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Effect of aerosol radiative forcing uncertainty on projected exceedance year of a 1.5 °C global temperature rise

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Abstract

Anthropogenic aerosol emissions are predicted to decline sharply throughout the 21st century, in line with climate change and air quality mitigation policies, causing a near-term warming of climate that will impact our trajectory towards 1.5 °C above pre-industrial temperatures. However, the persistent uncertainty in aerosol radiative forcing limits our understanding of how much the global mean temperature will respond to near-term reductions in anthropogenic aerosol emissions. We quantify the model and scenario uncertainty in global mean aerosol radiative forcing up to 2050 using statistical emulation of a perturbed parameter ensemble for emission reduction scenarios consistent with three Shared Socioeconomic Pathways. We then use a simple climate model to translate the uncertainty in aerosol radiative forcing into uncertainty in global mean temperature projections, accounting additionally for the potential correlation of aerosol radiative forcing and climate sensitivity. Near-term aerosol radiative forcing uncertainty alone causes an uncertainty window of around 5 years (2034–2039) on the projected year of exceeding a global temperature rise of 1.5 °C above pre-industrial temperatures for a middle of the road emissions scenario (SSP2-RCP4.5). A correlation between aerosol radiative forcing and climate sensitivity would increase the 1.5 °C exceedance window by many years. The results highlight the importance of quantifying aerosol radiative forcing and any relationship with climate sensitivity in climate models in order to reduce uncertainty in temperature projections.

1. Introduction

The Paris Agreement of the United Nations Framework Convention on Climate Change aims to restrict global mean temperature change since the pre-industrial era to well below 2 °C and pursue efforts to limit global mean temperature change to 1.5 °C [1]. The year when a proportion of climate model realizations exceed a global mean temperature rise of 1.5 °C can be used to calculate the remaining carbon budgets at that point, and thereafter translate into guidance for climate change mitigation policies [2]. However, there are many uncertainties associated with the projected exceedance year of a global mean temperature rise of 1.5 °C. These include definitional ambiguities such as the pre-industrial reference year used for calculating a temperature anomaly, whether all warming or only human-induced warming is included, the future emission scenarios, and how the climate will respond to changes in emissions [3–5]. In particular, near-term projections of climate are sensitive to the emissions scenarios and climatic impacts of short lived climate forcers such as atmospheric aerosols, methane and tropospheric ozone [6].

Atmospheric aerosols affect the radiative balance of the planet by scattering and absorbing incoming solar radiation, altering the microphysics of clouds, and subsequent rapid atmospheric adjustments. Anthropogenic aerosol emissions have caused a negative radiative forcing over the industrial period of between −1.9 to −0.1 W m^{-2} [7], counteracting some of the warming of climate caused by greenhouse

gases. Regionally, anthropogenic aerosol emissions have declined over Europe and North America since the 1980s [8–10], and more recently anthropogenic SO_2 emissions have declined over China [11]. Future emissions scenarios predict further global reductions in anthropogenic aerosol emissions to combat poor air quality and in line with climate change mitigation policies [12, 13]. The projected reductions in anthropogenic aerosols will lead to a warming of climate in the near-term that will add to the warming effect of greenhouse gases [14, 15]. Due to the short lifetime of atmospheric aerosols relative to greenhouse gases, rapid reductions in anthropogenic aerosol emissions and other short lived climate forcers could be the main drivers of near-term climate change [16]. Consequently, changes in anthropogenic aerosol emissions will have a bearing on whether we exceed, and if so by how much, the target to limit global average temperature rise to 1.5 °C since the pre-industrial period as set by the Paris Agreement [17].

Estimates of aerosol radiative forcing are highly uncertain [18], limiting how well we understand the drivers of historical climate change and how accurately we can predict future climate [19]. Historical aerosol forcing uncertainty has been quantified using multi-model ensembles [20–22] and perturbed parameter ensembles [23–26]. Multi-model ensembles sample the spread in model output due to differing parameterizations and assumptions of physical processes in different models, known as model structural uncertainty. Perturbed parameter ensembles of models sample the spread in model output caused by the uncertainty in model parameters and process representations in an individual model, known as model parametric uncertainty. The spread in model output due to different emission scenarios, known as scenario uncertainty, causes an additional source of uncertainty in climate projections. Analyses of uncertainty in near-term aerosol forcing and climate impacts have so far been limited by the small range of aerosol emission pathways sampled by the Representative Concentration Pathways (RCPs) or by using a small number of models to assess model uncertainty [15, 16, 21, 22, 27–32]. Model parametric uncertainty in aerosol radiative forcing, can be as large as multi-model spread [33], but has so far largely been neglected in near-term climate projections of aerosol radiative forcing and climate response.

In this work we quantify the uncertainty in near-term projections of aerosol radiative forcing due to parametric model uncertainty and scenario uncertainty for a single model, and examine what impact this uncertainty has on predicting the exceedance year of a mean climate 1.5 °C global temperature rise since pre-industrial levels. We use a perturbed parameter ensemble (PPE) of our aerosol-climate model (HadGEM3-UKCA) and statistical emulation to sample aerosol radiative forcing uncertainty in near-term climate projections. We then use a simple climate model (FaIR v1.4) to translate our parametric uncertainty in near-term projections of aerosol radiative forcing to uncertainty in projected global temperature change. We highlight the importance of reducing aerosol radiative forcing uncertainty for improving predictions of the exceedance year of the 1.5 °C target set by the Paris Agreement.

