

# 1 Reviewer 1

## 1.1 General Comments

### Comment

Additionally, the reference list includes mostly papers authored by the authors themselves. A broader literature review is recommended.

### Response

We thank the reviewer for their comment regarding the cited literature. The authors of this manuscript do indeed span a number of research teams comprising much of the scenario literature, thus there are inevitably self-references. However, we do agree with the reviewer that our literature review could be more expansive. Therefore, we have increased, where applicable, references to the available literature not including authors on this paper. Notably, we expand our assessment in the user community of emissions scenarios and also with respect to uncertainties in species contribution to radiative forcing.

## 1.2 Specific Comments

### Comment

#### 2.1.3 Region-to-Country Downscaling

Some questions about region-to-country downscaling emerge, particularly about assumptions made. For instance, the use of a linear downscaling method “means that the fraction of regional emissions in each country stays constant over time” (page 9 line 30). This seems an oversimplification for sectors that may represent a large share of emissions in many countries today (mostly developing countries). However, this may not be true in the future, especially as countries develop and energy use increases. Thus, holding the share of LUC emissions constant over time overestimates their contribution to total emissions, and downplays the potential contribution of energy use in these countries. More importantly, it downplays any mitigation efforts potentially implemented by such countries. Is it reasonable to assume that in SSP1 the shares of Agricultural Waste Burning emissions will remain constant? Why?

This assumption is made without any justification or analysis of its validity and potential impacts on results. The reader is referred to the “downscaling wiki”, an online documentation site, but very little explanation is to be found there as well.

### Response

We apologize for the confusion. Emissions amounts do change over time, it is just the sub-regional distribution amongst countries that is constant for open-burning emissions. We will update the text to clarify that this as:

means that the fraction of regional emissions in each country stays constant over time. Therefore, the total amount of open-burning emissions allocated to each country will vary over time as economies evolve into the future, following regional trends from the native IAM. However there is no sub-regional change in the within-model-region spatial distribution of land-use related emissions over time. This is in contrast to other anthropogenic emissions, where the IPAT method is used to dynamically downscale to the country level as discussed above.

### **Comment**

Additionally, this linear method may well have different impacts on different GHG species. Aerosols in particular, especially as these are the only species for which the downscaling results are presented in Section 3.4. Surely, agricultural waste burning has an impact on aerosol formation so that the choice of downscaling method in the first step (region to country) is fundamentally important.

Wouldnt it be more appropriate to also use some form of convergence as is done for other sectors? It seems to me this assumption of constant shares for LUC emissions should be fully justified or, preferably, be the subject of sensitivity analysis of some form. This should be further explored, explained and justified. In my view, it should have its own section in the supplementary information. Understandably, there is high uncertainty with these categories of emissions, but that is only more reason to explicitly address it. Also, it would be useful to have a comment by the authors about how this assumption might impact results of the CMIP6 activities using these scenarios as input.

### **Response**

As noted above, open burning emissions are not constant over time. These evolve according to the parent IAMs modeling. The simple IPAT downscaling method was not used because this could lead to illogical results, such as ag waste burning emissions in one country becoming unrealistically large relative to agricultural land area. Certainly improved downscaling methods specific for each type of open-burning emissions are possible. Given that the code has been made available as open source, anyone can implement alternative downscaling methods and test their impact on, for example, aerosol loadings.

### **Comment**

Appendix C: Emissions Gridding

Page 30, line 5: “For each aggregate sector the spatial pattern of emissions within a country, therefore, does not change over time in the future scenarios, although the spatial pattern of total emissions will change due to changes in the sectoral distribution of emissions.”

This sentence is important and should be better formulated. I am having difficulty understanding what stays constant and what changes over time. Maybe the crux of the problem is what is meant by the word “total emissions”. Is meant as “global emissions”, as contrast with “emissions within a country”?

In my opinion, this section should be expanded to include the points I raised above in my previous comment on Section 2.3.1.

### **Response**

This section will be expanded, as follows, to better explain this concept. Note, a companion paper is being submitted that will more fully explain the gridding methodology, results, and implications.

Emissions data were mapped to a spatial grid generally following the methodologies described in Hoesly et al. (2018). A brief description is given here, and a fuller discussion of the gridding process will be provided in Feng (2019). For most anthropogenic sectors, emissions at the level of country and aggregate sector are mapped to a 0.5 spatial grid by scaling the 2010 base-year country-level spatial pattern. Open-burning emissions from forest fires, grassland burning, and agricultural waste burning on fields are mapped to a spatial grid in the same manner, except that the spatial pattern is taken to be the average from the last 10-years of the historical dataset (e.g., 2005-2014). For each aggregate gridding sector the spatial pattern of emissions within a country does not change over time in the future scenarios. This means that, for example, the ratio of energy-sector NO<sub>x</sub> emissions from Shannxi and Beijing provinces in China is constant over time, even though total NO<sub>x</sub> emissions from China vary over time. Because sectors are mapped to the grid separately, however, total anthropogenic emissions (e.g. sum from all sectors) from any two regions within a country will, in general, not have the same time evolution.

### **Comment**

Technical Corrections Page 2, line 32: “where” should be “were” Page 21 line 13: there is no Section 2.4

### **Response**

We have corrected both typographical errors identified by the reviewer. To note, we have updated all section numbers in Section 2. This was due to an erroneous use of `\subsubsection` instead of `\subsection`.

## 2 Reviewer 2

### 2.1 Specific Comments

#### Comment

Page 7, lines 10-13. This makes sense only if there's no trend in the data. Did you check whether there are increases or decreases in land burning? Please clarify.

#### Response

The reviewer here requests clarity on the use of a decadal mean as a harmonization value for land-burning sectors rather than using the value in the most recent historical period as is done for anthropogenic emissions sectors. The variability of emissions species in these sectors is largely due to weather and other climatic variation. Below in Figure 1 we show historical data for the past 25 years normalized to 2005 (the beginning of our data selection window). The harmonization window is shown in grey. While there are some inter-decadal trends, it is hard to observe any specific year-on-year trends. Furthermore, IAM scenarios do not model these year-to-year variations, but only provide a long-term trend. Thus, in order to capture these decadal trends without introducing noise from observations in any specific year, we harmonize to a decadal mean “climatology” as described in the text. We have added the below figure in the SI and referenced it for further clarity to the reader.

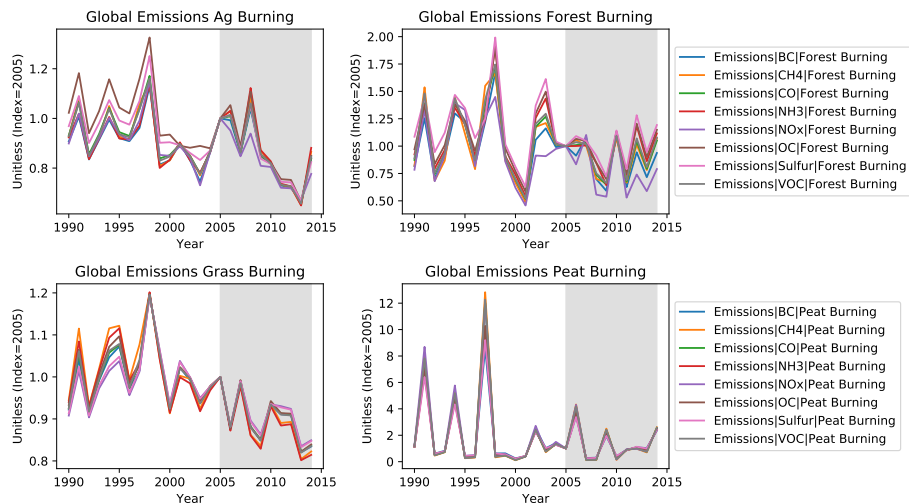


Figure 1: Historical global landuse emissions normalized to their species-specific values in 2005.

**Comment**

Eq. 3. If  $I_c$  is the growth rate, shouldn't the rhs be a sum rather than a multiplication? Please check whether this equation is correct.

**Response**

Equation 3 is correct, however the growth term was not clearly described in the text. It can more accurately be described as a growth factor. The text has been revised to clarify this, using a less ambiguous notation by introducing the growth factor as  $\beta$ . Equation 2, provides the annualized amount, as a multiplier, that the initial intensity should grow over time such that intensity will equal the convergence year intensity by the convergence year.

**Comment**

Eq. 5. Please define  $c'$ . I have problems understanding this equation.

**Response**

This equation simply normalizes results to the regional emissions as produced by a given model.  $c'$  here is an element of set  $R$  (all countries in a region), where the prime superscript is used to differentiate from the index  $c$ , which is used in the equation definition. This is common practice in describing elements of sets in order to differentiate the use of the index, thus any further comments here as to if this is still considered confusing would be appreciated (and we can incorporate accordingly). We have provided more clarifying text to describe this operation in the manuscript by explicitly stating it is a normalization.

**Comment**

Section 3.4. The manuscript does a good job describing the methodology for harmonizing the datasets, but it does not describe with the same level of detail the methodology for obtaining the spatial distribution of emissions. I think it's important to add more detail on this methodology to better understand the results presented in section 3.4. In particular, the section describes different values of emissions for the different scenarios in different countries. Since population and GDP change drastically over time and across scenarios, it is very difficult to make sense of sentences such as “. . . SSP1-2.6, emissions across countries decline dramatically such that by the end of the century, total emissions in China, for example, are equal to that of the USA today”. It'd be great if you help the reader by pointing out whether the results in emissions are driven mostly by changes in population, GDP or the other SSP drivers.

**Response**

We agree with the reviewer that more detail of the methodology is useful, and a companion paper describing this methodology in much more detail will be sub-

mitted to GMD ([https://www.geosci-model-dev.net/special\\_issue590.html](https://www.geosci-model-dev.net/special_issue590.html)) within the week. It is important to note, however, that different models have different regional resolutions. For example, IMAGE is used for SSP1-2.6 and models the USA and China directly. Therefore, there are no downscaling effects associated with the results cited. We strove to discuss the country-specific results where relevant for models in which they are explicitly accounted for. For models which provide country-specific resolution, there are myriad drivers which result in the analyzed emissions trajectories, including not only population, GDP, etc., but also inertia in socioeconomic and energy systems which are endogenously included by the models. Thus, it is hard (if not impossible) to point to a specific subset of these drivers as the primary constituents inducing such changes. In any case, we agree that this can be further clarified, and as such have added the following text to Section 3.4:

Original submission -

CO<sub>2</sub> and CH<sub>4</sub> are well-mixed climate forcers (Stocker et al., 2013) and thus their spatial variation have a higher impact from a political rather than physical perspective. Aerosols, however, have substantive spatial variability which directly impacts both regional climate forcing via scattering and absorption of solar radiation and cloud formation as well as local and regional air quality. Thus in order to provide climate models with more detailed and meaningful datasets, we downscale emissions trajectories from model regions to individual countries using the methodology described previously in Section 2.4, which are subsequently mapped to spatial grids (Feng, 2018). We here present global maps of two aerosol species with the strongest implications on future warming, i.e., BC in Figure 9 and sulfur in Figure 10. We highlight three cases which have relevant aerosol emissions profiles: SSP1-2.6 which has significantly decreasing emissions over the century, SSP3-7.0 which has the highest aerosol emissions, and SSP3-LowNTCF which has similar socioeconomic drivers as the SSP3 baseline but models the inclusion of policies which seek to limit emission of near-term climate forcing species.

Revision -

CO<sub>2</sub> and CH<sub>4</sub> are well-mixed climate forcers (Stocker et al., 2013) and thus their spatial variation have a higher impact from a political rather than physical perspective. Aerosols, however, have substantive spatial variability which directly impacts both regional climate forcing via scattering and absorption of solar radiation and cloud formation as well as local and regional air quality. Thus in order to provide climate models with more detailed and meaningful datasets, we downscale emissions trajectories from model regions to individual countries. **In most cases, models explicitly represent countries with large shares of emissions (e.g., USA, China, India, etc.). MESSAGE-GLOBIOM and REMIND-MAGPIE are notable**

exceptions; however, their regional aggregations are such that these important countries comprise the bulk of emissions in their aggregate regions (e.g., the MESSAGE-GLOBIOM North America region comprises the USA and Canada). For regions constituted by many countries, country-level emissions are driven largely by bulk region emissions and country GDP in each scenario (per Section 2.4). Afterwards, country-level emissions are subsequently mapped to spatial grids (Feng, 2018). We here present global maps of two aerosol species with the strongest implications on future warming, i.e., BC in Figure 9 and sulfur in Figure 10. We highlight three cases which have relevant aerosol emissions profiles: SSP1-2.6 which has significantly decreasing emissions over the century, SSP3-7.0 which has the highest aerosol emissions, and SSP3-LowNTCF which has similar socioeconomic drivers as the SSP3 baseline but models the inclusion of policies which seek to limit emission of near-term climate forcing species.

#### **Comment**

Conclusions. This section is relatively long and reads more like a summary. It can be improved by shortening it, focusing only on the main take home messages of the manuscript, and not summarizing it.

#### **Response**

We agree with the reviewer that the conclusions section could be more concise. Thus, we have revised the first few paragraphs in order to encapsulate the primary points of interest to the reader, while keeping the important points regarding data usage and availability.

### **3 Reviewer 3**

We thank Referee 3 for their very useful comments. The referee had broadly three main comments regarding first the citation of papers in preparation, second, clarity regarding model regional definitions, and third the clarity of the data availability section. We respond here to these in order.

#### **3.1 Specific Comments**

##### **Comment**

First of all, some of the key parts in the methodology are supported by unpublished documents that we cant find anywhere, such as Hurtt et al. (2018) for land use, Feng et al. (2018) for gridding, and Meinshausen (2018) for concentrations.

## **Response**

Regarding the citation of papers in preparation, we followed the guidance provided in [https://www.geoscientific-model-development.net/for\\_authors/manuscript\\_preparation.html](https://www.geoscientific-model-development.net/for_authors/manuscript_preparation.html), namely:

Works "submitted to", "in preparation", "in review", or only available as preprint should also be included in the reference list.

We include references to Hurtt et al. (2019) and Meinhausen et al. (2019) primarily for reference to the reader of forthcoming work encompassed in ScenarioMIP which is related to the overall ScenarioMIP experimental design either in parallel to (Hurtt) or derivative of (Meinhausen) this work. We agree with the reviewer that Feng et al. (2019) is of particular importance as a direct methodology and output related to this work. We have been in contact with the author team of that paper and while they expect it to be submitted in the immediate future, we are happy to provide the reviewers with a presubmission version of the manuscript.

## **Comment**

But we dont learn how exactly the authors dealt with the differences in the region definitions among different models. The authors only showed the differences in the region definitions by the numbers of the regions and did not explain well one of the challenging processes in the downscaling.

## **Response**

Regarding model region information, we have added a footnote to prior work that discusses regional definitions in more detail. In the paper, we state that emissions are harmonized individually for each model to their specified regional definition, and then each regional emission trajectory is downscaled independently using a consistent methodology as outlined in the manuscript.

## **Comment**

The authors could improve the code data available section, too. In my opinion, the author should provide the list of data they provide from this study with the names of the data.

## **Response**

With respect to the clarity of the data availability section of the paper, we appreciate the reviewer's suggestion and have thus implemented it. Specifically, we have provided additional information with respect to the location of bulk emissions trajectories and describe the filename on ESGF for gridded emissions.



# Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century

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**Abstract.** We present a suite of nine scenarios of future emissions trajectories of anthropogenic sources, a key deliverable of the ScenarioMIP experiment within CMIP6. Integrated Assessment Model results for 14 different emissions species and 13 emissions sectors are provided for each scenario with consistent transitions from the historical data used in CMIP6 to future trajectories using automated harmonization before being downscaled to provide higher emission source spatial detail. We find that the scenarios span a wide range of end-of-century radiative forcing values, thus making this set of scenarios ideal for exploring a variety of warming pathways. The set of scenarios are bounded on the low end by a  $1.9\text{W m}^{-2}$  scenario, ideal for analyzing a world with end-of-century temperatures well below  $2^\circ\text{C}$ , and on the high-end by a  $8.5\text{W m}^{-2}$  scenario, resulting in an increase in warming of nearly  $5^\circ\text{C}$  over pre-industrial levels. Between these two extremes, scenarios are provided such that differences between forcing outcomes provide statistically significant regional temperature outcomes to maximize their usefulness for downstream experiments within CMIP6. A wide range of scenario data products are provided for the CMIP6 scientific community including global, regional, and gridded emissions datasets.

## 1 Introduction

Scenario development and analysis play a crucial role in linking socioeconomic and technical progress to potential future climate outcomes by providing future trajectories of various emissions species including greenhouse gases, aerosols, and their precursors. These assessments and associated datasets allow for wide-ranging climate analyses including pathways of future warming, localized effects of pollution emissions, and impacts studies, among others. By spanning a wide range of possible futures, including varied levels of emissions mitigation, pollution control, and socioeconomic development, scenarios provide a large multivariate space of potential near, medium, and long-term outcomes for study by the broader scientific community.

The result of scenario exercises have been used widely by national and international assessment bodies and the global scientific community. They have informed previous Assessment Reports by the Intergovernmental Panel on Climate Change (Solomon et al., 2007; Stocker et al., 2013) as well as reports on more topical issues including the Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000). The SRES scenarios were used extensively in the 3rd Phase of the Coupled Model Intercomparison Project (CMIP3)(Solomon et al., 2007), whereas the following generation of scenarios denoted the “Representative Concentration Pathways” (RCPs) were used to generate emissions trajectories in CMIP5 (Moss et al., 2010; van Vuuren et al., 2011; Taylor et al., 2012). [These emissions scenarios have been used by a broad audience, including national governments \(e.g., Walsh et al. \(2014\); Hayhoe et al. \(2017\)\) and climate scientists \(e.g., Kawase et al. \(2011\); Lamarque et al. \(2013\); Holmes et al. \(2014\)\).](#)

As initially described in Moss et al. (2010), a new framework has been utilized to design scenarios that combine socioeconomic and technological development, named the Shared Socioeconomic Pathways (SSPs), with future climate radiative forcing (RF) outcomes (RCPs) in a scenario matrix architecture (O’Neill et al., 2013; Kriegler et al., 2014; van Vuuren et al., 2013). This new structure provides two critical elements to the scenario design space: first, it standardizes all socioeconomic assumptions (e.g., population, GDP, and poverty, among others) across modeled representations of each scenario; second, it allows for more nuanced investigation of the variety of pathways by which climate outcomes can be reached. Five different SSPs exist, with model quantifications that span potential futures of green or fossil-fueled growth (SSP1 (van Vuuren et al., 2017) and SSP5 (Kriegler et al., 2017)), high inequality between or within countries (SSP3 (Fujimori et al., 2017) and SSP4 (Calvin et al., 2017)), and a “middle of the road” scenario (SSP2 (Fricko et al., 2017)). For each SSP, a number of different RF targets can be met depending on policies implemented, either locally or globally, over the course of the century (Riahi et al., 2017).

