AerChemMIP: Quantifying the effects of chemistry and aerosols in CMIP6

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Abstract. The Aerosol Chemistry Model Intercomparison Project (AerChemMIP) is endorsed by the Coupled-Model Intercomparison Project 6 (CMIP6) and is designed to quantify the climate and air quality impacts of aerosols and chemically-reactive gases. These are specifically near-term climate forcers (NTCFs: tropospheric ozone and aerosols, and their precursors), methane, nitrous oxide and ozone-depleting halocarbons. The aim of AerChemMIP is to answer four scientific questions:

1. How have anthropogenic emissions contributed to global radiative forcing and affected regional climate over the historical period?
2. How will future policies (on climate, air quality and land use) affect these species and their climate impacts?
3. Can the uncertainties associated with anthropogenic emissions be quantified?
4. Can climate feedbacks occurring through changes in natural emissions be quantified?

These questions will be addressed through targeted simulations with CMIP6 climate models that include an interactive representation of tropospheric aerosols and atmospheric chemistry. These simulations build on the CMIP6 Diagnostic, Evaluation and Characterization of Klima (DECK) experiments, the CMIP6 historical simulations, and future projections performed elsewhere in CMIP6, allowing the contributions from aerosols and chemistry to be quantified. Specific diagnostics are requested as part of the CMIP6 data request to evaluate the performance of the models, and to understand any differences in behaviour between them.

1 Introduction

1.1 Motivation for AerChemMIP

Aerosols and chemically reactive gases in the atmosphere can exert important influences on global and regional air quality and climate. Scientific questions and uncertainties regarding chemistry-climate interactions are relevant to regional scale climate change (e.g., tropospheric ozone and aerosols interacting with regional meteorology), to long-range connections (e.g.,

hemispheric transport of air pollution, the impacts of lower stratospheric ozone and temperatures on surface climate) and globally integrated effects (e.g., the lifetimes of methane (CH_4) and nitrous oxide (N_2O)).

Past climate change has been forced by a wide range of chemically reactive gases, aerosols, and well-mixed greenhouse gases

5   (WMGHGs), in addition to CO_2. More specifically, anthropogenic effects on aerosol and ozone abundances (also known as near-term climate forcers, NTCFs) are estimated to have been responsible for a climate forcing that is presently nearly equal in magnitude to the CO_2 forcing (Shindell et al., 2013a; Myhre et al., 2013a). These emissions are thought to have led to a variety of global climate impacts including changes in regional patterns of temperature and precipitation (Rotstayn et al., 2015). In addition, NTCF forcing is inherently spatially inhomogeneous (Shindell et al., 2013a), and there is some evidence that the

10 (regional and global) climate response to a regional scale NTCF differs from that of an equivalent globally homogeneous radiative forcing (Shindell et al., 2012b; Shindell et al., 2015). Changes in the abundance of NTCFs can also induce rapid adjustments in meteorological quantities (such as atmospheric temperature, water vapour, clouds) through radiative heating/cooling and/or effects on cloud lifetime (Sherwood et al., 2015). These adjustments are in principle independent of surface temperature changes, although in practice the land surface temperature is allowed to respond. The contribution of rapid

15 adjustments to the change in Earth's energy budget following a perturbation of a radiatively active species can be incorporated into an effective radiative forcing (ERF), which has been shown to be a better predictor of the eventual surface temperature change than the traditional instantaneous or stratosphere-adjusted definitions of radiative forcing (Boucher et al. 2013; Myhre et al. 2013a, Sherwood et al., 2015).

NTCFs were also identified in IPCC AR5 (Myhre et al., 2013a) as the main source of uncertainty in the total anthropogenic

20 ERF since pre-industrial times. In particular, natural aerosols originating from biogenic sources, dust or sea-salt are a primary contributor to the uncertainty in present day aerosol forcing (Carslaw et al., 2013). This is because, due to the nonlinear response of aerosol-cloud interactions to the background level of aerosols, the response of the climate system to human-induced aerosol perturbations depends critically on the natural aerosol background (Carlton et al., 2010).

25 The forcing of climate by ozone changes has resulted from increases in ozone driven by changes in NO_X and VOC emissions and methane abundance (mostly affecting the troposphere) and decreases in ozone driven by ozone depleting substances (ODS), such as chlorofluorocarbons and hydrochlorofluorocarbons (mostly affecting the lower stratosphere) (Shindell et al., 2013b). The net ERF due to ozone is therefore the result of combined impacts from climate change and multiple emission changes. For example, one of the largest components of the ERF due to past CH_4 emissions comes from the associated increase

30 in tropospheric O_3 (Stevenson et al. 2013). In addition, stratospheric O_3 losses due to ODS since the 1970s have led to a significant cooling of the stratosphere (Shine et al., 2003), and the Antarctic ozone hole is linked to changes in tropospheric circulation and rainfall patterns in the southern hemisphere, especially during austral summer (WMO, 2014). In the Southern Hemisphere, future changes in summertime tropospheric circulation are expected to be controlled by both the rates of ozone recovery and WMGHG increases (McLandress et al., 2011; Polvani et al., 2011), indicating the need to account for ozone

35 changes in future climate projections.

Uncertainties in projecting emissions of chemically-reactive WMGHGs, as well as future air quality from global changes in climate and composition, were also identified in IPCC AR5 (Kirtman et al., 2013). Beyond aerosols, natural and managed ecosystems provide a large fraction of the CH_4 and N_2O WMGHGs, as well as O_3 precursors (e.g., through emissions of soil

40 nitrogen oxides, biogenic volatile organic compounds, and wildfires). These sources are likely to be affected by climate change, leading to a variety of feedbacks (Arneth et al., 2010) that to date have only been quantified from a limited number of studies (and models) and thus demand for a coordinated set of simulations that allows for a consistent and clean comparison between models.

NTCF precursor emissions are also responsible for driving regional and local air quality (Fiore et al., 2012). This has led to the recognition that a combined mitigation policy for climate change and air pollution has clear economic benefits compared to separate mitigation (IPCC 2014). Most, if not all, scenarios for the future actions of societies lead to changes in the emissions
5   and meteorology that determine air quality and create pollution episodes. The knowledge base used to manage air pollution to date must be updated based on more comprehensive information that CMIP6 will provide on the future evolution of atmospheric composition. The exposure risks of human health and assets (agriculture, built environment, ecosystems) will be driven by daily variations in surface ozone and particulate matter in addition to deposition of nitrate and sulfate and any interactions of atmospheric and land-use changes.

10   The Aerosol and Chemistry Model Intercomparison Project, AerChemMIP, contribute to CMIP6 by: 1) diagnosing climate forcings and feedbacks involving NTCFs (namely tropospheric aerosols and tropospheric O_3 precursors) and the chemically reactive WMGHGs (e.g., N_2O, CH_4, and some halocarbons; including impacts on stratospheric O_3), 2) documenting and understanding past and future changes in the chemical composition of the atmosphere, and 3) estimating the global-to-regional climate response from these changes.

15   Improving insight and understanding of the inner functioning of climate models and climate itself is a primary motivation for AerChemMIP. To characterise the overall ERF from all species, including NTCFs, requires extra efforts and has not been properly done in earlier CMIP experiments (Forster et al., submitted). Undiscovered feedback processes, which involve changes to the atmospheric composition of reactive gases and aerosols, may be the reason why a certain temperature response appears with a given WMGHG concentration level. Better documenting the changes in atmospheric composition in a changing
20   climate is of interest for many other purposes like choosing among different air quality mitigation options or understanding perturbations to ecosystems and biogeochemical cycles. Finally, additional simulations are requested to validate the models and detect systematic biases and to better constrain the role of aerosols and reactive gases on climate forcing.

1.2 Previous work

25   The contribution of tropospheric ozone precursors to radiative forcing (through changes in ozone and methane) has been considered in successive IPCC assessments since IPCC (1994) and the Second Assessment Report (IPCC 1996) where a combination of 2D and 3D chemistry models were used (PhotoComp in Olson et al. 1997). A more rigorous intercomparison of 3D chemistry transport models (OxComp in Prather et al. 2001; Gauss et al. 2003) provided information on the geographical distribution of ozone forcing for the IPCC Third Assessment Report (Ramaswamy et al. 2001). The IPCC Fourth Assessment
30   report (Forster et al. 2007) again used a multi model framework (ACCENT) to calculate maps of ozone radiative forcing (Gauss et al. 2006). Here the models were still nearly all offline chemistry transport models, and none of the CMIP3 climate models included tropospheric ozone chemistry. The radiative forcing of ozone in all cases was calculated using offline radiative transfer models, usually for 'pre-industrial', 'present' and one or two future timeslices. It was not until the CMIP5 project that a few of the climate models included interactive tropospheric chemistry. The aim of the Atmospheric Chemistry and Climate
35   Model Intercomparison Project (ACCMIP) (Lamarque et al. 2013) was to quantify the contribution of ozone and aerosols to the radiative forcing in the CMIP5 models that included these components. In practice, the model setups for CMIP5 and ACCMIP tended to be different so that ACCMIP was not able to fully characterise the forcings of most simulations submitted to the CMIP5 archive. ACCMIP combined the results from chemistry-climate models and offline chemistry transport models to quantify the central estimate and range of historical and future ozone and aerosol forcings, and the contributions of individual
40   ozone precursor emissions. These were diagnosed using a mixture of offline radiative transfer models and double call

diagnostics, whereby a model radiation scheme is called twice with the second call containing one or all radiative species set to fixed values.

The historical and future climate effects of ozone depletion were first addressed in multi-model studies using Chemistry-Transport Models in Atmospheric Composition Change European Network (ACCENT) (Gauss et al. 2006; Forster et al. 2007)
5   particularly focussing on changes in global radiative forcing. Son et al. (2008) highlighted the specific impact of the Antarctic ozone hole on regional surface climate by contrasting CMIP3 models with and without prescribed stratospheric ozone changes, and by comparing them to online coupled chemistry-climate models (CCMs) from the SPARC Chemistry-Climate Model Validation Activity phase 1 (CCMVal-1; Eyring et al., 2007), with follow-on studies using model simulations from the CCMVal phase 2 (Son et al., 2010; SPARC 2010; WMO, 2010; 2014). Most of the CCMs included stratospheric chemistry
10   only, while the newer generation CCMs available now encompass both tropospheric and stratospheric chemistry, with a few of these models being coupled to an ocean (Morgenstern et al., in preparation). A comprehensive assessment of the performance of these CCMs regarding stratospheric and tropospheric chemistry and dynamics is currently being performed within the SPARC/IGAC Chemistry-Climate Model Initiative (CCMI; Eyring et al., 2013a). In contrast to CMIP3 where half of the models prescribed a constant stratospheric ozone climatology, the CMIP5 models all considered time-varying ozone
15   either prescribed or calculated interactively (Eyring et al., 2013b). This has led to substantial improvements in the climate forcing by stratospheric ozone since the AR4 (Flato et al., 2013). The importance of "whole atmosphere" chemistry-climate coupling for the climate effects of ozone has also been recently highlighted, since changes in stratospheric ozone abundances, e.g. due to changes in ozone depleting substances, can affect tropospheric ozone through stratosphere-to-troposphere exchange (Shindell et al., 2013b; Banerjee et al., 2016).

