Response to review of "*Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways*" by Marianne T. Lund, Gunnar Myhre, and Bjørn H. Samset.

We thank the anonymous referee #1 for the careful and thorough review of our paper, and the useful suggestions. Responses to individual comments are given below.

L18-19: The differences between 2100 and 2015 reported here should equal the 1750-2100 values (given in L14-15) minus the 1750-2015 value (-0.61 W/m2) I'd expect, but they don't. Seems like a mistake and accidentally the opposite of the 1750-2100 values are given here instead of the differences for 2100 vs 2015 which I'd think are +0.57 and +0.10 W/m2, respectively (unless the values in L14-15 are wrong). Or if there is some non-linearity or incompatibility between the various estimates please revise so this is not so confusing to the reader.

We thank the reviewer for noticing this error. The mistake here is the value reported for 1750-2015, which was misplaced by the 1750-2014 number. The correct value is -0.55 Wm-2. Furthermore, the reference to 1750-2014 numbers in the results sections has been changed to 1750-2015 for consistency.

L43-44: Rather than the Li et al study cited here for air quality/health, which looked only at one country using one model, one of the worldwide multi-model studies by Silva et al would be a better choice (e.g. Silva et al, The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble, Atmos. Chem. Phys., 16, 9847-9862, 2016.)

Similarly, rather than (or in addition if you like) the Szopa et al and Westervelt et al studies, each of which looked at just one model, the reader could more usefully be pointed to the multi-model studies such as Shindell et al., Radiative forcing in the ACCMIP historical and future climate simulations, Atmos. Chem. Phys., 13, 2939–2974, 2013; and Rotstayn et al, Why does aerosol forcing control historical global-mean surface temperature change in CMIP5 models?, J. Climate, 28, 6608-6625, 2015.

Good suggestions, both citations have been added.

L56: Clearer to write as "continue to be high and are increasing" than "also continue to be high and increasing" as the 'also' seems not to relate to the previous sentence (about SO2) but an earlier one so is hard to follow.

Sentence modified.

L56-58: It would be good to include additional explanation here that the RCP aerosol emissions were based on the assumption that economic growth leads to decreasing emissions of precursors, a so-called environmental Kuznets' curve/behavior. An excellent discussion of the background to assumptions such as those is given in Amann et al, 2013. Regional and global emissions of air pollutants: recent trends and future scenarios. Annual Review of Environment and Resources, 38, pp.31-55; and a recent paper analysed the link between economic growth and aerosol precursor emissions and indeed supports the discussion here (and in Amann et al) that RCP projections are likely too optimistic as those emissions do not necessarily decline with growth in GDP or follow CO2 (see Ru et al, The long-term relationship between emissions and economic growth for SO2, CO2 and BC, Env. Res. Lett., 13, 124021, 2018.) This discussion would help set the context for the new approach in the SSPs where air pollution controls have independent settings, as described in the next paragraph.

An important issue that we did not originally think to mention. The text has been expanded with an additional paragraph and now reads:

“The aerosol and precursor emissions in the RCPs are generated following the assumption that economic growth leads to decreased emissions using the so-called environmental Kuznets curve. This real-world representativeness of this relationship has, however, been questioned (Amann et al., 2013; Ru et al., 2018). This, combined with the slow observed progress on alleviating air pollution, raises the question of whether previous projections of future emissions are too optimistic in terms of pollution control.”

L74: Replace ‘there is progress is slowed’ with just ‘progress is slowed’.

Corrected.

L90: Please also give the number of vertical layers and the model top as that’d help the reader get a general sense of the model in addition to the horizontal resolution.

Text modified to

“Here the model is run in a 2.25°x2.25° horizontal resolution, with 60 vertical levels (the uppermost centered at 0.1 hPa).”

L150: ‘Becomes’ -> ‘become’.

Corrected.

L186: Delete ‘the’ before ‘South Asia’.

Corrected.

L189: Add ‘the’ before ‘Sahara’.

Corrected.

L201: Add ‘that’ after ‘demonstrated’.

Corrected.

L220-221: The authors describe the conclusion drawn in the Stjern et al study about the semi-direct impact of BC here. They should also include the results of Allen et al., Observationally constrained aerosol–cloud semi-direct effects, npjCAS, 2, 16, 2019 as those suggest the semi-direct effect may not be well captured by the models used in Stjern et al and so drawing conclusions about the sign of the adjustment is less certain than the current text implies.

We have modified the text to account for both these studies and their contrasting results:

“Using data from several global models, Stjern et al. (2017) found that the rapid adjustments by clouds offset a significant fraction of the aerosols’ positive RFari, reducing the net BC climate impact. A recent study by (Allen et al., 2019) instead found a positive cloud rapid adjustment The latter finding would imply a much stronger non-cloud negative rapid adjustment than presented in (Smith et al., 2018) and methodological differences clearly need to be better resolved in order to understand the contrasting results.”

The same goes for text in L281-282 – might reduce temperature response not the more definitive ‘have been shown to’.

Modified.

L225-230: It would be helpful to be clear about the time periods for the forcing values quoted from these other two studies (for Fiedler, forcing when vs when; for Partanen, it is stated that it's for 2100, but relative to when?).

Both studies provide end-of-the-century values (mid-2090s and 2100, respectively) relative to 1850. The text has been modified accordingly.

L269-282: The discussion here starts to delve into the role of individual aerosol species, which is good. I like the current discussion regarding SO2 and BC. I'd like to see a bit more on this, however, in particular I would request that the authors extend their Table S1 to include the year 2100 (data they should already have), and add a discussion of the nitrate forcing towards the end of the century given the large increase in burden shown in Figure 1h for SSP3. That could be usefully compared with the results of the Bauer et al, Bellouin et al, and Shindell et al (see reference in comments on L43-44 for the latter, the other two are already cited) studies that discussed the possibility of substantial increases in negative RF from nitrate over the 21st century.

We have expanded the discussion, including a paragraph about nitrate and, guided by the comments by referee #2, uncertainties related to BC and co-emitted OA.

L318-320: Again could compare with the Silva et al results for future RCPs (see reference in comments on L43-44).

Text added:

"Silva et al. (2016) found avoided premature mortality in 2100 of between -2.39 and -1.31 million deaths per year for the four RCP."

L331: 'Impose' seems an odd word to use here, as usually things people don't want are imposed upon them whereas improved air quality is something people do want. I suggest changing to 'lead to' or something similar.

Good point. Text modified.

L332-347: The Methods section describes how only cloud albedo effects are analysed here (as RFaci is calculated offline). This section should point out that the calculations here not only neglect climate feedbacks, but neglect the entire cloud lifetime portion of RFaci, which may be important.

Added:

"Our estimates of RFaci exclude contributions from cloud lifetime changes. The estimates of cloud lifetime effect are generally lower in recent studies than in early work, but still give non-negligible contribution to the aerosol forcing (Storelvmo, 2017)."

L363: Useful for those not so familiar with the SSPs to add "(SSP3)" after "regionally fragmented world with slower mitigation progress" here.

Agree, added.

L365: "Increases" -> "increase" and "starts" -> "start".

Corrected.

Response to review of *"Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways"* by Marianne T. Lund, Gunnar Myhre, and Bjørn H. Samset.

We thank the anonymous referee #2 for the careful and thorough review of our paper, and the useful suggestions. Responses to individual comments are given below.

Abstract this text "aerosols under three different levels of air pollution control: strong (SSP1), medium (SSP2) and weak (SSP3). " should be revised, given that far more than air pollution controls impact emission levels in these three scenarios. It would be more accurate to describe these as representing three contrasting projections for air pollutant emission levels.

A valid point, we have modified according the referee's suggestion.

More context should be given in the introduction when the scenarios are introduced. It's too simplistic to simply call the scenarios simply high/low air pollution. Air pollution controls plus the magnitude of the various drivers of emissions (e.g., population levels, economic growth, rural access to modern energy, GHG emissions policy, etc.) all play a role in determining the ultimate emissions level. For example, referring to Rao et al. Figure 2, for the Ref case scenarios (e.g. no GHG emissions reduction policy) emissions can differ significantly between SSP1 and SSP5, even though both of these scenarios represent storylines with strong air pollution controls. Similarly, emission levels are generally quite a bit higher in SSP3 as compared to SSP4, even though the emission control assumptions are similar. Note also that the SSPs are from different projection models, which means that one also has be cautious in such comparisons.

