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Future air pollution in the Shared Socio-economic Pathways

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ABSTRACT

Emissions of air pollutants such as sulfur and nitrogen oxides and particulates have significant health impacts as well as effects on natural and anthropogenic ecosystems. These same emissions also can change atmospheric chemistry and the planetary energy balance, thereby impacting global and regional climate. Long-term scenarios for air pollutant emissions are needed as inputs to global climate and chemistry models, and for analysis linking air pollutant impacts across sectors. In this paper we present methodology and results for air pollutant emissions in Shared Socioeconomic Pathways (SSP) scenarios. We first present a set of three air pollution narratives that describe high, central, and low pollution control ambitions over the 21st century. These narratives are then translated into quantitative guidance for use in integrated assessment models. The resulting pollutant emission trajectories under the SSP scenarios cover a wider range than the scenarios used in previous international climate model comparisons. In the SSP3 and SSP4 scenarios, where economic, institutional and technological limitations slow air quality improvements, global pollutant emissions over the 21st century can be comparable to current levels. Pollutant emissions in the SSP1 scenarios fall to low levels due to the assumption of technological advances and successful global action to control emissions.

1. Introduction

Despite efforts to control atmospheric pollutant emissions, ambient air quality remains a major concern in many parts of the world. Air pollution has significant negative impacts on human health (Pope et al., 2002; Dockery et al., 1993; Jerrett et al., 2009).

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More than 80% of the world's population is exposed to pollutant concentrations exceeding the World Health Organization (WHO) recommended levels (Brauer et al., 2012) and around 3.6 million deaths can be attributed to ambient air pollution with another 4 million from household related sources (Lim et al., 2012). Moreover, air pollution can alter ecosystems, damage buildings and monuments, as well as influence earth's energy balance and therefore climate change.

Long-term global scenarios for air pollutant emissions have been used for atmospheric chemistry and Earth system model simulations intended to examine future changes in climate, air, and water systems. These scenarios reflect plausible future emissions based on socioeconomic, environmental, and technological trends. These scenarios are generally produced by integrated assessment models (IAMs) (Moss et al., 2010), which project economic growth, population, energy consumption, land-use and agriculture along with associated GHG and pollutant emissions. Recent examples include in particular, the Representative Concentration Pathway (RCP) scenarios (van Vuuren et al., 2011a), which were the multi-model global scenarios of greenhouse gases and air pollutants used in the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2011). The RCPs were developed to span a range of climate forcing levels and were not associated with specific socio-economic narratives. These scenarios reflected the prevailing view that air quality policies will be successfully implemented globally and that emissions control technology will continue to evolve and as a result show significant declines in particulate matter (PM) and ozone precursor emissions over the 21st century at a global level (Amann et al., 2013; van Vuuren et al., 2011b). More recent scenarios have included alternative assumptions on pollution control, in an effort to better understand the role of air pollution control in terms of reference scenario development and the co-benefits from climate policies (see for example Rogelj et al., 2014; Rao et al., 2013; West et al., 2013; Chuwah et al., 2013) . While providing a wider range of pollution futures, the assumptions on air pollution control in these scenarios are, however, still largely independent of underlying scenario narratives.

It is generally assumed in long-term scenarios, implicitly, that pollutant concentration goals will continue to be more ambitious over time, once incomes become sufficiently large. However, the time, stringency, and enforcement success of future targets for a particular region cannot generally be known and must ideally be treated as scenario variable. In a long-term scenario context, it is further necessary that assumptions on air pollution control are consistent with the underlying challenges to climate change mitigation and adaptation. Pollution outcomes in such scenarios can then be expected to be a cumulative result of a range of variables including socio-economic development, technological change, efficiency improvements and policies directed at pollution control as well as alternative concerns including climate change, energy access, and agricultural production.

The Shared Socio Economic Pathways (SSPs) (Kriegler et al., 2012) are a new generation of scenarios and storylines primarily framed within the context of climate change mitigation and adaptation. The SSP narratives (van Vuuren et al., 2014; O'Neill et al., 2014) comprise a textual description of how the future might unfold, including a description of major socio-economic, demographic, technological, lifestyle, policy, institutional and other trends. In this paper, our overarching goal is to develop plausible ranges of future air pollutant emission development pathways in the SSP scenarios, which are based on internally consistent and coherent assumptions on the degree and implementation of future air pollution control. Other papers in this Special Issue summarize parallel efforts in terms of elaboration of developments in the energy system, land use and greenhouse gas emissions in the SSP scenarios (Bauer et al., 2017; Popp et al., 2017).

The structure of the paper is as follows. We first describe the development of a set of alternative assumptions on the degree and implementation of 'pollution control' in the SSP scenarios. These assumptions then reflect historical evidence and prevailing attitudes and progress on pollution control and potential attitudes to the health and environmental impacts of air pollution in the future. We further postulate a link between these alternative development pathways for pollution control and a specific SSP narrative. We also describe quantitative guidance with regards to implementation of these assumptions in IAMs. Finally, the paper summarizes key results from different IAM interpretations of the SSP scenarios in terms of air pollutant emissions and regional ambient air quality.

2. Methodology

In the following sections, we first summarize the overall description of the SSP scenarios. We next describe the development of a set of qualitative assumptions on pollution control that can be linked to the overall SSP narratives and present a quantitative proposal for implementation of these assumptions in IAMs.

2.1. Description of SSP scenarios

The SSPs depict five different global futures (SSP1–5) with substantially different socio-economic conditions. Each SSP is described by a qualitative narrative (Kriegler et al., 2012). Four of the narratives (SSP1, SSP3, SSP4, and SSP5), are defined by the various combinations of high or low socio-economic challenges to climate change adaptation and mitigation. A fifth narrative (SSP2) describes medium challenges of both kinds and is intended to represent a future in which development trends are not extreme in any of the dimensions, but rather follow middle-of-the-road pathways. As part of the scenario development process, consistent and harmonized quantitative elaborations of population; urbanization and economic development have been developed for all the SSPs. The quantitative elaborations of the SSP narratives are then referred to as 'baseline' scenarios.

The SSP narratives themselves do not include explicit climate policies. However, additional climate mitigation runs have been developed that include for each SSP baseline, additional long-term radiative forcing targets of 2.6, 4.5 and 6.0 W/m^2 in 2100. Climate mitigation scenarios in the SSP framework further include a number of additional assumptions on specific issues related to the level of international cooperation; the timing of the mitigation effort over time; and the extent of fragmentation (particularly in the short-to medium-term). These are characterized as shared policy assumptions (SPAs) which describe for each SSP narrative, the most relevant characteristics of future climate mitigation policies, consistent with the overall SSP narrative as well as the SSP baseline scenario developments. The mitigation effort of the SSP scenarios is then a function of both the stringency of the target and the underlying energy and carbon intensities in the baselines. This could result in some cases in infeasibilities in terms of meeting mitigation targets (for a complete overview of the SSP baseline and climate mitigation scenarios (see Riahi et al., 2017).