2. Methods

2.1. Climate model: HadGEM3-UKCA

The base model used in this work is the Met Office Hadley Centre Climate Model, HadGEM3 [34]. HadGEM3 was run at a N96 resolution (1.25° in latitude, 1.875° in longitude), with 85 vertical levels up to 85 km above sea level. This model uses the 4th Global Atmosphere configuration (GA4) [35]. The model was run in atmosphere-only mode with sea surface temperatures and sea ice prescribed using reanalysed monthly varying fields. Horizontal wind speeds and temperature fields were nudged between approximately 1 km and 60 km to Medium-Range Weather Forecast ERA-Interim reanalysis.

The model incorporates version 8.4 of the UK Chemistry and Aerosol (UKCA) model. UKCA is an atmospheric chemistry and aerosol model, which simulates the evolution of particle size distribution and size-resolved chemical composition of aerosol [36]. The modal version of the GLObal Model of Aerosol Processes (GLOMAP-mode) is used to simulate new particle formation, gas-to-gas particle transfer, aerosol coagulation, cloud processing of aerosol, and aerosol deposition [37]. In this model setup GLOMAP-mode resolves sulfate, organic carbon, black carbon, sea salt and dust in seven modes. The degree of atmospheric nudging in this model setup allows for the diagnosis of instantaneous effects of aerosol-radiation interactions and aerosol-cloud interactions (direct and first indirect aerosol radiative forcing).

2.2. A perturbed parameter ensemble of HadGEM3-UKCA

A PPE of the model setup described above was created to quantify and constrain uncertainty in model output due to uncertain aerosol parameters [38]. Twenty six uncertain parameters that sample the uncertainty in aerosol emissions, processes, and removal were perturbed. Expert elicitation was used to define the probability distribution representing uncertainty in each parameter. The definition of the 26 parameters perturbed and their trapezoidal distribution are given in the supporting information (table A1, available online at stacks.iop.org/ERL/15/0940a6/mmedia).

Once the uncertain parameters were selected, Maximin Latin Hypercube sampling was used to design model simulations that span the 26-dimensional space of the parameter uncertainties,

producing an ensemble of simulations that can be used for statistical techniques, such as emulation [39]. The PPE consists of a set of 235 single-year global model simulations with anthropogenic aerosol emissions prescribed for the year 2008. The pre-industrial to present day aerosol forcing in the PPE is stronger (more negative), but spans a similar range, to multi-model experiments, as shown by a visual comparison in figure A2. A more detailed methodology for the model and perturbed parameter set up used in this paper can be found in Yoshioka *et al* [38].

2.3. Using statistical emulation to estimate uncertainty in future aerosol forcing

The design of the perturbed parameter ensemble allows for Gaussian process emulation [39]. Gaussian process emulation provides a statistical representation of model output across the multi-dimensional parameter space that enables model output to be predicted for any parameter combination within the ranges of the PPE. We used emulation, as described below, to estimate the uncertainty in near-term projections of aerosol radiative forcing for selected aerosol emission reduction scenarios consistent with the Shared Socioeconomic Pathways (SSPs). A schematic that illustrates our methods is shown in figure 1.

Firstly, we built an emulator for global mean top of atmosphere flux (shortwave and longwave). The emulator is trained from 183 model simulations from the PPE described above, and then validated against a further 52 model simulations from the PPE to ensure the emulator can predict model output accurately.

The anthropogenic aerosol emissions parameters (anthropogenic SO_2, carbonaceous fossil fuel and carbonaceous biofuel) in the PPE were perturbed over a wide range of values above and below their 2008 values, with the lowest values mostly comparable to the aerosol emissions expected between 2035 and 2060 in the SSPs. We are therefore able to use our emulators of 2008 shortwave and longwave top of atmosphere flux to predict the top of atmosphere flux for future years that have lower anthropogenic aerosol emissions.

To predict top of atmosphere flux for future years, we scale global mean values of our three anthropogenic aerosol emission parameters to match global mean values in a particular year (2000, 2005, 2010, 2015, 2020, 2030, 2040, and 2050) of the Shared Socioeconomic Pathway emission scenarios (figure 2). This approach effectively scales the 2008 emissions patterns of the PPE up or down. Then, for each scenario, we use the emulators of shortwave and longwave top of atmosphere flux to predict 270 000 values of top of atmosphere flux for each interval and corresponding emission scaling in our near-term future time series. In these 270 000 predictions of top of atmosphere flux, the values for the remaining 23 parameters in the PPE (related to aerosol processes and natural emissions) vary across their uncertainty range. We use 2000 as our baseline and calculate the difference in top of atmosphere flux between 2000 and each of the points in the future, giving us a time series of 270 000 predictions of aerosol radiative forcing. The spread in these 270 000 predictions of aerosol radiative forcing accounts for the uncertainty in our model's aerosol process and removal parameters, which is our model uncertainty.

The advantage of our approach is that we are able to estimate the model and scenario uncertainty in aerosol radiative forcing out to 2050 for emissions pathways consistent with the Shared Socioeconomic Pathways, without the computational expense of designing a new PPE that specifically samples the uncertainty in future aerosol radiative forcing. We acknowledge that there are limitations in our approach. For example, since we are applying a scaling to the existing pattern of 2008 aerosol emissions within our PPE, we can represent regions of future emissions reductions across most of the world, but not opposing regions of increasing emissions, for example in India (figure 2). However, India has been shown to have a small global mean cooling response induced by its aerosol emissions [40]. Nevertheless, we focus our analysis on global mean values, rather than at a regional level. Also, using this technique, we are limited to the minimum and maximum values of anthropogenic aerosol emission parameters covered by the PPE. For anthropogenic SO_2, the lower limit of the perturbation represents a 40% reduction in anthropogenic SO_2 relative to the original 2008 emissions. Therefore, scenarios such as SSP1-RCP2.6 that represent rapid near-term reductions in anthropogenic aerosol are outside of our perturbation boundary. In this case, we have used emission changes to extrapolate top of atmosphere radiative flux to give an impression of what aerosol radiative forcing might be, which is explained in more detail in the supporting information (section A5).