We thank the reviewer for these reflections. For detailed descriptions of the assumptions underlying the scenarios and how they drive the differences in emissions, we refer to the cited literature. However, we have rewritten the paragraphs describing the projections to clarify the connection between the air pollution storylines and SSP baseline marker and climate mitigation scenarios, and to emphasize the complexity of the interplaying factors. While the strong/medium/weak terminology is kept for consistency with Rao et al, recognizing that this is a generalization, we include the high/medium/low challenges to mitigation and adaptation that characterizes the given SSP later in the text as well.

The impact of inter-annual variability should be discussed given that meteorology for just one year is used. How much does the selection of that year influence results?

Good point. The effect of different meteorological data sets on aerosol abundances in the OsloCTM3 was investigated in a recent documentation paper by Lund et al. (2018, GMD). Here we add a brief summary and add the following text:

"All simulations are performed with meteorological data for 2010. Lund et al. (2018) investigated the impact of meteorology on the simulated aerosol abundances using data for two years with opposite El Niño–Southern Oscillation (ENSO) index. Differences in global burden of up to 10% for some aerosol species where found, with larger values in localized regions over the tropical Pacific and Atlantic Oceans."

Line 47 - "generally reflect the assumption that stringent air quality regulations will be successfully implemented globally (Rao et al., 2017" Suggest replacing stringent with a somewhat more neutral word (perhaps "substantial""). The RCP's represented a somewhat middle of the road air pollutant emission control assumptions, but by no means were they at maximally feasible levels (which is what might be read by "stringent"). The more important point to be made here is that there was limited variation in air pollution control assumptions across the RCP scenarios.

Modified to substantial. Based on a comment from referee #1 we have also added a paragraph about the underlying environmental Kuznets curve assumption, which limits the variation across RCPs, hence more explicitly addressing this point.

Line 95-105 What was assumed for open burning? These are also supplied in the future scenarios, (but are from van Marle et al 2017, not Hoesly et al., 2018). Note that these are not "natural" emissions, as much of these emissions are due to human activity.

We use the biomass burning emissions supplied by in the future scenarios. The "vegetation" emissions referred to as "natural" is biogenic VOCs. This has been specified in the text now.

Line 123 While I understand why this "For simplicity we refer to SSP1-1.9 as SSP1, SSP2-4.5 as SSP2 and SSP3-7.0 as SSP3 throughout the text." is done, however, this is inaccurate and may lead to misunderstanding on the part of readers, as there can be systematic differences even between scenarios with the same storyline. SSP1-1.9, for example, is a very strong GHG mitigation scenario which means that fossil fuel use is drastically reduced (and what fossil fuel that is used tends to have lower air pollutant emissions). So emissions will tend to be on the low side of what is already a low reference scenario. Emissions can be much lower than the reference case SSP1, particularly in earlier years. Similarly for SSP2-4.5, emissions here can be significantly influenced by the fact that the 4.5 scenario contains policies to limit greenhouse gas emissions. I suggest first, as mentioned above, that a little additional context be given for these scenarios. It would help, on first introducing the scenarios, that the fuller version of the scenario name that also contains the model name is used. That will help enforce to the readers that these are from different projection models. The presence, or not, of a climate policy should be mentioned (e.g. present in SSP1-1.9 and SSP2-4.5) should be mentioned in this introduction, since this can have a strong influence on the emissions pathway. Some of the figures have the fuller scenario names and some do not. Suggest that all figures have the names that contain the forcing target. I suggest the fuller scenario names (e.g., SSP1-1.9) be returned to in the discussion and conclusion section. This will help remind the reader of these issues. This will also facilitate comparisons with other literature results (for example, the detailed data in Gidden et al. 2019 for each scenario.).

We see the point and have included full names with forcing target throughout the text. We have also expanded the introduction and methodology sections.

Line 133 - "the similar characteristics" -> "similar characteristics"

Corrected.

Line 141 - The assumptions behind the RCPs were not "homogeneous" (each RCP was produced by different models, and assumptions were not harmonized between models). The assumptions would be more accurately described as "relatively similar", or some such wording.

Modified.

Line 156 "increased global ammonia (NH_3) emissions (not shown)," (would be useful to reference Gidden et al. 2019 Figure E3 here as these are shown there.)

Included.

Line 187 "However, towards the end of the century North Africa and the Middle East reaches similar levels." Its not clear what this line means, since there is no one behavior for this region. For SO2 (Figure 2), NAF-MDE either stays at current levels, or declines (depending on scenario), while BC either increases somewhat, or declines.

Similar to South and East Asia. Text has been clarified and now reads:

"Towards the end of the century North Africa and the Middle East are projected to experience levels similar to those in South and East Asia."

Line273: "whereas the mainly residential, and therefore more challenging, BC sources remain largely unchecked, the aerosol forcing may follow a different path than estimated here" This is too oversimplified, since residential sources also emit copious amounts of OC, which means that the net forcing from residential sources depends on the balance between BC/OC emissions, and the relative per Tg forcing of each in any particular model. The result is that the net forcing from residential emissions is quite uncertain, likely even as to sign (particularly since rapid adjustments reduce the impact of BC), and trends even more so.

As noted, this is a highly illustrative case meant to initiate discussion around whether there's a possibility that emissions of different species may follow different pathways in the coming decades. The RF estimates provided also include both OA and nitrate, and the rapid adjustments of BC are noted. However, following this comment and input from the anonymous referee #1, we have expanded the discussion with more on the role of nitrate, as well as the uncertainties surrounding the forcing of OA, which could also have a non-negligible absorption (brown carbon).

Line 307 " find no evidence that aerosol emissions reductions drive a particularly rapid near-term warming in this scenario. " Perhaps point out here that this points to the significant inter-model differences in aerosol response.

Yes, good suggestion. Included.

Line 331 "impose" is an odd word here, perhaps "drive"?

Modified to "lead to"

general: It would make this work more helpful for readers if the time series of global and regional forcing could be provided in the supplement. Also, forcing by species (sulfate, nitrate, BC, OC, etc.) (+ aerosol cloud interactions) should also be provided. These are, in part, discussed in the manuscript, but a table with numerical values should be provided.

Full time series of total RFari and RFaci has been added. Forcing by species is only available for the direct aerosol effect and for the selected years presented in Table S1.

Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways

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Abstract

Emissions of anthropogenic aerosols are expected to change drastically over the coming decades, with potentially significant climate implications. Using the most recent generation of harmonized emission scenarios, the Shared Socioeconomic Pathways (SSPs) as input to a global chemistry transport and radiative transfer model, we provide estimates of the projected future global and regional burdens and radiative forcing of anthropogenic aerosols under three contrasting pathways for ~~different levels of~~ air pollution levels: ~~control: strong~~ ~~(SSP1~~SSP1-1.9~~)~~, ~~medium (~~SSP2-4.5~~)~~ and ~~weak (~~SSP3-7.0~~)~~. We find that the broader range of future air pollution emission trajectories spanned by the SSPs compared to previous scenarios translates into total aerosol forcing estimates in 2100 relative to 1750 ranging from -0.04 W m^{-2} in ~~SSP1~~SSP1-1.9 to -0.51 W m^{-2} in SSP3-7.0. Compared to our 1750-2015 estimate of -0.55~~61~~ W m^{-2}, this shows that depending on the success of air pollution policies and socioeconomic development over the coming decades, aerosol radiative forcing may weaken by nearly 95% or remain close to the pre-industrial to present-day level. In all three scenarios there is a positive forcing in 2100 relative to 2015, from 0.51 W m^{-2} in ~~SSP1~~SSP1-1.9 to 0.04 W m^{-2} in SSP3-7.0. Results also demonstrate significant differences across regions and scenarios, especially in South Asia and Africa. While rapid weakening of the negative aerosol forcing following effective air quality policies will unmask more of the greenhouse gas-induced global warming, slow progress on mitigating air pollution will significantly enhance the atmospheric aerosol levels and risk to human health in these regions. In either case, the resulting impacts on regional and global climate can be significant.

1 Introduction

Understanding the contribution of aerosols and other short-lived climate forcers to the total anthropogenic radiative forcing (RF) is becoming increasingly important considering the ambitious goals of the Paris Agreement. Under scenarios compliant with keeping global warming below 1.5°C, global greenhouse gas emissions must generally be reduced to net zero by the middle of the century, placing added focus on the evolution and relative importance of emissions of other climate-relevant substances for the net future climate impact (IPCC, 2018). Additionally, aerosols play a key role in shaping regional climate and environment, by modulating clouds, circulation and precipitation and air quality. In South and East Asia, currently the largest emission source regions, air pollution is one of the major health risks, estimated to have been responsible for 1.2 million deaths in 2017 in India alone (Balakrishnan et al., 2019). In the same region, aerosols may have masked up to 1 °C of surface warming (Samset, 2018), and the sensitivity of the regional climate to reductions in aerosol emissions has been found to be high (Samset et al., 2018a).