A number of IAMs ran the elaborations of SSP scenarios. These include IMAGE (van Vuuren et al., 2017); MESSAGE-GLOBIOM (Fricko et al., 2017); AIM/CGE (Fujimori et al., 2017); GCAM (Calvin et al., 2017); REMIND-MAgPIE (Kriegler et al., 2017); and WITCH-GLOBIOM (Emmerling et al., 2016). Detailed information on the models can be found in the Supplementary Information (SI). For simplification, for each of the five SSPs, one marker IAM has been identified (representative of a specific SSP from a single IAM). The selection was guided by consideration of internal consistency

Table 1
Summary of scenarios.

Identifier	Descriptor	Marker IAM	Also computed by (non-marker IAMs)	Central SPA assumptions for Climate Mitigation
SSP1	Sustainability	IMAGE (van Vuuren et al., 2017)	All	Early accession with global collaboration as of 2020
SSP2	Middle-of-the-road	MESSAGE-GLOBIOM (Fricko et al., 2017)	All	Some delays in establishing global action with regions transitioning to global cooperation between 2020 and 2040
SSP3	Regional rivalry	AIM/CGE (Fujimori et al., 2017)	IMAGE, GCAM, MESSAGE-GLOBIOM, WITCH-GLOBIOM	Late accession – higher income regions join global regime between 2020 and 2040, while lower income regions follow between 2030 and 2050
SSP4	Inequality	GCAM	AIM/CGE, WITCH-GLOBIOM	Same as SSP1
SSP5	Fossil-fuelled development	REMIND-MAgPIE	AIM/CGE, GCAM, WITCH-GLOBIOM	Same as SSP2

across different SSP interpretations as well as the ability of a model to represent the specific storylines. This helped to ensure also that the differences between models were well represented in the final set of marker SSPs. Additional replications of the SSPs from 'non marker' models then provide insights into possible alternative projections of the same storyline. The multi-model approach was important for understanding the robustness of the results and the uncertainties associated with the different SSPs.

Table 1 summarizes the SSP scenario set.

2.2. Pollution control in the SSP narratives

In this section, we now describe the development of a set of assumptions on pollution control that can be used to guide the interpretation of SSP narratives.

While there is no unique relationship between either pollutant levels or emission controls and income (Stern, 2005; Carson, 2010; Smith et al., 2005), a continued tightening of pollution targets can be considered a consequence of growing attention given to health outcomes with increasing income, or perhaps also as a result of new research that ties additional morbidity and mortality modalities to air pollution. The adverse impacts of air pollution are well documented and costs of control technologies have generally declined over time. This means that developing countries can benefit from past experience and have often implemented pollution controls well in advance, relative to income, as compared to historical experience in currently more affluent regions. Countries have, however, different physical, economic and institutional circumstances that impact both the amount and effort needed to achieve pollution goals. Pollutant emission densities in the developing world are sometimes quite high and, even with more advanced technology, reaching pollution targets may be more difficult. The same level of pollution control will result in different concentration levels in different locations.

Policies to control the adverse impacts of air pollution are numerous and regionally diverse. They are generally aimed at avoiding exceeding specified targets for concentration levels (for example, sulfur-di-oxide, ozone, and particulate matter) but goals for ecosystem protection (e.g., from acidification and eutrophication) have also been pursued in several regions. Pollution targets are periodically revised at both the global level (e.g. WHO) and by national and regional bodies. Levels of pollution control are also often different across sectors. Further, in some circumstances, traditional 'end-of pipe' pollution control may have less of a role in reducing emissions than the effects of socio-economic growth and related fuel and technological shifts (Rafaj et al., 2014). Thus 'pollution control' itself could refer to a wide range of policies and developments. For example, policies addressing climate change often, as a co-benefit, reduce atmospheric emissions, thus improving ambient air quality (McCollum et al., 2013; van Vuuren et al., 2006; Bollen, 2008) . Conversely, policies targeting air pollution will have also climate impacts, e.g., (Carmichael, 2008; Shindell et al., 2012), although climate co-benefits may be smaller than previously expected (Smith and Mizrahi, 2013; Stohl et al., 2015). Technological availability can also be a key influence on the degree of pollution control, especially if few or only costly options are available. In practice damages are, either implicitly or explicitly, balanced against the economic costs of pollution control, for which technology characteristics, particularly costs of pollution control or lower emission alternatives are a key driver.

We cannot capture all these complexities within current integrated scenarios. We first simplify our approach by identifying three characteristics for air pollution narratives:

1. Pollution control targets (e.g. concentration standards), which we specify relative to those in current OECD countries.
2. The speed at which developing countries 'catch up' with these levels and effectiveness of policies in current OECD countries.
3. The pathways for pollution control technologies, including the technological frontier that represents best practice values at a given time.

Based on these characteristics, we developed three alternative assumptions for future pollution controls (strong, medium and weak), which are further mapped to specific SSP scenarios. This terminology follows the same convention as other studies used to inform the SSP scenario design process (KC and Lutz, 2017; Crespo Cuaresma, 2017).

The *medium pollution control* scenario (SSP2) envisions a world that continues following current trends. Due to the diffusion of technology and knowledge, there is some 'catch-up', where countries achieve levels of emission control and policy efficacy in advance, in terms of income levels, of the historical record in current OECD countries. Pollution concentration targets become more ambitious over the century as income grows, the commitment to set and enforce pollution targets becoming increasingly effective, and more value is placed on health and environment protection. To reach these targets, some regions will ultimately require implementation of very efficient technologies, some perhaps requiring advances over current technology levels. Regions with large population densities or adverse physical conditions (e.g. geographic features that lead to frequent high pollution episodes) may not achieve their desired outcomes.

The *strong pollution control* scenarios (SSP1 and SSP5) assume that increasing health and environmental concerns result in successful achievement of pollutant targets substantially lower than current levels in the medium to long term. Associated with this scenario is a faster rate of pollution control technology development, with greater effectiveness as compared to current technologies. The ambitious air quality goals in the strong pollution control scenario would require, in some regions, implementation of current best available technology (and perhaps even beyond) and assure overall enforcement of environmental laws supported by efficiently operating institutions.

Weak pollution control scenarios (SSP3 and SSP4) assume that the implementation of pollution controls is delayed and less ambitious in the long-term compared to the *medium* scenario. This may be due to the large challenges several regions face, including, high emission densities in developing countries' megacities, failure to develop adequate air quality monitoring, and/or weaker institutions resulting in poor enforcement of respective legislation. The problems are aggravated by the assumption that international cooperation is weaker resulting in low ambition or slow development of international laws that also leads to slower rates of technological improvements and *trans*-boundary pollution contributes to higher background concentrations in many regions.

These pollution control storylines are matched to the SSP scenario narratives as shown in Table 2. The strong pollution control narrative is assumed for the SSP1 and SSP5 scenarios due to their high levels of development, focus on human capital, and reduced inequality. Conversely, we associate the low pollution control narrative with the SSP3 and SSP4 scenarios due to their lower levels of development and greater inequality. The SSP2 scenario is mapped to the medium pollution control narrative. The speed and absolute value to which country groups converge is differentiated across the SSPs. While we qualify three sets of assumptions on pollution control that are mapped to the five SSP scenarios, we note that even with similar assumptions on pollution control, pollution outcomes in specific SSP scenarios will differ due to varying assumptions on economic and population growth, energy consumption patterns, and other scenario characteristics.