We identify the causes of aerosol radiative forcing uncertainty in our near-term projections using variance-based sensitivity analysis [41], as described in Lee *et al* [42]. The sensitivity analysis enables us to calculate the proportion of variance in aerosol forcing that could be explained if an uncertain parameter was known precisely.

2.4. Shared Socioeconomic Pathways (SSPs)

The SSPs are a range of emission, land use and energy projections based on five narratives describing how the future may unfold with differing socioeconomic developments. The five socioeconomic narratives of the SSPs are: SSP1—sustainable development, SSP2—middle of the road development, SSP3—regional rivalry, SSP4—inequality, and SSP5—fossil-fuelled development [12]. Each SSP scenario combines with the RCPs. The RCPs describe emission and land-use scenarios that represent the net forcing of all anthropogenic forcing agents at the year 2100 [13]. The SSP pathways are designed to depict a

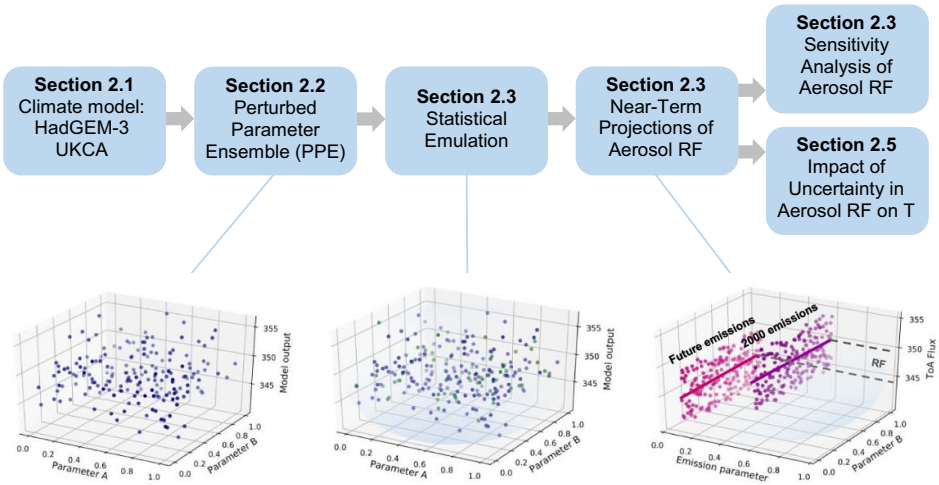

Figure 1. This schematic illustrates the steps used to quantify the uncertainty in near-term aerosol radiative forcing. The figure to the left shows a 2-dimensional example of a perturbed parameter ensemble. The middle figure illustrates a statistical emulator (blue cloud) trained from the perturbed parameter ensemble model output (blue dots), and validated against further model output (green dots). The figure to the right illustrates how by using the emulator, an anthropogenic emission scaling can be applied to predict a range of aerosol radiative forcing that represents the aerosol–climate model uncertainty.

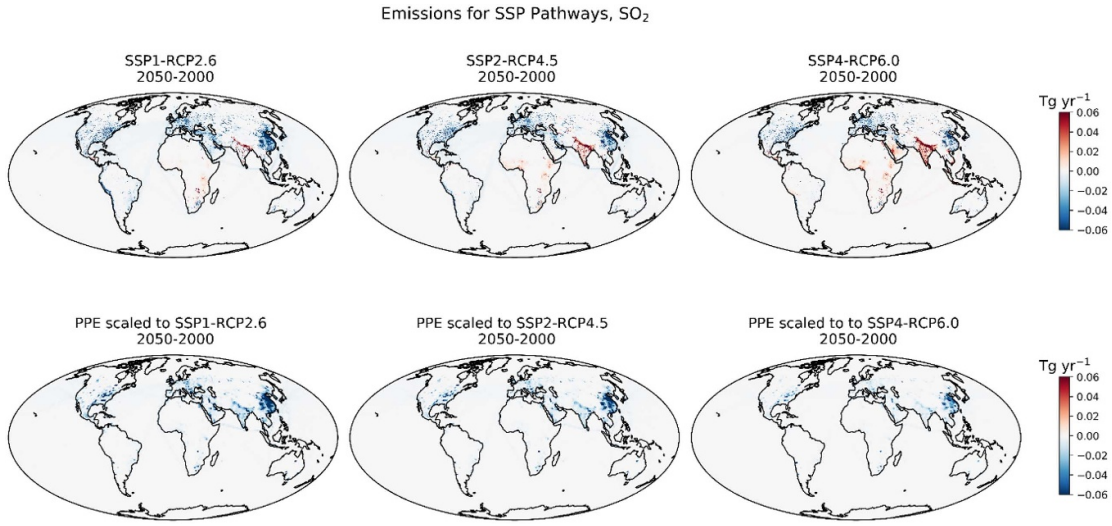

Figure 2. Changes in anthropogenic SO_2 emissions between 2000–2050 for the Shared Socioeconomic Pathways scenarios SSP1-RCP2.6, SSP2-RCP4.5 and SSP4-RCP6.0 used in this paper (top row), in comparison to the scalings applied to our 2008 emissions from the PPE simulations (bottom row).