Several long-term scenarios for air pollutant emissions exist. Among the most recent examples are the Representative Concentration Pathways (RCPs) (Granier et al., 2011). The RCPs formed the basis for the Coupled Model Intercomparison Project Phase 5 (CMIP5) and have been used in a number of studies to estimate the potential impact of future changes in aerosols on air quality and health (e.g., Li et al., 2016; Partanen et al., 2018; Silva et al., 2016), radiative forcing and temperature (e.g., Chalmers et al., 2012; Shindell et al., 2013; Szopa et al., 2013; Westervelt et al., 2015) and precipitation and other climate variables (Nazarenko et al., 2015; Pendergrass et al., 2015; Rotstayn et al., 2014).

The RCPs were developed to span a range of climate forcing levels and were not associated with specific socio-economic narratives. The RCPs generally reflect the assumption that ~~stringent~~ air quality regulations will be successfully implemented globally (Rao et al., 2017). As a result, emissions of aerosols and aerosol precursors are projected to decline rapidly in all scenarios, even under high forcing and greenhouse gas emission levels. However, despite efforts to control pollutant emissions, ambient air quality continues to be a major concern in many parts of the world. Global emissions of black and organic carbon (BC, OC) have increased rapidly over recent decades (Hoesly et al., 2018). Global emissions of sulfur dioxide (SO_2) have declined, driven by legislation in Europe and North America, the collapse of the former Soviet Union and, more recently, air quality policies in China (Li et al., 2017; Zheng et al., 2018). However, in other regions of the world, most notably South Asia, SO_2 emissions ~~also~~ continue to be high and are increasing. The aerosol and precursor emissions in the RCPs are generated following the assumption that economic growth leads to decreased emissions, i.e., following the so-called environmental Kuznets curve. The real-world representativeness of this relationship has, however, been questioned (Amann et al., 2013; Ru et al., 2018). Combined with ~~T~~the slow observed progress on alleviating air pollution, ~~raises~~ the question of whether previous projections of future emissions are too optimistic in terms of pollution control arises. More recent scenario development has included alternative assumptions to better understand the mechanisms and interlinkages with reference scenarios and climate policy co-benefits (Chuwah et al., 2013; Rao et al., 2013; Rogelj et al., 2014). These provide a wider range of possible developments but are still largely independent of underlying narratives.

To provide a framework for combining future climate scenarios with socioeconomic development, the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014) were produced. The SSPs provide five narratives for plausible future evolution of society and natural systems in the absence of climate change and combine these with seven different climate forcing targets using integrated assessment modeling, building a matrix of emission scenarios with socioeconomic conditions on one axis and climate change on the other. Associated narratives for ~~projections of~~ air pollution emissions have been developed, representing ~~where~~ three levels of ~~different assumptions for future~~ pollution control (strong, medium and weak) based on characteristics of control targets, rate of implementation of effective policies and technological progress ~~are mapped to specific SSPs~~ (Rao et al., 2017). These pollution storylines are then matched with SSP baseline marker and climate mitigation narratives. In ~~the strong pollution control scenarios (~~SSP1 and SSP5~~)~~, the combination of strong pollution control, high level of development and increasing health and environmental concerns result in reduced ~~lower than current~~ air pollution emission levels in the medium to long term. A similar, but slower development is seen under medium control and medium challenges to societal development (SSP2), whereas with ~~under~~ weak control and greater inequality in ~~(~~SSP3 and SSP4~~)~~ ~~there is~~ progress is slowed and regionally fragmented. The numerous drivers influencing future development~~is~~ results in a broad range in projected emissions, between ~~in the~~ baseline marker scenarios and for a given SSP depending on the climate mitigation targets, generally with the highest emissions in SSP3, followed by SSP4, and the lowest in SSP1 or SSP5 (Rao et al., 2017).

Here we use three of the SSP scenarios as input to a global chemical transport model and offline radiative transfer calculations (Sect. 2) in order to quantify the future evolution of aerosols under strong, medium and weak air pollution control. We present results for both global and regional developments in aerosol loadings and radiative forcing (Sec. 3) and discuss implications of the findings in the context of previous generation emission scenarios and outlooks for more detailed studies of the wider climate implications of potential air quality policies (Sect. 4). Conclusions are given in Sect.5.

2 Method

Atmospheric concentrations of aerosols are simulated with the OsloCTM3 (Søvde et al., 2012). The OsloCTM3 is a global, offline chemistry-transport model driven by meteorological forecast data from the European Center for Medium Range Weather Forecast (ECMWF) OpenIFS model. Here the model is run in a 2.25°x2.25° horizontal resolution, with ~~using fixed meteorological data for 2010.~~ 60 vertical levels (the uppermost centered at 0.1 hPa). The present-day aerosol distributions simulated by the OsloCTM3 were recently documented and evaluated by Lund et al. (2018). We refer to the same paper for detailed descriptions about the aerosol modules and treatment of scavenging and transport in the OsloCTM3. All simulations are performed with meteorological data for 2010. Lund et al. (2018) investigated the impact of meteorology on the simulated aerosol abundances using data for two years with opposite El Niño–Southern Oscillation (ENSO) index. Differences in global burden of up to 10% for some aerosol species where found, with occasional larger values in localized regions over the tropical Pacific and Atlantic Oceans.

Simulations with SSP air pollution emissions from fossil fuel, biofuel and biomass combustion are performed for the years 2015, 2020, 2030, 2050 and 2100, keeping the meteorology fixed. Nine emissions scenarios have been g~~G~~ridded ~~data for each scenario~~ and ~~has been~~ harmonized with the Community Emission Data System (CEDS) historical emissions (Gidden et al., 2019) and are available via Earth System Grid Federation (ESGF) by the Integrated Assessment Modeling Consortium (IAMC). ~~Specifically, we~~Here, we use the IMAGE (van Vuuren et al., 2017) SSP1-1.9, MESSAGE-GLOBIOM (Fricko et al., 2017) SSP2-4.5 and AIM (Fujimori et al., 2017) SSP3-7.0 scenarios. SSP1-1.9 represents a pathway with strong air pollution control, low climate forcing level and low mitigation and adaptation challenges, while weak air pollution control, high climate forcing and high mitigation and adaptation challenges characterizes SSP3-7.0. SSP2-4.5 is an intermediate pathway. Air pollution emissions in the remaining scenarios largely ~~Several additional SSPs exist, but these largely~~ fall in the range between SSP1-1.9 and SSP3-7.0. Each simulation is run for 18 months, discarding the first six as spin-up. Natural emission sources (soil, ocean, biogenic organic compounds from vegetation) are kept at the present-day level and the data sets described in Lund et al. (2018). See Sect. 4 Discussion for comments on the potential implications of this choice.

Using the same model setup as in the present study, Lund et al. (2018) recently calculated the historical (1750-2014) evolution of aerosols following the Community Emission Data System (CEDS) inventory (Hoesly et al., 2018). The future projections from the present study are combined with this historical time series. Furthermore, whereas Lund et al. (2018) only assessed the direct aerosol RF, we here include an estimate of the radiative forcing due to aerosol-cloud interactions.

We calculate the instantaneous top-of-the atmosphere radiative forcing due to aerosol-radiation interactions (RFari) (Myhre et al., 2013b) using offline radiative transfer calculations with a multi-stream model using the discrete ordinate method (Stamnes et al., 1988). The same model has been used in earlier studies of RFari (Bian et al., 2017; Myhre et al., 2013a) with some small recent updates to aerosol optical properties (Lund et al., 2018). The radiative forcing of aerosol-cloud interactions (RFaci) (earlier denoted ~~as~~ the cloud albedo effect or Twomey effect) is calculated using the same radiative transfer model. To account for the change in cloud droplet concentration resulting from anthropogenic aerosols, which alter the cloud effective radius and thus the optical properties of the clouds, the approach from Quaas et al. (2006) is used. This method has also been applied in earlier studies (Bian et al., 2017).