2.3. Implementation in IAMs

For quantitative interpretation of the storylines, there is a further need to bridge the gap between the complexity in estimating pollution emissions and their impacts, the ability of available measures, such as emission controls, to mitigate these impacts, and the need for simplified representations of these processes in IAMs. Given that IAMs do not generally represent explicit air pollution control technologies on a detailed level, we detail below an approach where scenario parameters are broadly represented in terms of changes in emission factors derived from a more detailed air pollution model. This approach has been used in a number of recent studies (Riahi et al., 2012) and allows for a relatively simplistic method to represent quantitatively, concepts related to the speed and degree of implementation of pollution control developed and described earlier.

We base our quantitative guidance on a dataset of regional emission factors (i.e., emissions per unit of energy) for energy-related combustion and transformation sectors until 2030 based on current policies and technological options derived from the GAINS model (Amann et al., 2011, Klimont et al., in Preparation). This dataset includes emission factors for 26 world regions for sulfur dioxide (SO_2), nitrogen oxides (NO_x), organic carbon (OC), black carbon (BC), carbon monoxide (CO), non-methane volatile organic carbons (NMVOC), and ammonia (NH_3) from all energy combustion and process sources. The detailed emissions factor data was processed to accommodate the aggregate structure and resolution of the IAMs (see supplementary information (SI) Section 1 for further details). The emission factors used include:

CLE: 'current legislation' – These emission factors assume efficient implementation of existing environmental legislation. It thus describes a scenario of pollution control where countries implement all planned legislation until 2030 with adequate institutional support. The CLE emission factors are "fleet average" values that are the aggregate emission factor of all ages of equipment operating in the given year.

MTFR: 'maximum technically feasible reduction' – These emission factors assume full implementation of 'best available technology' as it exists today by 2030 independent of their costs but considering economic lifetime of technologies and selected other constraints that could limit applicability of certain measures in specific regions. While, the full penetration of MTFR measures in the near-term is not a feasible scenario, these values serve rather as ultimately achievable air pollutant emission factors for conventional technologies considered being available at the present time.

In order to develop trajectories for emission factors that could be consistent with the SSP storylines, we draw on experience and results from a number of existing and forthcoming studies including (Rao et al., 2013; Riahi et al., 2012) where similar sets of emission factors have been used in a single IAM in conjunction with a full scale atmospheric chemistry model, thus providing an indication of the implication of such emission factor development in terms of resulting atmospheric concentrations of PM2.5 and corresponding health impacts in the medium-term. We identify two main components in terms of emission factor development:

Table 2
Qualitative framework for pollution control in the SSPs.

Policy strength	Policy targets		Technological innovation	SSP link	Key relevant characteristics of SSPs
	High Income countries	Medium and Low income countries			
Strong	Policies over the 21st century aim for much lower pollutant levels than current targets in order to minimize adverse effects on population, vulnerable groups, and ecosystems.	Comparatively quick catch-up with the developed world (relative to income)	Pollution control technology costs drop substantially with control performance increasing.	SSP1, SSP5	Sustainability driven; rapid development of human capital, economic growth and technological progress; prioritized health concerns
Medium	Lower than current targets	Catch-up with the developed world at income levels lower than when OECD countries began controls (but not as quick as in the strong control case).	Continued modest technology advances.	SSP2	Middle of the road scenario
Weak	Regionally varied policies.	Trade barriers and/or institutional limitations substantially slow progress in pollution control.	Lower levels of technological advance overall.	SSP3, SSP4	Fragmentation, inequalities

Until 2030, emission factors assumed in the different SSP scenarios reflect assumptions on the attitudes to health and environment and the institutional capacity to implement pollution control in the near-term. They include full implementation of CLE pollution control measures in the medium scenario but allow for partial and additional control in the weak and strong pollution control scenarios.

After 2030, the trajectories are assumed to depend on the extent to which economic development implies that lower-income regions catch-up to OECD levels in terms of implementation (e.g. emission factor reductions) and the extent of technological change, i.e., the progress towards MTFR levels of emission factors. The MFTR values are assumed to be static themselves and do not change with time and we do not speculate about impact of innovation on further improving the reduction efficiency of the best measures we included. Thus, while in some sense, we may be conservative for the pathways and regions with high penetration of MTFR equivalent technology, on the other hand, given that most MFTR values here are based on current small-scale applications, we assume that technological progress in the scenarios will mature these technologies and allow for wide application over the longer-term.

Fig. 1 shows a conceptual representation of the development of pollution control policy and associated emission factor change in the different SSPs. A more detailed illustration of how the emission factors in the dataset can be used to emulate the above guidelines is presented in section 1.2 of the SI.

The IAMs use the emission factor data provided and quantitative guidelines described to individually develop the SSP scenarios. The emission factors are implemented in the baseline scenarios describing the SSP narratives, while the climate mitigation scenarios then describe the additional impacts of climate policies on air pollution emissions and air quality, compared to the baselines. Thus, the climate mitigation scenarios do not include further policies on air pollution control compared to the baseline scenarios. It is important to note that the models use different inventories for the 2000–2010 periods, and are not benchmarked to a single source. The differences across models in this period then reflect the uncertainty in inventory data and to some extent, the regional and sector aggregation of the IAMs. For land-use, international shipping, and other sectors not covered in the emission factor dataset, additional assumptions are made (see SI [3943] for more details on inventories and drivers for emissions across the IAMs.). The assumptions for methane (CH_4) from energy, waste and land-use sectors are separately described in Bauer et al. (2017) and Popp et al. (2017) and summarized in the SI.

3. Results

In this section, we summarize key results for the SSP scenarios in terms of air pollution emissions and regional air quality. We describe the full range of marker and non-marker ranges for the SSP scenarios. In terms of climate mitigation, we only focus on central SPA case for each SSP.

Results are mainly presented at a global scale and further discussed for five aggregate regions:

- OECD90 countries and new EU member states and candidates (OECD);
- reforming economies of Eastern Europe and the Former Soviet Union (excluding EU member states) (REF);
- countries of the Middle East and Africa (MAF);
- countries of Latin America and the Caribbean (LAM); and
- Asian countries (with the exception of the Middle East, Japan and Former Soviet Union states) (ASIA).

3.1. Emissions of selected air pollutants

Fig. 2 shows potential emissions futures across the SSP scenarios in the 2005–2100 period for selected pollutants. Results for remaining pollutants are summarized in the SI. We include emission ranges from the RCP scenario set as well as the entire range of scenarios from the IPCC Fifth Assessment Report, in order to place the SSP scenarios in context. Differences in historical emissions between the models (2000–2010) are due to use of different inventories by IAMs (Table S1 and individual model descriptions) and are within uncertainty ranges (Granier et al., 2011; Lamarque et al., 2010). For example, for SO_2, historical global emissions uncertainty has been estimated at about 10%, with larger uncertainties for some regions (Smith et al., 2010). Uncertainty is much larger for black carbon emissions, estimated to be a factor of two (Bond et al., 2004). Beyond uncertainties in activity data and emissions factors, additional aspects include the relatively aggregate representation of sectors in IAMs and the large uncertainties in land-use and land-use change emissions (see Popp et al., 2017 for full description of land-use sector).