Scenarios provide critical input for climate models through their description and quantification of both land-use change as well as emissions trajectories. Of the total population of newly available scenarios produced with Integrated Assessment Models (IAMs), nine have been chosen for inclusion for study in ScenarioMIP, one of the dedicated CMIP6-endorsed MIPs (Eyring et al., 2016). The selection of scenarios is designed to allow investigation of two primary scientific questions: “How does the Earth system respond to climate forcing?” and “How can we assess future climate changes given climate variability... and uncertainties in scenarios?” (O’Neill et al., 2016). In order to support an experimental design that can address these fundamental questions, scenarios [where were](#) chosen that explore a wide range of future climate forcing that both complement

and expand on prior work in CMIP5. While a given forcing pathway could be met with potentially many different SSPs, a specific SSP is chosen for each pathway according to three governing principles: “[maximizing] facilitation of climate research, minimizing differences in climate between outcomes produced by the [chosen] SSP, and ensuring consistency with scenarios that are most relevant to the IAM and Impacts, Adaptation, and Vulnerability (IAV) communities” (O’Neill et al., 2016, p. 5 3469).

Selected scenarios sample a range of forcing outcomes ( $1.9\text{--}8.5\text{ W m}^{-2}$ , calculated with the simple climate model MAGICC6 (Meinshausen et al., 2011a)), with sufficient spacing between forcing outcomes to provide statistically significant regional temperature outcomes (Tebaldi et al., 2015; O’Neill et al., 2016). The nine selected scenarios can be divided into two groups: four scenarios update the RCPs studied in CMIP5, achieving forcing levels of 2.6, 4.5, 6.0, and  $8.5\text{ W m}^{-2}$ , whereas five 10 scenarios fill gaps not previously studied in the RCPs, including, a lower-bound  $1.9\text{ W m}^{-2}$  scenario (Rogelj et al., 2018) corresponding to the most optimistic interpretation of Article 2 of the Paris Agreement (United Nations, 2016). Additionally, a new ‘overshoot’ scenario is included in the Tier 2 set in which forcing peaks and then declines to  $3.4\text{ W m}^{-2}$  by 2100 in order to assess the climatic outcomes of such a pathway.

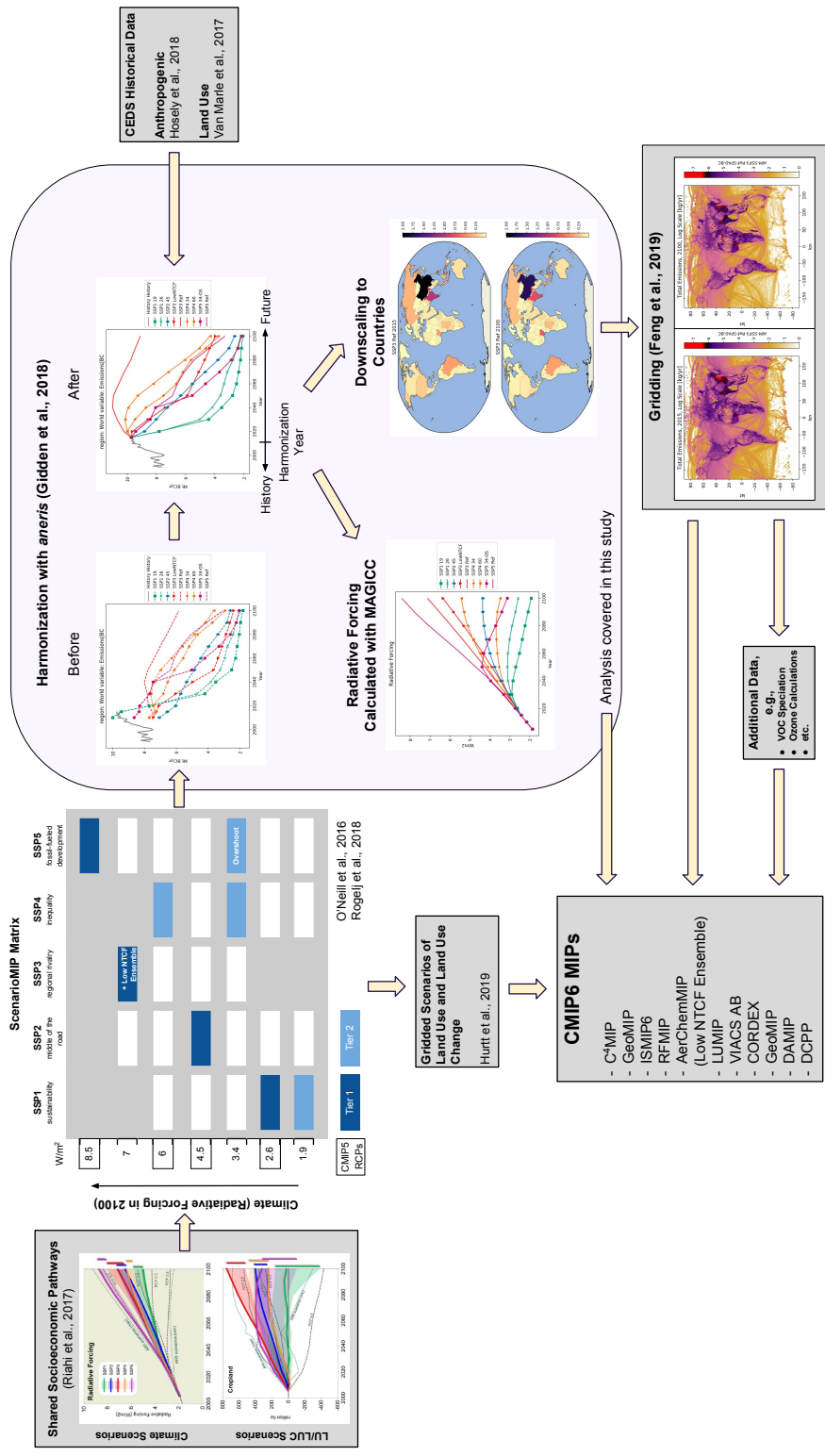
In order to provide historically consistent and spatially detailed emissions datasets for other scientists collaborating in 15 CMIP6, scenario results are processed using methods of harmonization and downscaling, respectively. Harmonization refers to the alignment of model results with a common historical dataset. Historical data consistency is paramount for use in climate models which perform both historic and future runs, for which there must be smooth transitions between the two sets of emissions trajectories. Harmonization has been applied in previous studies (e.g., in SRES (Nakićenović et al., 2000) and the RCPs (van Vuuren et al., 2011; Meinshausen et al., 2011b)); however, systematic harmonization for which common rules and 20 algorithms are applied across all models has not heretofore been performed (Rogelj et al., 2011). We harmonize emissions trajectories, therefore, with a newly-available methodology and software (*aneris*) (Gidden, 2017; Gidden et al., 2018) in order to address this need. We further downscale these results from their native model region spatial dimension to individual countries using techniques which take into account current and future emissions levels as well as socioeconomic progress (van Vuuren et al., 2007). An overview of the scenario selection and processing steps that comprise this study as well as its contributions to 25 the broader CMIP6 community is shown in Figure 1.

The remainder of the paper is as follows. First, we discuss scenario selection, historical data aggregation, harmonization, and downscaling methods in Section 2. We then present harmonized model results, focusing on overall emissions trajectories, climate response outcomes, and the spatial distribution of key emissions species in Section 3. Finally, in Section 4, we discuss conclusions drawn from this study as well as guidelines for using the results presented herein in further CMIP6 experiments.

## 30 2 Data and Methods

### 2.1 Socioeconomic and Climate Scenarios

The global IAM community has developed a family of scenarios that describe a variety of possible socioeconomic futures (the SSPs). The formation, qualitative, and quantitative aspects of these scenarios have been discussed widely in the literature



**Figure 1.** The role of ScenarioMIP in the CMIP6 ecosystem. From a population of over 40 possible SSPs, nine are downselected in order to span the climatic and social dimensions of the ScenarioMIP SSP-RCP Matrix. Emissions trajectories developed from these scenarios then undergo harmonization to a common and consistent historical dataset, downscaling, and gridding. The resulting emissions datasets are then provided to the CMIP6 scientific community, in conjunction with future scenarios of land use (Hurtt, 2019), concentrations (Meinshausen, 2019), and other domain-specific datasets (e.g., VOC speciation and ozone concentrations).

(O'Neill et al., 2017; KC and Lutz, 2014; Dellink et al., 2015; Jiang and O'Neill, 2015). We briefly summarize here relevant narratives of the baseline SSPs concerning socioeconomic development (see, e.g., Figure A1), energy systems (Bauer et al., 2017), land use (Popp et al., 2017), Greenhouse Gas (GHG) emissions (Riahi et al., 2017), and air pollution (Rao et al., 2017).

SSPs 1 and 5 describe worlds with strong economic growth via sustainable and fossil-fuel pathways, respectively. In both scenarios, incomes increase substantially across the globe and inequality within and between countries is greatly reduced; however, this growth comes at the expense of potentially large impacts from climate change in the case of SSP5. Demand for energy and resource intensive agricultural commodities such as ruminant meat is significantly lower in SSP1 due to changes in behavior and advances in energy efficiency. In both scenarios, pollution controls are expanded in high-income economies with other nations catching up relatively quickly with the developed world, resulting in reductions in air pollutant emissions. SSP2 is a so-called “middle of the road scenario” with moderate population growth and slower convergence of income levels across countries. In SSP2, food consumption especially for resource-intensive livestock based commodities, is expected to increase and energy generation continues to rely on fossil fuels at approximately the same rates as today, resulting in continued growth of GHG emissions. Efforts at curbing air pollution continue along current trajectories with developing economies ultimately catching up to high-income nations, resulting in an eventual decrease in pollutant emissions. Finally, SSPs 3 and 4 depict futures with high inequality between countries (i.e., “regional rivalry”) and within countries, respectively. Global GDP growth is low in both scenarios and concentrated in currently high-income nations whereas population increase is focused in low and middle-income countries. Energy systems in SSP3 see a resurgence of coal dependence whereas reductions occur in SSP4 as the high-tech energy and economy sectors see increased developments and investments leading to higher diversification of technologies (Bauer et al., 2017). Policy making (either regionally or internally) in areas including land-use regulation, air pollution control, and GHG emission limits are less effective. Thus policies vary regionally in both SSPs with weak international institutions resulting in the highest levels of pollutant and aerosol emissions [and potential effect on climate outcomes \(Shindell et al., 2013\)](#)

A matrix of socioeconomic-climate scenarios relevant to the broad scientific community was created with SSPs on one axis and climate policy futures (i.e. mitigation scenarios) delineated by end-of-century (EOC) RF on the other axis (see Figure 1). The scenarios selected for inclusion in ScenarioMIP, shown in Table 1, are comprised of both baseline and mitigation cases, in which long-term climate policies are lacking or included, respectively. They are divided into Tier-1 scenarios, which span a wide range of uncertainty in future forcing and are utilized by other MIPs, and Tier-2 scenarios, which enable more detailed studies of the effect of mitigation and adaptation policies which fall between the Tier-1 forcing levels. Each scenario is run by a single model within ScenarioMIP, comprised of the AIM/CGE, GCAM4, IMAGE, MESSAGE-GLOBIOM, and REMIND-MAgPIE modeling teams. We provide a short discussion here on their selection and refer the reader to (O'Neill et al., 2016, Section 3.2.2) for fuller discussion of the experimental design.

The Tier-1 scenarios include SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, designed to provide a full range of forcing targets similar in both magnitude and distribution to the RCPs as used in CMIP5. Each EOC forcing level is paired with a specific SSP which is chosen based on the relevant experimental coverage. For example, SSP2 is chosen for the 4.5 W m<sup>-2</sup> experiment because of its high relevance as a reference scenario to IAV communities as a scenario with intermediate vulnerability and

**Table 1.** All scenarios and associated attributes used in the ScenarioMIP experiment ensemble.

Scenario Name	SSP	Target Forcing Level ( $\text{W m}^{-2}$ )	Scenario Type	Tier	IAM	Contributing to other MIPs
SSP1-1.9	1	1.9	Mitigation	2	IMAGE	ScenarioMIP
SSP1-2.6	1	2.6	Mitigation	1	IMAGE	ScenarioMIP
SSP2-4.5	2	4.5	Mitigation	1	MESSAGE-GLOBIOM	ScenarioMIP, VIACS AB, CORDEX, GeoMIP, DAMIP, DCPD
SSP3-7.0	3	7	Baseline	1	AIM/CGE	ScenarioMIP, AerChemMIP, LUMIP
SSP3-LowNTCF	3	6.3	Mitigation	2	AIM/CGE	ScenarioMIP, AerChemMIP, LUMIP
SSP4-3.4	4	3.4	Mitigation	2	GCAM4	ScenarioMIP
SSP4-6.0	4	6	Mitigation	2	GCAM4	ScenarioMIP, GeoMIP
SSP5-3.4-OS	5	3.4	Mitigation	2	REMIND-MAGPIE	ScenarioMIP
SSP5-8.5	5	8.5	Baseline	1	REMIND-MAGPIE	ScenarioMIP, C4MIP, GeoMIP, ISMIP6, RFMIP

climate forcing and its median positioning of land use and aerosol emissions (of high importance for DAMIP and DCPD) whereas SSP3 is chosen for the  $7.0 \text{ W m}^{-2}$  experiment as it allows for quantification of avoided impacts (e.g. relative to SSP2) and has significant emissions from near-term climate forcing (NTCF) species such as aerosols and methane (also referred to as Short-Lived Climate Forcers, or SLCF).

- 5 The Tier-2 scenarios include SSP1-1.9, SSP3-LowNTCF, SSP4-3.4, SSP4-6.0, and SSP5-3.4-Overshoot (OS), chosen to both complement and extend the types of scenarios available to climate modelers beyond those analyzed in CMIP5. SSP1-1.9 provides the lowest estimate of future forcing matching the most ambitious goals of the Paris Agreement (i.e., “pursuing efforts to limit the [global average] temperature increase to  $1.5^\circ\text{C}$  above pre-industrial levels”). The SSP3-LowNTCF scenario provides an important experimental comparison to scenarios with high NTCFs for use in AerChemMIP (Collins et al.,
- 10 [2017](#)) contrasting with SSP3-7.0 ([see SI Section C for more detail on differences in assumptions between SSP3-7.0 and SSP3-LowNTCF](#)). Both SSP4 scenarios fill gaps in Tier-1 forcing pathways and allow investigations of impacts in scenarios with relatively strong land use and aerosol climate effects but relatively low challenges to mitigation. Finally, SSP5-3.4-OS allows for the study of a scenario in which there is large overshoot in RF by mid-century followed by the implementation of substantive policy tools to limit warming in the latter half of the century. It is specifically designed to be twinned with SSP5-8.5,
- 15 following the same pathway through 2040, and support experiments examining delayed climate action.

### 2.1.1 ~~Historical Emissions Data~~

## 2.2 Historical Emissions Data

We construct a common dataset of historical emissions for the year 2015<sup>1</sup>, the transition year in CMIP6 between historic and future model runs, using two primary sources developed for CMIP6. Hoesly et al. (2018) provides data over 1750-2014 for anthropogenic emissions by country. They include a detailed sectoral representation (59 sectors in total) which has been aggregated into nine individual sectors (see SI Table B1), including Agriculture, Aircraft, Energy, Industry, International Shipping, Residential and Commercial, Solvent Production and Application, Transportation, and Waste. Values for 2015 were approximated by extending fossil fuel consumption using aggregate energy statistics (BP, 2016) and trends in emission factors from the GAINS ECLIPSE V5a inventory (Klimont et al., 2017; Stohl et al., 2015). Sulfur (SO<sub>x</sub>) emissions in China were trended from 2010 using values from Zheng et al. (2018).

van Marle et al. (2017) provide data on historical emissions from open burning, specifically including burning of Agricultural Waste on Fields (AWB), Forests, Grasslands, and Peatlands out to 2015. Due to the high amount of inter-annual variability in the historical data which is not explicitly modeled in IAMs, we use a decadal mean over 2005-2014 to construct a representative value for ~~2015-2015~~ (see, e.g., Figure A2). When used in conjunction with model results, we aggregate country-level emissions to the individual model regions of which they are comprised.

Emissions of N<sub>2</sub>O and fluorinated gas species were harmonized only at the global level, with 2015 values from other data sources. Global N<sub>2</sub>O emissions were taken from PRIMAP (Gütschow et al., 2016) and global emissions of HFCs were developed by Velders et al. (2015). The HFC-23 and total PFC and SF<sub>6</sub> emissions were provided by Guus Velders, based on Carpenter et al. (2014) mixing ratios and were extended from 2012 to 2015 by using the average 2008-2012 trend.

### 20 2.2.1 ~~Automated Emissions Harmonization~~

## 2.3 Automated Emissions Harmonization

Emissions harmonization is defined as a procedure designed to match model results to a common set of historical emissions trajectories. The goal of this process is to match a specified base-year dataset while retaining consistency with the original model results to the best extent possible while also providing a smooth transition from historical trajectories. This non-disjoint transition is critical for global climate models when modeling projections of climate futures which depend on historical model runs, guaranteeing a smooth functional shape of both emissions and concentration fields between the historical and future runs. Models differ in their 2015 data points in part because the historical emissions datasets used to calibrate the models differ (e.g., PRIMAP (Gütschow et al., 2016), EDGAR (Crippa et al., 2016), CEDS (Hoesly et al., 2018)). Another cause of differences is that 2015 is a projection year for all of these models (the original scenarios were originally finalized in 2015).

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<sup>1</sup>For sulfur emissions in China, we include values up to 2017, due to a drastic reduction in these emissions in the most recently available datasets.

**Table 2.** Harmonized Species and Sectors, adapted from Gidden et al. (2018) with permission of the authors. A mapping of original model variables (i.e., outputs) to ScenarioMIP sectors is shown in SI Table B2.

Emissions Species	Sectors
Black Carbon (BC)	Agricultural Waste Burning <sup>c</sup>
Hexafluoroethane (C <sub>2</sub> F <sub>6</sub> ) <sup>a</sup>	Agriculture <sup>c</sup>
Tetrafluoromethane (CF <sub>4</sub> ) <sup>a</sup>	Aircraft <sup>b</sup>
Methane (CH <sub>4</sub> )	Energy Sector
Carbon Dioxide (CO <sub>2</sub> ) <sup>c</sup>	Forest Burning <sup>c</sup>
Carbon Monoxide (CO)	Grassland Burning <sup>c</sup>
Hydrofluorocarbons (HFCs) <sup>a</sup>	Industrial Sector
Nitrous Oxide (N <sub>2</sub> O) <sup>a</sup>	International Shipping <sup>b</sup>
Ammonia (NH <sub>3</sub> )	Peat Burning <sup>c</sup>
Nitrogen Oxides (NO <sub>x</sub> )	Residential Commercial Other
Organic Carbon (OC)	Solvents Production and Application
Sulfur Hexafluoride (SF <sub>6</sub> ) <sup>a</sup>	Transportation Sector
Sulfur Oxides (SO <sub>x</sub> )	Waste
Volatile Organic Compounds (VOCs)	

<sup>a</sup> Global total trajectories are harmonized due to lack of detailed historical data.