20   The radiative forcing from historical aerosol emissions was quantified on the basis of one model (Langner and Rodhe 1991) in IPCC (1994) and the Second Assessment Report (IPCC 1995). The effects started to be included online in some climate models by the Third Assessment Report (Penner et al. 2001) but CTMs continued to play an important role even in the Fourth and Fifth Assessment Reports. Radiative forcing estimates for anthropogenic aerosol components were largely derived from a multimodel ensemble through the Aerosol Comparison (AeroCom) initiative (Schulz et al., 2006; Myhre et al. 2013b).
25   AeroCom is a long-standing activity of aerosol model intercomparison (Textor et al., 2006, Kinne et al., 2006, Schulz et al., 2006), which provided estimates of radiative forcings from a large set of global aerosol (mostly offline) models for AR4 and AR5. The complex path from precursor emissions to aerosol loads, to optical and cloud-perturbing properties, to finally forcing has been simulated with well documented diversity (Schulz et al., 2006; Myhre et al. 2013b, Ghan et al., 2016). More recently, aerosol forcing was quantified in ACCMIP, with more models using the same setups as used in CMIP5 enabling a closer
30   comparison than for ozone, and these results were combined with additional simulations under CMIP5 to quantify the central estimate and range of historical to present-day aerosol ERF, whereas other historical and future ERF estimates relied solely on ACCMIP (Shindell et al., 2013a). It was problematic in CMIP5 to properly quantify the effective radiative forcing by aerosols in the historic period and future scenarios, in most GCM models. This was mainly due to missing experiments, diagnostics and insufficiently characterised feedbacks involving natural aerosols. The lessons learned in AeroCom, ACCMIP and CCMI
35   largely contributed to the design of AerChemMIP.

2 Science questions

This section provides the scientific justification for the four science questions that AerChemMIP will address. Owing to the strong connection between clouds and aerosols (Boucher et al., 2013), AerChemMIP will provide crucial information to support the World Climate Research Program (WCRP) Grand Challenge on "Clouds, Circulation and Climate sensitivity". In
40   addition, through the importance of natural sources on WMGHGs and NTCFs, the proposed research questions in

AerChemMIP are well-aligned with the WCRP theme "Biogeochemical forcings and feedbacks". The AerChemMIP proposal focuses on four broad questions, listed and discussed below.

2.1 How have anthropogenic aerosols and reactive gases contributed to global ERF and regional climate change over the historical period?

Anthropogenic non-CO_2 emissions (e.g., NTCFs, in addition to WMGHGs like halocarbons and N_2O) have led to a climate forcing that is commensurate to the CO_2 forcing in some regions, especially over the last few decades (Myhre et al., 2013a). There are many complex couplings between different chemically and radiatively active species that remain to be fully understood. For example, in addition to its direct climate forcing of 0.48 ± 0.05 W m^{-2} (Myhre et al., 2013a), methane acts as a precursor to tropospheric ozone (Fiore et al., 2012), and is the largest sink of the hydroxyl radical (OH; Naik et al., 2013). As such, changes in methane emissions will also affect aerosol oxidation and indirectly emissions of natural aerosol precursors. Furthermore, methane is a source of water vapour in the stratosphere; this is an important contributor to stratospheric ozone depletion, especially away from the polar regions. Stratospheric water vapour is also a greenhouse gas and changes in methane thus have a further indirect radiative forcing through their effect on water vapour (Myhre et al., 2013a). As the methane concentration has more than doubled since pre-industrial times (from 722 ± 25 ppb in 1750 to 1803 ± 2 ppb by 2011, it is imperative to quantify its historical forcing and the combined climate impacts associated with those changes. Furthermore the large uncertainty in the ERF due to ozone and aerosols since pre-industrial times is a key factor behind the large uncertainty in constraining climate sensitivity using observations over the historical record.

The ERF due to NTCFs has an inhomogeneous spatial distribution and the degree of regional temperature and precipitation responses due to such heterogeneous forcing remains an open question within the scientific community. There is also evidence that NTCFs, which are primarily located over Northern Hemisphere midlatitude land areas, have led to a larger climate response, both there and globally, relative to the more homogeneous ERF from WMGHGs (Shindell, 2014; Shindell et al., 2015; Rotstayn et al., 2015; Marvel et al., 2016). Climate response to regional forcings is not limited to the region of origin, however. Instead, remote responses have been clearly demonstrated in numerical experiments (Teng et al., 2012; Levy et al., 2013; Bollasina et al., 2013; Shindell et al. 2015). In particular, the position of the ITCZ has been shown to depend on the differential rate of aerosol forcing between hemispheres (Hwang et al., 2013).

A particularly unambiguous regional response to inhomogeneous climate forcing concerns the Southern hemisphere summertime surface circulation changes induced by the Antarctic ozone hole as an indirect response to stratospheric ozone depletion from increasing halocarbons. These changes have been argued to lead to changes in the subtropical jet position, rainfall patterns, ocean circulation, and possibly sea-ice cover (Arblaster and Meehl, 2006; McLandress et al., 2011; Polvani et al, 2011). The relative role of these ozone-induced changes for observed Southern hemisphere summertime climate compared to other anthropogenic forcings and natural variability is not fully resolved by the scientific community with some contradictory studies (WMO, 2014). Hence there is a need for a multi-model ensemble of simulations that resolve stratospheric chemistry to isolate the role of stratospheric ozone depletion.

2.2 How will future policies (on climate/AQ/land use) affect the abundances of NTCFs and their associated climate impacts?

In the upcoming decades, climate policies can be categorized in three broad areas: 1) climate change policies (targeting mostly WMGHGs), 2) air quality policies (targeting mostly NTCF emissions including CH_4 that are precursors of tropospheric aerosols and ozone) and 3) land-use policies. AerChemMIP aims to identify the patterns of chemical change at the global and

regional levels, as well as the ERF associated with NTCF mitigation efforts (focusing on policy choices in areas 1 and 2 above), and their climate (surface temperature and precipitation) and environmental (health, ecosystem, visibility, ...) impacts between 2015 and 2055 (as the time frame over which aerosol and precursor emissions are expected to be significant; Shindell et al., 2012a; Fiore et al., 2015). Such impact analysis can be performed by contrasting two simulations: a) a reference with relatively

5   high aerosol emissions (such as Shared Socio-economic Pathway 3 with 7.0 Wm^{-2} forcing at 2100 (SSP3-7.0) from the Scenario Model Intercomparison Project (ScenarioMIP), see Figure 1) and b) a perturbation experiment where air quality policies (or maximum feasible reductions) are applied to the SSP3-7.0 NTCF emissions, and therefore lead to much reduced NTCF emissions. These perturbations are designed in collaboration with ScenarioMIP (O'Neill et al., 2016) to ensure that the NTCF perturbations are consistent with the underlying storyline of the SSP3-7.0 scenario. A comparison of the reference and

10   perturbation simulation will provide the background for understanding the effects of air quality policies over the next few decades. Analysis of results from these simulations will be critical to understand the interactions between NTCFs (aerosols in particular) and weather systems, as prior studies indicate mixed results (Jacob and Winner, 2009; Leibensperger et al., 2012; Racherla and Adams, 2006). In addition, the ScenarioMIP Tier 2 ensemble for SSP3-7.0 provides an extensive set of reference simulations to increase the likelihood of identifying statistically significant differences.

15 **2.3. How does radiative forcing depend on uncertainties in anthropogenic emissions?**

The primary focus of this question is to understand the sensitivity of present-day ERF to uncertainties in estimates of NTCF emissions (as discussed in Granier et al., 2011; Smith et al., 2011; Bond et al., 2013). For that purpose, global NTCF emissions or methane concentrations will be artificially increased by 10%. 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

20   composition. Inter-model differences will document their varying sensitivities to emissions.

2.4. Can climate feedbacks occurring through changes in natural emissions be quantified?

In a recent assessment of 28 modelled factors that could be a source of uncertainty in simulated cloud brightness, Carslaw et al. (2013) identified that approximately 45% of the variance came from natural aerosols, especially from dimethysulfide (DMS) and volcanic SO_2 emissions. This can be compared with 34% of the variance due to anthropogenic aerosols. Additional studies

25   have highlighted the role of marine biogenic aerosols (McCoy et al., 2015) and isoprene emissions (Archibald et al., 2010) in. These are all examples of couplings and potential climate feedbacks involving diverse biogeochemical cycles, terrestrial (Isaksen et al., 2009; Arneth et al., 2010) and marine ecosystems (Cameron-Smith et al., 2011). The purpose of the proposed AerChemMIP simulations is therefore to quantify the climate impacts associated with specific biogeochemical cycles, focusing on 6 different topics: 1) dust emissions, 2) sea salt emissions, 3) DMS emissions, 4) fire emissions,5) NOx emissions from

30   lightning, 6) biogenic VOC emissions. Each will have a specified perturbation experiment. The comparison of each simulation with the CMIP DECK (Diagnostic, Evaluation and Characterization of Klima) pre-industrial control experiment (Eyring et al., 2016a) will enable a quantification of the importance of the considered climate-emission feedbacks.

3 Experimental design

The AerChemMIP experiments focus primarily on understanding atmospheric composition changes (from NTCFs and other

35   chemically-active anthropogenic gases) and their impact on climate. We have devised a series of experiments that enable the forcing of various NTCFs to be contrasted with that of WMGHGs for historical and future climate change. In addition, the proposed chemistry-climate simulations will enable diagnosis of changes in regional air quality through changes in surface ozone and particulate matter. The effective radiative forcings are calculated from the net top of atmosphere flux difference between atmosphere-only simulations with identical SSTs, but differing composition (Forster et al. submitted, Pincus et al.,

2016). The climate responses are calculated from the differences in climate between atmosphere-ocean simulations with differing composition.

AerChemMIP is designed to elucidate the climate effects of interactive aerosols, tropospheric chemistry and stratospheric chemistry. Ideally participating models will include all three components; however, we realise that this may not always be possible or practical. Many CMIP models include emission-driven interactive aerosol schemes, but with limited or no further tropospheric chemistry. To understand their overall behaviour we encourage such models to participate in those AerChemMIP experiments that are relevant to quantifying the climate effects of the aerosols. For models with tropospheric chemistry, but lacking a stratospheric, chemistry, we encourage participation in all experiments except those explicitly addressing the effects of ODSs. For tropospheric-only chemistry, the CMIP6-specified stratospheric ozone dataset should be used (Hegglin et al., in preparation). Modelling groups with full chemistry and aerosol models are encouraged to perform all simulations they deem relevant to their objectives. Note that, for consistency, the concentrations of chemically and radiatively active species should be the same in the radiation and chemistry schemes. Tables 1 to 6 list the minimum model configurations required for each experiment. The suffix "CHEM" indicates interactive chemistry is needed for these experiments (as well as interactive aerosols). The suffix "AER" indicates that interactive aerosols are needed, but not necessarily interactive chemistry. Models with an interactive chemistry capability should still include this even for runs labelled as "AER".

To participate in AerChemMIP, climate models must be run for the CMIP DECK and CMIP6 *historical* (atmosphere-ocean simulation with forcings evolving over 1850-2014) experiments with the same setup, i.e. with the same levels of sophistication activated in the chemistry and aerosol schemes, and the AerChemMIP diagnostics as specified in section 4. It is likely that groups will first spin up their model to pre-industrial conditions without interactive chemistry. This would then be followed with a shorter spin up with fully interactive chemistry for as long as is needed to ensure the chemistry does not introduce any drift. This process will be quicker if the non-chemistry spin up uses ozone and oxidants from a prior run of the interactive chemistry model (e.g. Collins et al. 2011). The length of the *piControl* (or *esm-piControl*) needs to be at least as long as the experiments. For AerChemMIP this is 205 years (164 years historical + 41 years future), although note that Eyring et al. (2016) recommend 500 years. It will be essential to have CMIP6 *historical* simulations with the same chemistry and aerosols as in AerChemMIP as this is used as the baseline. The AerChemMIP configured *abrupt-4xCO2* should be run for at least 150 years as recommended in Eyring et al. (2016), to quantify the climate-chemistry feedbacks.