wide range of future scenarios, and hence encompass a wide range of future air quality emission scenarios, in contrast to the RCPs which assume similar air pollution pathways [43]. Within each SSP pathway, scenarios are produced for each RCP forcing level, and also a baseline scenario which assumes no future mitigation for climate change, giving the notation style SSPX-RCPX or SSPX-baseline. Each SSP pathway has an associated air pollution control strength. In this paper we have chosen three SSP scenarios selected from the Scenario Model Intercomparison Project (ScenarioMIP) for the Coupled Model Intercomparison Project Phase 6 (CMIP6) [44]. Our chosen scenarios: SSP1-RCP2.6, SSP2-RCP4.5, SSP4-RCP6.0 assume strong, medium and weak pollution controls respectively, and therefore sample a wide range of scenario uncertainty in anthropogenic aerosol emissions. We use global mean values from these three scenarios to scale our 2008 pattern of anthropogenic aerosol emissions. These three scenarios also have differing greenhouse gas (GHG) representations that are relevant for the temperature projections section of this paper, with SSP1-RCP2.6 having strong mitigation of GHG emissions, to SSP4-RCP6.0 having weaker mitigation of GHG emissions by mid-century. As our focus is on capturing scenario uncertainty associated with near-term aerosol reductions, we have not used a scenario that has the weakest mitigation of GHG emissions, such as SSP5-RCP8.5, that will have the largest increase in global mean temperature by the end of century [45].

2.5. Temperature projection with a simple climate model

Simple climate models represent the most important aspects of fully coupled climate models, and are commonly used to translate global radiative forcing or emissions scenario inputs into global temperature change. We use version 1.4 of the Finite Amplitude Impulse Response model (FaIR), to translate our uncertainty in aerosol radiative forcing in near-term projections into uncertainty in global temperature change [46, 47]. FaIR has been validated against carbon cycle and earth system models from the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC), and is used, for example within the IPCC Special Report on Global Warming of 1.5 °C (SR1.5), to estimate the temperature impacts of differing emissions scenarios [48–50]. For aerosol-radiation interactions, FaIR assumes a linear relationship between global emissions and global aerosol forcing. For aerosol-cloud interactions, FaIR uses a logarithmic dependence of aerosol forcing as a function of sulfate and primary organic aerosol. FaIR then uses a forcing efficacy of 1 for all forcing agents apart from black carbon on snow, to convert global mean radiative forcings to temperature change. Shindell *et al* suggest that the asymmetric pattern of aerosol forcing can lead to a larger temperature response to aerosols than that to greenhouse gases, and hence the temperature response of aerosols may be underestimated in simple climate models that do not take the spatial pattern of aerosol forcing into account [51]. The use of a single model could introduce biases in the projected temperature change, due to differing climate responses to emission changes across simple climate models, based on the assumptions and parameterizations used in each model. Schwarber *et al* explored the temperature response to concentration impulse tests amongst simple climate models, and showed FaIR v1.0 had a weaker response to a CO_2 impulse than other simple climate models [52]. Furthermore, FaIR has been shown to have a weaker near-term warming trend than the simple climate model MAGICC [48]. On this basis we might expect the years of exceedance of 1.5 °C to shift if the conversion of aerosol forcing to temperature was treated differently, or if a different simple climate model was used.

Firstly, we run FaIR with its default settings that include constrained estimates of equilibrium climate sensitivity (ECS) and transient climate response (TCR) of 2.75 K and 1.6 K respectively to calculate a forcing time series from emissions prescribed by the SSP scenarios. To isolate the impact of our parametric uncertainty in near-term aerosol radiative forcing on the exceedance year of 1.5 °C, we substitute in our calculated aerosol radiative forcing from 2000 onwards, and run FaIR in forcing driven mode to obtain the temperature projections that account for near-term aerosol forcing uncertainty. At 2000 we also normalize the temperature projections from FaIR to the observed global mean temperature from the HadCRUT4 data set, to account for any deviations in global mean temperature that may have arose through the historical period [53].

Previous studies have shown a statistical relationship between historical aerosol forcing and equilibrium climate sensitivity emerges in generations of climate models up to CMIP5 when ensembles of simulations are constrained by the historical temperature record, and also such a relationship exists between historical aerosol forcing and transient climate response in FaIR v1.3 [47, 54, 55]. Hence, we illustrate the effect of a statistical relationship between aerosol forcing and climate sensitivity on projecting the exceedance year of 1.5 °C by combining our weak, mean, and strong aerosol radiative forcing with a relevant ECS and TCR from the IPCC AR5 likely range [56]. For example, from 2000, we combine the strong aerosol radiative projection with a higher value of ECS of 4.5 K and TCR of 2.5 K. The values for ECS and TCR that are selected for each projection strand are shown in figure 4 and table A4. We note that this is an illustrative approach to show the potential implications of a statistical relationship between climate sensitivity and aerosol forcing based on historical assumptions. We do not address the implications of any physical relationships between forcing and feedback, as described in Gettelman *et al* [57], that may alter climate sensitivity. For both the approaches described in this section we calculate the mean climate temperature anomaly relative to an 1850–1900 baseline, in line with the definition of a 1.5 °C temperature rise adopted in the IPCC SR1.5 [4].

3. Results

3.1. Quantifying uncertainty in near-term aerosol radiative forcing

Here we examine the spread in aerosol radiative forcing in near-term climate projections caused by the effect of uncertain aerosol parameters within our aerosol-climate model (HadGEM3-UKCA). We focus on three Shared Socioeconomic Pathways: SSP1-RCP2.6, SSP2-RCP4.5 and SSP4-RCP6.0 that span different socio-economic narratives and air quality policies. The use of multiple scenarios allows us to compare the scenario uncertainty to parametric model uncertainty. Figure 3 shows predictions of global mean aerosol radiative forcing relative to the year 2000. The spread of predictions in a single scenario (shaded regions) represents the parametric model uncertainty from 270 000 combinations of uncertain aerosol parameters.