<sup>b</sup> Global sectoral trajectories are harmonized due to lack of detailed historical data.

<sup>c</sup> A global trajectory for AFOLU CO<sub>2</sub> is used; non-land-use sectors are harmonized for each model region.

Harmonization can be simple in cases where a model's historical data is similar to the harmonization dataset. However, when there are strong discrepancies between the two datasets, the choice of harmonization method is crucial for balancing the dual goals of accurate representation of model results and reasonable transitions from historical data to harmonized trajectories.

The quantity of trajectories requiring harmonization increases the complexity of the exercise. In this analysis, given the available sectoral representation of both the historical data and models, we harmonize model results for 14 individual emissions species and 13 sectors as described in Table 2. The majority of emissions-sector combinations are harmonized for every native model region<sup>2</sup> (Table 3). Global trajectories are harmonized for fluorinated species and N<sub>2</sub>O, aircraft and international shipping sectors, and CO<sub>2</sub> agriculture, forestry, and other land-use (AFOLU) emissions due to historical data availability and regional detail. Therefore between 970 and 2776 emissions trajectories require harmonization for any given scenario depending on the model used.

We employ the newly available open-source software *anemis* (Gidden et al., 2018; Gidden, 2017) in order to perform harmonization in a consistent and rigorous manner. For each trajectory to be harmonized, *anemis* chooses which harmonization method to use by analyzing both the relative difference between model results and harmonization historical data as well as the

<sup>2</sup>Further information regarding the model region definitions is available via the IAMC Wiki at <https://www.iamcdocumentation.eu> and Calvin et al. (2019)



**Table 3.** The number of model regions and total harmonized emissions trajectories for each IAM participating in the study. The number of trajectories are calculated from Table 2, including gas species for which global trajectories are harmonized.

Model	Regions	Harmonized Trajectories
AIM/CGE	17	1486
GCAM4	32	2776
IMAGE	26	2260
MESSAGE-GLOBIOM	11	970
REMIND-MAGPIE	11	970

behavior of the modeled emissions trajectory. Available methods include ratio and offset methods, which utilize the quotient and difference of unharmonized and harmonized values respectively, as well as convergence methods which converge to the original modeled results at some future time period. We refer the reader to Gidden et al. (2018) for a full description of the harmonization methodology and implementation.

5 Override methods can be specified for any combination of species, sectors, and regions which are used in place of the default methods provided by *anemis*. Override methods are useful when default methods do not fully capture either the regional or sectoral context of a given trajectory. Most commonly, we observed this in cases where there are large relative differences in the historical datasets, the base-year values are small, and there is substantial growth in the trajectory over the modeled time period, thereby reflecting the large relative difference in the harmonized emissions results. However, the number of required  
 10 override methods is small: 5.1% of trajectories use override messages for the IMAGE model, 5.6% for MESSAGE-GLOBIOM, and 9.8% for REMIND. The AIM model elected not to use override methods, and GCAM uses a relatively large number (35%).

Finally, in order to provide additional detail for fluorinated gases (F-gases) we extend the set of reported HFCs and CFCs species based on exogenous scenarios. We take scenarios of future HFCs from Velders et al. (2015) which provide detailed emissions trajectories for F-gases. We downscale the global HFC emissions reported in each harmonized scenario to arrive at  
 15 harmonized emissions trajectories for all constituent F-gases, deriving the HFC-23 from the RCP emission pathway. We further include trajectories of CFCs as reported in scenarios developed by the World Meteorological Organization (WMO) (Carpenter et al., 2014) which are not included in all model results.

### 2.3.1 ~~Region-to-Country Downscaling~~

### 2.4 Region-to-Country Downscaling

20 Downscaling, defined here as distributing aggregated regional values to individual countries, is performed for all scenarios in order to improve the spatial resolution of emissions trajectories, and as a prelude to mapping to a spatial grid (discussed in SI Section D). We developed an automated downscaling routine that differentiates between two classes of sectoral emissions: those related to AFOLU and those related to fuel combustion and industrial and urban processes. In order to preserve as much of the original model detail as possible, the downscaling procedures here begin with harmonized emission data at the level of

native model regions and the aggregate sectors (Table 2). Here we discuss key aspects of the downscaling methodology and refer the reader to the downscaling documentation<sup>3</sup> for further details.

AFOLU emissions, including Agricultural Waste Burning, Agriculture, Forest Burning, Peat Burning, and Grassland Burning are downscaled using a linear method. Linear downscaling means that the fraction of regional emissions in each country stays constant over time. Therefore, the total amount of open-burning emissions allocated to each country will vary over time as economies evolve into the future, following regional trends from the native IAM. However there is no sub-regional change in the spatial distribution of land-use related emissions over time. This is in contrast to other anthropogenic emissions, where the IPAT method is used to dynamically downscale to the country level as discussed above. Note that Peat Burning emissions were not modeled by the IAMs and are constant into the future. ~~→~~

All other emissions are downscaled using the Impact, Population, Affluence, and Technology (IPAT) (Ehrlich and Holdren, 1971) based method developed by van Vuuren et al. (2007), where population and GDP trajectories are taken from the SSP scenario specifications (KC and Lutz, 2014; Dellink et al., 2015). The overall philosophy behind this method is to assume that emission intensity values (i.e., the ratio of emissions to GDP) for countries within a region will converge from a base year,  $t_i$  (2015 in this study), over the future. A convergence year,  $t_f$ , is specified beyond 2100, the last year for the downscaled data, meaning that emission intensities do not converge fully by 2100. The choice of convergence year reflects the rate at which economic and energy systems converge toward similar structures within each native model region. Accordingly, the SSP1 and SSP5 scenarios are assigned relatively near-term convergence years of 2125, while SSP3 and SSP4 scenarios are assigned 2200, and SSP2 an intermediate value of 2150.

The downscaling method first calculates an emission intensity,  $I$ , for the base and convergence years using emission level,  $E$ , and  $GDP$ .

$$I_t = \frac{E_t}{GDP_t} \quad (1)$$

An ~~emission intensity growth rate~~, emissions intensity growth factor,  $\beta$ , is then determined for each country,  $c$ , within a model region,  $R$ , using convergence year emission intensities,  $I_{R,t_f}$ , determined by extrapolating from ~~growth rates over~~ the last 10 years (e.g., 2090 to 2100) of the scenario data.

$$\beta_c = \frac{I_{R,t_f}^{\frac{1}{t_f-t_i}}}{I_{c,t_i}} \quad (2)$$

Using base-year data for each country and scenario data for each region, future downscaled emission intensities and patterns of emissions are then generated for each subsequent time period.

$$I_{c,t} = \beta_c I_{c,t-1} \quad (3)$$

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<sup>3</sup>[https://github.com/iiasa/emissions\\_downscaling/wiki](https://github.com/iiasa/emissions_downscaling/wiki)

$$E_{c,t}^* = I_{c,t}GDP_{c,t} \quad (4)$$

These spatial patterns are then scaled with (i.e., normalized to) the model region data to guarantee consistency between the spatial resolutions, resulting in downscaled emissions for each country in each time period

$$E_{c,t} = \frac{E_{R,t}}{\sum_{c' \in R} E_{c',t}^*} E_{c,t}^* \quad (5)$$

5 For certain countries and sectors the historical dataset has zero-valued emissions in the harmonization year. This would result in zero downscaled future emissions for all years. Zero emissions data occurs largely for small countries, many of them small island nations. This could either be due to lack of actual activity in the base-year, or missing data on activity in those countries. In order to allow for future sectoral growth in such cases, we adopt, for purposes of the above calculations, an initial emission intensity of  $\frac{1}{3}$  the value of the lowest country in the same model region. We then allocate future emissions in the same  
 10 manner discussed above, which is consistent with our overall convergence assumptions. Note that we exclude the industrial sector (Table 2) from this operation as it might not be reasonable to assume the development of substantial industrial activity in these countries.

Finally, some scenarios (~~notably energy~~) include negative CO<sub>2</sub> emissions at some point in the future (notably from energy use). For CO<sub>2</sub> emissions, therefore, we apply a linear rather than exponential function to allow a smooth transition to negative  
 15 emissions values for both the emissions intensity growth ~~rate factor~~ and future emission intensity calculations. In such cases, Equations 2 and 3 are replaced by 6 and 7, respectively.

$$\beta_c = \left( \frac{I_{R,t_f}}{I_{c,t_i}} - 1 \right) \frac{1}{t_f - t_i} \quad (6)$$

$$I_{c,t} = (1 + \beta_c)I_{c,t-1} \quad (7)$$

### 3 Results

20 Here we present the results of harmonization and downscaling applied to all nine scenarios under consideration. We discuss in Section 3.1 the relevance of each selected scenario to the overall experimental design of ScenarioMIP, focusing on their RF and mean global temperature pathways. In Section 3.2, we discuss general trends in global trajectories of important GHGs and aerosols and their sectoral contributions over the modeled time horizon. In Section 3.3, we explore the effect of harmonization on model results and the difference between unharmonized and harmonized results. Finally, in Section 3.4, we provide an  
 25 overview of the spatial distribution of emissions species at both regional and spatial grids.

### 3.1 Experimental Design and Global Climate Response

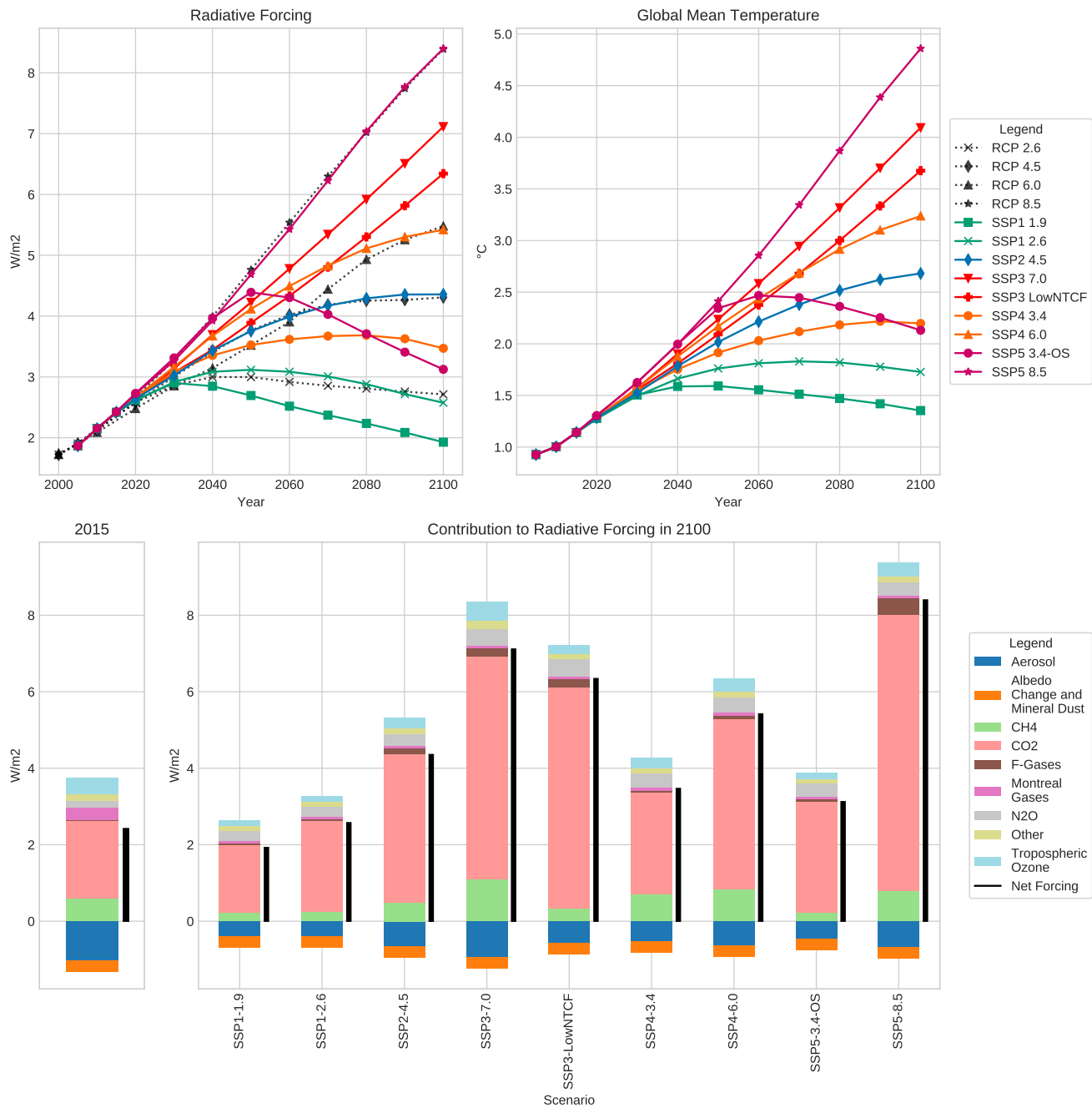
The nine ScenarioMIP scenarios were selected to provide a robust experimental design space for future climate studies as well as IAV analyses with the broader context of CMIP6. Chief among the concerns in developing such a design space is both the range and spacing of the global climate response within the portfolio of scenarios (Moss et al., 2008). Prior work for the RCPs studied a range of climate outcomes between  $\sim 2.6$ - $8.5 \text{ W m}^{-2}$  at EOC. Furthermore, recent work (Tebaldi et al., 2015) finds that statistically significant regional temperature outcomes ( $>5\%$  of half the land surface area) are observable with a minimum separation of  $0.3^\circ\text{C}$ , which is approximately equivalent to  $0.75 \text{ W m}^{-2}$  (O'Neill et al., 2016). Given the current policy context, notably the recent adoption of the UN Paris Agreement, the primary design goal for the ScenarioMIP scenario selection is thus twofold: span a wider range of possible climate futures ( $1.9$ - $8.5 \text{ W m}^{-2}$ ) in order to increase relevance to the global climate dialogue and provide a variety of scenarios between these upper and lower bounds such that they represent statistically significant climate variations in order to support a wide variety of CMIP6 analyses.

We find that the selected scenarios meet this broad goal, as shown in Figure 2, by using the simple climate model MAGICC6 with central climate-system and gas-cycle parameter settings for all scenarios to calculate pathways of both RF and the resulting response of global mean temperature (see SI Table B3 for a listing of all EOC RF values).

We also present illustrative global-mean temperature pathways. EOC temperature outcomes span a large range, from  $1.4^\circ\text{C}$  at the lower end to  $4.9^\circ\text{C}$  for SSP5-8.5, the scenario with highest warming emissions trajectories. Notably, two scenarios (SSP1-1.9, which reaches  $1.4^\circ\text{C}$  by EOC and SSP1-2.6, reaching  $1.7^\circ\text{C}$ ) can be used for studies of global outcomes of the implementation of the UN Paris Agreement, which has a desired goal of “[h]olding the increase in the global average temperature to well below  $2^\circ\text{C}$  above pre-industrial levels and pursuing efforts to limit the temperature increase to  $1.5^\circ\text{C}$  above pre-industrial levels” (United Nations, 2016, Article 2.1(a)). The difference between scenario temperature outcomes is statistically significant in nearly all cases, with a minimum difference of  $0.37^\circ\text{C}$  (SSP1-1.9 and SSP1-2.6) and maximum value of  $0.77^\circ\text{C}$  (SSP3-7.0 and SSP5-8.5). The EOC difference between SSP4-3.4 and SSP5-3.4-OS is not significant ( $0.07^\circ\text{C}$ ); however global climate outcomes are likely sensitive to the dynamics of the forcing pathway (Tebaldi et al., 2015).

A subset of four scenarios (SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5) were also designed to provide continuity between CMIP5 and CMIP6 by providing similar forcing pathways to their RCP counterparts assessed in CMIP5. We find that this aspect of the scenario design space is also met by the relevant scenarios. SSP2-4.5 and SSP5-8.5 track RCP4.5 and RCP8.5 pathways nearly exactly. We observe slight deviations between SSP1-2.6 and RCP2.6 as well as SSP4-6.0 and RCP6.0 at mid-century due largely to increased methane emissions in the historic period (i.e., methane emissions broadly follow RCP8.5 trajectories after 2000 resulting in higher emissions in the harmonization year of this exercise; see Figure 3 below).

The remaining five scenarios were chosen to “fill gaps” in the previous RCP studies in CMIP5 and enhance the potential policy relevance of CMIP6 MIP outputs (O'Neill et al., 2016). SSP3-7.0 was chosen to provide a scenario with relatively high vulnerability and land use change with associated near-term climate forcer (NTCF) emissions resulting in a high RF pathway. We find that it reaches an EOC forcing target of  $\sim 7.1 \text{ W m}^{-2}$  and greater than  $4^\circ\text{C}$  mean global temperature increase. While contributions to RF from  $\text{CO}_2$  in SSP3-7.0 are lower than that of SSP5-8.5, methane and aerosol contributions are considerably



**Figure 2.** Trajectories of RF and global mean temperature (above pre-industrial levels) are presented as are the contributions to RF for a number of different emissions types native to the MAGICC6 model. The RF trajectories are displayed with their RCP counterparts analyzed in CMIP5. For those scenarios with direct analogues, trajectories are largely similar in shape and match the same EOC forcing values.