The emissions of anthropogenic aerosols and reactive species are provided by Smith et al. (in prep). Models should use their own schemes for natural emissions. The WMGHGs (CH_4, N_2O, halocarbons) will be specified as CMIP-specified concentrations, either throughout the troposphere or at the surface.

We also realise that valuable contributions to answering the AerChemMIP scientific questions can be made by groups unable to participate in CMIP6, such as those running offline CTMs. Participation from these groups is welcomed and encouraged in the wider Chemistry-Climate Model Initiative (CCMI; Eyring et al., 2013b) and AeroCom projects, but the data will not form part of the official CMIP6 submission.

The total simulation years requested (excluding DECK and simulations in common with other MIPS) are 1628 for Tier 1, 1265 for Tier 2 and 221 for Tier 3.

3.1 Historical (in support of Science question 2.1)

These experiments are designed to quantify the contributions of aerosols and ozone (tropospheric and stratospheric) to climate change over the historical period. For aerosol and tropospheric ozone precursor emissions the model simulations will span

1850-2014, for stratospheric ozone depleting substances (ODSs) the simulations will span 1950-2014, since ODSs only significantly increased after 1950. The latter experiments will enable the relative role of ozone depletion compared to other anthropogenic forcings and natural variability in determining past changes in southern hemisphere summertime climate (WMO, 2014). Note that here we exclude N_2O and CH_4 from the definition of ODSs. Methane and N_2O have indirect climate

5 effects as their chemistry affects tropospheric ozone production, stratospheric ozone chemistry, and aerosol oxidation.

The historical increases in aerosols and tropospheric ozone have inhomogeneous spatial distributions, and the degree of regional temperature and precipitation responses to such heterogeneous forcing remains an open question within the scientific community which these experiments and their pairwise ERF experiments described in Section 3.1.2 should help to answer.

10 These will also enable the community to quantify whether NTCFs, which are primarily located over Northern Hemisphere midlatitude land areas have led to a larger climate response there, relative to forcing from WMGHGs (Shindell 2014). To distinguish between the warming effects of ozone and the cooling effects of aerosols, further experiments separate the two groups. NO_X is a precursor to both ozone and nitrate aerosol, but we choose to allocate it to the ozone precursor group as this is where it has the largest climate impact.

15 The experimental setup has been designed to pair coupled-ocean simulations with specified SST atmosphere-only experiments to calculate the ERFs due to each category of forcing agent (see section 3.1.2 for more details). Comparison between the temperature and precipitation changes in the coupled-ocean simulations with the ERFs (top of atmosphere, and surface) will provide information on the efficacies of the forcings to drive changes in climate.

3.1.1. Transient historical coupled-ocean simulations

20 These simulations parallel *historical*, and differ only by fixing the anthropogenic emissions or concentrations of a specified class of species. All other forcing agents must evolve as in *historical*. Perturbations to the total NTCF emissions (*hist-piNTCF*) or aerosol component (*hist-piAer*) start at the same point in the 1850 control as *historical* with the anthropogenic emissions fixed at that point. Perturbations to the ODSs branch from the *historical* run at 1950 with chlorofluorocarbon and hydrochlorofluorocarbon concentrations fixed at that point (*hist-1950HC*), as specified in Table 1.

25 The individual climate signals from the proposed perturbations are likely to be small compared to internal climate variability, therefore we request at least three ensemble members for each experiment, using different ensemble members of *historical* as the starting points. The climate impacts of the NTCFs, aerosols and ODSs can then be diagnosed by subtracting the perturbed runs from the *historical* climate. Models without interactive chemistry should only run *hist-piAer*, and use the same ozone climatology as *historical*.

30 The total simulation years requested are 684 for Tier 1 and 492 for Tier 2.

3.1.2. Transient historical prescribed SSTs simulations

In order to calculate the ERFs that drive the above climate changes, a set of simulations repeats the above sensitivity runs in 3.1.1, but using atmosphere-only configurations with prescribed sea-surface temperatures (SSTs) and sea-ice. The SSTs and sea ice should be specified as the monthly mean time-evolving values from one ensemble member of the historical simulations.

35 This differs from the usual definition of ERF where the SSTs are specified to be a fixed repeating climatology throughout the simulation, usually taken from a preindustrial control experiment. Including evolving SSTs means that the underlying climate state is consistent with the *historical* simulation that is used as the reference for all these experiments. It is possible that using an inconsistent background climate state such as the pre-industrial control (with different cloud cover and natural emissions) could affect the diagnosed time-varying ERFs. However, such effects are likely to be small (Forster et al., submitted). This is

40 further discussed in section 5.1 The top of atmosphere radiative fluxes in the all forcing prescribed SST historical experiment are not likely to be significantly different from the coupled-ocean historical, but we request this simulation for consistency

with the rest of the experiments. There are tier-2 experiments to calculate separately the ERFs from aerosol and ozone precursors, as specified in Table 2.

The total simulation years requested are 556 for Tier 1 and 492 for Tier 2.

5   The chemical contributions of historical methane and N_2O to radiative forcing have previously been calculated in piecemeal ways (Myhre et al. 2013a). In AerChemMIP, the transient historical ERFs will be calculated for models that have reactive gas chemistry, at least in the troposphere. The ERF pattern from these simulations is expected to be relatively homogeneous, although their chemical effects on ozone and secondary aerosols may be less so. The climate response to homogeneous forcing is quantified in *hist-GHG* (as *historical*, but only the WMGHG forcings evolve) in Detection and Attribution Model

10 Intercomparison Project (DAMIP) so the ERF experiments for methane and N_2O do not need parallel coupled-ocean simulations in AerChemMIP. The ERFs for each species or group of species will be diagnosed by subtracting the top of atmosphere and surface radiative fluxes in the perturbed runs from those in histSST. Models without interactive gas-phase chemistry should only run *histSST-piAer*, and use the same ozone climatology as *histSST*.

15 **3.2. Future simulations (in support of Science question 2.2)**

AerChemMIP further aims to identify the patterns of change in surface temperature and precipitation at the global and regional levels associated with future NTCF mitigation efforts. These experiments focus on the time frame from 2015 to 2055, as this is when reductions in aerosol and ozone precursor emissions are expected to be significant. As well as socio-economic scenarios, the SSPs include representations of different levels of controls on air quality pollutants – low medium and high

20 (Figure 1). To detect the largest signal we choose the reference scenario to be SSP3-7.0 "Regional Rivalry" (experiment *ssp370*) as this has the highest levels of short-lived climate pollutants and "Low" levels of air quality control measures (O'Neill et al. 2016). The *ssp370* ScenarioMIP simulation will need to have been run with the AerChemMIP setup and diagnostics, or repeated here. The perturbation experiment to this within AerChemMIP will use the same socio-economic scenario, but with "High" levels of air quality control measures SSP3-7.0-lowNTCF. The energy use and levels of climate mitigation are the

25 same in these two scenarios. Levels of WMGHGs (including methane) will be unchanged unless they are directly affected by the air quality control measures. Differences in climate, ERF, chemical composition and air quality between the two scenarios will be solely due to the alternative air quality control measures. The specific definition of SSP3-7.0-lowNTCF is still being discussed in collaboration with the ScenarioMIP team. Full details are expected to be available by the final publication of this paper.

30 **3.2.1. Transient future coupled ocean**

The two transient future coupled ocean experiments start in January 2015 from the end of *the historical* simulation and are run for 41 years (to December 2055) following the SSP3-7 and SSP3-7-lowNTCF scenarios for WMGHG and NTCF emissions (experiments *ssp370* and *ssp370-lowNTCF*, see Figure 2 and Table 3). Note the *ssp370* reference simulation is the same as in ScenarioMIP; it is therefore required that the ScenarioMIP *ssp370* is performed using the same model configuration as for

35 AerChemMIP. The climate and air quality signals will be derived by subtracting the experiment ("clean") from the reference. This signal is expected to be globally small (commensurate with a forcing on the order of 0.1 Wm^{-2}, although much larger locally), so at least 3 ensemble members are requested as continuation from existing historical ensemble members.

The total simulation years requested are 123 (all Tier 1).

3.2.2. Transient future prescribed SSTs simulations

As for the historical experiments (section 3.1), the above scenarios (SSP3-7.0 and SSP3-7.0-lowNTCF) are repeated with prescribed SSTs. These SSTs (and sea ice) are taken from the monthly mean evolving values from one of the ensemble members of the coupled *ssp370* run. The differences in radiative fluxes between the reference and "clean" simulations will give the TOA and atmospheric ERFs. Comparison between the magnitudes and patterns of ERF and the previous coupled model simulations will allow quantification of the efficacy of the NTCFs to affect climate.

The contributions of the different groups of NTCFs to future climate will be quantified by further simulations in which only a subset of the emissions follow the "clean" scenario with the rest following the reference SSP3-7.0. All these perturbation experiments are tier 1 (see Figure 3 and Table 4).

An additional experiment (*ssp370SST-lowLu*) will study the atmospheric chemical impacts of land-use changes through natural emissions (biogenic VOCs, fire, dust) and surface uptake. This will be parallel to *ssp370SST* using the same WMGHGs and anthropogenic NTCF emissions, but with land use specified according to the SSP1-2.6 scenario. The ERFs calculated with respect to the *ssp370SST* control will include the effects of albedo changes as well as NTCFs. The pair *ssp370SST - ssp370SST-ssp126Lu* are the prescribed-SST equivalents of the coupled-ocean Land Use Model Intercomparison Project (LUMIP) pair *ssp370 - ssp37-ssp126Lu* (Lawrence et al. 2016).

The total simulation years requested are 205 for Tier 1, 41 for Tier 2 and 41 for Tier 3.

3.3. Timeslice historical ERF simulations (in support of Science questions 2.1 and 2.3)

The quantification of pre-industrial to present day ERFs due to different drivers (such as in Myhre et al. 2013a, figure 8.17) is used widely. The AerChemMIP timeslice experiments will provide the data to generate a consistent table of present day ERFs for the reactive gases and aerosols. The ERFs are calculated by comparing the change in net TOA radiation fluxes between two runs with the same prescribed SSTs, but with NTCF emissions or WMGHGs (methane, N_2O, halocarbons) concentrations perturbed from their preindustrial to present day values. Internal variability (mainly clouds) generates considerable interannual variability in ERFs; therefore, up to 30 years of simulation are needed to characterize the present day ERF from some species (Forster et al, submitted.).

The control simulation for these experiments will use 1850 concentrations of WMGHGs and emissions of NTCFs, run for 30 years in atmosphere-only mode with SSTs and sea-ice prescribed as a (monthly-varying) climatology taken from the pre-industrial control (experiment piClim; see Table 5) following the Radiative Forcing Model Intercomparison Project (RFMIP) specification (Pincus et al., 2016). Provided this experiment is run with the same interactive chemistry and aerosols as the model configuration contributing to AerChemMIP, this will be the same control as in RFMIP. The TOA radiative fluxes from this control are expected to be very similar to the climatology from the coupled pre-industrial control. However, this extra simulation ensures consistency with the ERF definition and with RFMIP.