Initially the aerosol radiative forcing is negative relative to 2000 as global historical anthropogenic aerosol emissions continue to increase within the SSPs. As anthropogenic aerosol emissions decline from

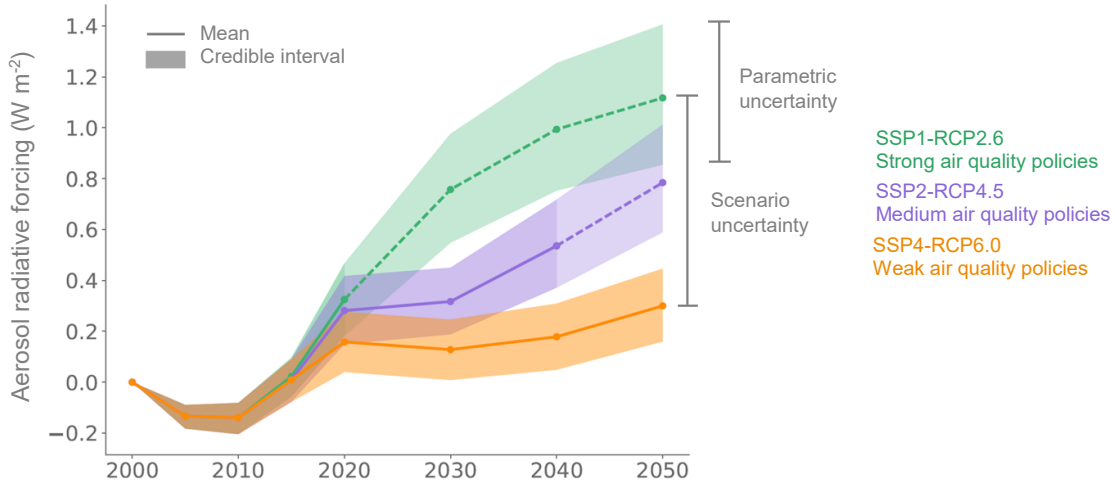

Figure 3. Global mean radiative forcing relative to the year 2000 for anthropogenic aerosol emission (anthropogenic SO_2, carbonaceous fossil fuel, carbonaceous biofuel) reductions scaled to match three SSP emission scenarios. The solid line represents the mean of radiative forcing predictions, with the shaded area representing the 95% credible interval that represents the parametric uncertainty within the aerosol-climate model. The dashed line and lighter shaded areas represent where aerosol radiative forcing has been extrapolated.

2010 onwards within the SSP pathways, we see a positive radiative forcing relative to 2000. Reductions in anthropogenic SO_2 are the main driver of the positive radiative forcing (figure A10). The implementation of strong air quality policies in SSP1-RCP2.6 and therefore the rapid reductions in anthropogenic aerosols lead to a more positive radiative forcing than in SSP4-RCP6.0 which assumes weak air quality policies. The three scenarios SSP1-RCP2.6, SSP2-RCP4.5 and SSP4-RCP6.0 cause a mean global aerosol radiative forcing by 2050 relative to 2000 of 1.12, 0.78 and 0.30 W m^{-2} respectively. The spread in the forcing of 0.82 W m^{-2} between the scenarios reflects the scenario uncertainty.

In the middle of the road scenario (SSP2-RCP4.5), the mean radiative forcing by 2050 is 0.78 W m^{-2}, with a 95% credible interval of 0.59–1.01 W m^{-2} that represents the parametric model uncertainty. Overall, by mid-century the scenario uncertainty is larger than parametric model uncertainty in near-term aerosol radiative forcing projections. However, the model uncertainty in this single scenario (SSP2-RCP4.5), is equivalent to 52% of the scenario uncertainty. The model uncertainty increases with the magnitude of radiative forcing as the model is being perturbed further away from its baseline state (radiative forcing in 2000) where we have assumed no uncertainty, and therefore the parametric model uncertainty in a single scenario increases from 35% to 67% of the scenario uncertainty between SSP4-RCP6.0 to SSP1-RCP2.6 which has increasingly stringent pollution controls. When accounting for both model and scenario uncertainty, the combined uncertainty is larger with a spread of 1.35 W m^{-2}, in comparison to 0.82 W m^{-2} when scenario uncertainty is considered alone. Hence, the parametric model uncertainty contributes an important component of the overall uncertainty in near-term aerosol forcing.

It is difficult to compare our single model spread in near-term aerosol radiative forcing to multi-model spread because previous multi-model ensembles calculated aerosol radiative forcing at 2100 relative to the present day or pre-industrial. Zelinka *et al* report a pre-industrial to present day aerosol radiative forcing of -1.40 ± 0.56 W m^{-2} (standard deviation) that represents the spread in the current generations of climate models [58]. In comparison, the pre-industrial to present day aerosol radiative forcing within our PPE is -2.12 ± 1.29 W m^{-2} (90% credible interval) [38]. Industrial era aerosol forcing in our PPE is stronger and the spread larger than current multi-model ensembles. Therefore, we expect our aerosol radiative forcing in near-term projections to be stronger, and the spread larger than what would be diagnosed in a similar experiment using a multi-model ensemble. Further detail on the aerosol radiative forcing in our PPE in context of multi-model studies is provided in the supporting information (section A2). Given the perturbed parameters in our climate model have analogues in most other climate models, we expect, but cannot confirm, that other models would have similarly large parametric uncertainty.