3 Results

In the following, we first document the future global emissions and abundances of aerosols, according to our three chosen SSP scenarios. We then show the resulting regional aerosol burden levels, and finally global and regional radiative forcing. ~~For simplicity we refer to SSP1-1.9 as SSP1, SSP2-4.5 as SSP2 and SSP3-7.0 as SSP3 throughout the text.~~

Figure 1a-d shows annual global emissions (fossil fuel, biofuel and biomass burning) of BC, OC, SO_2 and nitrogen oxides (NOx) from 1950 to 2100 in the CEDS inventory and the SSPs used in the present analysis. For comparison, we also include the RCP2.6 (van Vuuren et al., 2007), RCP4.5 (Smith & Wigley, 2006) and RCP8.5 (Riahi et al., 2007) 2015-2100 emissions. Total emissions excluding biomass burning are shown in Fig. S1. For all four species, the temporal evolution and difference between scenarios have ~~the~~ similar characteristics. In ~~SSP1~~SSP1-1.9 ~~(strong air pollution control)~~, emissions are projected to decline from 2015. This decline is particularly rapid for BC and SO_2, with emissions falling to around 25% of their 2015 levels already by 2040. For NOx and OC, emissions are projected to go down by around 80% by the end of the century. Apart from SO_2, SSP3-7.0~~ (weak air pollution control)~~ sees an increase in emissions by towards the mid-21st century (by 10-20% above 2015 levels), followed by a decline back to, or slightly below the present-day by 2100. Emissions in SSP2-4.5 ~~(medium air pollution control)~~ follow an intermediate pathway; a decline throughout the century, but less steep and with a higher end-of-century levels than ~~SSP1~~SSP1-1.9. As a result of the relatively similar~~homogeneous~~ underlying assumptions about the level of air pollution mitigation, the RCPs display much smaller spread and emissions fall throughout the century. All three RCPs generally lie between ~~SSP1~~SSP1-1.9 and ~~SSP2~~SSP2-4.5. There is also a decline in biomass burning emissions in ~~SSP1~~SSP1-1.9 and ~~SSP2~~SSP2-4.5, where emissions are around 30%-40% lower in 2100 compared to 2015. Rao et al. (2017) note that changes in biomass burning emissions are not necessarily driven by air pollution policies but can be linked to assumptions about the land-use sector in the respective integrated assessment models.

The rapidly decreasing anthropogenic emissions in ~~SSP1~~SSP1-1.9 result in global total burdens (Fig. 1e-h) of BC, primary organic aerosol (POA) and sulfate that are 30%, 45% and 60%, respectively, of the present-day level by 2100. Under this pathway, biomass burning sources become~~s~~ relatively more important over the century: fossil fuel and biofuel emissions constitute 70% of the total BC burden in 2015, but only 36% by 2100. Similar end-of-century changes are found under ~~SSP2~~SSP2-4.5, but in this case the decline mainly occurs after 2050. In ~~SSP3~~SSP3-7.0, the global aerosol burdens increase toward the mid-century followed by a small or negligible change to 2100 compared to 2015. The global burden of nitrate is twice as high in 2100 compared to 2015 in ~~SSP3~~SSP3-7.0. This is due to the combination of increased global ammonia (NH_3) emissions (not shown here, see Gidden et al. (2019)), which are 30% higher by 2100, a small net change in NOx emissions and a decrease in SO_2 emissions, resulting in less competition for available ammonia by sulfate aerosols. The potentially more important role of nitrate aerosols under certain emission pathways has been documented in previous studies as well (Bauer et al., 2007; Bellouin et al., 2011). In ~~SSP1~~SSP1-1.9 and ~~SSP2~~SSP2-4.5, there is negligible net change in NH_3 emissions over the century, while NOx emissions decline, resulting in a lower burden also of nitrate. Figure 1i-j shows the simulated anthropogenic global-mean aerosol optical depth (AOD) and absorption aerosol optical depth (AAOD) (calculated as the difference between each year and the 1750 value, with~~ as the~~ meteorology and hence contribution from natural aerosols~~ is~~ constant). The anthropogenic AOD falls from 0.026 in 2015 to 0.0005 in 2100 in ~~SSP1~~SSP1-1.9 and 0.006 in ~~SSP2~~SSP2-4.5. These changes correspond to a reduction of the total AOD of 20% (15%) in 2100 in ~~SSP1~~SSP1-1.9 (~~SSP2~~SSP2-4.5) from the present-day level of 0.13. In ~~SSP3~~SSP3-7.0, the anthropogenic AOD increases by 12% to 2050 before returning approximately to its present-day value. Similar magnitude decreases in anthropogenic AAOD are found. The decline in anthropogenic AOD is stronger than implied by the burden changes. We note that the sulfate and nitrate burdens include also smaller contributions from natural (ocean and vegetation) sources that remain constant to 2100. In ~~SSP1~~SSP1-1.9 we find a small, negative AAOD value in 2100. This results from emissions on BC and OC being lower in 2100 than in 1750. The stronger decline in anthropogenic AAOD relative to AOD in ~~SSP1~~SSP1-1.9 is reflected in the total (anthropogenic and natural aerosols) Single Scattering Albedo (SSA) (Fig. 1k) which increases to above pre-1970s levels by mid-century and is notably higher than in ~~SSP3~~SSP3-7.0 by the end of the century. As the mechanisms that link aerosol emissions to climate impacts are markedly different for scattering and absorbing aerosols (Ocko et al., 2014; Samset et al., 2016; Smith et al., 2018), this reduction highlights a need for regional studies of aerosol impacts that go beyond the total top-of-atmosphere effective radiative forcing.

The global-mean time series hide significant spatiotemporal differences in aerosol trends. Figure 2 shows the time series of the BC and sulfate burdens, the two dominant species, averaged across 9 regions: North America (NAM), Europe (EUR), Russia (RBU), East Asia (EAS), South Asia (SAS), South East Asia (SEA), North Africa and the Middle East (NAF_MDE), South Africa (SAF) and South America (SAM). The well-known geographical shift in historical emission is clearly reflected, where the largest aerosols loadings were located over North America, Europe and Russia in the 1970s and 80s, but later peaking over Asia. In the coming decades, ~~the~~ South and East Asia will continue to experience the highest aerosol loadings under ~~SSP2~~SSP2-4.5 and ~~SSP3~~SSP3-7.0. ~~However, t~~Towards the end of the century North Africa and the Middle East are projected to experience ~~reaches similar~~ levels similar to those in South and East Asia. Africa south of the Sahara is presently the third largest BC emission source region (Fig. S2). Under ~~SSP3~~SSP3-7.0, anthropogenic (fossil and biofuel) emissions are projected to increase strongly over the century in ~~Africa south of Sahara~~ and the region surpasses East Asia as the largest source in 2100, although levels stay below current emission levels in China. Figure 2 shows that a slightly decreasing BC burden is projected over the region in all three SSPs. In this case, the increase in fossil fuel emissions is offset by a decrease in biomass burning emissions, which constitute a significant fraction of the total BC source here. Despite lower emissions in the latter region, BC burdens in SAF and NAF_MDE~~southern and northern parts of Africa~~ are of the same order of magnitude. One reason for this is likely differing scavenging pathways, where aerosols are more effectively removed, and the atmospheric residence time is shorter, further south. Moreover, we note that the regionally averaged burden does not directly link to regional emissions, as they are also influenced by long-range transport. Using multi-model data from the Hemispheric Transport of Air Pollution (HTAP2) experiments, studies have demonstrated that while for most receptor regions, within-region emissions dominates, there are the important contribution from long-range transport from e.g., Asia to aerosols over North America, Middle East and Russia (e.g., Liang et al., 2018; Stjern et al., 2016; Tan et al., 2018). Hence, the projected emission changes in this region can have far reaching impacts.

The radiative forcing of anthropogenic aerosols relative to 1750 is shown for the period 1950 to 2100 in Fig. 3, for RFari, RFaci, and the total aerosol RF (RFtotal), separately. Results from the present study are complimented by results based on simulations from Lund et al. (2018) (see Methods) for the historical period. We calculate a net aerosol-induced RF in 2015~~4~~, relative to 1750, of -0.55~~61~~ W m^{-2}, whereof -0.14~~7~~ W m^{-2} is due to aerosol-radiation interactions, as also shown in Lund et al. (2018), and -0.42~~4~~ W m^{-2} due to aerosol-cloud interactions. Due to the rapid emission reductions projected over the next couple of decades, the RF is less than half in magnitude to its present-day value in ~~SSP1~~SSP1-1.9 already by 2030, continuing to weaken at a slower rate after. In 2100 (relative to 1750), the RFtotal is -0.04 W m^{-2} in ~~SSP1~~SSP1-1.9 and -0.20 W m^{-2} in ~~SSP2~~SSP2-4.5. With emissions following ~~SSP3~~SSP3-7.0, the temporal evolution of RF is nearly flat through the 21st century and is -0.51 W m^{-2} in 2100, only 8~~15~~% lower in magnitude than in 2015~~4~~. Even with weak air pollution control (~~SSP3~~SSP3-7.0) end-of-the-century emissions are slightly lower than the present-day level. Hence, looking only at the period 2015-2100, we estimate a positive aerosol forcing in all three scenarios considered. The RFtotal in 2100 relative to 2015 is 0.51 W m^{-2}, 0.35 W m^{-2} and 0.04 W m^{-2} in ~~SSP1~~SSP1-1.9, ~~SSP2~~SSP2-4.5 and ~~SSP3~~SSP3-7.0, respectively. The estimates presented here do not account for the rapid adjustments (or semi-direct effects) associated with BC. Using data from several global models, Stjern et al. (2017) ~~, which has been suggested~~found that the rapid adjustments by clouds ~~to~~ offset a significant fraction of the aerosols' positive~~ BC~~ RFari, reducing ~~sulting a lower than previously found~~ the net BC climate impact~~ of BC aerosols~~. In contrast, a recent study by Allen et al. (2019) ~~Allen et al. (2019)~~ found positive cloud rapid adjustment.~~(Stjern et al., 2017).~~ The latter finding would imply a much stronger non-cloud negative rapid adjustment than presented in Smith et al. (2018) and methodological differences hence clearly need to be better resolved in order to understand the contrasting results.