The perturbation experiments are run for 30 years following the control, using the same control SST and sea-ice, but with the concentrations (for WMGHGs) or emissions (for short-lived species) of the selected species set to present day (2014) values (Table 5). The WMGHG experiments should allow as complete a representation of the chemical effects on aerosol oxidation, tropospheric and stratospheric ozone, and stratospheric water vapour as the models are capable. Note that in this setup methane concentrations are fixed and do not respond to changes in oxidation rate. The ozone ERF estimates are not broken down by their location (tropospheric or stratospheric), but whether they are driven by changes in ozone precursors or ODSs. Models without interactive chemistry should only run *piClim-Aer* and *piClim-BC*, and use the same ozone climatology as *piClim*.

The total simulation years requested are 60 for Tier 1, 180 for Tier 2 and 60 for Tier 3.

3.4. Natural emissions simulations (in support of Science question 2.4)

Climate change will affect the natural emissions of natural NTCFs and reactive WMGHGs. These natural emissions will have a radiative effect and so feedback on to climate change. To simplify the experimental setup, the experiments detailed here simply double the natural emissions. The radiative effect of natural WMGHGs (e.g., methane from natural sources) are not

5 calculated as these can be obtained from experiment *piClim-CH4*. The control simulation is the 30 year 1850 fixed-SST piClim as for the timeslice ERFs. Each experiment parallels the 30 year control except the emission fluxes from an interactive parameterization are doubled (see Table 6). For models that do not interactively parameterize particular emissions, the fluxes from the 1850 climatological dataset should be doubled.

The radiative perturbation from these experiments can be diagnosed with ERF as for anthropogenic components scaled by the

10 simulated changes in fluxes from the DECK $4xCO_2$ and 1% CO_2 to determine the feedback parameter given as Wm^{-2} per K in surface temperature.

The total simulation years requested are 60 for Tier 2 and 120 for Tier 3.

4 Diagnostics

15 The AerChemMIP specific diagnostics are designed to answer the following questions: How large are forcing, feedback and response associated to NTCFs in the models participating in CMIP6 historical and scenario simulations? Which processes and mechanisms need to be represented in the models for a credible description of climate-chemistry-aerosol interactions? How well do models reproduce the observed spatial distribution and historical evolution of NTCF concentrations, depositions, optical properties and observable interactions with climate?

20 To guide the diagnostic process, the data request is structured according to overarching analysis subjects. Categories chosen are: Climate response (CLIM), Forcing (FORC), Feedbacks (FDBCK), Chemistry-Climate Interactions (CC), Air Quality (AQ), Evaluation of model performance (VAL). Considerable experience has been gained in previous model intercomparison exercises (namely CCMVal, CCMI, AeroCom, ACCMIP, Hemispheric Transport of Air Pollution (HTAP) and CMIP5), but all too often model versions were different from those used in CMIP. AerChemMIP provides a unique opportunity to generate

25 a complete data set, requested directly from those GCMs providing climate sensitivity and scenario information to CMIP6. A specific problem may be the expected diversity in model complexity, as mentioned in section 3. Models may contain interactive aerosols, tropospheric chemistry, stratospheric chemistry and any combination of these. AerChemMIP requests all output unless unavailable from an individual model configuration with good reason.

The diagnostics requested for the AerChemMIP experiments are assembled in two Excel sheets (available at

30 https://wiki.met.no/aerocom/aerchemmip/diagnostics), and the definitive and detailed request will be found in the CMIP6 data request (https://earthsystemcog.org/projects/wip/CMIP6DataRequest; Juckes et al., in preparation). Since the AerChemMIP model versions are requested to also perform the DECK experiments, the data request contains suggestions for output limitations for these experiments (see for details final data request). Here we provide an overview along the analysis subjects mentioned above. Suggestions for best practice of diagnosing processes and outputting variables are given in some cases, in

35 particular where previous model intercomparison projects failed to harmonize model output. The specific AerChemMIP request is divided in 6 sheets: AerChemMIP-Mon3d, AerChemMIP-Mon2d, AerChemMIP-MonDay2d, AerChemMIP-hr, AerChemMIP-Zonal2d, AerChemMIP-Zonal. Modellers are asked to read the explanatory notes found for each CF standard name on the CF website and the specific explanatory remarks in the AerChemMIP data request and corresponding excel worksheet.

4.1 Climate (CLIM)

The characterisation of the climate response to NTCF forcing requires a set of diagnostics, which are fairly standard to all CMIP experiments. They include the variables that altogether describe the state of the atmosphere, the ocean and cryosphere, land surfaces including essential biosphere and carbon cycle parameters. We have chosen to request output according to the

5   following tables for all AerChemMIP experiments: Amon, Lmon, day_ss, day_oth, 3hr, cfMon_3dstd, cfMon_2d and cfSites. Oceanic diagnostics are described in the Omon_3d, Omon_oth, but are not needed for the fixed-SST simulations. In addition, we encourage the modellers to provide the output requested by the Dynamical Variability Model Intercomparison Project (DynVarMIP) for specific AerChemMIP simulations that allow for the investigation of the influence of the Antarctic ozone hole on Southern hemisphere surface climate.

10   Specific attention should be devoted to an extension of the COSP simulator data, which AerChemMIP models are encouraged to install. A better understanding of cloud and aerosol interactions may be possible if models add specific diagnostic aerosol calls, consistent with the COSP diagnostic package. Of particular interest is the observable aerosol backscatter coefficient, which provides, since the arrival of the CALIOP satellite lidar in the A-train, a constraint for the global 3D distribution of aerosols. For simplicity modellers are asked to provide 3D daily fields of aerosol extinction and backscatter coefficient for the

15   DECK Atmospheric Model Intercomparison Project (AMIP) period (1979-2014).

4.2 Forcing (FORC)

For a better documentation of which forcing is actually present in a given climate model, several sets of diagnostics are needed: 1) flux parameters providing ERF from fixed-SST simulations, 2) 3D mass mixing ratios and optical thickness in transient simulations, and 3) a repeated aerosol-free call to the radiation code (with aerosol scattering and absorption set to zero) in

20   transient climate simulations (Ghan et al., 2012). The last component is strongly recommended for the reference historical simulation and ERF time slice experiments aimed at diagnosing aerosol forcing, but not essential if it is not possible to implement. Combined with additional RFMIP diagnostics, this will generate a fairly complete forcing characterisation.

ERF will be derived in the 30 year long fixed-SST simulations (see section 3) by investigating clear-sky and all-sky shortwave and longwave fluxes at the top of the atmosphere and at the surface. In the same simulations a range of auxiliary variables are

25   requested which characterise emissions, 3D mass mixing ratios, aerosol optical properties and cloud properties to complement the radiative fluxes with actual composition diagnostics. With these, forcing efficiencies may be established to be used for the interpretation of transient simulations.

Characterising the atmospheric forcing in transient simulations of a fully coupled model poses problems, because the climate system response alters cloud cover, lapse rates and even cryosphere and land surface properties. To first order and for most

30   components atmospheric forcing is proportional to the amount of the species perturbing the pristine atmosphere – with the important exception of interactions involving clouds. 3D fields of mass mixing ratios and column integrated optical thickness for aerosol species allow tracking of the extent to which perturbations are present.

Tracking the anthropogenic fraction of column loads would require additional tracers. For a first order analysis, we will use diagnosed anthropogenic-only emissions to compute the average anthropogenic fraction in transient simulations, as compared

35   to the preindustrial reference in 1850. Some emissions may include natural components, which may have changed along with climate change, such as NO_X from lightning and soil degradation and biogenic volatile organic compounds. Here anthropogenic emissions as such should be output, possibly just as a check for the year 2014 to see if the CMIP emission forcing data set, the pre-industrial emission background and the anthropogenic contribution add up.

The 3D fields of mass mixing ratios provide also the vertical distribution, which are useful for the understanding of forcing

40   components (semi-direct, direct, cloud-aerosol interaction) of heterogeneously distributed species - in particular black carbon and other anthropogenic aerosols. Indeed, positive forcing (warming) and the semi-direct of black carbon has received recently

more attention. 3D fields of black carbon mass mixing ratios and column integrated absorption optical depth have been used widely for analysing the black carbon forcing efficiency.

A source of confusion has been the aerosol optical thickness (AOT) diagnostics (e.g., Flato et al. 2013 figure 9.29) in CMIP models. Natural and anthropogenic aerosols have been blended together in different ways in models. Since dust and sea salt

5   contribute a considerable amount of total aerosol optical thickness, they should be subtracted when the anthropogenic perturbation is going to be analysed. Speciated AOT diagnostics are suggested to provide more insight into the reasons for differences in AOT between models.

Providing 3D fields of mass mixing ratios and AOT consistently will allow to analyse differences in optical property calculation, changes in humidity growth in a changing climate and changing emission patterns. Documenting both in transient

10 climate simulations allows for a rather complete analysis of feedback processes, see below.

Another problem is the different ambient humidity for which AOT is calculated. Some models compute an all-sky AOT, including AOT in cloudy fractions with high humidities, while others restrict output to clear-sky AOT. The latter is preferred here, because it may be compared to that AOT which is observed under clear-sky conditions from satellites and sun photometers. Aerosol radiation interactions are also most effective in clear-sky scenes and it is thus more relevant to base

15 forcing efficiencies on clear-sky AOT.

Aerosol-cloud interactions are still among the most uncertain of forcing components. Here we have selected rather standard parameters which are also used in the Cloud Feedback Model Intercomparison Project (CFMIP) and which allow for a 3D characterisation of cloud fraction, cloud liquid water path and cloud as well as ice number concentrations. The fixed-SSTs approach can further be applied with additional radiation calls to diagnose the various aerosol-cloud effects (Ghan et al., 2012).

20 Most models will provide all-sky and clear-sky radiative fluxes, by computing fluxes with a repeated double call to the radiation routine neglecting cloud scattering. Here we propose a repeated "aerosol-free" call invoking this all-sky / clear sky double call to radiation once more, by setting the aerosol scattering and absorption properties to zero. Fluxes for this repeated call have to be stored separately. To limit computational burden we propose to invoke this call during the DECK historical simulation and the aerosol-oriented ERF experiments. This repeated clean-aerosol call allows the establishment of a fairly

25 accurate split of aerosol forcing into direct and indirect forcing, including estimates of e.g. aerosol absorption effects above clouds (Ghan, 2013, Vuolo et al., 2014). In all cases, separate diagnostics for shortwave and longwave changes are applied.

4.3 Feedback (FDBK)

Feedback processes are suspected to change natural emissions of reactive gases and aerosols. These emission changes may happen in humid or wet climates and may alter thus loads with different effectivity. The short-lived nature of dust, sea salt,

30 biogenic gases and aerosols as well as reactive nitrogen components will exert a rather rapid feedback loop if triggered. A thorough documentation of emissions and 3D fields is needed.

To relate natural emission changes to forcing, specific experiments are designed in AerChemMIP which resemble the ERF experiments. In these feedback experiments radiation flux and cloud variables are requested as in the ERF forcing experiments. Several variables are added which allow the analysis of processes (fires, dynamics, volcanic perturbation, land cover change,

35 sea ice change) involved in the feedback process. Deposition of nutrients such as nitrogen and dust has been suspected to be involved in feedback processes. Their output is thus requested too.