3.2. Sources of uncertainty in near-term aerosol radiative forcing

In order to reduce the uncertainty in the aerosol radiative forcing, it is first useful to understand which parameters within the PPE are the main causes of spread in the aerosol radiative forcing uncertainty. Sensitivity analysis allows us to decompose the variance in aerosol radiative forcing predictions into

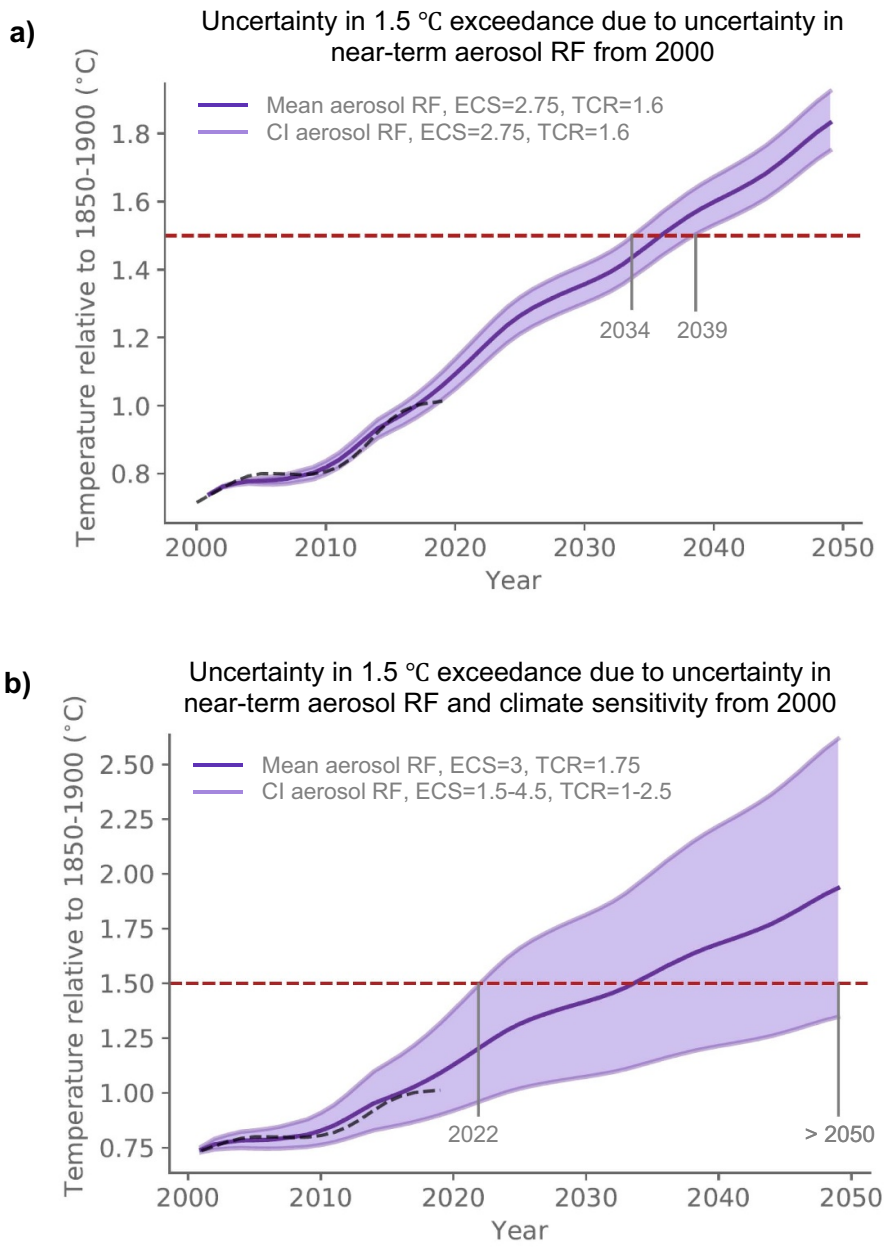

Figure 4. Global mean temperature change relative to 1850–1900 for SSP2-RCP4.5. We prescribe our aerosol radiative forcing (RF) from 2000 for anthropogenic aerosol emissions changes. All other forcings are calculated by FaIR v1.4 from SSP2-RCP4.5 prescribed emissions. The top figure (a) shows the impact of model uncertainty in aerosol radiative forcing from 2000, with the darker shaded line representing our mean radiative forcing value translated to temperature and the shaded region representing the 95% credible interval (CI) for aerosol radiative forcing, with the black dashed like representing observations from HadCRUT4. The bottom figure (b) displays an illustrative range in exceedance year of 1.5 °C if a statistical relationship between uncertainty in aerosol radiative forcing and climate sensitivity is accounted for from 2000, for example if stronger values of our aerosol forcing range are paired with higher values of ECS and TCR, and weaker values of our aerosol forcing range are paired with lower values of ECS and TCR. The range of values selected for ECS and TCR in each projection is displayed in the figure legend.

individual contributions from the uncertain aerosol parameters within our aerosol-climate model.

The sensitivity analysis for global mean radiative forcing over the period 2010–2040 for SSP2-RCP4.5 is shown in figure A11. The sea spray emission flux (Sea_Spray) accounts for 60% of the variance in our near-term projections of aerosol radiative forcing, with the standard deviation of updraft velocities (Sig_W) causing a further 17% of the variance.