Few modeling-based estimates for comparison with our results exist so far. In a recent study, Fiedler et al. (2019b) used a simple plume parameterization of optical properties and cloud effects of anthropogenic aerosols and scaled the present-day aerosol optical depth by the SSP emissions to derive estimates of future forcing. An effective radiative forcing (ERF) (comparable to our RFtotal) in the mid-2090s relative to 1850 ranging from -0.15 W m^{-2} for ~~SSP1~~SSP1-1.9~~-1.9~~ to -0.54 W m^{-2} for SSP3-7.0 was calculated. This is in reasonable agreement with the estimates derived in the present analysis, although we find a weaker forcing in ~~SSP1~~SSP1-1.9. Using two idealized scenarios to span a broader range of emissions than represented in the RCPs, Partanen et al. (2018) also estimated a broad range in aerosol ERF, from -0.02 W m^{-2} to -0.82 W m^{-2}, in 2100 (relative to 1850). The latter is significantly stronger than our ~~SSP3~~SSP3-7.0 estimate. While not directly comparable due to differing emission inventories and methodologies, these studies reinforce our finding that weak air pollution control over the 21st century result in sustained strong negative aerosol forcing.

The spatiotemporal differences in trend documented above translates into effects on global and regional RF. In Fig. 4 we therefore show the change in RFtotal over four time periods, 1750-2015, 1750-1990, 1990-2015 and 2015-2030 (for each SSP). Figure S3 show the corresponding results for RFari and RFaci separately. Whereas the impact of anthropogenic aerosols is a negative RFtotal everywhere except over the high-albedo deserts and snow-covered regions when taken over the entire historical period 1750-2015, a positive RF is ~~found~~ seen over North America, Europe and Russia after the 1990-2015 period, driven by decreased SO_2 emissions (and somewhat offset by a simultaneous decline in BC emissions). This positive RF is largely driven by aerosol-radiation interactions. Over South and East Asia, Africa and most of South America the RFtotal remains negative, although a significant fraction of the total impact since pre-industrial has already been realized before 1990. This weaker negative forcing is due to a combination of increasing BC emissions and a leveling off in SO_2 emissions in China in the CEDS inventory (Hosely et al. 2018). Globally, the combined effect is an increase in global-mean RFtotal over the 1990-2015 period of +0.09 W m^{-2}. Using the ECLIPSE emission inventory, Myhre et al. (2017) estimated an increase in the multi-model RF due to combined changes in aerosols and ozone from 1990 to 2015 of +0.17

W m^{-2}, with about two-thirds of this from aerosols, i.e., similar to our results using the CEDS/SSP emissions.

Distinct regional differences are seen also during the period 2015-2030 under the different SSPs. With emissions following ~~SSP1~~SSP1-1.9, we estimate a positive global-mean RFtotal of 0.33 W m^{-2}, more than three times the RFtotal over the 1990-2015 period. In contrast to the 1900-2015 period, the strongest RF now comes from aerosol-cloud interactions, as emissions over continental northern hemisphere regions are low to begin with. The RFtotal is especially large over South and East Asia, and of opposite sign from what the region has experienced during the past decades. Smaller positive global mean RFtotal of 0.08 W m^{-2} is estimated also under ~~SSP2~~SSP2-4.5 and ~~SSP3~~SSP3-7.0 during this period. In contrast to ~~SSP1~~SSP1-1.9, the RF remains negative over India under ~~SSP2~~SSP2-4.5 and ~~SSP3~~SSP3-7.0 where a continued increase in emissions of SO_2 is projected over the next decades. In all SSPs, the RFtotal over China switches from negative in the past decades to positive over the 2015-2030 period. Recent studies suggest that Chinese SO_2 emissions have declined even more than captured by the CEDS until 2014, indicating that this pattern of forcing may already have been partly realized (Li et al., 2017; Zheng et al., 2018). In contrast, emissions of India are projected to increase, at least initially. The potential implications of this feature are discussed in a separate paper (Samset et al., 2019). Weak RF is found over the African continent in the ~~SSP2~~SSP2-4.5 and SSP3-7.0 scenarios. However, as shown in Figure 2, aerosols will continue to affect local climate and air quality in this region.

4 Discussion

Under a given scenario, emissions of all species generally follow the same~~ general~~ global trend, although the rate of change differs between regions. However, over the recent years, emissions of SO_2 have declined, whereas BC emissions have increased (Hoesly et al., 2018). Considering a hypothetical and simplified case where the mainly industrial, and perhaps easier to mitigate, SO_2 emissions begin to decline rapidly also in other high emitting regions, whereas the mainly residential, ~~and therefore~~ more challenging, BC sources remain largely unchecked, the aerosol forcing may follow a different path than estimated here. As an illustrative example, we calculate the contribution to RFari in 2020 and 2050 (relative to 1750) from individual components under ~~SSP1~~SSP1-1.9 and ~~SSP3~~SSP3-7.0 (Table S1). Taking the sum of the sulfate forcing from ~~SSP1~~SSP1-1.9 and the remaining components from ~~SSP3~~SSP3-7.0, the total RFari is -0.018 W m^{-2} in 2020, i.e., significantly weaker than when all emissions follow ~~SSP1~~SSP1-1.9, and 0.15 W m^{-2} in 2050. Continuing along the recent emission development of declining SO_2 emissions and increasing BC could imply a different development in the total aerosol effect relative to pre-industrial than shown by the three scenarios here, at least towards the mid-century. We emphasize that these numbers are meant to be illustrative and note that significant uncertainties surround the climate impact of both BC and the co-emitted organic aerosols. ~~Hence, continuing along the recent emission development could mean a net positive direct aerosol effect relative to pre-industrial, at least towards the mid-century, adding to the greenhouse gas induced warming.~~ As noted above, our estimates ~~this~~ do~~es~~ not~~, however,~~ account for the rapid adjustments which might ~~have been~~

~~shown to~~ reduce the global surface temperature response to BC perturbations. Additionally, the role of absorption by so-called brown carbon remains an important uncertainty (Samset et al., 2018b). Previous work has also pointed to the possibility of substantial increases in radiative forcing by nitrate over the 21st century (Bauer et al., 2007; Bellouin et al., 2011; Shindell et al., 2013), and a notable increase in nitrate burden is also estimated in the present study when emissions follow SSP3-7.0. This translates into a nitrate RF that is almost a factor 2 stronger in 2100 than in 2020 and constitutes a correspondingly larger fraction of the RFtotal in this scenario (Table S1)

We present projected future aerosol RF based on single-model simulations. Aerosols, however, remain one of the most uncertain drivers of climate change, with significant model spread resulting from several factors, including differences in the simulated aerosol distributions, optical properties and cloud fields. Myhre et al. (2013a) calculated a present-day aerosol RFari (relative to 1850) varying from -0.016 W m^{-2} to -0.58 W m^{-2} between 16 global models participating in the AeroCom Phase II experiment. Prescribing the distribution of anthropogenic aerosols, optical properties and effect on cloud droplet number concentration in six Earth System Models, Fiedler et al. (2019a) find a model spread in aerosol ERF of -0.4 W m^{-2} to -0.9 W m^{-2}. Among the important consequences of high aerosol forcing uncertainty is the challenge it poses for estimating climate sensitivity. While in a scenario with declining aerosol emissions, combined with an increase in greenhouse gases, the uncertainty in the total anthropogenic forcing can be expected to decrease substantially even without scientific progress (Myhre et al., 2015), the high emission ~~SSP3~~SSP3-7.0 pathway suggest that aerosols may continue to be a confounding factor for constraining climate sensitivity.