4.4 Chemistry-climate interactions (CC)

Chemistry-climate interactions involve impacts of composition on climate (as discussed in 4.1, CLIM), but also crucially the

40 effect of climate change on atmospheric composition (here treated within the analysis subject CC), which happens through both changes in transport and chemistry. The availability of stratosphere-troposphere resolving chemistry-climate model

simulations thereby provides the unique opportunity to look at these chemistry-climate interactions in a more comprehensive way than what was hitherto possible based on the models contributing to CMIP5. The stratosphere has been identified as potentially important contributor to model-differences for both tropospheric ozone (Young et al., 2013) and the OH budget (Voulgarakis et al., 2013). Particular focus within AerChemMIP will be placed on the study of how physical climate parameters

5 such as temperature, wind, clouds, and precipitation affect tropospheric composition and the oxidizing capacity of the atmosphere in addition to changing emissions. To study and disentangle key processes that lead to model differences, a comprehensive list of monthly mean 3D-output of key meteorological parameters (standard variables temperature and precipitation, convective mass fluxes (mcu), lightning NOx production (emilnox) and chemical species (also annual loss terms of methane, carbon monoxide, and nitrous oxides) is requested. In addition, a set of new transport tracers will help to track

10 changes in tropospheric transport (including the artificial tracers aoa_nh and nh_50). In the coupled troposphere-stratosphere system, climate will affect tropospheric composition and its oxidation capacity also through changes in the stratospheric circulation and resulting changes in the stratospheric distribution of ozone and stratosphere-troposphere transport of ozone (Collins et al. 2003; Stevenson et al., 2006; Hegglin and Shepherd, 2009). A tagged stratospheric ozone variable (o3ste) is defined to diagnose stratosphere-troposphere exchange, with the simulations *hist-1950HC* and *histSST-1950HC* designed to

15 help disentangle the impact of ODSs and climate change on the stratospheric influence on tropospheric composition. Loss terms of CO, CH$_4$, O$_3$ and N$_2$O are suggested to help interpretation of their budget in a changing climate.

4.5 Air Quality (AQ)

The simulations in the AerChemMIP provide the opportunity to retrieve from historical and scenario runs air quality related parameters which relate the broadly used CMIP emissions to a transient description of climate to air quality metrics. An

20 ensemble of models can be used to establish consequences for air quality. Most interest is on particulate matter concentrations and high ozone peaks. Since air pollution standards have been defined as exceedances for a given time window, we request hourly data at surface level for some few key substances, such as ozone, PM$_{25}$ and NO$_2$. From these frequencies of daily maximum, diurnal cycles in different climate regimes, boundary layer characteristics can be obtained, which do characterise the model also in terms of chemical reactivity but also with respect to boundary layer mixing. The output is required for the

25 fully coupled *historical* and the two SSP3-7.0 scenarios.

4.6 Evaluation (EVAL)

Part of the output requested refers to variables which have been observed by observational networks or satellite sensors. Comparison to these data will enable investigation of model bias, but may also help to rank models with respect to their ability to capture critical variability. The output is strictly only useful for the "observational period", which comprises for reactive

30 gases and aerosols roughly the period after 1980. Modellers are encouraged to have increased output for evaluation in the AMIP period (1979-2014). However, for deposition (dust, sulphate, nitrate, BC) the instrumental record is longer through cores retrieved from glaciers and ocean as well as lake sediments. If possible, modellers may restrict output according to these rough guidelines.

Of particular importance are variables as assembled in the framework of Global Atmospheric Watch (GAW) and observations

35 for Model Intercomparison Projects (obs4MIP) (Teixeira et al., 2014; Ferraro et al., 2015). Several variables are included as being essential for forcing, feedback, chemistry climate interactions and air quality analysis. Outputting such variables would serve therefore multiple purposes. Specific constraints are possible from an observational angle by adding in addition: aerosol optical thickness at several wavelengths, 3D backscatter coefficients and extinction coefficients, mass mixing ratios of chemical precursors to aerosols and ozone.

AerChemMIP will ensure that the requested variables are analysed by contributing chemistry-aerosol diagnostics to the development of the Earth System Model Evaluation Tool (ESMValTool; Eyring et al., 2016b; Righi et al., 2015) and the AeroCom tools (Textor et al., 2006, Schulz et al., 2006), and by applying them to the CMIP6 model simulations.

5 Relations with other MIPs

5.1 Radiative Forcing MIP (RFMIP)

There are considerable synergies between AerChemMIP and RFMIP (Pincus et al., 2016). RFMIP addresses the ERF due to all drivers for the historical and future periods. AerChemMIP specifically looks to quantify the ERFs for reactive species and aerosols, and to separate individual components of these. RFMIP also contains other components related to the assessment of model radiation code performance and simulations with prescribed aerosol distributions and aerosol optical properties for *historical* following a similar philosophy to the "Easy Aerosol" project.

For the prescribed-SST experiments to diagnose transient ERFs, RFMIP uses the pre-industrial conditions as the reference and perturbs one group of species at a time to evolve following *historical* (e.g. in *piClim-histaerO3*); consequently RFMIP specifies a pre-industrial SST and sea ice climatology. AerChemMIP uses the evolving conditions (*historical*) as the reference with one group of species perturbed back to the pre-industrial conditions (e.g. in *histSST-piNTCF*); therefore AerChemMIP specifies a time evolving monthly SST and sea ice distribution taken from a coupled *historical* experiment. The impacts of different approaches for specifying SSTs and sea ice on the total ERF over the satellite era have been estimated to be small in one climate model (Forster et al., submitted).

For models with interactive chemistry, *piSSTclim-NTCF* and *piSSTclim-aerO3* are identical and only need to be run once. For models without interactive chemistry, RFMIP specifies that *piSSTclim-aerO3* uses the present day tropospheric and stratospheric ozone climatology, whereas AerChemMIP specifies that *piSSTclim-NTCF* uses the control (pre-industrial) ozone climatology.

5.2 Detection and Attribution MIP (DAMIP)

There is some overlap between the AerChemMIP coupled model experiments and those requested in DAMIP (Gillett et al. 2016). For example, AerChemMIP requires the extra *historical* runs from DAMIP to increase the ensemble size to at least 3 members.

The DAMIP historical runs use the pre-industrial as the control and have one class of species evolving at a time (e.g. *histAer* parallels *historical*, but with only aerosol forcing evolving) with all others fixed to pre-industrial levels. In contrast, AerChemMIP uses *historical* as the control and fixes one class of species at a time to pre-industrial levels (e.g. *hist-piAer*).

The DAMIP *hist-stratO3* run has only stratospheric ozone evolving, using either the prescribed CMIP6 ozone dataset (Hegglin et al., in prep.) or ozone output from the previous historical run. In the troposphere ozone is fixed to pre-industrial levels. The equivalent experiment for the models with stratospheric chemistry in AerChemMIP fixes halocarbon concentrations at 1950s levels allowing the model chemistry to generate the difference in ozone compared to *historical*. DAMIP will use SSP2-4.5 as its future scenario, with *ssp245-ghg* and *ssp245ae*r as variants, so this does not overlap with the AerChemMIP future experiments.

5.3 Other MIPs

The future scenario SSP3-7.0 (experiment *ssp370*) is prescribed as a tier 1 scenario in ScenarioMIP (O'Neil et al., 2016), with extra ensemble members as tier 2. A total of three members (using the AerChemMIP model configuration) are required as the baseline for the AerChemMIP future experiments.

The future land-use ERF calculations in AerChemMIP (section 3.2.2) parallel the full climate land-use perturbation in LUMIP (Lawrence et al., 2016). If the same model configurations are used for both, this will allow direct quantification of the efficacy of land-use changes.

6 Summary

5 Advances in climate model development mean that for CMIP6 a larger set of climate models will include interactive simulation of aerosols than at the time of CMIP5, and many will include interactive chemistry of the troposphere and/or stratosphere. AerChemMIP has therefore been designed to quantify the effects of these NTCFs and reactive WMGHGs on climate and also on atmospheric composition and surface air quality.

A focus is on comparing the climate responses (both global and regional) to the heterogeneous forcing patterns generated by
10 changes in emissions of NTCFs and their precursors over the historical period and in future scenarios. The future scenarios consist of a pair differing only in their levels of ambition in air quality policy. The results from these will provide information on the impacts of air quality policies on climate. The forcings are characterised by the ERFs using model simulations with fixed SSTs and sea ice; the responses are characterised by changes in surface temperature and precipitation (amongst others) using model simulations with coupled oceans.

15 AerChemMIP will identify the contributions to the present day climate (in terms of ERF) made by aerosol emissions, tropospheric ozone production, stratospheric ozone depletion, and changes in the reactive gases methane and nitrous oxide. To add to the forcing-response relationships AerChemMIP will also provide information on climate feedbacks by calculating the radiative effect of natural emissions of aerosols or ozone precursors in the same way as ERFs of anthropogenic species. Combining these ERFs with diagnosed changes in natural emissions from 1pctco2 or abrupt4co2 would give the climate
20 feedback parameters. AerChemMIP is therefore key to understanding the behaviours of models with aerosols and chemistry in CMIP6 and we would encourage all such models to participate.

Data Availability

The climate model output from AerChemMIP experiments described in this paper will be distributed through the Earth System Grid Federation (ESGF) with DOIs assigned. As in CMIP5, the model output will be freely accessible through data portals
25 after registration. In order to document CMIP6's impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6 and the participating modelling groups (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip). In order to run the experiments, datasets for natural and anthropogenic forcings are required. These forcing datasets are described in separate invited contributions to this Special Issue. The forcing datasets will be made available through the ESGF with version control and DOIs assigned.

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35 ## References

Arblaster, J. M., and Meehl G. A.:, Contributions of external forcings to southern annular mode trends, J. Clim., 19, 2896–2905, doi:10.1175/JCLI3774.1, 2006

Archibald, A. T., Cooke, M. C., Utembe, S. R., Shallcross, D. E., Derwent, R. G., and Jenkin, M. E.: Impacts of mechanistic changes on HO$_x$ formation and recycling in the oxidation of isoprene, Atmos. Chem. Phys., 10, 8097-8118, doi:10.5194/acp-10-8097-2010, 2010.

Arneth, A., Harrison, S. P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P. J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S., Vesala, T: Terrestrial biogeochemical feedbacks in the climate system, Nature Geosci., 3, 525–532, 2010

Banerjee, A., Maycock A. C., Archibald A. T., Abraham N. L., Telford, P., Braesicke P., and Pyle J.A.:. Drivers of changes in stratospheric and tropospheric ozone between year 2000 and 2100, Atmos. Chem. Phys., 16, DOI: 10.5194/acp-16-2727-2016, 2016

Bollasina, M. A., Ming, Y., and Ramaswamy V.: Earlier onset of the Indian monsoon in the late twentieth century: The role of anthropogenic aerosols, Geophys. Res. Lett., 40, 3715–3720, doi:10.1002/grl.50719, 2013

Bond, T. C., et al.: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res., 118, 5380–5552, doi:10.1002/jgrd.50171, 2013

Boucher, O., et al., Clouds and Aerosols, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, pp. 571-657, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 2013

Cameron-Smith, P., Elliott S., Maltrud M., Erickson D., and Wingenter O.: Changes in dimethyl sulfide oceanic distribution due to climate change, Geophys. Res. Lett., 38, L07704, doi:10.1029/2011GL047069, 2011

Carlton, A.G., Pinder R. W., Bhave P. V., and Pouliot G. A.: To what extent can biogenic SOA be controlled?, Environ. Sci. Technol., 44, 3376–3380, doi:10.1021/es903506b, 2010

Carslaw, K. S., Lee L. A., Reddington C. L., Pringle K. J., Rap A., Forster P. M., Mann G. W., Spracklen D. V., Woodhouse M. T., Regayre L. A., Pierce J. R.: Large contribution of natural aerosols to uncertainty in indirect forcing. Nature, 503, 7474, 10.1038/nature12674, 2013

Cionni, I., Eyring, V., Lamarque, J. F., Randel, W. J, Stevenson, D. S., Wu, F., Bodeker, G. E., Shepherd, T. G., Shindell, D. T., Waugh, D. W.: Ozone database in support of CMIP5 simulations: results and corresponding radiative forcing, Atmos. Chem. Phys., 11, 11267-11292, 2011

Collins, W.J., Derwent, R.G., Garnier, B., Johnson, C.E., Sanderson, M.G., Stevenson, D.S.,. The effect of stratosphere–troposphere exchange on the future tropospheric ozone trend. Journal of Geophysical Research 108. doi:10.1029/2002JD002617, 2003

Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S.: Development and evaluation of an Earth-System model – HadGEM2, Geosci. Model Dev., 4, 1051–1075, doi:10.5194/gmd-4-1051-2011, 2011.