The sea spray emission flux parameter within our PPE is a scaling factor for sea spray aerosol emissions. Sea spray aerosol emissions greatly influence background aerosol concentrations over marine regions. When sea spray emissions are higher, radiative forcing (particularly indirect radiative forcing) has a lower sensitivity to changes in anthropogenic aerosol emissions, as the background aerosol concentration is higher [23]. Therefore, natural aerosol emission parameters such as sea spray

will become increasingly important contributors to aerosol forcing uncertainty as anthropogenic aerosol concentrations return to a more natural baseline state. Furthermore, there may be feedbacks between the changing climate and natural aerosols emissions, although we do not account for such feedbacks in this study [59].

The standard deviation of updraft velocities (Sig_W), is the second most important parameter in causing variance in our aerosol radiative forcing projections, and controls the width of the distributions of sub-grid updraft velocities that are used to calculate the activation of aerosol into cloud droplets. A larger value of this parameter will widen the distribution of updraft velocities, allowing larger updraft velocities. Larger updraft velocities for a given supersaturation will cause a greater number of aerosol particles to activate to cloud droplets, increasing cloud droplet concentrations and cloud albedo, and thus strengthening indirect radiative forcing. Updraft velocity uncertainty is particularly important over polluted land regions where cloud droplet number concentrations are updraft-limited [60]. The remaining variance is caused by small contributions (<5%) from each of the other parameters (figure A11).

To reduce the uncertainty in uncertain parameters and aerosol radiative forcing, observational constraint is required. Recent observational constraint on our PPE has shown that ground and marine observations of aerosol properties can successfully constrain the probability distributions of some of the most uncertain parameters within the PPE, and reduce the confidence interval of pre-industrial to present-day radiative forcing from aerosol-cloud interactions by around 21% [61, 62], and presumably an equivalent constraint would reduce our near-term aerosol radiative forcing uncertainty by a similar amount.

3.3. Impact of uncertainty in aerosol radiative forcing on temperature projection

Next we examine how aerosol radiative forcing uncertainty impacts our ability to predict temperature change. Specifically, we focus on how the projected exceedance year of the 1.5 °C target set by the Paris Agreement (United Nations Convention on Climate Change, 2015) is affected by taking the parametric uncertainty in aerosol forcing into account. At short lead times, such as the timescales of predicting the exceedance year of 1.5 °C, it has been shown that model uncertainty represents the largest fractional source of uncertainty in global temperature projections [63]. Therefore, as in previous studies, we focus on mean temperature change and do not take into account fluctuations due to internal variability when calculating the year of exceedance of a 1.5 °C temperature rise. We use the simple climate model FaIR v1.4 [46, 47] to translate our radiative forcing values into temperature change. Previous studies have shown a statistical relationship between aerosol forcing and ECS [54, 55], although emerging evidence suggests such relationship may not exist in the latest generation of models as configured in CMIP6 [64]. We first isolate the effect of the uncertainty in near-term aerosol radiative forcing only on the exceedance year of a 1.5 °C temperature rise, and secondly, we show an illustrative effect of accounting for a relationship between aerosol forcing and climate sensitivity.

The results in this section focus on the SSP pathway SSP2-RCP4.5, which is a middle of the road scenario in terms of its socioeconomics and the underlying narrative, with moderate reductions in emissions of GHGs and aerosols to address climate change and air quality. Importantly, it is also the only scenario to be simulated by CMIP6 which has global emissions in 2030 consistent with the Nationally Determined Contributions (NDCs). The NDCs embody efforts by each country to reduce national emissions and are at the heart of the Paris Agreement and efforts to achieve long-term climate goals, yet the IPCC SR1.5 is clear that the current NDCs are insufficient to limiting warming to 1.5 °C or 2 °C [48]. As such, until additional pledges on emissions in 2030 and beyond are in place, SSP2-RCP4.5 is the most relevant of the CMIP6 scenarios to the current status of international emission reduction agreement.

Figure 4 shows the mean climate global temperature change relative to the 1850–1900 average using our estimated range of aerosol forcings from 2000, with the temperature at 2000 normalized relative to the HadCRUT4 estimate [53]. Taking into account the uncertainty in near-term aerosol radiative forcing only, the mean of our aerosol radiative forcings projects an exceedance of 1.5 °C in 2036, with the credible interval exceeding 1.5 °C between 2034 and 2039 for SSP2-RCP4.5. Additionally, if we take into account an illustrative correlation between aerosol radiative forcing and climate sensitivity then the window of exceedance extends from 2022 until after 2050 (assuming an ECS of 4.5 K, TCR of 2.5 K for the strong forcing and an ECS of 1.5 K, TCR of 1 K for the weak forcing). If we take into account a smaller range of uncertainty in climate sensitivity, for example an ECS of 3 K–4.5 K (in line with the central estimate from CMIP6 models [65]), then the exceedance window of 1.5 °C for SSP2-4.5 narrows to between 2022 and 2036, as shown in figure A17. In our illustrative approach of taking the uncertainty in climate sensitivity and transient climate response into account, the rate of change in the temperature projection that follows a high climate sensitivity and strong aerosol forcing is higher than in observations over recent decades. Hence, although a high climate sensitivity and strong aerosol forcing may represent a combination that is plausible in some models, based on the statistical relationship obtained with historical temperature constraint, it does not necessarily represent a plausible combination in all models over the recent decades, nor into the future. A probabilistic analysis

of ECS and aerosol forcing may result in a narrower plausible exceedance range.