While the scope of the present analysis is limited to radiative forcing, the calculated spread in end-of-century forcing under the SSPs will translate into a wide range of possible climate impacts. A number of studies have examined the future aerosol-induced radiative forcing and climate impacts using the RCP projections; see e.g., Westervelt et al. (2015) for a summary of papers published until 2013. While the magnitude of both present-day and future estimates differs between studies, the general characteristic is a significant weakening of the aerosol RF until 2100 in all scenarios. Other studies have investigated the potential for this rapid decline to drive near-term warming (Chalmers et al., 2012; Gillett & Von Salzen, 2013). However, while Chalmers et al. (2012) find a higher near-term warming in RCP2.6 than in RCP4.5 despite lower greenhouse gas forcing in the former, suggesting an important impact of falling aerosol emissions, Gillett and Von Salzen (2013) find no evidence that aerosol emissions reductions drive a particularly rapid near-term warming in this scenario. This points to the importance of inter-model differences in the response to aerosol perturbations. Under ~~SSP1~~SSP1-1.9, aerosol emissions are projected to decline even more rapidly than in RCP2.6 over the coming couple of decades (Fig. 1). If in fact associated with a rapid warming, this development could further hinder the realization of the already ambitious temperature goals of the Paris agreement and this feature hence needs to be better quantified. Previous work also demonstrate effects of falling aerosol emissions also other climate variables such as mean and extreme precipitation (Navarro et al., 2017; Pendergrass et al., 2015) and atmospheric dynamics (Rotstayn et al., 2014). The numerous and significant impacts of aerosols underline the need to encompass the full range of projected emissions, regionally and globally, in future assessment, in particular in light of the crucial role of aerosols in shaping regional climate, regional assessments are needed to capture the impact of different trends.

It is well-established that future changes in aerosols will critically affect local air quality. Silva et al. (2016) found avoided premature mortality in 2100 of between -2.39 and -1.31 million deaths per year for the four RCP. Partanen et al. (2018) estimated almost 80% fewer PM2.5-induced deaths per year in 2100 under RCP4.5 compared to 2010. In contrast, ~~Conversely, ~~an idealized high aerosol scenario resulted in 17% increase in premature mortality by 2030. These numbers where estimated using present-day population density. Under all SSPs, considerable increases in population density is projected in Africa, the Middle East and South Asia (Jones & O'Neill, 2016) – regions that are also identified as hotspots for exposure and vulnerability to multi-sector climate risk (Byers et al., 2018). In the present study, we estimate an increase in the average surface concentration of anthropogenic aerosols (i.e., BC, POA, sulfate and fine mode nitrate) of 17% and 25% by 2100 under ~~SSP3~~SSP3-7.0 in South Asia and North Africa plus the Middle East, respectively. Air pollution issues are not limited to developing countries. While all scenarios project reductions in surface aerosol concentrations in Europe, North America and Russia, there are substantial differences in the magnitude, from 35-20% lower by 2100 in ~~SSP3~~SSP3-7.0 to around 70% lower in ~~SSP1~~SSP1-1.9, highlighting the potential for further~~stringent policies to impose~~ air quality improvements globally.

Our estimates of RFaci exclude contributions from cloud lifetime changes. The estimates of cloud lifetime effect are generally lower in recent studies than in early work, but still give non-negligible contribution to the aerosol forcing (Storelvmo, 2017). Our study does not account for potential impacts of climate change on circulation, precipitation or chemistry, which can affect the lifetime and transport pathways, as well as emissions, of the aerosols. For instance, Bellouin et al. (2011) found increasing atmospheric residence times over the 21st century as wet deposition rates decreased. Including both changing climate and emissions, Pommier et al. (2018) suggested that concentrations of particulate matter ($PM_{2.5}$) will increase by up to 6.5% over the Indo-Gangetic Plain to 2050, driven by increases in dust, particulate organic matter and secondary inorganic aerosols through changes in precipitation, biogenic emissions and wind speed. Hence, by keeping natural sources of emissions fixed at present-day levels, our results may underestimate the future aerosols loads. Moreover, a recent review of climate feedbacks on aerosol distributions suggests that in regions where anthropogenic aerosol loadings decrease, the impacts of climate on the variability of natural aerosols increase (Tegen & Schepanski, 2018). Changing climatic conditions may also affect the radiative forcing through changing cloud distributions and surface albedo. While our approach clearly disentangles and assesses the changes in aerosols resulting from changes in anthropogenic emissions, representation and knowledge of feedback processes are important for understanding the full role of future aerosols in the climate system.

5 Conclusions

Using a global chemistry transport model and radiative transfer modeling, we have estimated the projected future loading and radiative forcing of anthropogenic aerosols under the most recent generation of scenarios, the Shared Socioeconomic Pathways. These new air pollution scenarios link varying degrees of air pollution control to the socioeconomic narratives underlying the SSPs and climate forcing targets, spanning a much broader range of plausible future emission trajectories than previous scenarios. Here we have used three scenarios: SSP3-7.0 (weak air pollution control, high mitigation and adaptation challenges), ~~SSP2~~SSP2-4.5~~-4.5~~ (medium pollution control, medium mitigation and adaptation challenges) and ~~SSP1~~SSP1-1.9 (strong pollution control, low mitigation and adaptation challenges). In all three scenarios, we estimate a positive aerosol forcing over the period 2015-2100, although with very different timing and magnitude depending on stringency of air pollution control. The end-of-century aerosol forcing relative to 2015 is 0.51 W m^{-2} with emissions following ~~SSP1~~SSP1-1.9, 0.35 W m^{-2} in ~~SSP2~~SSP2-4.5 and 0.04 W m^{-2} in ~~SSP3~~SSP3-7.0. While effective air pollution control and socioeconomic development following ~~SSP1~~SSP1-1.9 results in a rapid weakening of the aerosol RF compared to the pre-industrial to present-day level already by 2030, there is little change in the global mean aerosol forcing over the 21st century in a regionally fragmented world with slower mitigation progress (SSP3-7.0). Significant spatiotemporal differences in trends are also highlighted. Most notably, under weak air pollution control, aerosol loadings in East and South Asia temporarily increase~~s~~ from present levels but start~~s~~ to decline after 2050 and return to current levels of slightly below by 2100. North Africa and the Middle East reaches the levels of South Asia by the end of the century and there is no declining trend this century. The present analysis is limited to the documentation of radiative forcing and aerosol loads. Under both rapidly declining and sustained high emissions, aerosols will play an important role in shaping and affect regional and global climate.

Code availability

Oslo CTM3 is stored in a SVN repository at the University of Oslo central subversion system and is available upon request. Please contact m.t.lund@cicero.oslo.no. In this paper, we use the official version 1.0, Oslo CTM3 v1.0.

Data availability

The gridded SSP anthropogenic emission data are published within the ESGF system https://esgf-node.llnl.gov/search/ input4mips/ (last access: December 2018). Model output and post-processing routines are available upon request from Marianne T. Lund (m.t.lund@cicero.oslo.no).

Author contributions

MTL performed the Oslo CTM3 experiments and led the analysis and writing. GM performed the radiative transfer modeling and BHS contributed with graphics production. All authors contributed during the writing of the paper.

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Competing interests

The authors declare that they have no conflict of interest.