Eyring, V., et al.,: Multimodel projections of stratospheric ozone in the 21st century. *J. Geophys. Res. Atmos.*, 112, D16303, 2007

Eyring, V., et al.: Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments, SPARC Newsletter, *40*, 48-66, 2013a

Eyring, V., Arblaster J. M., Cionni I., Sedlacek J., Perlwitz J., Young P. J., Bekki S., Bergmann D., Cameron-Smith P., Collins W. J., Faluvegi G., Gottschaldt K.-D., Horowitz L. W., Kinnison D. E., Lamarque J.-F., Marsh D. R., Saint-Martin D., Shindell D. T., Sudo K., Szopa S., and Watanabe S.:, Long-term ozone changes and associated climate impacts in CMIP5 simulations, J. Geophys. Res. Atmos, 118, 5029-5060, 2013b

Eyring, V., Bony, S., Meehl, G. A., Senior, C., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958, doi:10.5194/gmd-9-1937-2016, 2016a.

Eyring, V., Righi, M., Lauer, A., Evaldsson, M., Wenzel, S., Jones, C., Anav, A., Andrews, O., Cionni, I., Davin, E. L., Deser,
5   C., Ehbrecht, C., Friedlingstein, P., Gleckler, P., Gottschaldt, K.-D., Hagemann, S., Juckes, M., Kindermann, S., Krasting, J., Kunert, D., Levine, R., Loew, A., Mäkelä, J., Martin, G., Mason, E., Phillips, A. S., Read, S., Rio, C., Roehrig, R., Senftleben, D., Sterl, A., van Ulft, L. H., Walton, J., Wang, S., and Williams, K. D.: ESMValTool (v1.0) – a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP, Geosci. Model Dev., 9, 1747-1802, doi:10.5194/gmd-9-1747-2016, 2016b.

10 Ferraro, R., Waliser, D. E., Gleckler, P., Taylor, K. E., and Eyring, V.: Evolving obs4MIPs to Support the Sixth Coupled Model Intercomparison Project (CMIP6), B Am Meteorol Soc, doi: 10.1175/BAMS-D-14-00216.1, 2015.

Fiore, A. M., Naik V., Spracklen D., Steiner A., Unger N., Prather M., Bergmann D., Cameron-Smith P. J., Collins W., Dalsøren S., Folberth G., Ginoux P., Horowitz L. W., Josse B., Lamarque J.-F., Nagashima T., O'Connor F., Rumbold S., Shindell D. T., Skeie R. B., Sudo K., Takemura T., Zeng G.: Global Air Quality and Climate, Chemical Society Reviews, 41,
15 6663-6683, doi: 10.1039/C2CS35095E, 2012

Fiore, A.M., Naik V., Leibensperger E.M.: Air quality and climate connections J. Air Waste Manag. Assoc., 65 pp. 645–685, doi:10.1080/10962247.2015.1040526, 2015

Flato, G., Marotzke J., Abiodun B., Braconnot P., Chou S.C., Collins W., Cox P., Driouech F., Emori S., Eyring V., Forest C., Gleckler P., Guilyardi E., Jakob C., Kattsov V., Reason C. and Rummukainen M: Evaluation of Climate Models. In: Climate
20 Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013

Forster, P., et al.: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical
25 Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 129-234 , 2007

Forster, P.M., Richardson, T., Maycock, A.C., Smith, C.J., Samset, B.H., Myhre, G., Andrews, T., Pincus, R., Schultz, M.: Recommendations for diagnosing effective radiative forcing from climate models for CMIP6, J. Geophys. Res., submitted.

30 Gauss, M., Myhre, G., Pitari, G., et al.: Radiative forcing in the 21st century due to ozone changes in the troposphere and lower stratosphere, J. Geophys. Res., 108, 4292, doi:10.1029/2002JD002624, 2003

Gauss, M., et al.: Radiative forcing since preindustrial times due to ozone changes in the troposphere and the lower stratosphere, Atmos. Chem. Phys., 6, 575–599, 2006

Ghan, S. J., Liu X., Easter R. C., Zaveri R., Rasch P. J., Yoon J.-H., and Eaton B.: Toward a minimal representation of aerosols
35 in climate models: Comparative decomposition of aerosol direct, semi-direct and indirect radiative forcing, J. Clim., 25, 6461–6476, doi: 10.1175/JCLI-D-11-00650.1, 2012

Ghan, S. J.: Technical Note: Estimating aerosol effects on cloud radiative forcing, Atmos. Chem. Phys., 13, 9971-9974, doi:10.5194/acp-13-9971-2013, 2013.

Ghan, S., Wang, M., Zhang, S., Ferrachat, S., Gettelman, A., Griesfeller, J., Kipling, Z., Lohmann, U., Morrison, H., Neubauer,
40 D., Partridge, D. G., Stier, P., Takemura, T., Wang, H., Zhang, K.: Challenges in constraining anthropogenic aerosol effects on cloud radiative forcing using present-day spatiotemporal variability, Proceedings of the National Academy of Sciences, 2016

Gillett N. P., Shiogama H., Funke B., Hegerl G., Knutti R., Matthes K., Santer B. D., Stone D., and Tebaldi C.: Detection and Attribution Model Intercomparison Project (DAMIP). Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-74, 2016.

45 Granier, C., Bessagnet, B., Bond, T., D'Angiola, A., Denier van der Gon, H., Frost, G. J., Heil, A., Kaiser, J. W., Kinne, S.,Klimont, Z., Kloster, S., Lamarque, J.-F., Liousse, C., Masui, T., Meleux, F., Mieville, A., Ohara, T., Raut, J.-C., Riahi, K.,

Schultz, M. G., Smith, S. J., Thompson, A., van Aardenne, J., van der Werf, G. R., and van Vuuren, D. P.: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period, Climatic Change, 109, 163–190, doi:10.1007/s10584-011-0154-1, 2011.

Gregory, J. M., Ingram W. J, Palmer M. A., Jones G. S., Stott P. A., Thorpe R. B., Lowe J. A., Johns T. C., and Williams K. D.: A new method for diagnosing radiative forcing and climate sensitivity, Geophysical Research Letters, 31(3), L03205, 2004

Hwang, Y. T., Frierson D. M., and Kang S. M.: Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century, *Geophys. Res. Lett.*, 40, 2845–2850, doi:10.1002/grl.50502, 2013

IPCC: Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios, J.T. Houghton, L.G. Meira Filho, J. Bruce, Hoesung Lee, B.A. Callander, E. Haites, N. Harris and K. Maskell (eds.). Cambridge University Press, Cambridge, UK, 339 pp., 1994

IPCC: Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 572 pp., 1996

IPCC: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of WorkingGroup III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014

Hegglin, M. I., and Shepherd T. G.: Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux, Nature Geosci., 2, 687–691, 2009

Isaksen, I.S.A., Granier C., Myhre G., Berntsen T.K., Dalsøren S.B., Gauss M., Klimont Z., Benestad R., Bousquet P., Collins W.: Atmospheric composition change: climate–chemistry interactions, Atmos. Environ., 4, 5138–5192, 2009

Jacob, D.J., Winner D.A., Effect of climate change on air quality, *Atmos. Environ.*, 43, 51–63. doi:10.1016/j.atmosenv.2008.09.05, 2009

Kinne, S., Schulz M., Textor C., Guibert S., Balkanski Y., Bauer S.E., Berntsen T., Berglen T.F., Boucher O., Chin M., Collins W., Dentener F., Diehl T., Easter R., Feichter J., Fillmore D., Ghan S., Ginoux P., Gong S., Grini A., Hendricks J., Herzog M., Horowitz L., Isaksen I., Iversen T., Kirkevåg A., Kloster S., Koch D., Kristjansson J.E., Krol M., Lauer A., Lamarque J.F., Lesins G., Liu X., Lohmann U., Montanaro V., Myhre G., Penner J., Pitari G., Reddy S., Seland O., Stier P., Takemura T., and Tie X.: An AeroCom initial assessment optical properties in aerosol component modules of global models. Atmos. Chem. Phys., 6, 1815-1834, 2006

Kirtman, B., et al.: *Chapter 11. Near-term Climate Change: Projections and Predictability in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press Cambridge, United Kingdom, 2013

Lamarque, J. F., et al.: The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): Overview and description of models, simulations and climate diagnostics. *Geosci. Model Dev.*, 6, 179–206 , 2013

Langner, J. and Rodhe H.: A global three-dimensional model of the tropospheric sulphur cycle. *J. Atmos. Chem.*, 13, 255-263 , 1991

Lawrence, D. M., Hurtt, G. C., Arneth, A., Brovkin, V., Calvin. K. V., Jones, A. D., Jones, C. D., Lawrence, P. J., de Noblet-Ducoudré, N., Pongratz, J., Seneviratne, S. I., Shevliakova, E.: The Land Use Model Intercomparison Project (LUMIP): Rationale and experimental design, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-76, 2016.

Leibensperger, E. M., Mickley, L. J., Jacob, D. J., Chen, W.-T., Seinfeld, J. H., Nenes, A., Adams, P. J., Streets, D. G., Kumar, N., and Rind, D.: Climatic effects of 1950–2050 changes in US anthropogenic aerosols – Part 2: Climate response, Atmos. Chem. Phys., 12, 3349–3362, doi:10.5194/acp-12-3349-2012, 2012

Levy, H., Horowitz L. W., Schwarzkopf M. D., Ming Y., Golaz J.-C., Naik V., and Ramaswamy V.: The roles of aerosol direct and indirect effects in past and future climate change, *J. Geophys. Res. Atmos.*, 118, 4521–4532, doi:10.1002/jgrd.50192, 2013

Marvel, K., Schmidt, G.A., Miller, R.L., Nazarenko, L.S.: Implications for climate sensitivity from the response to individual forcings. *Nature Climate Change*, 6, doi:10.1038/nclimate2888, 2016

5 McCoy et al. Natural aerosols explain seasonal and spatial patterns of Southern Ocean cloud albedo, *Sci. Adv.*;1:e1500157, 2015

McLandress, C., Shepherd T. G., Scinocca J. F., Plummer D. A., Sigmond M., Jonsson A. I., and Reader M. C.: Separating the dynamical effects of climate change and ozone depletion. Part II Southern Hemisphere troposphere, *J. Clim.*, 24(6), 1850–1868, 2011

10 Myhre, G., et al.: Anthropogenic and Natural Radiative Forcing, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, pp. 659-740, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013a

Myhre, G., Samset, B. H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., Bian, H., Bellouin, N., Chin, M., Diehl, T.,
15 Easter, R. C., Feichter, J., Ghan, S. J., Hauglustaine, D., Iversen, T., Kinne, S., Kirkevåg, A., Lamarque, J.-F., Lin, G., Liu, X., Luo, G., Ma, X., Penner, J. E., Rasch, P. J., Seland, Ø., Skeie, R. B., Stier, P., Takemura, T., Tsigaridis, K., Wang, Z., Xu, L., Yu, H., Yu, F., Yoon, J.-H., Zhang, K., Zhang, H., and Zhou, C.: Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations, Atmos. Chem. Phys., 13, 1853-1877, doi:10.5194/acp-13-1853-2013, 2013b.