The SSP3 baseline shows an increase in future emissions over the short-term across all pollutants examined here, due to large population growth and relatively slower and heterogeneous economic growth. At a global level, emissions continue increasing for the next two to three decades and by 2100 show only a slight decline from current levels. The SSP4 baseline, which has

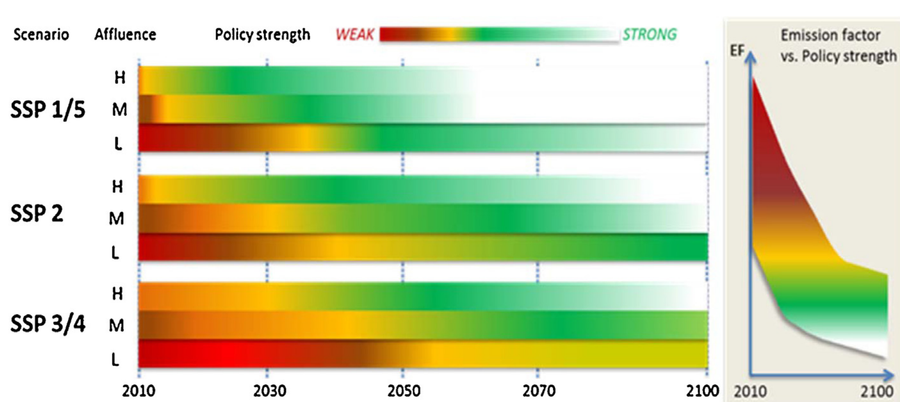

Fig. 1. Proposed Pathways for Air Pollution Policy in SSPs over time. Right hand inset shows schematic development of emission factors. We use here identical definitions of income country groups (low income (L) countries, middle income (M) countries, and high income (H) countries) as used in the SSP process for development of economic projections, based on recent World Bank classifications. https://secure.iiasa.ac.at/web-apps/ene/SspDb/static/download/ssp_suplementary%20text.pdf.

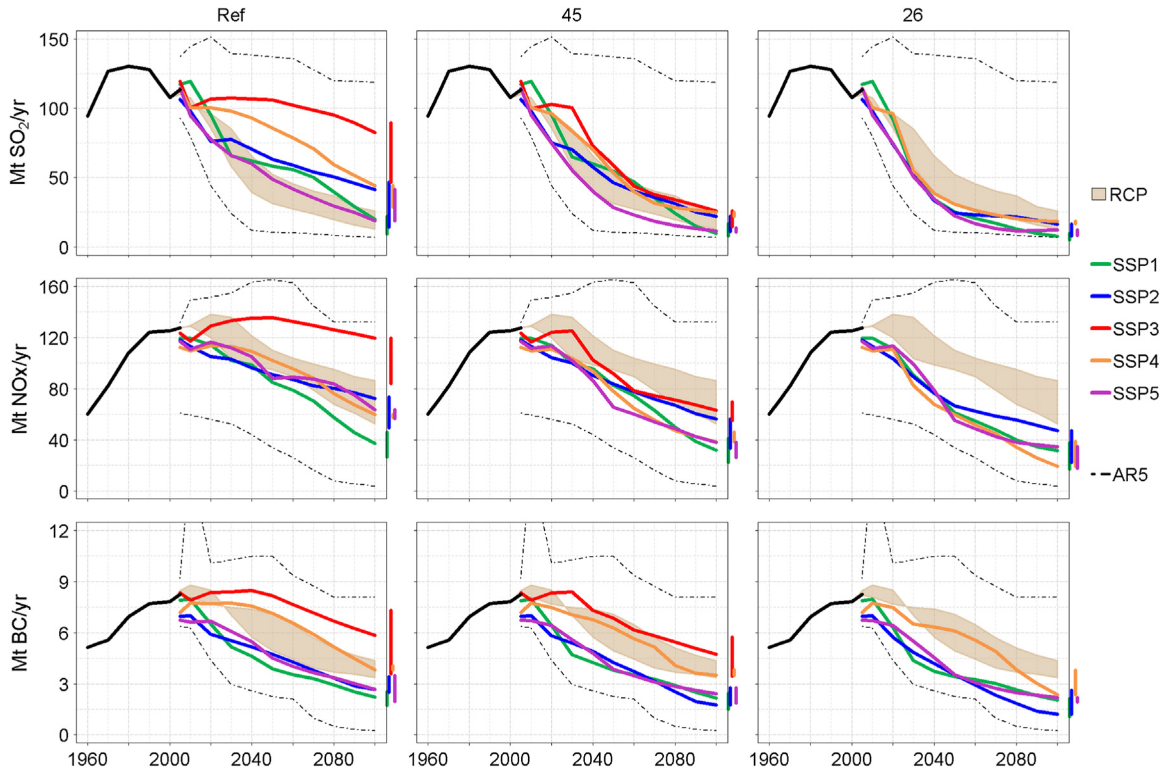

Fig. 2. Emissions of SO_2, NO_X and BC in SSP marker baselines (Ref) and 4.5 (labeled as 45) and 2.6 (labeled as 26) W/m^2 climate mitigation cases. Shaded area indicates range of total emissions from RCP scenario range from (van Vuuren et al., 2011a). Assessment Report (AR5) range refers to the full range of scenarios reviewed in the Fifth Assessment Report (AR5) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC) https://tntcat.iiasa.ac.at/AR5DB/; Historical values are derived from (Lamarque et al., 2010); Colored bars indicate the range of all models (markers and non-markers) in 2100.

identical assumptions on pollutant controls, shows lower emissions than SSP3 for all pollutants as a result of different evolution of the energy system (see text below). The SSP2 shows a consistent decline in all pollutants throughout the century while SSP1 and SSP5 exhibit a more rapid decline as a result of more effective pollution control and lower fossil fuel intensities resulting in lowest emissions in the second half of the century.

Pollutant emissions in the SSP scenarios span across a much wider range than the RCP scenarios. In general, baseline SSP3 emissions are significantly higher than the largest RCP values, with NO_x and BC emissions in the SSP1 baseline case lower than the lowest RCP value. While scenario dynamics and assumptions on transportation and access to clean energy for cooking in developing countries are major drivers of emission outcomes of NO_x and BC, respectively, another aspect is the updated set of pollutant control assumptions and the emission factors used in this study. Results for remaining pollutants show similar trends (see SI).

The climate mitigation scenarios (Fig. 2 illustrates 4.5 W/m^2 (45) and 2.6 W/m^2 (26) cases) result in most cases in co-benefits in terms of lower pollutant emissions than the baselines. The largest co-benefits from climate policy occur in the weak pollution control, SSP3 scenario, which also has the highest corresponding baseline emissions, while the SSP1/5 scenarios show more limited reductions in air pollutants from climate policies. While SO_2 and NO_x emissions show the largest reductions and the model ranges within the SSPs are much smaller than in baseline cases, BC emissions do not decline as much as a result of assumptions on fuel-substitution in the residential sector (see discussion in Section 3.3).