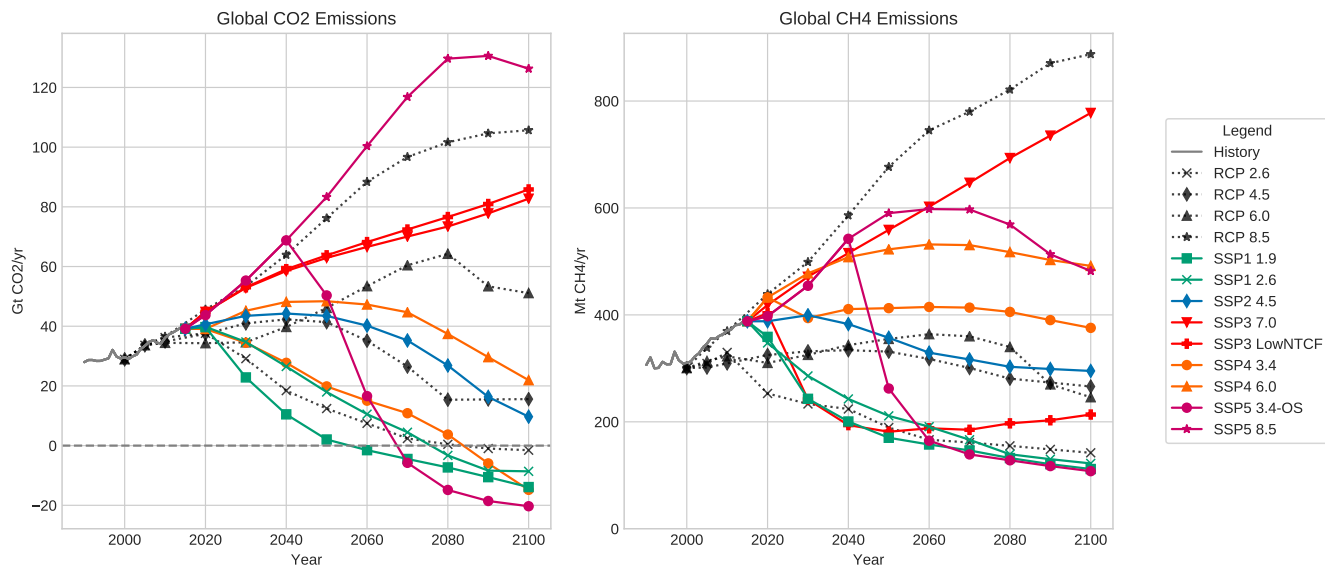
higher ([see, e.g., Etmann et al. \(2016\) for a discussion on the effect of shortwave forcing on methane's contribution to overall RF](#)). A companion scenario, SSP3-LowNTCF, was also included in order to study the effect of NTCF species in the context of AerChemMIP. Critically, emissions factors of key NTCF species are assumed to develop similar to an SSP1 (rather than SSP3) scenario. SSP3-LowNTCF sees substantially less contributions to EOC forcing from NTCF emissions (notably SO<sub>x</sub> and methane), resulting in a forcing level of 6.3 W m<sup>-2</sup> and global mean temperature increase of 3.75°C by the end of the century. This significant reduction is largely due to updating emissions coefficients for air pollutants and other NTCF to match the SSP1 assumptions. SSP4-3.4 was chosen to provide a scenario at the lower end of the range of future forcing pathways. Reaching a EOC mean global temperature between SSP2-4.5 and SSP1-2.6 (~2.25°C), it is an ideal scenario for scientists to study the mitigation costs and associated impacts between forcing levels of 4.5 and 2.6 W m<sup>-2</sup>.

The final two scenarios, SSP1-1.9 and SSP5-3.4-OS were chosen to study policy-relevant questions of near and medium-term action on climate change. SSP1-1.9 provides a new low-end to the RF pathway range. It reaches an EOC forcing level of ~1.9 W m<sup>-2</sup> and an associated global mean temperature increase of ~1.4°C (with temperature peaking in 2040), in line with the goals of the Paris Agreement. SSP5-3.4-OS, on the other hand, is designed to represent a world in which action towards climate change mitigation is delayed but vigorously pursued after 2050, resulting in a forcing and mean global temperature “overshoot”. A peak temperature of 2.5°C above pre-industrial levels is reached in 2060 after which global mitigation efforts reduce EOC warming to ~2.25°C. In tandem, and including SSP2-4.5 (which serves as a reference experiment in ScenarioMIP (O’Neill et al., 2016)), these scenarios provide a robust experimental platform to study the effect of the timing and magnitude of global mitigation efforts which can be especially relevant to science-informed policy discussions.

### 3.2 Global Emissions Trajectories

Emissions contributions to the global climate system are myriad but can broadly be divided into contributions from Greenhouse Gases (GHGs) and aerosols. The models used in this analysis explicitly represent manifold drivers and processes involved in the emissions of various gas species. For a fuller description of these scenario results see the original SSP quantification papers (van Vuuren et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Calvin et al., 2017; Kriegler et al., 2017). Here, we focus on emissions species that most strongly contribute to changes in future mean global temperature and scenarios with the highest relevance and uptake for other MIPs within CMIP6, namely the Tier-1 scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Where insightful, we provide additional detail on results from other scenarios; however results for all scenarios are available in SI Section E.

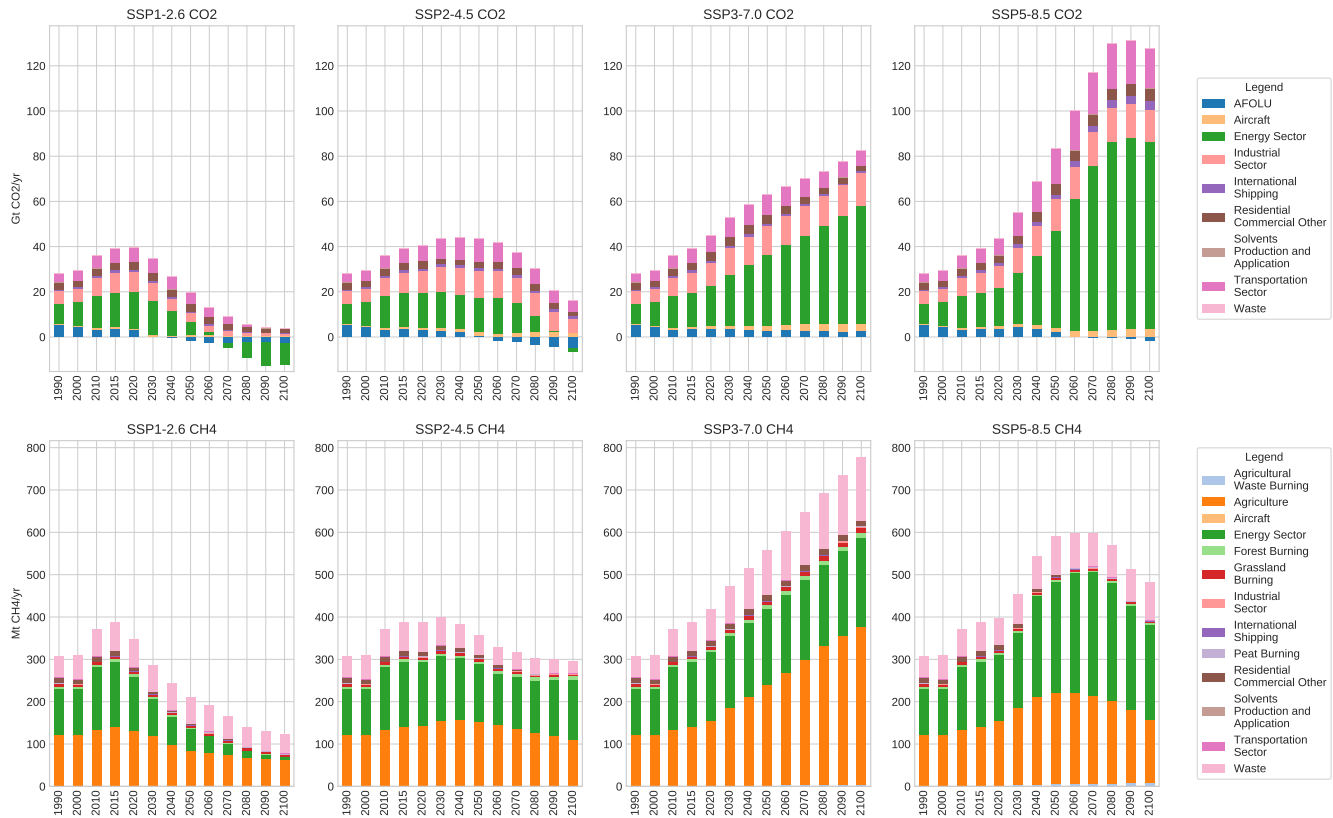
CO<sub>2</sub> emissions have a large span across scenarios by the end of the century (-20 Gt/yr to 125 Gt/yr), as shown in Figure 3. Scenarios can be categorized based on characteristics of their trajectory profiles: those that have consistent downwards trajectories (SSP1, SSP4-3.4), those that peak in a given year and then reduce in magnitude (SSP2-4.5 in 2040 and SSP4-6.0 in 2050), and those that have consistent growth in emissions (SSP3). SSP5 scenarios, which model a world with fossil-fuel driven development, have EOC emissions which bound the entire scenario set, with the highest CO<sub>2</sub> emissions in SSP5-8.5 peaking in 2080 and the lowest CO<sub>2</sub> emissions in SSP5-3.4-OS resulting from the application of stringent mitigation policies after 2040 in an attempt to stabilize RF to 3.4 W m<sup>-2</sup> after overshooting this limit earlier in the century. A number of scenarios



**Figure 3.** Trajectories of CO<sub>2</sub> and CH<sub>4</sub>, primary contributors to GHG emissions, including both historical emissions, emissions analyzed for the RCPs, and all nine scenarios covered in this study.

exhibit negative net CO<sub>2</sub> emissions before the end of the century. SSP1-1.9, the scenario with the most consistent negative emission trajectory, first reports net negative emissions in 2060 with EOC emissions of -14 Gt/yr. SSP5-3.4-OS, SSP1-2.6, and SSP4-3.4 each cross the 0-emissions threshold in 2070, 2080, and 2090, respectively.

Global emissions trajectories for CO<sub>2</sub> are driven largely by the behavior of the energy sector in each scenario, as shown in Figure 4. Positive emissions profiles are also greatly influenced by the industry and transport sectors whereas negative emissions profiles are driven by patterns of agriculture and land-use as well as the means of energy production. In SSP1-2.6, early-mid century emissions continue to be dominated by the energy sector with substantial contributions from industry and transport. Negative emissions from land use are observed as early as 2030 due to large-scale afforestation (Popp et al., 2017; van Vuuren et al., 2017) while net negative emissions from energy conversion first occur in 2070. Such net negative emissions are achieved when carbon dioxide removal from bioenergy with CCS exceeds residual fossil CO<sub>2</sub> emissions from the combustion of coal, oil and gas. Emissions contributions from the transport sector diminish over the century as heavy and light-duty transport fleets are electrified. Emissions from industry peak and then reduce over time such that the residential and commercial sector (RC) provides the majority of positive CO<sub>2</sub> emissions by the end of the century. SSP2-4.5 experiences similar trends among sectors but with smaller magnitudinal changes and temporal delays. Negative emissions, for example, are experienced in the land-use sector for the first time in 2060 and are not experienced in the energy sector until the end of the century. Energy-sector CO<sub>2</sub> emissions continue to play a large role in the overall composition until 2080, at which point the industrial sector provides the plurality of CO<sub>2</sub>. Emissions from the transport sector peak at mid-century, but are still a substantive component of positive



**Figure 4.** The sectoral contributions to CO<sub>2</sub> and CH<sub>4</sub> emissions for Tier-1 scenarios.

CO<sub>2</sub> emissions at the end of the century. Finally, the SSP5-8.5 scenario's emission profile is dominated by the fossil-fueled energy sector for the entirety of the century. Contributions from the transport and industrial sectors grow in magnitude but are diminished as share of total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from the AFOLU sector decrease steadily over time. By the end of the century, the energy sector comprises almost 75% of all emitted CO<sub>2</sub> in this scenario relative to 50% today.

- 5 Methane (CH<sub>4</sub>) is an emissions species with substantial contributions to potential future warming mainly due to its immediate GHG effect, but also because of its influence on atmospheric chemistry, as a tropospheric ozone precursor, and its eventual oxidation into CO<sub>2</sub> in the case of CH<sub>4</sub> from fossil sources (Boucher et al., 2009). At present, approximately 400 Mt/yr of CH<sub>4</sub> is emitted globally, and the span of future emissions developed in this scenario set range from 100 to nearly 800 Mt/yr by the end of the century. Global emissions of methane in SSP1 scenarios follow similar trajectories to CO<sub>2</sub>, with large emissions reductions; SSP2 follows suit, with emissions peaking in 2030 and then reducing throughout the rest of the century; in SSP3's baseline scenario, emissions continue to grow while in the NTCF scenario, they are reduced drastically as policies are implemented to reduce forcing from short-lived emissions species; SSP4 is characterized by growing (SSP4-6.0) or mostly stable (SSP4-3.4) CH<sub>4</sub> emissions until the middle of the century which peak in 2060 and then decline; and finally SSP5's baseline
- 10

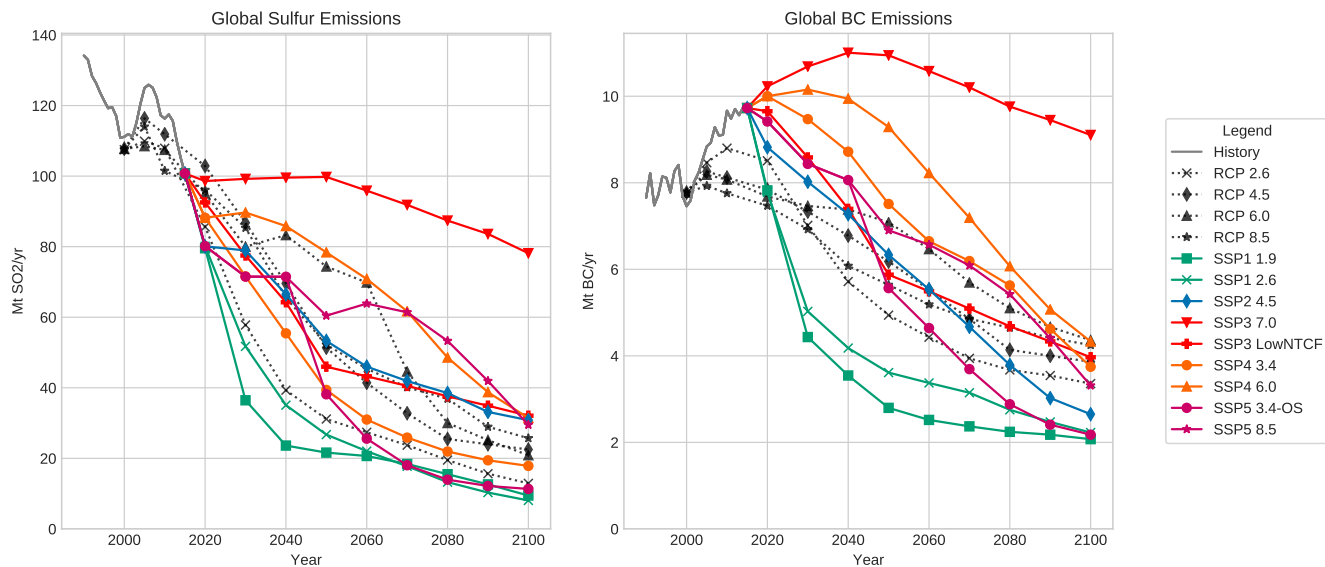


scenario sees a plateauing of CH<sub>4</sub> emissions between 2050 and 2070 before their eventual decline while the overshoot scenario has drastic CH<sub>4</sub> emissions reductions in 2040 corresponding to significant mid-century mitigation efforts in that scenario.

Historically, CH<sub>4</sub> emissions are dominated by three sectors: energy (due to fossil fuel production, and natural gas transmission), agriculture (largely enteric fermentation from livestock and rice production), and waste (i.e., landfills). In each scenario, global emissions of CH<sub>4</sub> are largely dominated by the behavior of activity in each of these sectors over time. For example, in the SSP1 scenarios, significant reductions in energy emissions are observed as energy supply systems shift from fossil to renewable sources while agriculture and waste-sector emissions see only modest reductions as global population stabilizes around mid-century. In the SSP2 scenario, emissions from the energy sector peak in 2040 as there is continued reliance on energy from natural gas but large expansions in renewables in the future; however, emissions from the agricultural and waste sectors are similar to today's levels by the end of the century. Finally, CH<sub>4</sub> emissions in SSP5's baseline scenario is characterized by growth in energy sector from continued expansion of natural gas and a peak and reduction in agricultural emission resulting in 20% higher emissions at the end of the century relative to the present as population grows in the near term before contracting globally.

GHG emissions are broadly similar between the main scenarios in CMIP5 (RCPs) and CMIP6 (SSPs). Notably, we observe that the SSPs exhibit slightly lower CO<sub>2</sub> emissions in the 2.6 W m<sup>-2</sup> scenarios and higher emissions in the 8.5 W m<sup>-2</sup> scenarios due to lower and higher dependence on fossil fuels relative to their RCP predecessors. CH<sub>4</sub> emissions are largely similar at EOC for 2.6 and 4.5 W m<sup>-2</sup> scenarios between the RCPs and SSPs, with earlier values differing due to continued growth in the historical period (RCPs begin in 2000 whereas SSPs begin in 2015). The 8.5 W m<sup>-2</sup> scenario exhibits the largest difference in CH<sub>4</sub> emissions between the RCPs and SSPs because of the SSP5 socioeconomic story line depicting a world which largely develops out of poverty in less-developed countries, reducing CH<sub>4</sub> emissions from waste and agriculture. This contrasts with a very different story line behind RCP-8.5 (Riahi et al., 2011).

In nearly all scenarios, aerosol emissions are observed to decline over the century; however, the magnitude and speed of this decline is highly dependent on the evolution of various drivers based on the underlying SSP story lines, resulting in a wide range of aerosol emissions, as shown in Figure 5. For example, sulfur emissions (totaling 112 Mt/yr globally in 2015) are dominated at present by the energy and industrial sectors. In SSP1, where the world transitions away from fossil-fuel related energy production (namely coal in the case of sulfur), emissions decline sharply as the energy sector transitions to non-fossil based fuels and end-of-pipe measures for air pollution control are ramped up swiftly. The residual amount of sulfur remaining at the end of the century (~10 Mt/yr) is dominated by the industrial sector. SSP2-4.5 sees a similar transition but with delayed action: total sulfur emissions decline due primarily to the decarbonization of the energy sector. SSP5 also observes declines in overall sulfur emissions led largely by an energy mix that transitions from coal dependence to dependence on natural gas, as well as strong end-of-pipe air pollution control efforts. These reductions are similarly matched in the industrial sector, where natural gas is substituted for coal use as well. Thus, overall reductions in emissions are realized across the scenario set. Only SSP3 shows EOC sulfur emissions equivalent to the present day, largely due to increased demand for industrial services from growing population centers in developing nations with a heavy reliance on coal-based energy production, and weak air pollution control efforts.