Naik, V., Voulgarakis, A., Fiore, A. M., Horowitz, L. W., Lamarque, J.-F., Lin, M., Prather, M. J., Young, P. J., Bergmann,
20 D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsøren, S. B., Doherty, R., Eyring, V., Faluvegi, G., Folberth, G. A., Josse, B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., van Noije, T. P. C., Plummer, D. A., Righi, M., Rumbold, S. T., Skeie, R., Shindell, D. T., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., and Zeng, G.: Preindustrial to present-day changes in tropospheric hydroxyl radical and methane lifetime from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys., 13, 5277–5298, doi:10.5194/acp-13-5277-2013, 2013.

25 Olson, J., Prather M., Berntsen T., Carmichael G., Chatfield R., Connell P., Derwent R., Horowitz L., Jin S., Kanakidou M., Kasibhatla P., Kotamarthi R., Kuhn M., Law K., Penner J., Perliski L., Sillman S., Stordal F., Thompson A., and Wild O.: Results from the Intergovernmental Panel on Climatic Change Photochemical Model Intercomparison (PhotoComp) J. Geophys., Res., 102, D5, 5979-5991, 1997

O'Neill, B.C., Tebaldi C., van Vuuren D., Eyring V., Friedlingstein P., Hurtt G., Knutti R., Kriegler E., Lamarque J.-F., Lowe,
30 J. Meehl J., Moss R., Riahi K., and. Sanderson B. M, The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev. Discuss.,* doi:10.5194/gmd-2016-84, 2016

Penner, J.E., et al.: Aerosols, their direct and indirect effects. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 289–348, 2001

35 Pincus, R., Forster, P.M., Stevens, B.: The Radiative Forcing Model Intercomparison Project, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-88, 2016

Polvani, L. M., Waugh D. W., Correa G. J. P., and Son S. W.: Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere, *J. Clim.*, 24(3), 795–812, 2011

Prather, M., et al. Atmospheric Chemistry and Greenhouse Gases, in Climate Change 2001: The Scientific Basis,
40 edited by: Houghton, J. T., Ding, Y., Griggs, D. J., et al., Cambridge University Press, Cambridge, UK, pp. 239–287, 2001

Racherla P.N., Adams P.J.: Sensitivity of global tropospheric ozone and fine particulate matter concentrations to climate change, J. Geophys. Res., 111 [D24103], 2006

Ramaswamy, V., et al.: Radiative forcing of climate change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J.T. Houghton, Y. Ding,
45 D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 349-416., 2001

Righi, M., V. Eyring, K.-D Gottschaldt, C. Klinger, F. Frank, P. Jöckel, and I. Cionni, Quantitative evaluation of ozone and selected climate parameters in a set of EMAC simulations, Geosci. Model Dev., 8, 733-768, doi:10.5194/gmd-8-733-2015, 2015.

5   Rotstayn, L., Collier M., Shindell D., and Boucher O., Why does aerosol forcing control historical global-mean surface temperature change in CMIP5 models?, J. Climate, 28, 6608-6625, 2015.

Schulz, M., Textor C., Kinne S., Balkanski Y., Bauer S., Berntsen T., Berglen T., Boucher O., Dentener F., Grini A., Guibert S., Iversen T., Koch D., Kirkeveg A., Liu X., Montanaro V., Myhre G., Penner J., Pitari G., Reddy S., Seland X., Stier P., and Takemura T.: Radiative forcing by aerosols as derived from the AeroCom present-day and pre-industrial simulations. Atmos
10   Chem Phys, 6, 5225-5246, 2006.

Sherwood, S. C., Bony S., and Dufresne J. L.: Spread in model climate sensitivity traced to atmospheric convective mixing, *Nature*, 505, 37-42, 2014

Sherwood, S., Bony S., Boucher O., Bretherton C., Forster P., Gregory J., and Stevens B.: Adjustments to the forcing-feedback framework for understanding climate change, Bull. Amer. Meteorol. Soc., 96, 217-228, 2015.

15   Shindell, D. T.: Inhomogeneous forcing and transient climate sensitivity, *Nature Climate Change*, 4, 274–277, doi:10.1038/nclimate2136, 2014

Shindell, D., et al.: Simultaneously mitigating near-term climate change and improving human health and food security, *Science*, 335, 183–189, 2012a

Shindell, D. T., Voulgarakis A., Faluvegi G., and Milly G.: Precipitation response to regional radiative forcing. Atmos. Chem.
20   Phys., 12, 6969-6982, 2012b

Shindell, D. T., Lamarque J.-F., Schulz M., Flanner M., Jiao C., Chin M., Young P. J., Lee Y., Milly G., Faluvegi G., Balkanski Y., Collins W. J.,. Conley A. J, Dalsoren S., Easter R., Ghan S. J., Horowitz L., Liu X., Myhre G., Nagashima T., Naik V., Rotstayn L., Rumbold S., Skeie R., Sudo K., Szopa S., Takemura T., Yoon J.-H.: Radiative forcing in the ACCMIP historical and future climate simulations, Atmos. Chem. Phys., 13, 2939-2974, doi:10.5194/acp-13-2939-2013, 2013a.

25   Shindell, D. T., Faluvegi G.,. Nazarenko L, Bowman K., Lamarque J.-F., Voulgarakis A., Schmidt G., Pechony O., Reudy R., Attribution of historical whole atmosphere ozone forcing. Nature Climate Change, 3, 567–570, doi:10.1038/nclimate1835, 2013b.

Shindell, D. T., Faluvegi, G., Rotstayn, L., Milly, G., Spatial patterns of radiative forcing and surface temperature response, *J. Geophys. Res.*, 120, 5385-5403, 2015

30   Shine, K. P., Bourqui, M. S., de Forster, P. M., Hare, S. H. E., Langematz, U., Braesicke, P., Grewe, V., Ponater, M., Schnadt, C., Smith, C. A., Haigh, J. D., Austin, J., Butchart, N., Shindell, D. T., Randel, W. J., Nagashima, T., Portmann, R. W., Solomon, S., Seidel, D. J., Lanzante, J., Klein, S., Ramaswamy, V., and Schwarzkopf M. D.: A comparison of model-simulated trends in stratospheric temperatures, Q. J. Roy. Meteorol. Soc., 129, 1565–1588, 2003

Smith, S. J., van Aardenne, J., Klimont, Z., Andres, R. J., Volke, A., and Delgado Arias, S.: Anthropogenic sulfur dioxide
35   emissions: 1850–2005, Atmos. Chem. Phys., 11, 1101-1116, doi:10.5194/acp-11-1101-2011, 2011.

Son, S.-W., Polvani L. M., Waugh D. W., Akiyoshi H., Garcia R., Kinnison D., Pawson S., Rozanov E., Shepherd T. G., and Shibata K.: The impact of stratospheric ozone recovery on the Southern hemisphere westerly jet, *Science*, 320, 1486-1489., 2008

Son, S.-W., Gerber E. P., Perlwitz J., et al.: Impact of Stratospheric Ozone on Southern Hemisphere Circulation Change: A
40   Multimodel Assessment, J. Geophys. Res., 115, D00M07, doi:10.1029/2010JD014271 , 2010

SPARC: SPARC CCMVal Report on the Evaluation of Chemistry-Climate Models. V. Eyring, T. Shepherd and D. Waugh (Eds.), SPARC Report No. 5, WCRP-30/2010, WMO/TD - No. 40, available at www.sparc-climate.org/publications/sparc-reports/, 2010

Stevenson, D. S., et al.: Multimodel ensemble simulations of present-day and near-future tropospheric ozone. J. Geophys. Res. Atmos., 111, D08301, 2006

Stevenson, D. S., et al.: Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys., 13, 3063-3085, doi:10.5194/acp-13-3063-2013, 2013

Teixeira, J., Waliser, D., Ferraro, R., Gleckler, P., Lee, T., and Potter, G.: Satellite Observations for CMIP5: The Genesis of Obs4MIPs, B Am Meteorol Soc, 95, 1329-1334, 2014.

Teng H., Washington W. M., Branstator G., Meehl G. A., and Lamarque J. F.: Potential impacts of Asian carbon aerosols on future US warming, Geophys. Res. Lett., 39, L11703, doi:10.1029/2012GL051723, 2012

Textor, C., Schulz M., Guibert S., Kinne S., Balkanski Y., Bauer S., Berntsen T., Berglen T., Boucher O., Chin M., Dentener F., Diehl T., Easter R., Feichter H., Fillmore D., Ghan S., Ginoux P., Gong S., Grini A., Hendricks J., Horowitz L., Huang P., Isaksen I., Iversen T., Kloster S., Koch D., Kirkevåg A., Kristjansson J.E., Krol M., Lauer A., Lamarque J.F., Liu X., Montanaro V., Myhre G., Penner J., Pitari G., Reddy S., Seland Ø., Stier P., Takemura T., and Tie X.: Analysis and quantification of the diversities of aerosol life cycles within AeroCom, Atmos. Chem. Phys., 6, 1777-1813, 2006

Voulgarakis, A., Naik, V., Lamarque, J.-F., Shindell, D. T., Young, P.J., Prather, M. J., Wild, O., Field, R. D., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsøren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Folberth, G. A., Horowitz, L.W., Josse, B., MacKenzie, I. A., Nagashima, T., Plummer, D. A., Righi, M., Rumbold, S. T., Stevenson, D. S., Strode, S. A., Sudo, K., Szopa, S., and Zeng, G.: Analysis of present day and future OH and methane lifetime in the ACCMIP simulations, Atmos. Chem. Phys., 13, 2563–2587, doi:10.5194/acp-13-2563-2013, 2013.

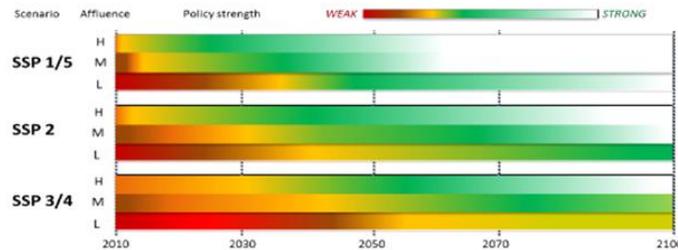
Vuolo, M. R., Schulz, M., Balkanski, Y., and Takemura, T.: A new method for evaluating the impact of vertical distribution on aerosol radiative forcing in general circulation models, Atmos. Chem. Phys., 14, 877-897, doi:10.5194/acp-14-877-2014, 2014.

WMO: Scientific Assessment of Ozone Depletion 2010. Global Ozone Research and Monitoring Project Report, 52. World Meteorological Organisation, Geneva, 2010.

WMO: Scientific Assessment of Ozone Depletion 2014. Global Ozone Research and Monitoring Project Report, 55. World Meteorological Organisation, Geneva, 2014.