3.2. Emission intensities

Fast economic growth and high emission intensities (emissions per unit of energy used) in many Asian countries have led to severe pollution episodes across the continent. In spite of the efforts to cut air pollutant emissions from key sources, the intensities remain well above those observed in OECD countries (Fig. 3) where air quality standards are presently the highest. Emission intensities in the OECD are thus already low, and planned legislation is expected to reduce these even further by 2030.

In the SSP baselines, emission intensities in ASIA decline significantly by 2050 in all SSPs. Economic growth and the average income in ASIA in 2030 differs significantly across SSPs, with a low value of 10 billion US2005$ in SSSP3 and a high value of 28 billion US2005billion$ in SSP5 (see also (Crespo Cuaresma, 2017) for details on economic assumptions in SSPs). Thus, countries could be expected to adopt pollution controls with varied schedules, depending on individual institutional, financial and technological capacities (see previous discussion in Section 2).

The relative contribution of pollutant control measures in terms of actual reductions in air pollution will depend on the SSP baseline pathway. Major energy transitions in the SSP scenarios occur gradually and assumptions for pollution control can be assumed to be particularly important in the first few decades in terms of reducing emission intensities. For example, coal based electricity evolves relatively similarly until 2050 across the SSPs and consequently the differences in development of emission intensities in ASIA within this time frame is a direct reflection of pollution control.

Over the longer term, the scenarios diverge significantly in terms of energy and fuel structures. The SSP1 and SSP5 baselines

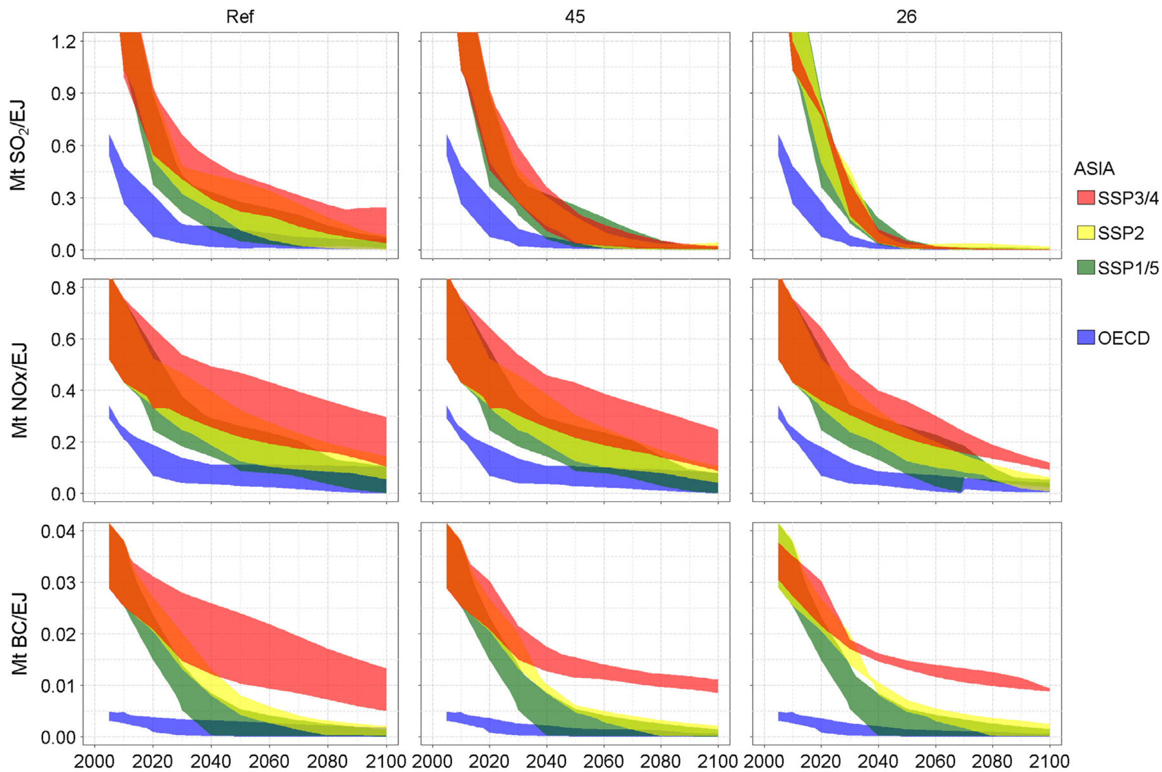

Fig. 3. Emissions intensities for major pollutants in ASIA and OECD in SSP baselines and 26 and 45 mitigation scenarios (both marker and non-marker scenarios included). Emission intensities defined differently for pollutants; SO_2 intensity is in reference to energy supply, NOx and BC in reference to final energy from respective sectors.

show a transition towards less polluting fuels and technologies, and thus result in a rapid and sustained reduction in emission intensities in ASIA. Conversely in the SSP3 and SSP4 worlds, relatively weaker technological change and higher fossil fuel intensities in the energy system lead to higher levels of pollutant emissions. The SSP2 scenario shows large-scale electrification- for example, electrification in ASIA grows rapidly and by 2030 has a similar share of final energy as current OECD levels. In the transportation sector, liquid fuels are the major fuel until mid-century in all SSP scenarios. The SSP1 shows only a slight decline in liquids while, SSP5 shows the largest increase. This reflects alternative narratives of future mobility resulting from differences in lifestyles, preferences and technology.

We note that for BC emissions from the residential sector in ASIA, emission intensities remain high throughout the century in the SSP3 and SSP4 baseline scenarios mainly because of continued biomass use. In the SSP3 scenario, for example, biomass use in ASIA is close to 20 EJ in 2100, almost the same as today's levels. In the SSP1, the assumption of rapidly increasing access to cleaner cooking fuels means that BC emissions decline substantially and by 2030 emission intensities converge to OECD levels.

Assuming proper enforcement of air pollution policies in the OECD region, climate policies have very little impact in terms of pollutant emission intensities. In ASIA, climate policies decrease emission intensities for SO_2 and NO_x, with more limited impact on BC, in fact, a slight increase is indicated in the SSP3 scenario (see discussion on sector impacts of climate policies and co-benefits in Section 3.3).

3.3. Sector emissions

The SSP scenarios offer a wide diversity of future growth patterns and how they relate to regional energy demand convergence and modernization of energy use (see Bauer et al., 2017 for details). In order to understand the impacts of alternative energy developments, we look at broad developments of pollutants across sectors (Fig. 4).

3.3.1. Baseline scenarios

The energy sector emissions are dominated by electricity production, which currently contributes a major share of SO_2 and in the developing countries also of NO_x. Both emission control assumptions and technology assumptions, such as those for clean coal or non-fossil technologies, can have a substantial impact on future emissions.