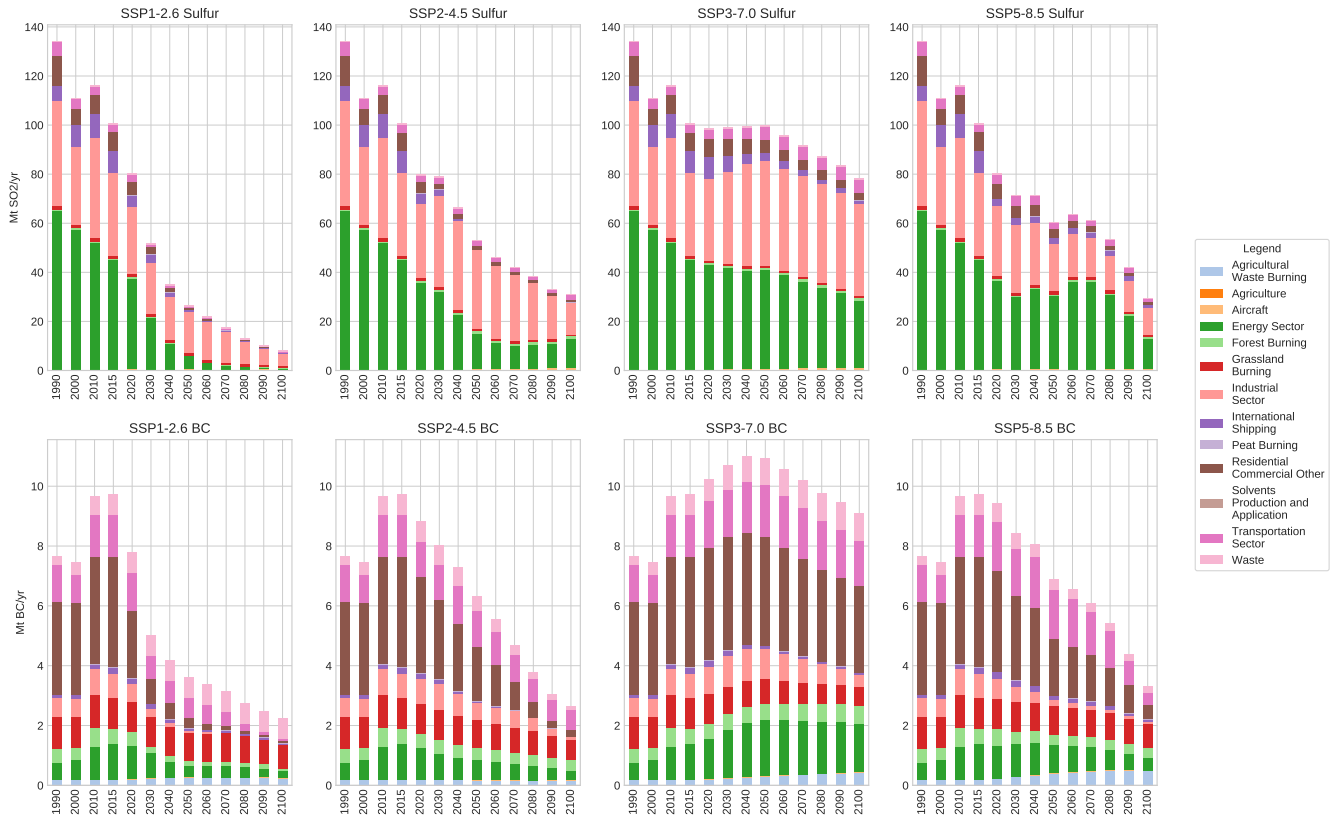


**Figure 5.** Emissions trajectories for sulfur and black carbon (BC), for history, the RCPs, and all nine scenarios analyzed in this study. SSP trajectories largely track with RCP values studied in CMIP5. A notable difference lies in BC emissions, which have seen relatively large increases in past years, thus providing higher initial emissions for the SSPs.

Aerosols associated with the burning of traditional biomass, crop, and pasture residues, as well as municipal waste, such as black carbon (BC) and organic carbon (OC, see SI Figure E3) are affected most strongly by the degree of economic progress and growth in each scenario, as shown in Figure 6. For example, BC emissions from the residential and commercial sector comprise nearly 40% of all emissions in the historical time period with a significant contribution from mobile sources. By the end of the century, however, emissions associated with crop and pasture activity comprise the plurality of total emissions in each of SSPs 1, 2, and 5 due to a transition away from traditional biomass usage based on increased economic development and population stabilization and emissions controls on mobile sources. Only SSP3, in which there is continued global inequality and the persistence of poor and vulnerable urban and rural populations, is there continued quantities of BC emissions across sectors similar to today. OC emissions are largely from biofuel and open burning and follow similar trends: large reductions in scenarios with higher income growth rates with a residual emissions profile due largely to open burning-related emissions. Other pollutant emissions (e.g.,  $\text{NO}_x$ , carbon monoxide (CO), and volatile organic carbon (VOC)) also see a decline in total global emissions at rates depending on the story line (Rao et al., 2017).

### 3.3 The Effects of Harmonization

Harmonization, by definition, modifies the original model results such that base-year values correspond to an agreed-upon historical source, with an aim for future values to match the original model behavior as much as possible. Model results are



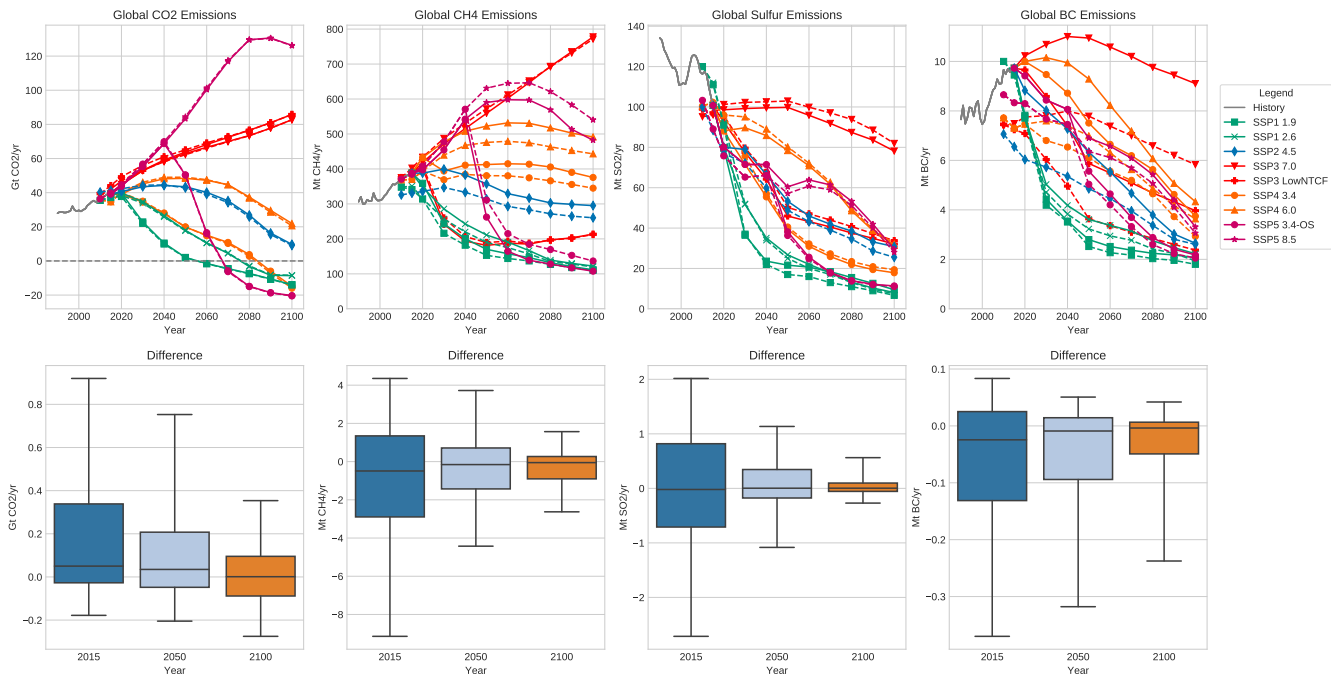
**Figure 6.** The sectoral contributions to sulfur and black carbon emissions for Tier-1 scenarios.

harmonized separately for each individual combination of model region, sector, and emissions species. In the majority of cases, model results are harmonized using the default methods described in Section 2.3; however, it is possible for models to provide harmonization overrides in order to explicitly set a harmonization method for a given trajectory.

We assess the impact that harmonization has on model results by analyzing the harmonized and unharmonized trajectories.

- 5 Figure 7 shows global trajectories for each scenario of a selected number of emissions species. Qualitatively, the CO<sub>2</sub> and sulfur emissions trajectories match relatively closely to the magnitude of model results due to general agreement between historical sources used by individual models and the updated historical emissions datasets. This leads to convergence harmonization routines being used by default. In the case of CH<sub>4</sub> and BC, however, there is larger disagreement between model results and harmonized results in the base year. In such cases, *aneris* chooses harmonization methods that match the shape of a given
- 10 trajectory rather than its magnitude in order to preserve the relationship between driver and emission for each model.

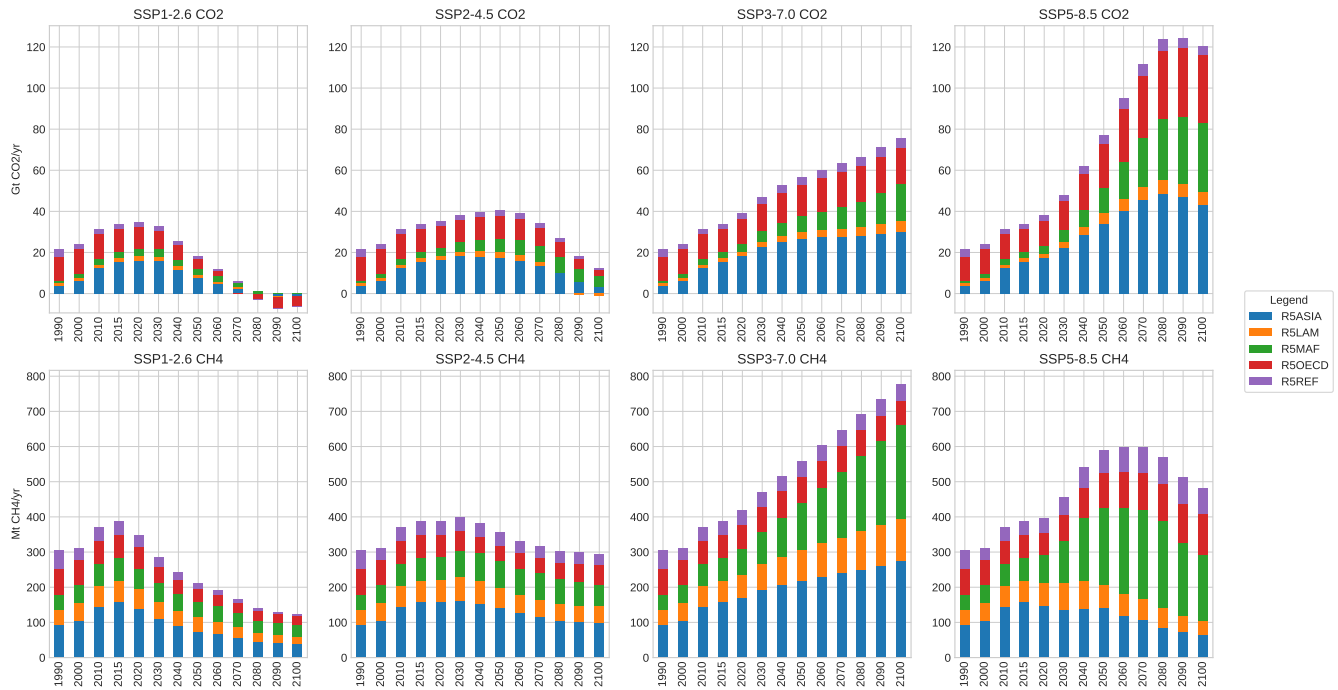
We find that across all harmonized trajectories the difference between harmonized and unharmonized model results decreases over the modeled time horizon. The lower panel in Figure 7 shows the distribution of all 15,954 trajectories (unharmonized less harmonized result) for the harmonization year (2015) and two modeled years (2050 and 2100). Each emissions species data



**Figure 7.** Harmonized (solid) and unharmonized (dashed) trajectories are shown in the upper panel. The lower panel depicts the distribution of differences (harmonized less unharmonized) for every modeled region. All box plots show upper and lower quartiles as solid boxes, median values as solid lines, and whiskers extending to 10th and 90th percentiles. Median values for all are near zero, however, the deviation reduces with time as harmonized values begin to more closely match unharmonized model results largely due to the use of convergence methods.

population exhibits the same trend of reduced difference between modeled and harmonized results. Not only do the deviation of result distributions reduce over time, but the median value also converges toward zero in all cases.

The trajectory behavior for a number of important emissions species are dominated by certain sectors, as [discussion previously in Section 3.1](#) and shown in SI Figure F1. Notably, the energy sector tends to dominate behavior of CO<sub>2</sub> emissions, agriculture dominates CH<sub>4</sub> emission trajectories, the industrial sector largely determines total sulfur emissions, and emissions from the residential and commercial sectors tend to dominate BC emissions across the various scenarios. Accordingly, we further analyzed the harmonization behavior of these sector-species combinations. Importantly, we again observe an overall trend towards convergence of results at the end of the century; thus harmonized results largely track unharmonized results for these critical emissions sectors. The deviation of distributions of differences consistently reduce with time for all scenarios, and nearly all medians converge consistently towards zero, save for energy-related CO<sub>2</sub> SSP5-8.5 which has a higher growth rate than convergence rate, thus larger differences in 2050 than 2015. Overall, we find the harmonization procedure successfully harmonized results historical base year and closely matches model results across the scenarios by EOC.



**Figure 8.** Regional emissions for five global regions for CO<sub>2</sub> and CH<sub>4</sub> in each Tier-1 scenario.

### 3.4 Spatial Distribution of Emissions

The extent to which reductions or growth of emissions are distributed regionally varies greatly among scenarios. The regional breakdown of primary contributors to future warming potential, CO<sub>2</sub> and CH<sub>4</sub>, is shown in Figure 8. While present-day CO<sub>2</sub> emissions see near-equal contributions from the OECD and Asia, future CO<sub>2</sub> emissions are governed largely by potential developments in Asia (namely China and India). For SSP1-2.6, in which deep decarbonization and negative CO<sub>2</sub> emissions occur before the end of the century, emissions in Asia peak in 2020 before reducing to zero by 2080. Mitigation efforts occur across all regions, and the majority of carbon reduction is focused in the OECD; however, all regions have net negative CO<sub>2</sub> emissions by 2090. Asian CO<sub>2</sub> emissions in SSP2-4.5 peak in 2030, and most other regions see overall reductions except Africa, in which continued development and industrialization results in emissions growth. Notably, Latin America is the only region in which negative emissions occur in SSP2-4.5 due largely to increased deployment of biomass-based energy production and carbon sequestration. Sustained growth across regions is observed in SSP5-8.5, where emissions in Asia peak by 2080, driving the global emissions peaking in the same year. Other scenarios (see SI Figure G1) follow similar trends with future CO<sub>2</sub> emissions driven primarily by developments in Asia.

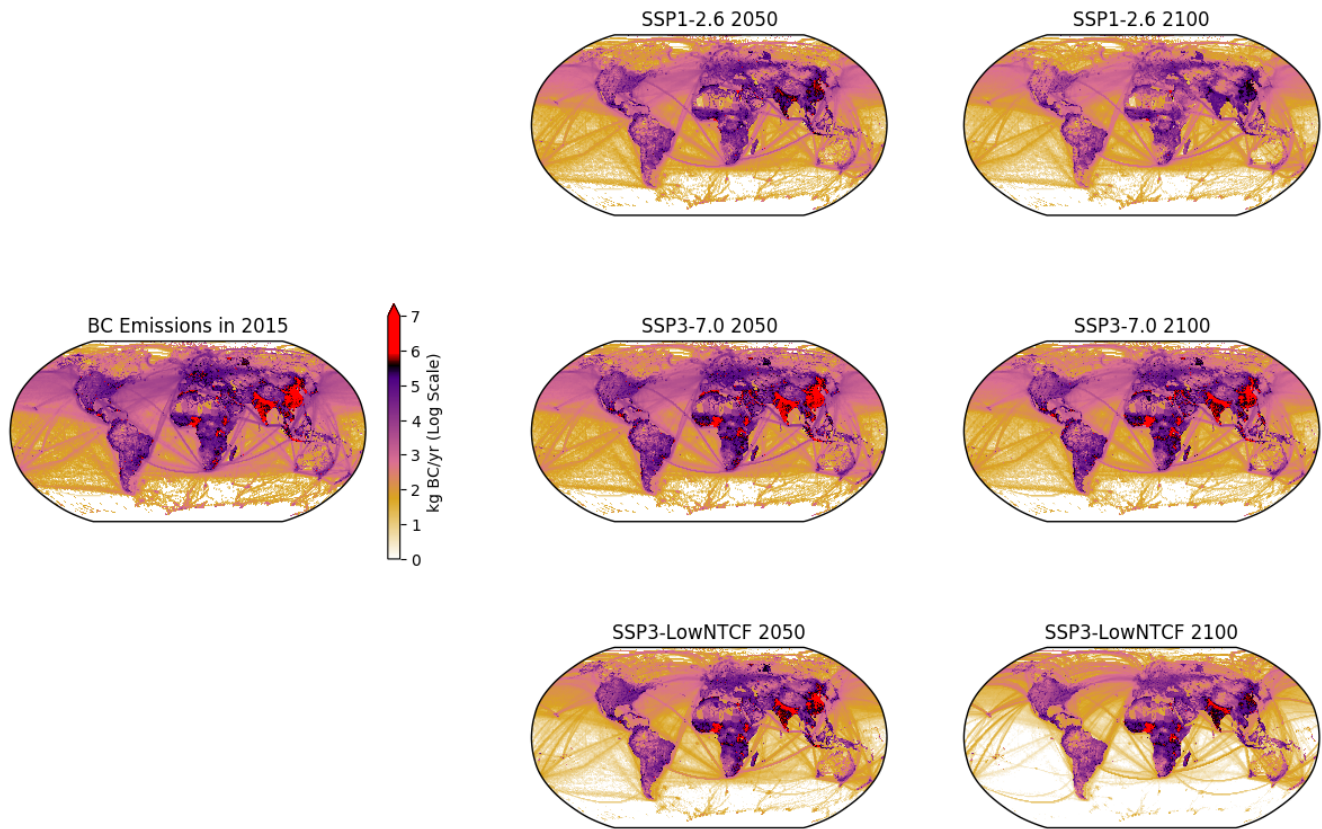
CH<sub>4</sub> emissions, resulting from a mix of energy use, food production, and waste disposal, show a different regional breakdown across scenarios. In SSP1-2.6, CH<sub>4</sub> emissions are reduced consistently across regions as energy systems transition away

from fossil fuel use (notably natural gas) and the husbandry of livestock is curtailed globally. CH<sub>4</sub> emissions in other scenarios tend to be dominated by developments in Africa. In SSP5-8.5, for example, emissions in Africa begin to dominate the global profile by mid-century, due largely to expansion of fossil-fuel based energy production. SSPs 3 and 4 see continued growth in African CH<sub>4</sub> emissions across the century, even when global emissions are reduced as in the case of SSP4 scenarios.