Young, P. J., Archibald, A. T., Bowman, K. W., Lamarque, J. F., Naik, V., Stevenson, D. S., Tilmes, S., Voulgarakis, A., Wild, O., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsoren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Horowitz, L. W., Josse, B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Plummer, D. A., Righi, M., Rumbold, S. T., Skeie, R. B., Shindell, D. T., Strode, S. A., Sudo, K., Szopa, S., and Zeng, G.: Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys., 13, 2063-2090, 10.5194/acp-13-2063-2013, 2013.

Air pollution policy assumptions (Storylines, exposure, targets)

Policy Strength	Policy Targets (exposure/concentrations)		Technological Innovation
	High Income Countries	*Medium and Low Income*	
Strong	Much lower than current targets in order to minimize adverse effects on both general population, vulnerable groups, and ecosystems.	Comparatively quick catch-up with the developed world (relative to income)	Pollution control technology costs drop substantially with control performance increasing.
Central	Lower than current targets	Catch-up with the developed world at income levels lower than when OECD countries began controls (but not as quick as in the strong control case).	Continued modest technology advances.
Weak	Regionally varied policies.	High emissions levels and/or institutional limitations substantially slower progress in pollution control.	Lower levels of technological advance overall.

5   **Figure 1: The different air quality scenarios in the SSP framework.**

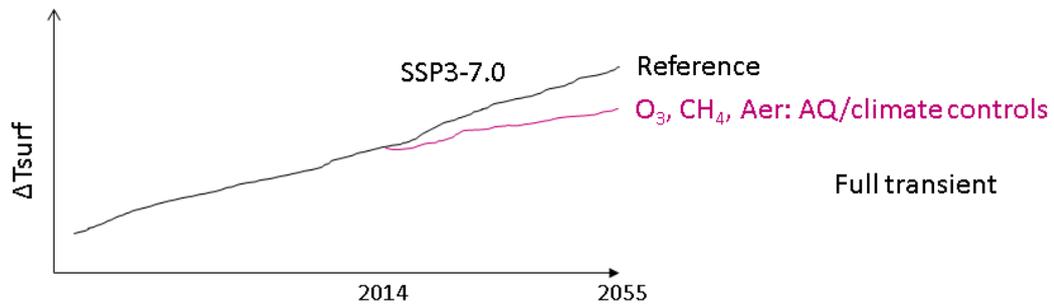



Figure 2: Schematic of future coupled-ocean simulations based on the SSP3-7.0 scenario.

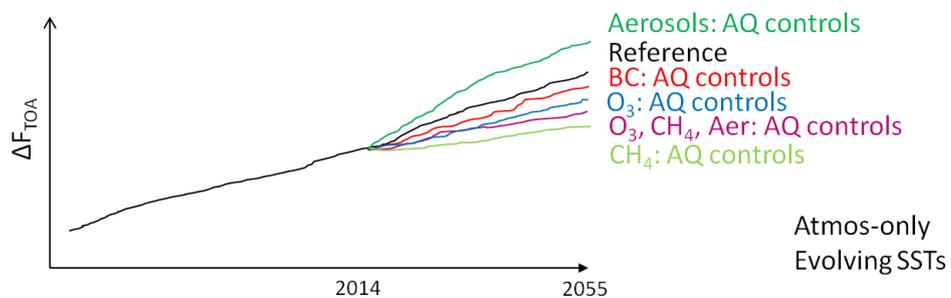



Figure 3: Schematic of future prescribed SST simulations based on the SSP3-7.0 scenario.

Experiment ID	Minimum model configuration	CH$_4$	N$_2$O	Aerosol Precursors	Ozone precursors	CFC/ HCFC	Tier
hist-piNTCF	AOGCM-CHEM	Hist	Hist	**1850**	**1850**	Hist	1
hist-piAer	AOGCM-AER	Hist	Hist	**1850**	Hist	Hist	2
hist-1950HC	AOGCM-CHEM*	Hist	Hist	Hist	Hist	**1950**	1

Table 1: List of historical coupled-ocean experiments. Experiments cover the period between 1850-2014, except *hist-1950HC* which starts in 1950. The "AER" suffix means that at least interactive aerosols are required. The "CHEM" suffix means that both interactive aerosols and chemistry are required. A "*" means that only models with stratospheric chemistry should run this experiment. The species columns refer to the specifications for concentrations (CH$_4$, N$_2$O and CFC/HCFC) or emissions (Aerosol and Ozone precursors). "Hist" means the concentrations or emissions should evolve as for the CMIP6 historical simulation, a year means the concentrations or emissions should be fixed to that year. Three ensemble members are requested for each experiment.

Experiment ID	Minimum model configuration	CH$_4$	N$_2$O	Aerosol Precursors	Ozone precursors	CFC/ HCFC	Tier
histSST	AGCM-AER	Hist	Hist	Hist	Hist	Hist	1
histSST-piNTCF	AGCM-CHEM	Hist	Hist	**1850**	**1850**	Hist	1
histSST-piAer	AGCM-AER	Hist	Hist	**1850**	Hist	Hist	2
histSST-piO3	AGCM-CHEM	Hist	Hist	Hist	**1850**	Hist	2
histSST-1950HC	AGCM-CHEM*	Hist	Hist	Hist	Hist	**1950**	1
histSST-piCH4	AGCM-CHEM	**1850**	Hist	Hist	Hist	Hist	1
histSST-piN2O	AGCM-CHEM*	Hist	**1850**	Hist	Hist	Hist	2

Table 2: List of historical prescribed SST experiments. Experiments cover the period between 1850-2014, except *histSST-1950HC* which starts in 1950. The "AER" suffix means that at least interactive aerosols are required. The "CHEM" suffix means that both interactive aerosols and chemistry are required. A "*" means only models with stratospheric chemistry should run this experiment. The species columns refer to the specifications for concentrations (CH$_4$, N$_2$O and CFC/HCFC) or emissions (Aerosol and Ozone precursors). "Hist" means the concentrations or emissions should evolve as for the CMIP6 historical simulation, a year means the concentrations or emissions should be fixed to that year. Note that the N$_2$O and HC runs will have a small forcing, but will provide valuable information on their historical impacts on stratospheric ozone changes.

Experiment ID	Minimum model configuration	CH$_4$	Aerosol Precursors	Ozone precursors	Tier
ssp370	AOGCM-AER	Reference	Reference	Reference	1
ssp370-lowNTCF	AOGCM-AER	Reference	**Clean**	**Clean**	1

Table 3: List of future coupled ocean experiments. Experiments cover the period 2015 to 2055. The "AER" suffix means that at least interactive aerosols are required. The species columns refer to the specifications for concentrations (CH$_4$, N$_2$O) or emissions (Aerosol
5 **and Ozone precursors). "Reference" means the concentrations or emissions should evolve as for the SSP3-7.0, "Clean" means the concentrations or emissions should evolve following a version of SSP3-7.0 with cleaner air quality policies. CFC/HCFC concentrations should follow the SSP3-7.0 scenario in both cases. Three ensemble members are requested for each experiment.**

Experiment ID	Minimum model configuration	CH$_4$	Aerosol Precursors	Ozone precursors	Tier
ssp370SST	AGCM-AER	Reference	Reference	Reference	1
ssp370SST-lowNTCF	AGCM-CHEM	Reference	**Clean**	**Clean**	1
ssp370SST-lowAer	AGCM-AER	Reference	**Clean**	Reference	1
ssp370SST-lowBC	AGCM-AER	Reference	Reference (non BC) **Clean** (BC)	Reference	1
ssp370SST-lowO3	AGCM-CHEM	Reference	Reference	**Clean**	1
ssp370SST-lowCH4	AGCM-CHEM	Clean	Reference	Reference	3
ssp370SST-lowLu	AGCM-CHEM	Reference	Reference (anthropogenic)		2

10 **Table 4: List of future prescribed SST simulations. Experiments cover the period 2015 to 2055. The "AER" suffix means that at least interactive aerosols are required. The "CHEM" suffix means that both interactive aerosols and chemistry are required. The species columns refer to the specifications for concentrations (CH$_4$, N$_2$O) or emissions (Aerosol and Ozone precursors). "Reference" means the concentrations or emissions should evolve as for the SSP3-7.0, "Clean" means the concentrations or emissions should evolve following a version of SSP3-7.0 with cleaner air quality policies. CFC/HCFC concentrations should follow the SSP3-7.0**
15 **scenario in all cases. For *ssp370SST-lowLu* the land use mask from the SSP1-2.6 scenario should be used for the interactive natural emission schemes (and for the climate); anthropogenic emissions should follow the SSP3-7.0 scenario.**

Experiment ID	Minimum model configuration	CH$_4$	N$_2$O	Aerosol Precursors	Ozone Precursors	CFC/ HCFC	Tier
piSSTclim	AGCM-AER	1850	1850	1850	1850	1850	1
*piSSTclim-**NTCF***	AGCM-CHEM	1850	1850	**2014**	**2014**	1850	1
*piSSTclim-**Aer***	AGCM-AER	1850	1850	**2014**	1850	1850	2
*piSSTclim-**BC***	AGCM-AER	1850	1850	1850 (non BC) **2014** (BC)	1850	1850	2
*piSSTclim-**O3***	AGCM-CHEM	1850	1850	1850	**2014**	1850	2
*piSSTclim-**CH4***	AGCM-CHEM	**2014**	1850	1850	1850	1850	2
*piSSTclim-**N2O***	AGCM-CHEM*	1850	**2014**	1850	1850	1850	2
*piSSTclim-**HC***	AGCM-CHEM*	1850	1850	1850	1850	**2014**	2
*piSSTclim-**NOX***	AGCM-CHEM	1850	1850	1850	1850 (non NO$_X$) **2014** (NO$_X$)	1850	3
*piSSTclim-**VOC***	AGCM-CHEM	1850	1850	1850	1850 (non CO/VOC) **2014** (CO/VOC)	1850	3

Table 5: List of fixed SST ERF simulations. These are timeslice experiments of 30 years total, using pre-industrial climatological average SST and sea-ice distributions. The "AER" suffix means that at least interactive aerosols are required. The "CHEM" suffix means that both interactive aerosols and chemistry are required. A "*" means only models with stratospheric chemistry should run this experiment. The species columns refer to the specifications for concentrations (CH$_4$, N$_2$O and CFC/HCFC) or emissions (Aerosol and Ozone precursors). A year means the concentrations or emissions should be fixed to that year.

Experiment ID	Minimum model configuration	Flux to be doubled	Tier
piSSTclim-2xdust	AGCM-AER	Dust	2
piSSTclim-2xss	AGCM-AER	Sea salt	2
piSSTclim-2xDMS	AGCM-AER	Oceanic DMS	3
piSSTclim-2xfire	AGCM-AER	Fire (NOx, BC, OC, CO, VOCs…)	3
piSST-2xNOX	AGCM-CHEM	Lightning NO_X	3
piSST-2xVOC	AGCM-CHEM	Biogenic VOCs	3

Table 6: List of fixed SST simulations for ERFs of natural emitted species. These are timeslice experiments of 30 years total, using climatological average SST and sea-ice distributions. The "AER" suffix means that at least interactive aerosols are required. The "CHEM" suffix means that both interactive aerosols and chemistry are required. The specified natural emission flux should be doubled compared to the pre-industrial control, either scaling the parameterisations in an interactive scheme or the data files for specified emissions. All other forcing agents should be as in pre-industrial control.