The industrial sector remains an important source of SO_2 emissions in all SSP baselines and climate mitigation scenarios throughout the century. Fossil-fuel use in the industrial sector comprises a wide range of uses, including process heat, internal combustion engines, and process-specific uses such as steel-making over a range of scales, from small plants and boilers to large manufacturing centers. This sector has significant diversity in regulations on pollutant emissions depending on the type of industry. Experience so far has shown that industrial legislation lags behind energy or transportation sector in developed and developing countries. Another factor is that fossil fuels can be difficult to replace in some industrial activities, such as those related to high temperature process heat. Some processes such as steel making require specific fuels like coking coal, which also differ in pollutant intensity as compared to coal. In the SSP baseline cases, SSP2 and SSP3 show a continuously increasing coal use in this sector while it declines in SSP1 and SSP5, especially towards the end of the century resulting in strong reduction of emissions of SO_2 and NO_x. Coal use in small boilers, coke and brick production industry can be significant sources of BC (Bond et al., 2004). In the long term, a transition to more efficient and cleaner technologies

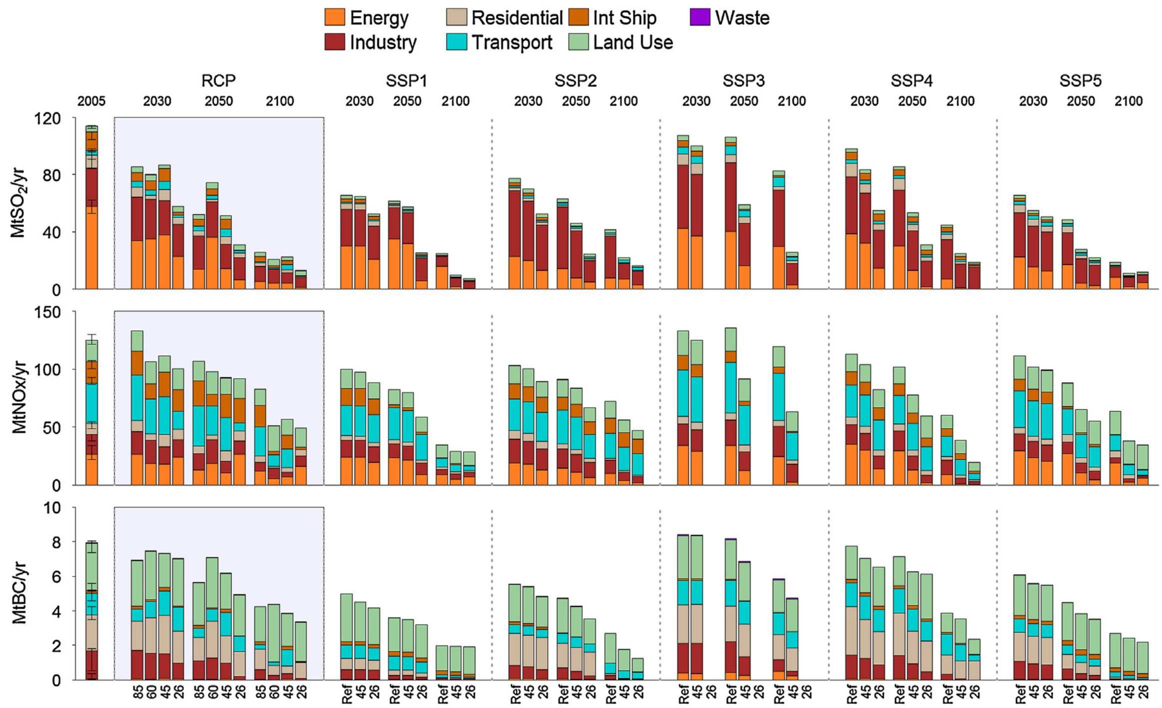

Fig. 4. World, Emissions by sector, Baselines and Climate Mitigation cases. RCP scenarios indicated for reference. Only marker SSP scenarios represented. Values for 2005 are from RCP8.5 while error bars show uncertainty across whole range of SSP and RCP scenarios.

will result in decline in emissions; in the SSP3 scenario this sector has a significant share of BC emissions until mid-century.

The transportation sector is a major source of NO_x and BC emissions through at least mid-century in nearly all SSP scenarios. As discussed earlier, continued use of liquid fuels means that NO_X emissions from the transport sector remain relatively high and only decline in the second half of the century. These differences are broadly reflected at the regional level as well (SI). The end of century decrease in the SSP1 is due to the widespread adoption of hydrogen-fueled vehicles. In the next decades, however, NO_X and BC emissions still remain relatively high even in the SSP1 scenario, mainly due to the large increase in liquid fuel use offsetting the increasing stringency of legislation, particularly in ASIA.

The residential sector is a major source of BC emissions as well as other products of incomplete combustion like organic carbon (OC) and carbon monoxide (CO). Except for SSP1 and SSP5, BC emissions from this sector remain fairly constant until mid-century across all SSPs but then decline substantially in the second half of the century except in the SSP3 and SSP4 scenarios. The latter scenarios assume sustained use of traditional biomass throughout the century. This substantiates recent findings that emissions from the buildings sector are driven more by assumptions about energy access than explicit pollution controls (Rao et al., 2016).

Emissions from international shipping reflect assumptions on the level of implementation of proposed international regulations in the near-term as well as specific assumptions on the changes in fuel use in the baselines and climate mitigation scenarios over the longer-term (see SI for assumptions). The International Convention for the Prevention of Pollution from Ships or Marine Pollution Convention (MARPOL) Annex VI (IMO, 2006) sets limits on sulfur content of fuels and NO_x emissions from ship exhaust. While to some extent there are differences across SSPs in terms of levels of implementation of such protocols, we see that emissions in all the baselines show a downward trend for SO_2 emissions (50–80% decline compared to 2005 in 2030).

The land-use sector (including open biomass burning) is an important source of BC emissions (close to 30% of BC emissions in 2005). The assumptions made by IAMs for this sector vary quite substantially in their level of detail (see SI for details). The development of air pollutant emissions from this sector does not necessarily follow the assumptions driving the air pollution policy in the SSPs but rather, land use practices related to deforestation and savannah burning. In most scenarios emissions from land open burning change only marginally in the mid-term with the long-term tendency to decline, especially in the SSP1.

3.3.2. Climate mitigation scenarios

The emission responses to a carbon policy can generally be linked to changes in fuel consumption or changes in underlying technologies. See SI for primary and final energy details in the SSP scenarios. The intensity of the climate policy target is also an important factor; although more stringent mitigation targets as in the 26 scenario do not necessarily always lead to larger pollutant reductions compared the less stringent 45 case.

The aggregate response of SO_2 emissions to a climate policy is similar in all SSPs. This is due largely to coal combustion being a common source of both SO_2 and CO_2, and a similar relative response to a climate policy in the electricity generation sector. SO_2 emissions fall in all models as coal-fired electricity production either decreases or shifts to carbon capture and storage (CCS) technologies. So for example, SSP4 and SSP2 show increased shares of gas-fired CCS and nuclear power because of the high social acceptance for these options in those storylines. Reductions from a climate policy are larger in the SSP3 and SSP4 scenarios as compared to SSP1. This can partly be explained by the weaker assumptions on pollution control in the SSP3/4. The much stronger transportation BC emission controls in the SSP1/5 scenario and resulting low emission levels, coupled with substantial use of synthetic fuels, mean that, in absolute terms, there is less room for emissions to further decrease as liquid fuel consumption decreases under a climate policy. The larger baseline case emissions in SSP3 result in a potential for a larger relative reduction in the climate policy case. SO_2 emissions from international shipping drop off by the end of the century in the climate mitigation scenarios. This response is mainly due to the effect of high carbon prices in this sector and the move towards alternative fuels like liquefied natural gas (LNG) in this sector.