5 CO<sub>2</sub> and CH<sub>4</sub> are well-mixed climate forcers (Stocker et al., 2013) and thus their spatial variation have a higher impact from a political rather than physical perspective. Aerosols, however, have substantive spatial variability which directly impacts both regional climate forcing via scattering and absorption of solar radiation and cloud formation as well as local and regional air quality. Thus in order to provide climate models with more detailed and meaningful datasets, we downscale emissions trajectories from model regions to individual countries ~~using the methodology described previously in Section 2.4,~~  
10 ~~which~~. In most cases, models explicitly represent countries with large shares of emissions (e.g., USA, China, India, etc.). MESSAGE-GLOBIOM and REMIND-MAGPIE are notable exceptions; however, their regional aggregations are such that these important countries comprise the bulk of emissions in their aggregate regions (e.g., the MESSAGE-GLOBIOM North America region comprises the USA and Canada). For regions constituted by many countries, country-level emissions are driven largely by bulk region emissions and country GDP in each scenario (per Section 2.4). Afterwards, country-level emissions are  
15 subsequently mapped to spatial grids (Feng, 2019). We here present global maps of two aerosol species with the strongest implications on future warming, i.e., BC in Figure 9 and sulfur in Figure 10. We highlight three cases which have relevant aerosol emissions profiles: SSP1-2.6 which has significantly decreasing emissions over the century, SSP3-7.0 which has the highest aerosol emissions, and SSP3-LowNTCF which has similar socioeconomic drivers as the SSP3 baseline but models the inclusion of policies which seek to limit emission of near-term climate forcing species.

20 At present, BC has the highest emissions in China and India due largely to traditional biomass usage in the residential sector and secondarily to transport-related activity. In scenarios of high socioeconomic development and technological progress, such as SSP1-2.6, emissions across countries decline dramatically such that by the end of the century, total emissions in China, for example, are equal to that of the USA today. In almost all countries, BC emissions are nearly eradicated by mid-century while emissions in southeast Asia reach similar levels by the end of the century. In SSP3-7.0, however, emissions from southeast Asia  
25 and central Africa increase until the middle of the century as populations grow while still depending on fossil-heavy energy supply technologies, transportation, and cooking fuels. By the end of the century in SSP3-7.0, global BC emissions are nearly equivalent to the present day (see, e.g., Figure 5), but these emissions are concentrated largely in central Africa, southeast Asia, and Brazil while they are reduced in North America, Europe, and Central Asia. By enacting policies that specifically target near-term climate forcers in SSP3-LowNTCF, the growth of emissions in the developing world is muted by mid-century and  
30 are cut by more than half of today's levels (~9 Mt/yr vs. ~4 Mt/yr) by the end of the century. These policies result in similar levels of BC emissions in China as in SSP1-2.6, while most of the additional emissions are driven by activity in India and central Africa due to continued dependence on traditional biomass for cooking and heating.

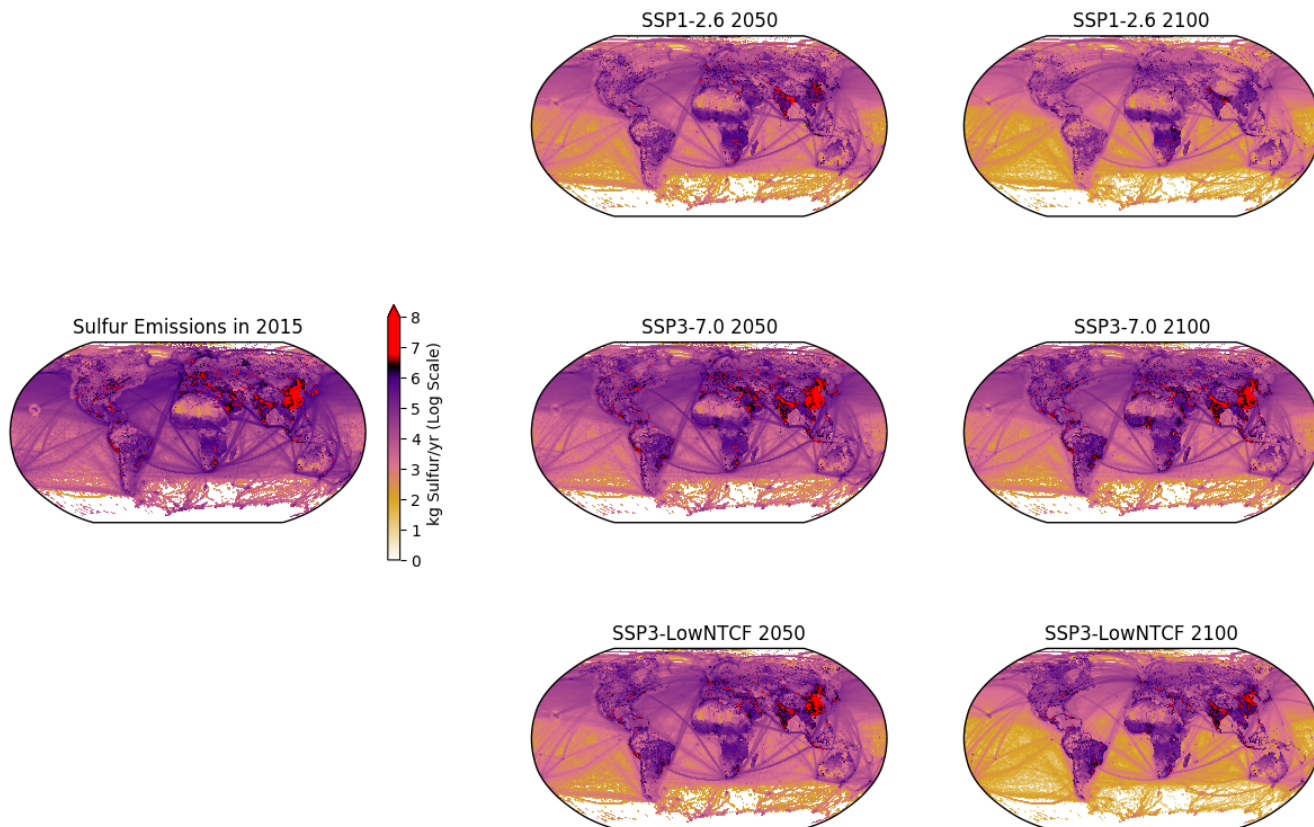
The spatial distribution of sulfur emissions varies from that of BC due to large contributions from energy and industrial sectors, and thus being driven by a country's economic size and composition, as opposed to household activity. Emissions today  
35 are largely concentrated in countries having large manufacturing, industrial, and energy supply sectors with heavy reliance on



**Figure 9.** Downscaled and gridded emissions of Black Carbon at present and in 2050 and 2100 for SSP1-2.6, SSP3-7.0, and SSP3-LowNTCF.

coal, such as the China, India, the USA, Russia, and some parts of the Middle East. Again, we observe in SSP1-2.6 a near elimination of sulfur emissions by the end of the century with some continued reliance on sulfur-emitting technologies in India and China in the middle of the century. In SSP3-7.0, although global sulfur emissions over the course of the century peak slightly before reducing to below current levels, increased emissions in southeast Asia offset reductions in emissions elsewhere

5 due to an expanding industrial sector with continued reliance on coal. Notably, emissions in India peak around mid-century before reducing to a magnitude lower than emissions levels today. In the SSP3-LowNTCF scenario, NTCF policies have the added effect of reducing sulfur emissions, resulting in more RF but less potential health impacts due to sulfur pollution. By the end of the century in SSP3-LowNTCF, only India, China, and Brazil have non-trivial quantities of emissions at significantly lower magnitudes than today.



**Figure 10.** Downscaled and gridded emissions of sulfur at present and in 2050 and 2100 for SSP1-2.6, SSP3-7.0, and SSP3-LowNTCF.

#### 4 Conclusions

We present a suite of nine scenarios of future emissions trajectories of anthropogenic sources, a key deliverable of the ScenarioMIP experiment within CMIP6. IAM results for 14 different emissions species and 13 individual sectors are provided for each scenario with consistent transitions from the historical data used in CMIP6 to future trajectories using automated harmonization before being downscaled to provide higher emission source spatial detail. Harmonized emissions at global, original native model region, and gridded resolution have been delivered to participating climate teams in CMIP6 for further analysis and study by a number of different MIPs.

Scenarios were selected from a candidate pool of over 40 different SSP realizations such that a range of climate outcomes are represented which provide sufficient spacing between EOC forcing to sample statistically significant global and regional temperature outcomes. Of the nine scenarios, four were selected to match forcing levels previously provided by the RCP scenarios used in CMIP5 (RCP2.6 aligns with SSP1-2.6, RCP4.5 with SSP2-4.5, RCP6.0 with SSP4-6.0, and RCP8.5 with SSP5-8.5). RF trajectories are largely comparable between two scenario sets, with relatively strong deviations in the



6.0 scenario forcing pathways (SSP4-6.0 has higher emissions in the mid-century period compared with RCP6.0, but both reach similar EOC forcing) and small differences in the 2.6 scenarios. Notably, SSP5-8.5 has significantly higher and lower emissions compared with RCP8.5, following SSP5's fossil-fuel-based and agricultural intensification SSP5 story line; however, their forcing trajectories are nearly identical. SSP2-4.5 is observed to have a strongly consistent forcing pathway compared to RCP4.5.

Five additional scenarios were analyzed in order to enrich the possible studies of physical and climate impact modeling teams as well as support the scientific goals of specific MIPs. For example, SSP3-7.0 and SSP4-3.4 fill gaps in the available EOC forcing targets provided in the RCPs (7.0 and 3.4, respectively). A variant of SSP3-7.0, SSP3-LowNTCF (which has similar trajectories but massively different trajectories, for example), is also provided to assess the role of near term climate forcers in the context of AerChemMIP. It furthermore serves as an additional EOC forcing target available to climate teams, reaching ~6.3. Additionally, SSP1-1.9, which sees forcing peak in 2030 at ~2.8 before declining to 1.9 by EOC resulting in EOC temperature increases well below 2°C, is the lowest forcing scenario assessed in ScenarioMIP and provides insights for policy-relevant analyses in the context of the Paris Agreement. Finally, an 'overshoot' scenario, SSP5-3.4-OS, is presented in order to study the effects of delayed climate action on long-term climate and related impacts. This scenario, which follows SSP5-8.5 until 2040, sees forcing peak in 2050 at ~4.5 before stringent climate action occurs resulting in EOC forcing at ~3.1. These additional scenarios achieve the overall goal of providing [The additional scenarios provide](#) both a variety of statistically different EOC climate outcomes as well as enhanced policy and scientific relevance of potential [studiesanalyses](#).

These emission data are now being used in a variety of multi-model climate model [projections studies](#) (e.g., Fiedler et al. (2018)), including ScenarioMIP, ~~in order to study a number of scientific questions, such as investigations of the role of uncertainty in future forcing trajectories, the effect of forcing peaking and its uncertain timing, and climate outcomes beyond the end of the century.~~ Identifying sources of uncertainties is a critical component of the larger exercise of CMIP6. As such, it is important that scientists using these datasets for further model input and analysis take care when assessing the uncertainty not only between scenarios but between model results for a certain scenario. While each scenario is presented by a single model in ScenarioMIP, models have also provided a wider range of results as part of the SSP process.

A multi-model dispersion<sup>4</sup> analysis is discussed in SI Section H in order to provide further insight into the robustness of results of emissions trajectories across models for specific forcing targets. Notably, we observe large disagreement between models for F-gas trajectories (>100% dispersion by EOC in certain cases); thus uncertainty for these species can be considered large by climate modeling teams. We further observe small but non-negligible EOC dispersion (>20%) for certain aerosol emissions species, including CO, NH<sub>3</sub>, OC, and sulfur. In general, dispersion between models of GHG species increases as EOC RF decreases as the wide array of mitigation options chosen to meet these lower climate targets can vary across models. The importance of this measure of uncertainty is also scenario dependent. For example, models in general report low emissions in SSP1 and high emissions in SSP3; thus, the impact of dispersion may have a higher relevance to climate modelers in SSP3 than SSP1.

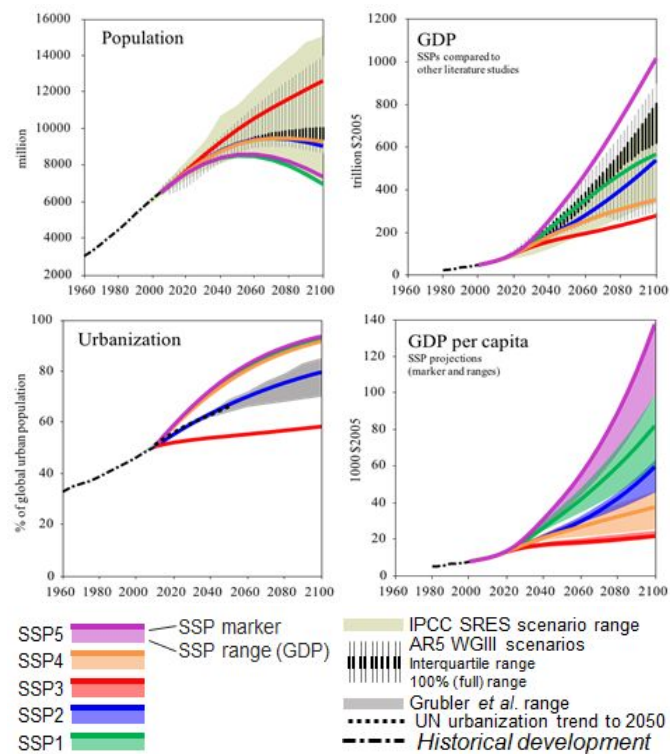
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<sup>4</sup>Dispersion here is defined as the coefficient of variation of model results. The coefficient of variation is defined here as the ratio of the standard deviation to mean (absolute value) of a given population of data. See further discussion in SI Section H.

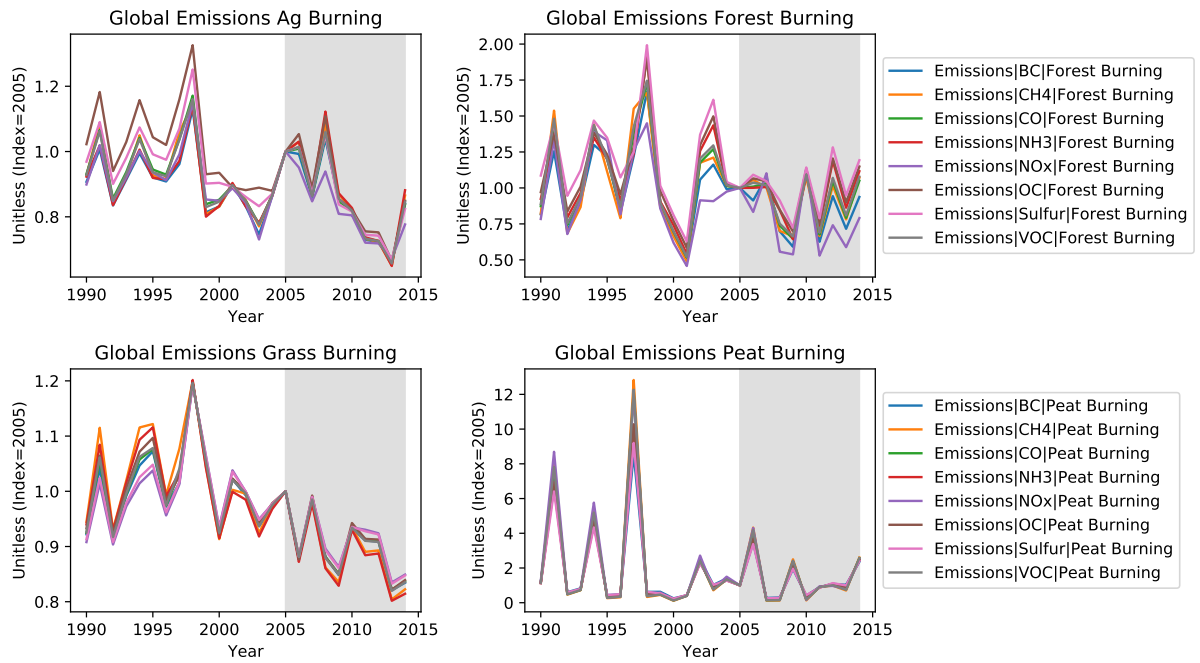
The ability for other IAM teams to generate and compare results with ScenarioMIP scenarios is also of considerable importance in conjunction with CMIP6 and, after its completion, for further scientific discovery and interpretation of results. As such, we have striven to make openly available all of the tools used in this exercise. The harmonization tool used in this study, *anemis*, is provided as open-source software on Github as is the downscaling and gridding methodology. Documentation for both is provided to users online. Such efforts and standardizations not only make the efforts of ScenarioMIP robust and reproducible, but also can prove useful for future exercises integrating a variety of complex models.

*Code and data availability.* The harmonization tool used in this study, *anemis*, is available at <https://github.com/iiasa/anemis> and documentation for using the tool is available at <http://software.ene.iiasa.ac.at/anemis/>. Similarly, the downscaling tool used is available at [https://github.com/iiasa/emissions\\_downscaling](https://github.com/iiasa/emissions_downscaling) and its documentation can be found at [https://github.com/iiasa/emissions\\_downscaling/wiki](https://github.com/iiasa/emissions_downscaling/wiki). Model data, both unharmonized and harmonized is publicly available at the SSP database v1.1 (<https://tntcat.iiasa.ac.at/SspDb>) via the “CMIP6 Emissions” tab while gridded data is available via the ESGF Input4MIPs data repository (<https://esgf-node.llnl.gov/projects/input4mips/>). Within ESGF, gridded data follows the naming convention `<species_specification>-em-<sector_specification>_input4MIPs_emissions_<MIP_specification>_IAMC-<model_specification>-<scenario_specification>-1-1_gn_<time_specification>.nc`, e.g., `BC-em-AIR-anthro_input4MIPs_emissions_ScenarioMIP_IAMC-AIM-ssp370-1-1_gn_201501-210012.nc`.

## Appendix A: **SSP-Drivers**Supplementary Figures



**Figure A1.** The primary socioeconomic assumptions associated with each SSP, including population (KC and Lutz, 2014), urbanization (Jiang and O'Neill, 2015), and GDP (Dellink et al., 2015). The figure is adapted from Riahi et al. (2017) with permission from the authors.