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Figures

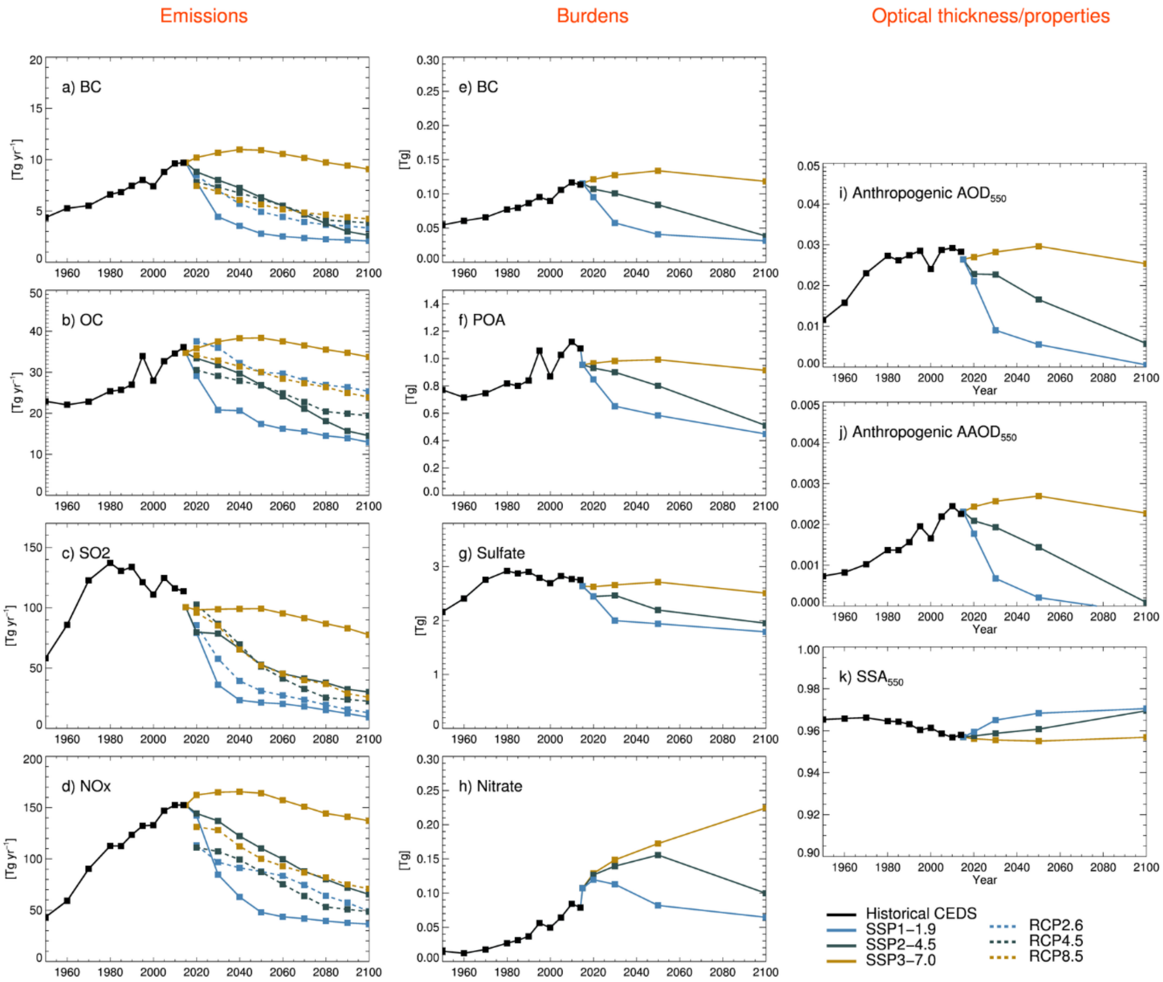
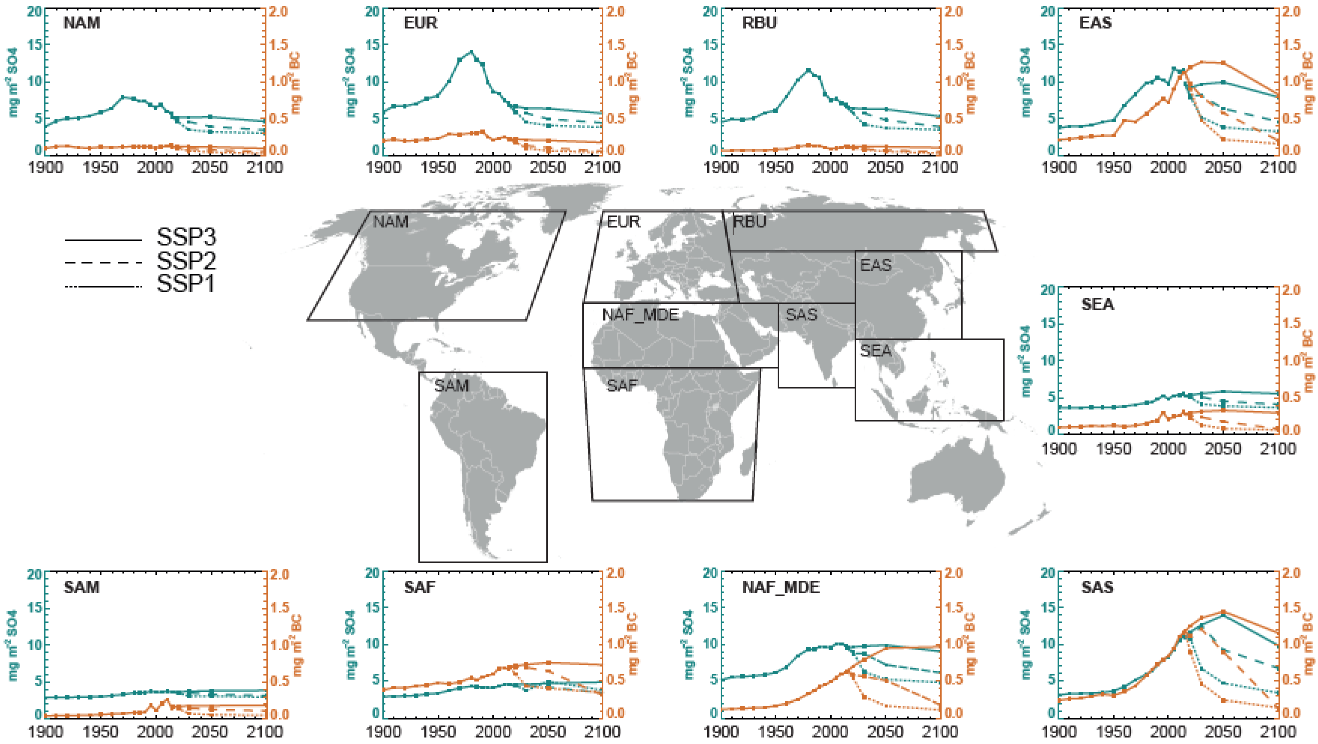


Figure 1. Left: Annual global emissions (fossil fuel, biofuel and biomass burning) of BC, OC, SO_2 and NOx over the period 1950 to 2100 from the CEDS historical inventory and ~~SSP1~~SSP1-1.9, SSP2-4.5 and SSP3-7.0 (solid colored lines). Emissions from RCP2.6, RCP4.5 and RCP8.5 (dashed lines) are added for comparison. Middle: Modeled total global burdens of BC, POA, sulfate and fine mode nitrate. Right: Anthropogenic AOD and AAOD, and total (anthropogenic and natural) SSA at 550nm.



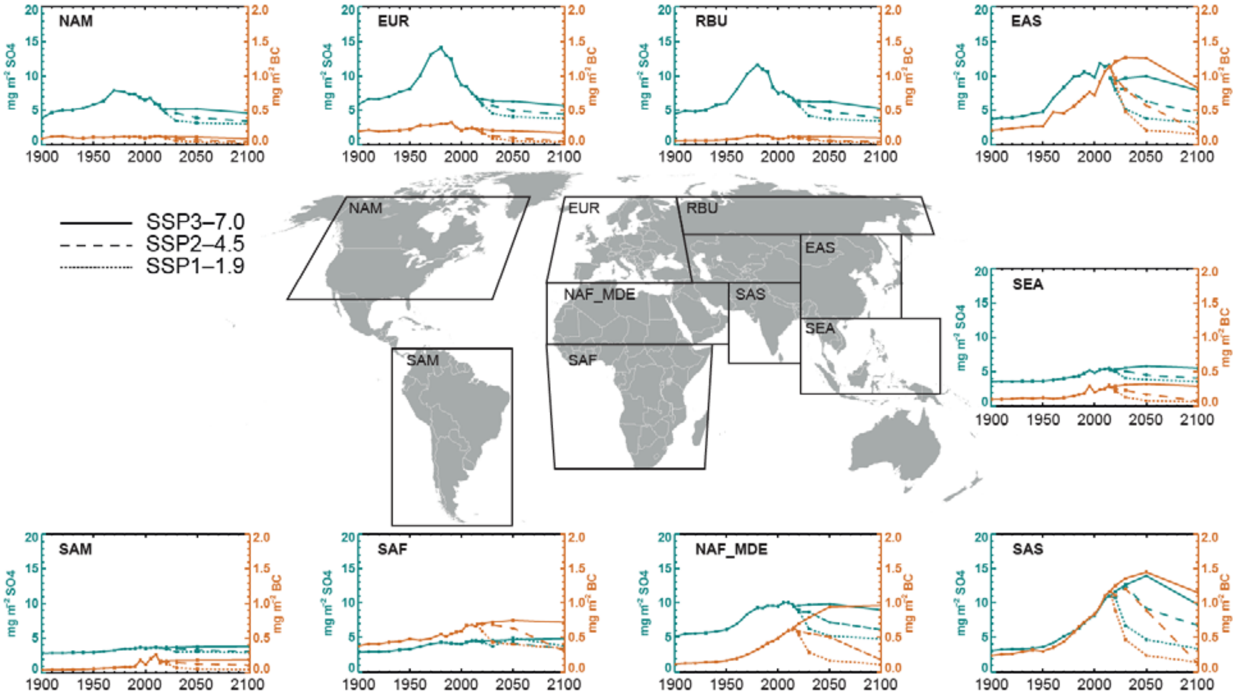


Figure 2: Regionally averaged burdens of BC and sulfate aerosols from 1900 to 2100 using CEDS historical emissions and SSP1-1.9, SSP2-4.5 and SSP3-7.0.