For NO_x emissions, we see that major reductions occur only mid-century. Before that, relative inertia in the energy system means that liquid fuels remain an important part of the fuel mix in this sector (close to or more than 90%). While pollutant controls in this sector are relatively numerous and stringent in many regions, continued oil use in this sector means that emissions do not decline rapidly even in the SSP1/5 scenarios. NO_x emission controls in the energy sector are usually less effective than SO_2 controls and as a result, we observe that NOx emissions response from this sector is less than that of SO_2 (see SI for summary of assumed controls).

The BC emissions reduction in response to a carbon policy is smaller and we find that for CO_2 emission reductions of up to about 50%, mid-century in the 45 and 26 scenarios, BC emissions are generally only reduced by 10–20%. The scenarios show a substantial reduction in BC emissions from the transportation sector due to reductions in liquid fuel consumption and shift to electricity, hydrogen, electricity, and biomass-based liquids. There is relatively small response in the industrial sector BC emissions to climate policy, due to the limited scope for reductions in this sector, the continued use of liquid fuels, and a requirement for some level of carbonaceous fuels. These differences in response in the industrial sector are due, in part, to different representations of industrial fuel demand in these models. Traditional biomass consumption in the residential sector is only mildly impacted by a climate policy in all of the models, with most of the shifts already occurring in the baselines due to other policies and assumptions on energy access. For example, in the SSP1 scenario with relatively rapid rates of modernization in developing countries and a switch to cleaner or less polluting sources for cooking, climate policy does not bring additional reductions. Although not explored in detail here, we note that it is possible that climate policy may negatively impact emissions from this sector as a result of high carbon prices which may in some cases result in an increase in biomass use for cooking in developing countries in the short-term (see also Rao et al., 2016).

4. Ranges for regional air quality outcomes

In order to gain an initial understanding of the regional air quality outcomes across SSP scenarios, we estimate air quality under the SSP scenarios using TM5-FASST model (Van Dingenen et al., 2009), a reduced-form global air quality source-receptor model (AQ-SRM). This allows us to provide an approximate estimate of air quality outcomes, although as noted below, more detailed analysis, for example in CMIP6, is warranted. This approach of linking emission outcomes from IAMs to a reduced form air quality model and allows us to compute multi-model, multi-scenario air quality outcomes (Rao et al., 2016) (see SI for detailed description of the FASST model and its application to the SSP scenarios). We estimate annual average PM2.5 concentrations (fine particulate matter with diameter less than 2.5 μm) as well as six-month average ozone concentrations (Fig. 5). We further provide a comparison of the fraction of population exposed across the SSP scenarios to WHO levels defined as recommended maximum exposure level or air quality guideline (AQG) (10 $\mu g/m^3$) and two intermediate levels (35 $\mu g/m^3$ and 25 $\mu g/m^3$) (WHO, 2006). For this purpose, we use here as a basis, a median population trajectory (Riahi et al., 2012), which is comparable to the SSP2 and SSP4 population projections in 2050 (see SI for comparison of population across the SSP scenarios). Thus, our results as presented here do not reflect the diversity in regional population growth across the range of SSP narratives and only reflect the differences in assumptions on pollution control and underlying energy and land-use development. Future analysis using SSP-specific spatially explicit population estimates will be useful in enhancing our understanding of in terms of changes within a region due to major shifts in population distribution patterns.

We find that the range of PM2.5 and ozone levels for the different SSP scenarios is consistent with the RCP range (which was estimated using the same model and population basis), but displays a larger variability among the SSP variants. Differences are largest in particular in ASIA, in line with the wider diversity in growth patterns reflected in the pollutant emission trends. In all regions, the full range of model outcomes for the weak pollution control scenarios (SSP3/4) show significantly higher concentrations compared to those with strong pollution control (SSP1/5). We also find that, except for ASIA and the MAF, in all regions, more than 95% of the population is currently under the 25 $\mu g/m^3$ exposure level for all scenarios. By 2050, OECD countries strongly improve under all SSP scenarios, reducing concentrations further with 80 to 95% of the population exposed to levels below 10 $\mu g/m^3$. In the MAF region, mineral dust is responsible for most of the exposure above 25 $\mu g/m^3$, explaining why climate and air pollution policies have little impact on the exposed population. Currently in ASIA, average concentrations are around 25 $\mu g/m^3$, and almost 90% of the population is exposed to levels above 10 $\mu g/m^3$ and 45% to levels above 25 $\mu g/m^3$. However there is a wide variation across different parts of ASIA, with China having an average of 32 $\mu g/m^3$; India with an average of 30 $\mu g/m^3$; other regions have an average PM2.5 concentration below 10 $\mu g/m^3$ and at least 2/3 of the population exposed to 10 $\mu g/m^3$ or below. Because the ASIA mean PM2.5 concentration is near 35 $\mu g/m^3$, a positive or negative trend in PM2.5 by 2050 will be reflected in population exposure to this limit level. Indeed, the strong pollution control scenarios (SSP1 and SSP5) decrease the population fraction in the above 35 $\mu g/m^3$ exposure class to about 15%, whereas the low pollution control variants (SSP3 and SSP4) increase the fraction with 25 and 18% respectively.

By 2050, climate policy leads to substantial co-benefits on pollution levels in ASIA, where PM2.5 levels decrease by 5–11 $\mu g/m^3$ relative to the baseline scenario. For the other regions, the maximal benefit is around 2 $\mu g/m^3$. The highest climate policy co-benefits are observed in scenarios SSP3/SSP4 direct air pollution policies were assumed to be less effective, in particular for ASIA (see also SI).

Ozone precursors are, in general, more difficult to control and ozone levels have a larger impact from remote sources as well as increasing methane concentrations. We find that in the SSP scenarios, regional ozone levels do show clear regional differences by 2050. ASIA as a whole is not able to stabilize ozone at present levels even under strong air pollution policies (SSP1 and SSP5), although also in this case large differences in trends are found between individual countries. India's ozone concentrations are estimated to increase (or stabilize) from 63 ppbv in 2005 to 2050 values of 63, 70, or 80 ppbv for the low, medium and high pollution control variant, respectively, while ozone in China decreases from 56ppbv in 2005 to 48, 50, or 53 ppbv respectively in 2050.