**Figure A2.** [Historic values for land-burning emissions from 1990 until 2014. All values for each emissions species are normalized to their value in 2005. The climatological mean window used for harmonization is shown in grey. While decadal trends are present for some sectors, year-on-year trends see large variation.](#)

## Appendix B: Supplementary Tables

**Table B1.** The sectoral mapping used to aggregate historical data to a common sectoral definition.

<b>CEDS Sectors</b>	<b>ScenarioMIP Sectors</b>
1A1a_Electricity-public	Energy Sector
1A1a_Electricity-autoproducer	Energy Sector
1A1a_Heat-production	Energy Sector
1A1bc_Other-transformation	Energy Sector
1A2a_Ind-Comb-Iron-steel	Industrial Sector
1A2b_Ind-Comb-Non-ferrous-metals	Industrial Sector
1A2c_Ind-Comb-Chemicals	Industrial Sector
1A2d_Ind-Comb-Pulp-paper	Industrial Sector
1A2e_Ind-Comb-Food-tobacco	Industrial Sector
1A2f_Ind-Comb-Non-metalic-minerals	Industrial Sector
1A2g_Ind-Comb-Construction	Industrial Sector
1A2g_Ind-Comb-transpequip	Industrial Sector
1A2g_Ind-Comb-machinery	Industrial Sector
1A2g_Ind-Comb-mining-quarrying	Industrial Sector
1A2g_Ind-Comb-wood-products	Industrial Sector
1A2g_Ind-Comb-textile-leather	Industrial Sector
1A2g_Ind-Comb-other	Industrial Sector
1A3ai_International-aviation	Aircraft
1A3aii_Domestic-aviation	Aircraft
1A3b_Road	Transportation Sector
1A3c_Rail	Transportation Sector
1A3di_International-shipping	International shipping
1A3dii_Domestic-navigation	Transportation Sector
1A3eii_Other-transp	Transportation Sector
1A4a_Commercial-institutional	Residential Commercial Other
1A4b_Residential	Residential Commercial Other
1A4c_Agriculture-forestry-fishing	Residential Commercial Other
1A5_Other-unspecified	Industrial Sector

<b>CEDS Sectors</b>	<b>ScenarioMIP Sectors</b>
1B1_Fugitive-solid-fuels	Energy Sector
1B2_Fugitive-petr-and-gas	Energy Sector
1B2d_Fugitive-other-energy	Energy Sector
2A1_Cement-production	Industrial Sector
2A2_Lime-production	Industrial Sector
2A6_Other-minerals	Industrial Sector
2B_Chemical-industry	Industrial Sector
2C_Metal-production	Industrial Sector
2D_Degreasing-Cleaning	Solvents Production and Application
2D3_Other-product-use	Solvents Production and Application
2D_Paint-application	Solvents Production and Application
2D3_Chemical-products-manufacture-processing	Solvents Production and Application
2H_Pulp-and-paper-food-beverage-wood	Industrial Sector
2L_Other-process-emissions	Industrial Sector
3B_Manure-management	Agriculture
3D_Soil-emissions	Agriculture
3I_Agriculture-other	Agriculture
3D_Rice-Cultivation	Agriculture
3E_Enteric-fermentation	Agriculture
3F_Agricultural-residue-burning-on-fields	Biomass Burning
11B_Forest-fires	Forest Burning
11B_Grassland-fires	Grassland Burning
11B_Peat-fires	Peat Burning
5A_Solid-waste-disposal	Waste
5E_Other-waste-handling	Waste
5C_Waste-incineration	Waste
6A_Other-in-total	Industrial Sector
5D_Wastewater-handling	Waste
7A_Fossil-fuel-fires	Energy Sector

**Table B2.** The sectoral mapping used to aggregate model output data to a common sectoral definition.

IAM Model Variable	ScenarioMIP Sectors
AFOLU Agriculture	Agriculture
AFOLU Biomass Burning	Agricultural Waste Burning
AFOLU Land Forest Burning	Forest Burning
AFOLU Land Grassland Pastures	Grassland Burning
AFOLU Land Grassland Burning	Grassland Burning
AFOLU Land Wetlands	Peat Burning
Energy Demand Industry	Industrial Sector
Energy Demand Other Sector	Industrial Sector
Energy Demand Residential and Commercial and AFOFI	Residential Commercial Other
Energy Demand Transportation Aviation	Aircraft
Energy Demand Transportation Road Rail and Domestic Shipping	Transportation Sector
Energy Demand Transportation Shipping International	International Shipping
Energy Supply	Energy Sector
Fossil Fuel Fires	Energy Sector
Industrial Processes	Industrial Sector
Other	Industrial Sector
Product Use Solvents	Solvents Production and Application
Waste	Waste

**Table B3.** EOC RF values for unharmonized, harmonized scenario results, and differences between the two. The ScenarioMIP design (O'Neill et al., 2016) states that absolute differences must be within  $\pm 0.75 \text{ W m}^{-2}$ , for which all scenarios fall well within the acceptable value.

Scenario	Unharmonized	Harmonized	Difference	Relative Difference
SSP1-2.6	2.624	2.581	0.043	1.6%
SSP2-4.5	4.269	4.38	-0.111	-2.6%
SSP3-Ref	7.165	7.213	-0.048	-0.7%
SSP4-3.4	3.433	3.477	-0.044	-1.3%
SSP4-6.0	5.415	5.431	-0.016	-0.3%
SSP5-Ref	8.698	8.424	0.274	3.2%

**Appendix C: [SSP3-LowNTCF Scenario Assumptions](#)**

SSP3-LowNTCF is the scenario of which basic socioeconomic assumptions are SSP3 but the assumptions concerned with near-term climate forcing (NTCF) species differ from SSP3-7.0 so that SSP3-LowNTCF can be used as a low NTCF scenario contrasting with SSP3-7.0. Here we list the assumptions additionally made to SSP3-7.0.

- 5 – Regarding CH<sub>4</sub>, the CH<sub>4</sub> emissions' reduction rates in SSP1-26 relative to SSP1-Baseline is adopted to SSP3-7.0. This implicitly assumes that SSP3-LowNTCF can reduce CH<sub>4</sub> as if SSP1's stringent climate mitigation policy is implemented in the SSP3 world.
- For air pollutant species (Sulfur, NO<sub>x</sub>, VOC, CO, NH<sub>3</sub>, BC, and OC), the emissions factors assumed in SSP1 is adopted. This assumption implicitly assumes that SSP1's air pollutant legislation and technological progress can be achieved in the SSP3 world.
- 10 – Other species such as CFC, HFC, SF<sub>6</sub>, and C<sub>2</sub>H<sub>6</sub> are identical with SSP3-Baseline

Along with these changes, CH<sub>4</sub> emissions reduction further changes other air pollutants and GHG emissions drivers. CH<sub>4</sub> reduction generates emissions abatement costs which changes economic outputs in all sectors and household consumption in AIM/CGE. Consequently energy consumption and CO<sub>2</sub> emissions in all sectors are affected, which causes small differences between SSP3-7.0 and SSP3-LowNTCF. Not only CO<sub>2</sub> but N<sub>2</sub>O, CH<sub>4</sub> and air pollutants emissions are also affected by these activity level changes although this indirect effect is relatively minor.

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#### **Appendix D: Emissions Gridding**

Emissions data were mapped to a spatial grid generally following the methodologies described in Hoesly et al. (2018). A brief description is given here, and a fuller discussion of the gridding process will be provided in Feng (2019). For most anthropogenic sectors, emissions at the level of country and aggregate sector are mapped to a 0.5° spatial grid by scaling the 2010 base-year country-level spatial pattern. ~~For each aggregate sector the spatial pattern of emissions within a country, therefore, does not change over time in the future scenarios, although the spatial pattern of total emissions will change due to changes in the sectoral distribution of emissions.~~ Open-burning emissions from forest fires, grassland burning, and agricultural waste burning on fields are mapped to a spatial grid in the same manner, except that the spatial pattern is taken to be the average from the last 10-years of the historical dataset (e.g., 2005-2014). For each aggregate gridding sector the spatial pattern of emissions within a country does not change over time in the future scenarios. This means that, for example, the ratio of energy-sector NO<sub>x</sub> emissions from Shaanxi and Beijing provinces in China is constant over time, even though total NO<sub>x</sub> emissions from China vary over time. Because sectors are mapped to the grid separately, however, total anthropogenic emissions (e.g. sum from all sectors) from any two regions within a country will, in general, not have the same time evolution.

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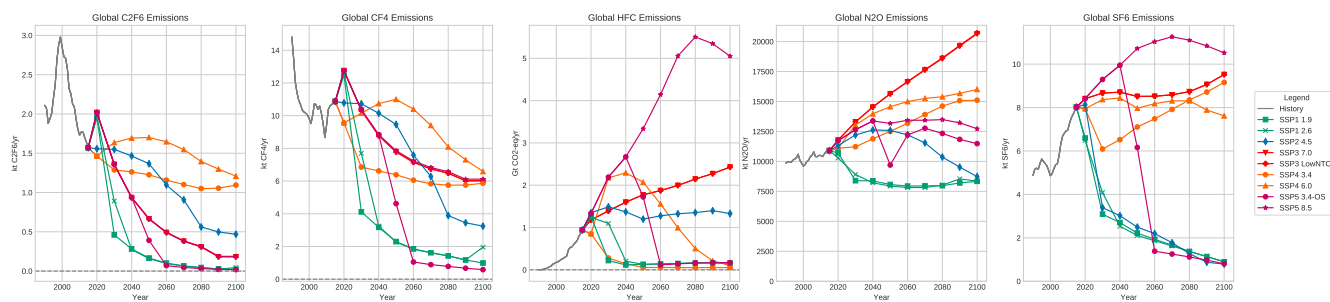
International shipping and aircraft emissions are gridded globally such that the global pattern does not change, only the overall emissions magnitude. One other exception occurs for net negative CO<sub>2</sub> emissions. Negative CO<sub>2</sub> emissions occur in these models when biomass feedstocks are used together with geologic carbon dioxide capture and storage (CCS). In

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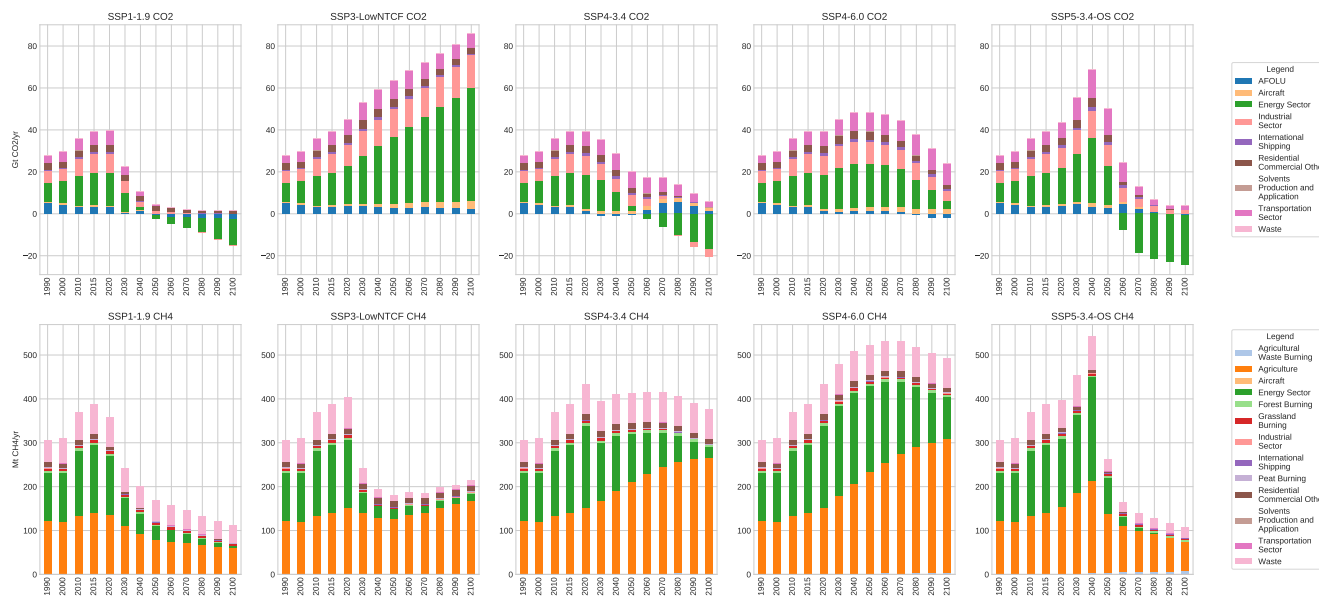


this case, physically, the emissions are taken out of the atmosphere at the locations where biomass is grown, not at the point of energy consumption. In order to avoid large, unphysical, net negative CO<sub>2</sub> point source emissions, net negative CO<sub>2</sub> quantities are, therefore, summed globally and mapped to a spatial grid corresponding to 2010 global cropland net primary production (NPP).

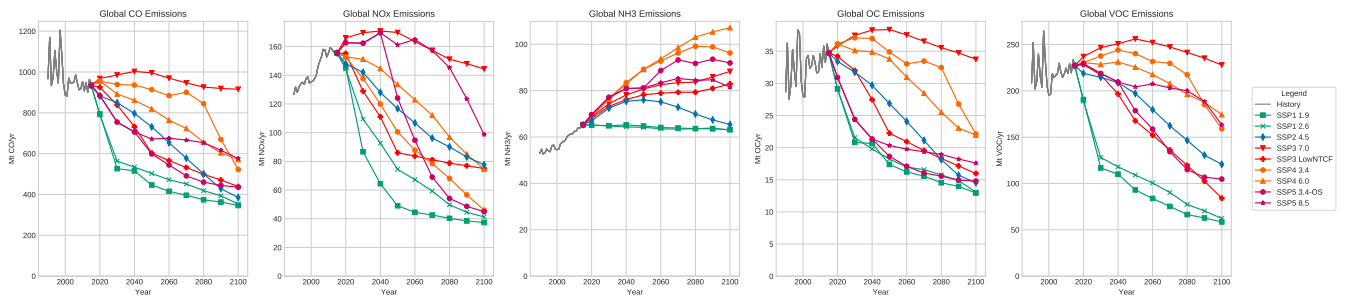
## 5 Appendix E: Global Emissions



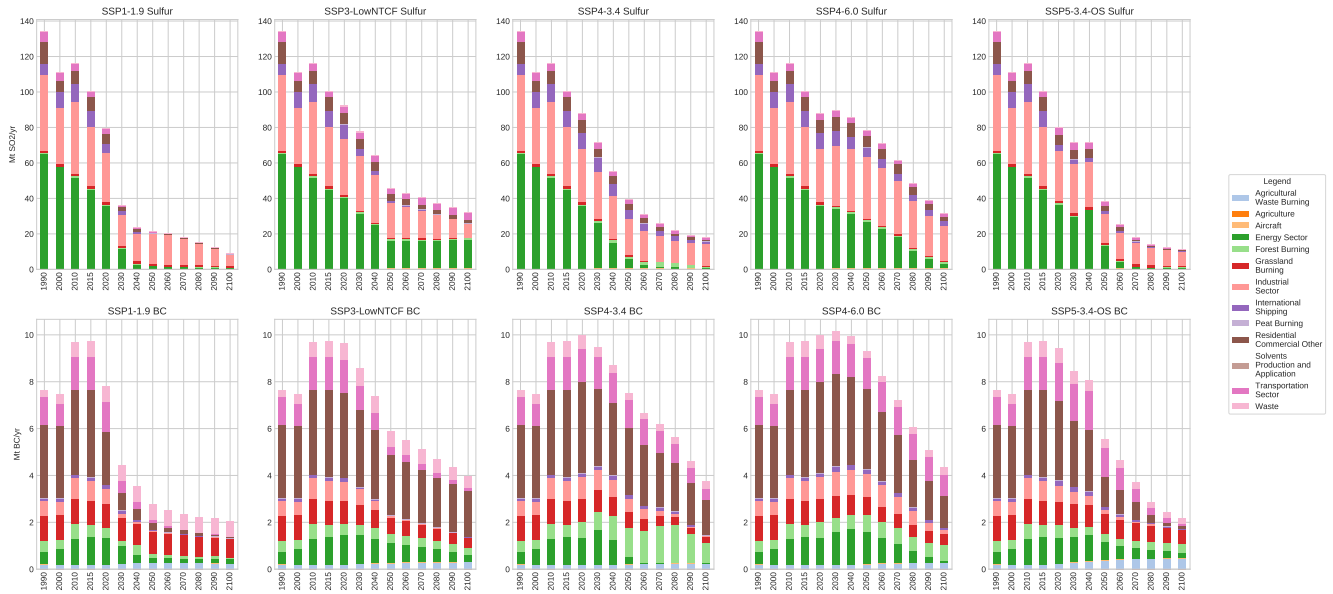
**Figure E1.** Emissions trajectories for all GHGs and all scenarios analyzed in this study.



**Figure E2.** Sectoral breakdown for CO<sub>2</sub> and CH<sub>4</sub> emissions per year for all scenarios analyzed in this study.

