARC CCMVal Report where process-oriented diagnostics and performance metrics have been defined and successfully applied to the CCMVal ensemble.

P14, L31-32: A reference to Lee et al. (2013) would be useful here.

This reference will be added.

P16, Data availability: DOIs should be assigned to each model's output for AerchemMIP so that proper credit can be given to each modeling group providing the data. Are there any plans for assigning DOIs to contributions to AerchemMIP?

AerChemMIP is a CMIP6-Endorsed MIP. All CMIP6 simulations will be assigned with DOIs as the sentence in the 'Data Availability' section already says: "The climate model output from AerChemMIP experiments described in this paper will be distributed through the Earth System Grid Federation (ESGF) with DOIs assigned."

P16, L27-28: https://pcmdi.llnl.gov/projects/input4mips/ can be referenced here.

This will be referenced

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