These results show that the exceedance year window due to the uncertainty in near-term aerosol radiative forcing uncertainty alone is comparable or larger than that induced from uncertainties in processes related to inter-annual variability, such as the phase of the Pacific Decadal Modulation [66]. However, as natural variability may lead to transient exceedances of 1.5 °C, uncertainty in aerosol radiative forcing will affect the mean climate projections, and is therefore more relevant to mitigation policy decisions, such as calculating remaining carbon budgets by using a threshold exceedance approach. When the collective uncertainty in climate sensitivity and near-term aerosol radiative forcing uncertainty is taken into account, the uncertainty in exceedance year of 1.5 °C is far greater. Thus, these results show, that in order to reduce the uncertainty in exceedance year of 1.5 °C we need to quantify and reduce the uncertainty in aerosol radiative forcing, and quantify any corresponding relationship between aerosol forcing and climate sensitivity.

4. Discussion and conclusion

The persistent uncertainty in aerosol radiative forcing limits our understanding of how the climate will respond to future reductions in anthropogenic aerosol emissions, and therefore it is important we acknowledge how single and multi-model uncertainty in aerosol radiative forcing affects near-term climate projections. We have used statistical emulation of a perturbed parameter ensemble of climate model simulations to sample the uncertainty due to aerosol emissions and processes in near-term (up to 2050) projections of aerosol radiative forcing. Then, using a simple climate model, FaIR v1.4, we have translated our aerosol radiative forcing uncertainty into projections of global mean temperature change.

Our results show a global mean positive radiative forcing in the near-term future due to reductions in anthropogenic aerosol emissions. The magnitude of aerosol radiative forcing is dependent on the air pollution controls assumed in each SSP pathway. Within the three SSP pathways used (SSP1-RCP2.6, SSP2-RCP4.5, SSP4-RCP6.0) that sample strong, medium and weak implementations of air quality policies there is a global mean aerosol radiative forcing of 0.30–1.12 W m^{-2} by 2050 relative to 2000, representing a large scenario uncertainty. This uncertainty increases to 0.16–1.41 W m^{-2} when the parametric model uncertainty is included. The uncertainty in aerosol radiative forcing due to our parameters in a single scenario is 35% to 67% of the uncertainty due to the differing emission scenarios. We note that the pre-industrial to present-day aerosol radiative forcing in our PPE is stronger than in multi-model studies. Therefore, we assume the magnitude of near-term aerosol radiative forcing in our ensemble is likely stronger than other models, but we expect the uncertainty range would be similar in models that represent the same uncertain processes that we have perturbed in our ensemble. Although scenario uncertainty is the dominant driver of uncertainty in our near-term aerosol radiative forcing projections, it cannot be reduced until strategic actions by multiple influential nations have been taken, and due to recent reductions in emissions from China for example, there may already be deviations from the emission inventories used for scenarios [67]. Therefore parametric model uncertainty in aerosol radiative forcing is large enough (as a component of the overall uncertainty) to warrant efforts to better understand its causes so that it can be reduced. Recent work using the PPE used in this study has shown it is possible to constrain the probability distributions of the uncertain parameters by using multiple point observations of aerosol properties, which can reduce the number of 1 000 000 model variants by up to 98%. However due to model equifinality, where multiple model variants can combine in ways to produce the same value of model output, the resultant constraint on radiative forcing due to aerosol-cloud interactions is more modest, at around 21% [61, 62].

Current emission reduction commitments suggest a global mean temperature rise of 1.5 °C since pre-industrial times will likely happen during the next two decades [48]. This gives little time to put in place mitigation measures that will limit global mean temperature rise, and as such, uncertainties in climate modelling that alter the projected exceedance year of a 1.5 °C temperature rise are important factors to consider. Hence, due to projected reductions in anthropogenic aerosols, the uncertainty in aerosol radiative forcing has relevance in predicting near-term human induced temperature change and thus the year of exceedance of a global mean temperature rise of 1.5 °C since the pre-industrial era. Our results show that for a scenario with moderate reductions in anthropogenic aerosol and greenhouse gases, SSP2-RCP4.5, the parametric model uncertainty in near-term aerosol radiative forcing alone can alter the predicted year of exceedance of 1.5 °C by 5 years (2034 to 2039). Furthermore, when taking an illustrative approach where the uncertainty in aerosol forcing and climate sensitivity are assumed to be correlated the exceedance window of 1.5 °C increases greatly (2022 to >2050). However, in accordance with the observed global mean temperature rise between 2000 and 2019, the outer limits of our climate sensitivity and aerosol forcing couplings are likely to be an out of bounds example. Over the historical period aerosol cooling and greenhouse gas warming have had counteracting effects on temperature change, and therefore a strong aerosol radiative forcing coupled with a high climate sensitivity has a similar projected global mean temperature change to a weak aerosol radiative

forcing coupled with a low climate sensitivity. Yet when such relationship is considered in the near-term future, when projected reductions in anthropogenic aerosols may cause a warming of climate, temperature projections with a combination of strong aerosol radiative forcing and high climate sensitivity diverge from those with a weak aerosol radiative forcing and low climate sensitivity, and hence accounting for the uncertainty in climate sensitivity greatly increases the exceedance window of 1.5 °C [55]. Therefore, if the uncertainty range of climate sensitivity were smaller, as may be the case in a probabilistic analysis, the exceedance window of 1.5 °C would narrow accordingly.

This study has shown aerosol radiative forcing uncertainty, and in particular the collective impact of aerosol forcing uncertainty and any statistical relationship with climate sensitivity on projecting exceedance year of 1.5 °C, illustrates the need for the continued effort in reducing aerosol radiative forcing uncertainty and quantifying the relationship between climate sensitivity and aerosol forcing, in order for successful implementation of climate change mitigation policies.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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