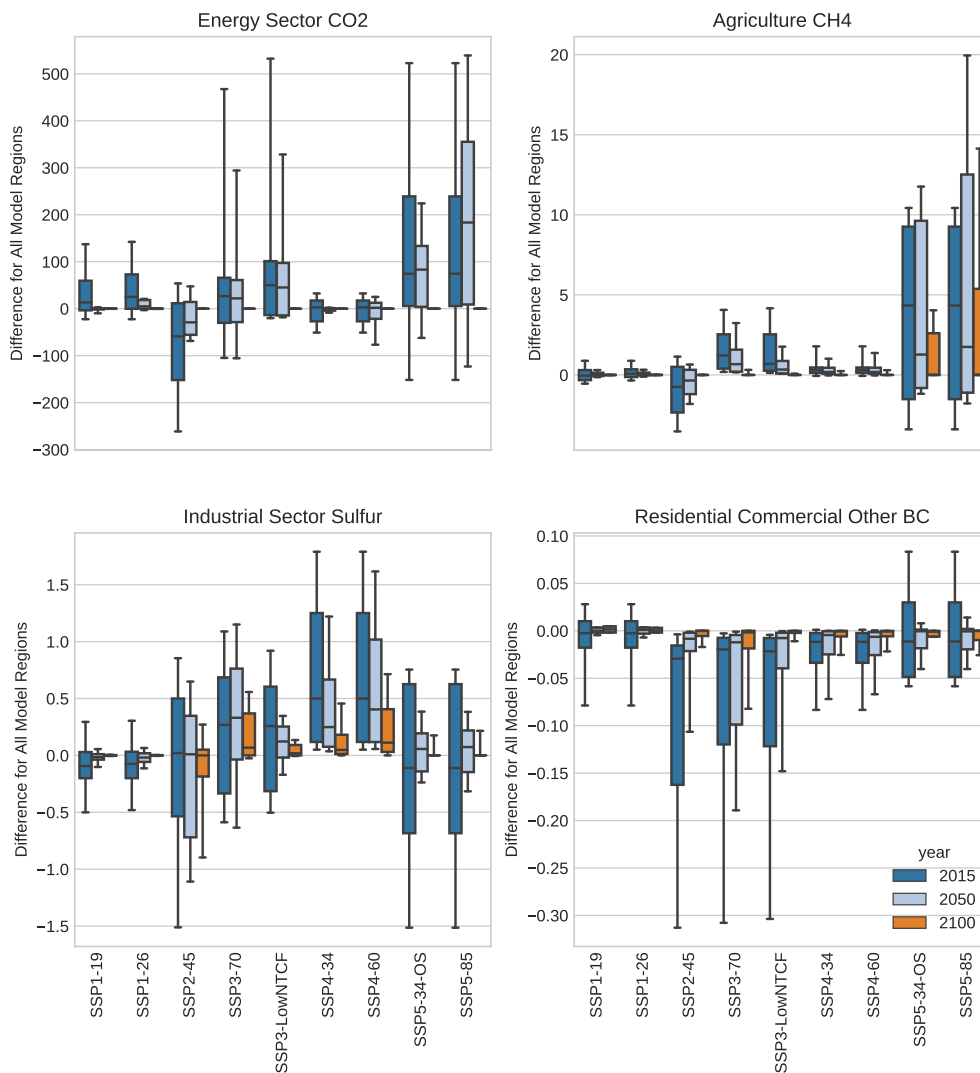


**Figure E3.** Emissions trajectories for all aerosols and all scenarios analyzed in this study.



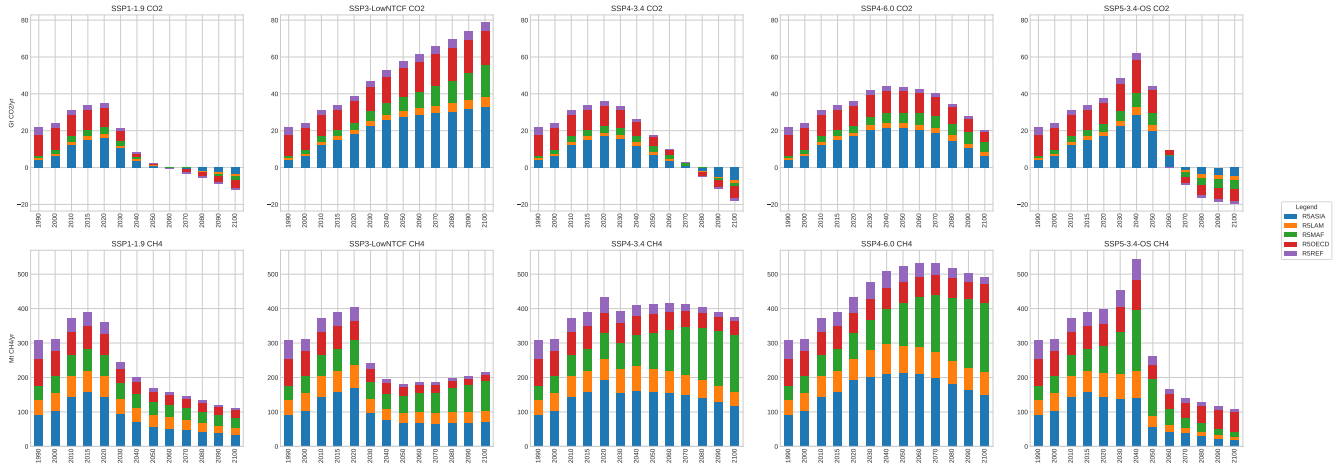
**Figure E4.** Sectoral breakdown for sulfur and BC emissions per year for all scenarios analyzed in this study.

## Appendix F: Harmonization



**Figure F1.** The relative difference between harmonized and unharmonized trajectories are shown for the primary sectoral contributor for various emissions species in each scenario. Boxes are comprised of the population of differences for all regions in a given model-scenario combination (see, e.g., Table 3). All box plots show upper and lower quartiles as solid boxes, median values as solid lines, and whiskers extending to 10th and 90th percentiles. In general, the largest deviations are observed in the base year. The spread of values decrease in time across almost all observations, with the convergence to zero or near-zero by EOC.

## Appendix G: Regional Emissions



**Figure G1.** Emissions for 5 global regions for all other scenarios analyzed in this study.

## Appendix H: Dispersion Analysis

We here discuss the results of a dispersion analysis measuring the variation of emissions trajectories across models for a given scenario. Dispersion is a measure the spread of model values for a given global emissions value in a given year. It is calculated in this context as the coefficient of variation ( $c_v$ ) shown in Equation H1 which is defined as the ratio of the standard deviation,  $\sigma$ , to mean,  $\mu$ , of a given population of data.

$$c_v = \frac{\sigma}{|\mu|} \quad (\text{H1})$$

In order to perform a consistent analysis, we select scenarios for which all participating models provide results: SSP1-2.6, SSP2-4.5, and SSP3-7.0. Scenario data is taken from the available SSP Database at <https://tntcat.iiasa.ac.at/SspDb> (Riahi et al., 2017). To note, dispersion has a non-zero value in the initial year of analysis due to model results not being harmonized in this dataset. We show the dispersion for GHGs (with aggregated F-gases) in Figure H1, individual F-gases in Figure H2, and aerosols in Figure H3.

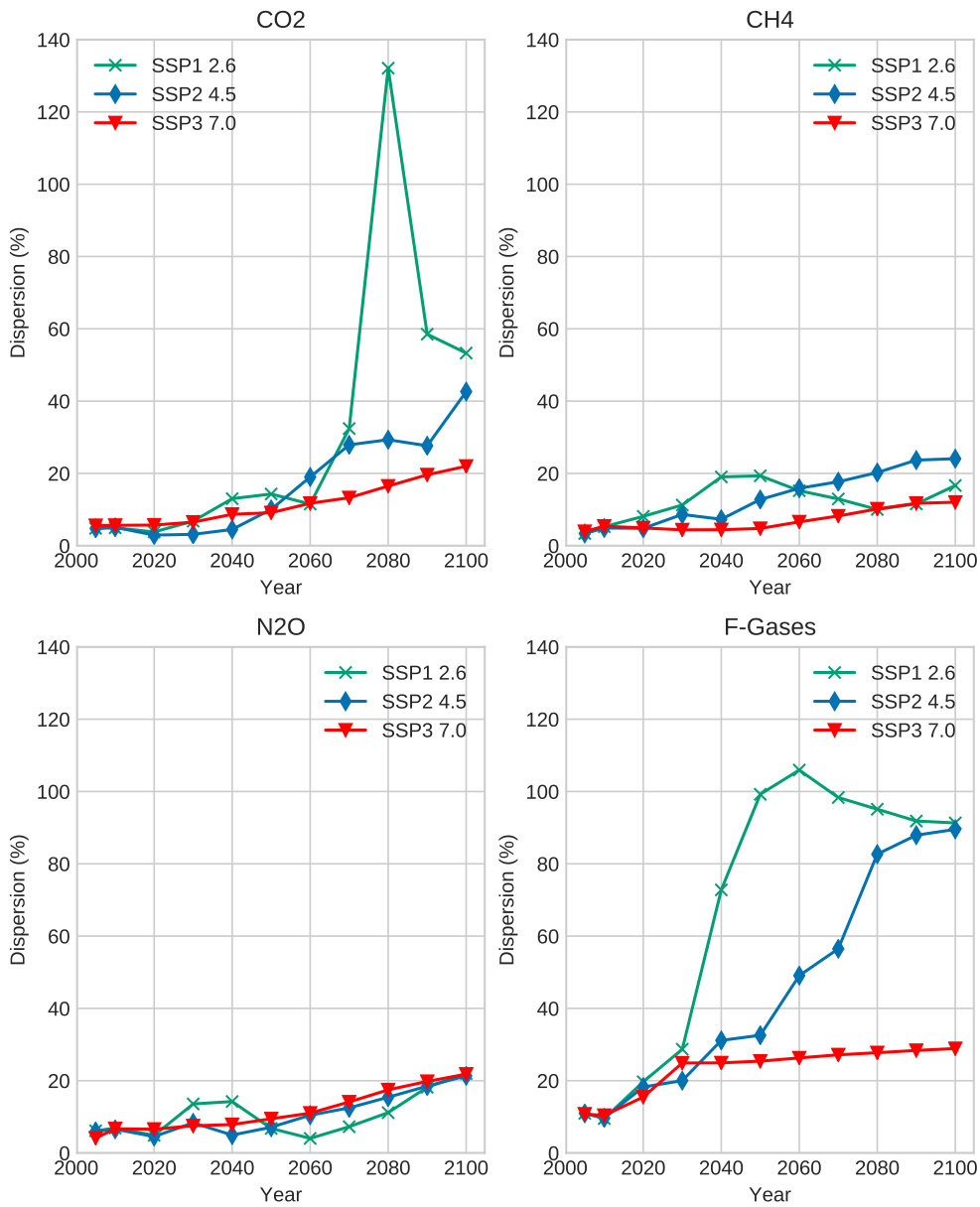
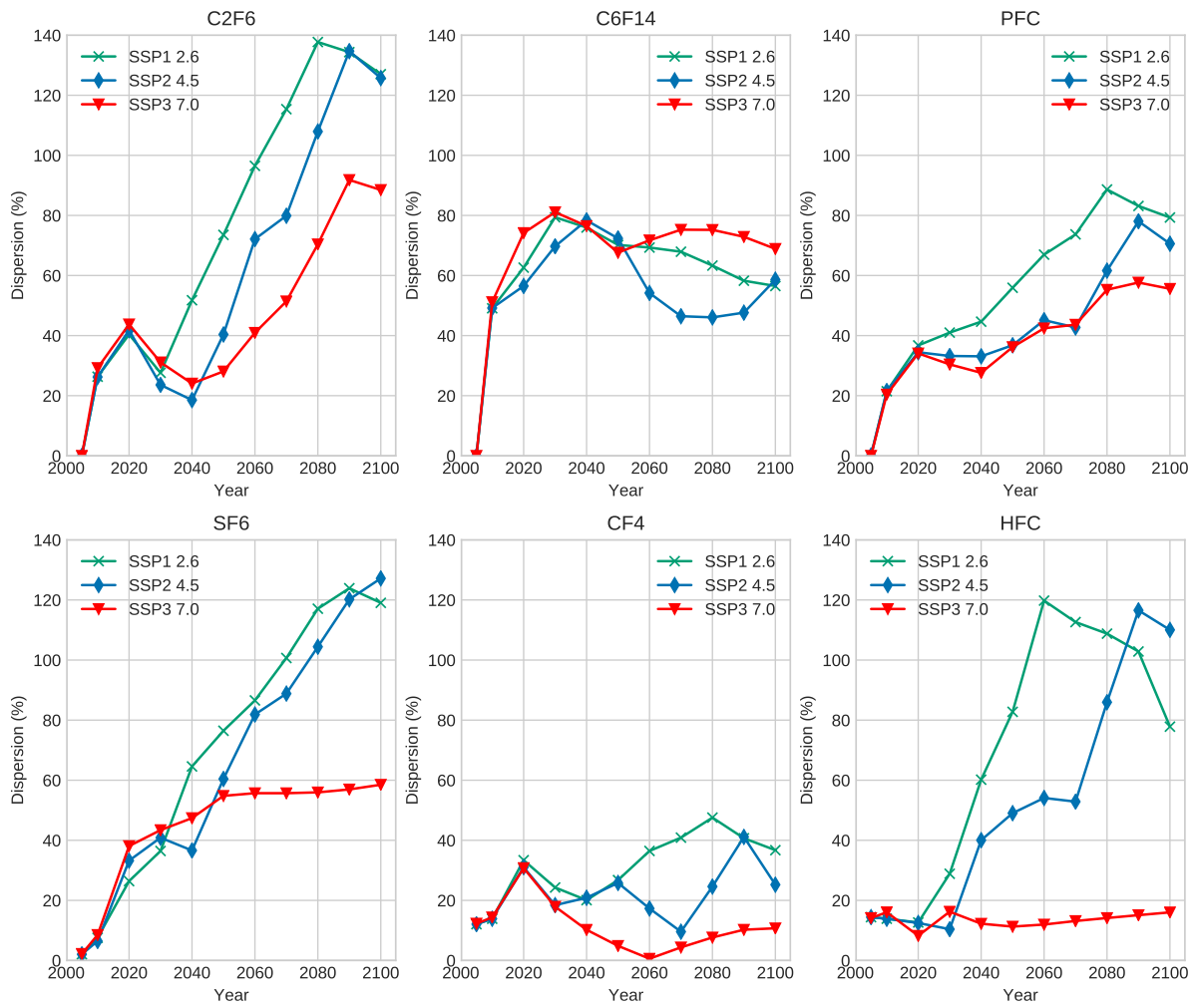
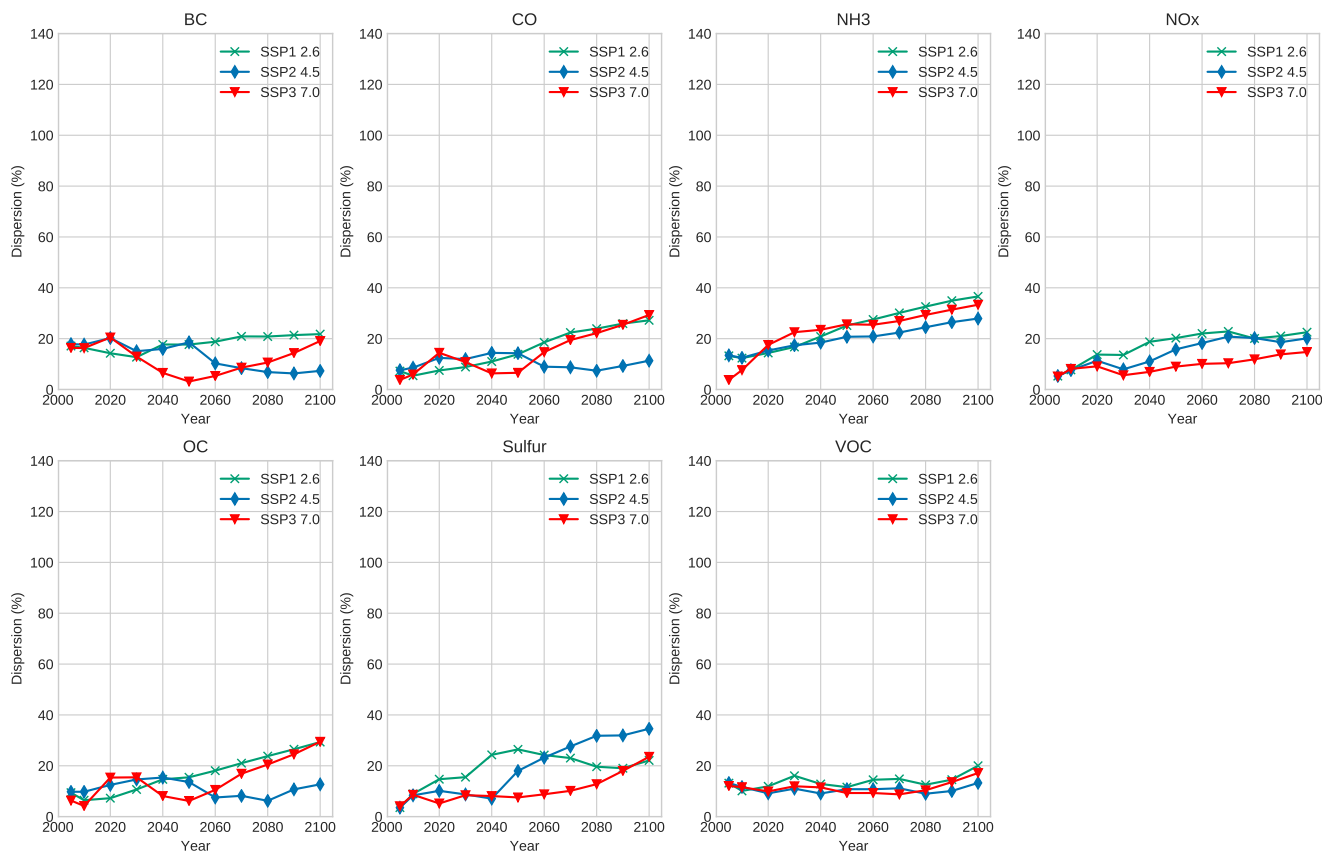


Figure H1. Dispersion analysis results for GHGs with aggregated F-gases.



**Figure H2.** Dispersion analysis results for individual F-gases.



**Figure H3.** Dispersion analysis results for aerosols.

Table H1 shows gas species with the largest values of dispersion. The highest dispersion occurs for F-gases, notably  $C_2F_6$ ,  $SF_6$ , and HFCs, implying that models generally do not agree on total magnitudes for these gases.  $CO_2$  is also observed to have relatively high dispersion in high mitigation scenarios. Finally, aerosol species such as  $NH_3$ , sulfur, and OC show relative high dispersion values (>30%). In almost every case, magnitudes of emissions with high dispersion decrease substantially with time, thus this measure, while important for understanding sources of error, may result in small total system error in climate models. There are important scenario-species combinations to take account of, however. First,  $CO_2$  dispersion in SSP1-2.6 can be of high consequence because this is a scenario with substantial negative emissions at the end of century. Additionally, users of the data should be aware of the dispersion for aerosols in SSP3, as many aerosol species have large EOC magnitudes, thus showing significant variation across models for these species-scenario combinations.

**Table H1.** The dispersion ( $c_v$ ) for the first modeled period and last modeled period for scenarios with maximum model representation. Here we show the 10 highest EOC dispersion values for a given scenario-species combination.

Scenario	Gas	2005	2100	Difference	Relative Difference (%)
SSP1-2.6	F-gases	10.96	91.31	80.34	7.33
SSP2-4.5	F-gases	10.96	89.52	78.56	7.16
SSP1-2.6	CO <sub>2</sub>	4.81	53.29	48.48	10.08
SSP2-4.5	CO <sub>2</sub>	4.80	42.63	37.83	7.89
SSP1-2.6	NH <sub>3</sub>	13.24	36.61	23.37	1.77
SSP2-4.5	Sulfur	3.54	34.57	31.03	8.77
SSP3-7.0	NH <sub>3</sub>	3.76	33.33	29.58	7.87
SSP3-7.0	OC	6.34	29.45	23.11	3.65
SSP1-2.6	OC	9.42	29.33	19.90	2.11
SSP3-7.0	CO	3.76	29.31	25.56	6.81

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