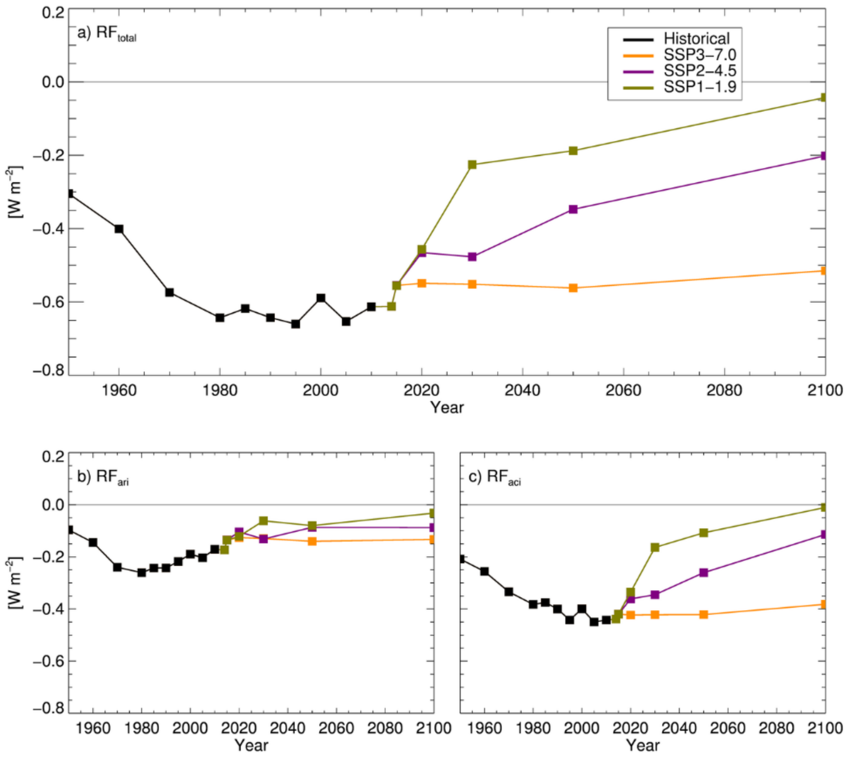
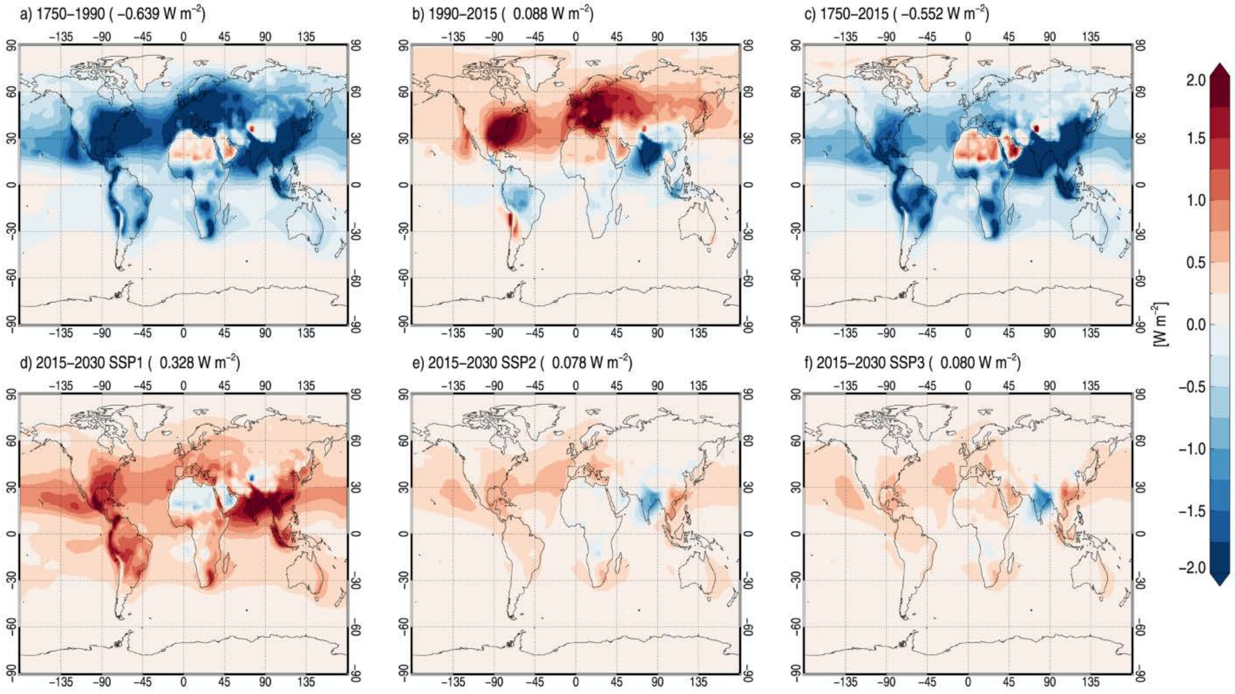


Figure 3: Radiative forcing of anthropogenic aerosol 1950-2100 relative to 1750: a) total aerosol RF (RFtotal), b) aerosol-radiation interactions (RFari) and c) aerosol-cloud interactions (RFaci).



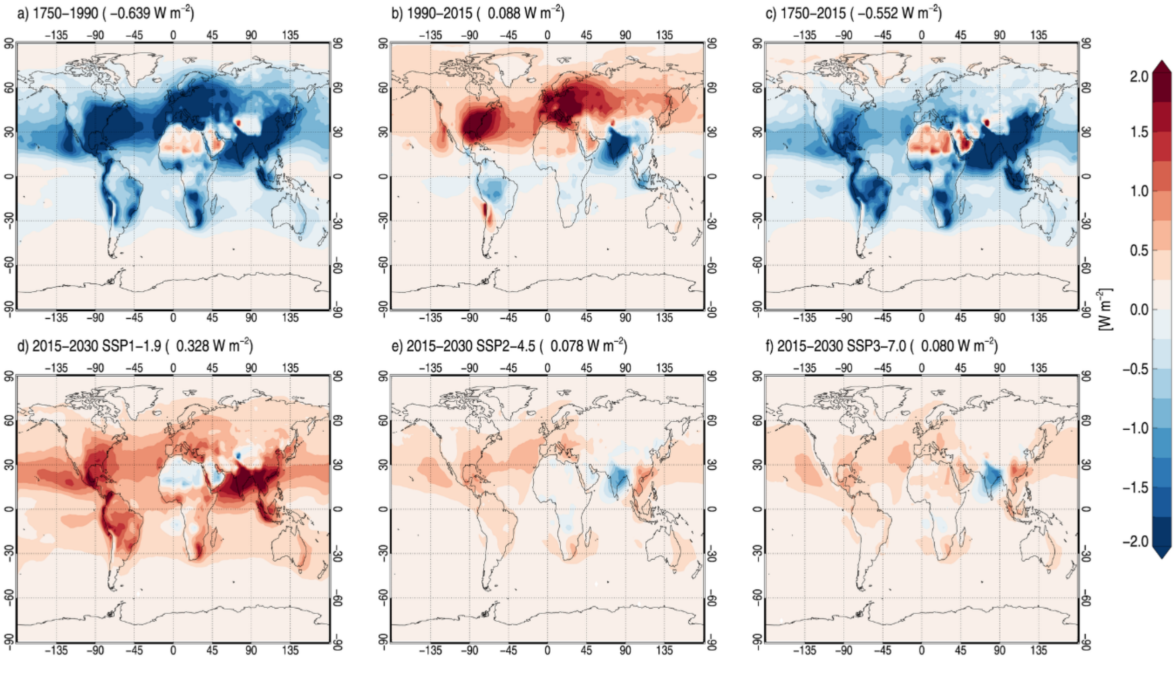


Figure 4~~3~~: Total aerosol RF over four time periods: 1750-1990, 1990-2015, 1750-2015, and 2015-2030~~,~~ for each of the three SSP scenarios considered here.