5. Discussion

The SSP scenarios were developed to include narratives on future air pollution control that are consistent with current trends

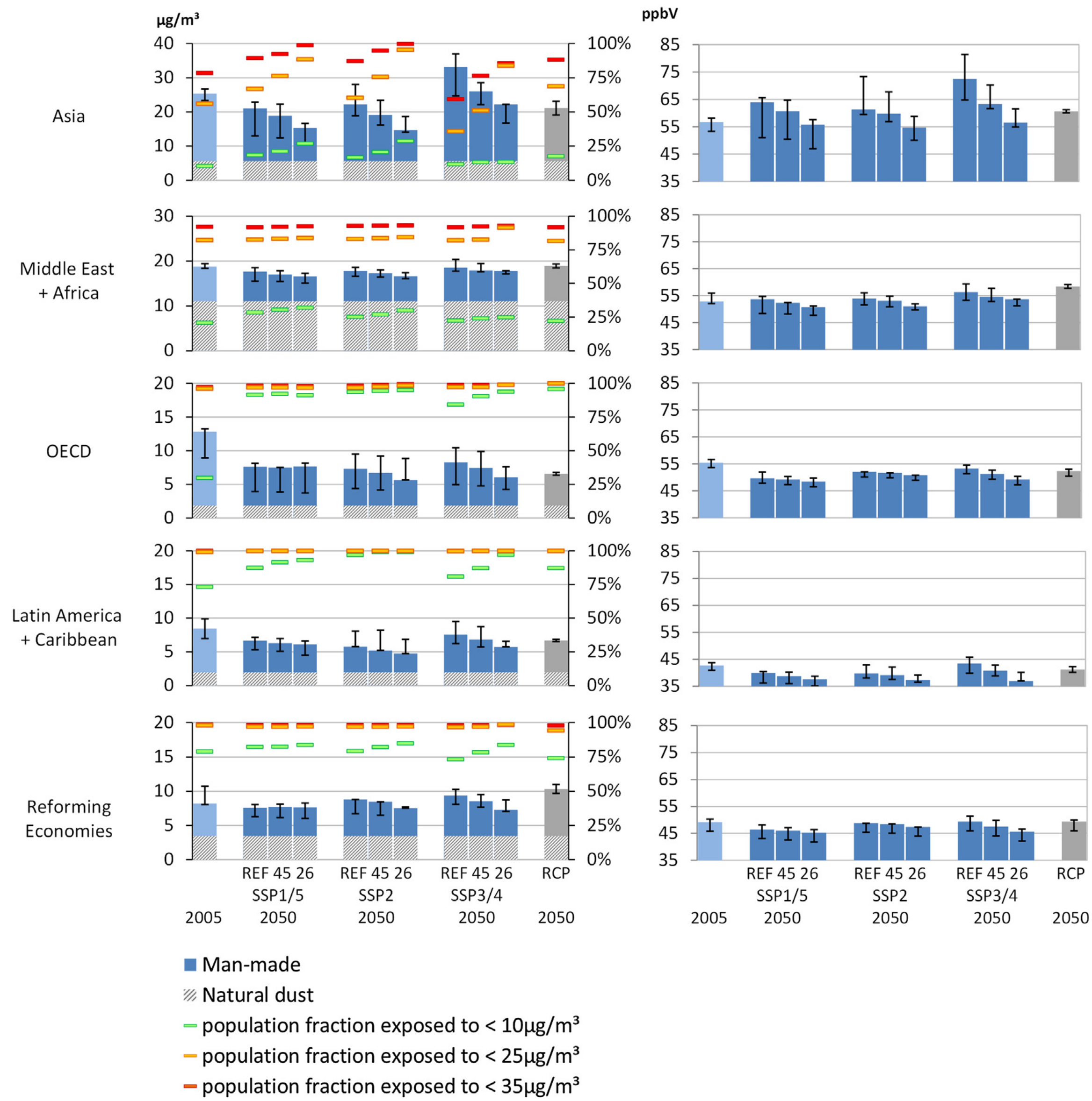

Fig. 5. Left panel: region-population weighted mean PM2.5 in µg/m^3 (left axis) from marker scenario (blue color bars) and average from the 3 RCP scenarios (grey bar), contribution of natural PM2.5 (hatched area) for the year 2005 (leftmost bar) and 2050. Green, orange and red colored markers indicate the fraction of the population exposed to <10, <25 and <35 µg/m^3 respectively (right axis). Right panel: mean ozone concentration (maximal 6-monthly mean of daily maximum ozone). For the grouped scenarios SSP1/5 and SSP3/4 the concentration represents the mean of the respective marker scenarios. Error bars show the concentration range (min/max) of regional averages from all models in the (set of) SSP scenarios shown, including non-marker. For the RCP bars, the error bar indicates the min/max range within the set of 3 RCP2.6, RCP4.5 and RCP8.5 scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in air quality policies; experience in control technology application ; and regional differences in affluence and degree of control.

This new generation of global scenarios results in a much wider range of air pollution emission trajectories than the RCPs. The baseline realizations of SSP3 scenario have global emissions at or above the highest level in the RCPs, while the SSP1 scenario is generally near the lower end or below the RCPs. Pollutant emissions in climate mitigation cases are lower still, with some SSP trajectories below the RCP emission levels. The SSP scenarios, thus, provide a wide range of future emissions, for use in global and regional studies of climate and sustainability.

The SSP1 and SSP5 scenarios, which include assumptions on globally successful implementation of strong pollution controls, bring the most significant reductions in air pollutant emissions; by mid-century emissions decline globally by 30–50% in the baseline scenarios and up to 70% in the climate mitigation scenarios. The SSP2, middle of the road scenario, generally achieves reductions by 2100 similar to SSP5. In the SSP3 scenario,where current pollution control plans are not fully achieved, global pollutant emissions do not substantially decline and even slightly increase in the mid-term. In spite of improving emission intensity in all regions, the improvements in the developing world are too small to offset growth in fossil fuel use and other emission drivers. Even by the end of the century when emission intensities in the highest polluting regions decline to the current OECD levels, global emissions remain high in SSP3, barely below the current levels. Except for the strongest climate policy cases considered, the air pollution control policies in SSP3 still result in relatively higher air pollutant emissions, although there are significant reductions in SO_2 and NO_X. The emission trajectories for the SSP4 marker scenario are similar, although lower than, those in SSP3. By the end of the century, however, SO_2, NO_x, and BC emission levels are comparable to those of SSP2.

Climate mitigation scenarios result in lower pollutant emissions than the corresponding baselines with the magnitudes of reductions depending on the baseline scenario emission levels. In the relatively more sustainable narratives,s, e.g., SSP1 and SSP5, climate policy does not bring large further reductions in air pollution; but in cases of more heterogeneous futures with uneven development and lower baseline pollutant control levels, e.g., SSP3 and SSP4, successful implementation of climate policies result in larger declines in air pollutant emissions. The co-benefits from climate policies accrue heterogeneously across pollutants and sectors with SO_2 and NO_x emissions showing the most reductions, primarily from electricity generation, industry and transportation sectors. BC emissions are primarily reduced from the residential sector, although in some cases, increasing biomass use as a result of high fossil fuel prices could imply an increase in emissions from this sector.

The SSP baseline scenarios, except SSP1 and SSP5, result in either deterioration or only marginal improvement of air quality in much of the low- to middle-income world by 2050. SSP1/5 brings larger improvements but still leaves a relatively large number of people exposed to levels of pollution above WHO recommended levels, especially in Asia. Lower emission levels are achieved in a strategy combining climate mitigation policy with energy access, however some densely populated regions such as South Asia, face pollution challenges in most scenarios. More detailed regional analysis is warranted to explore possible pathways for improved air quality in these regions.

Achieving sustainable low pollution futures will require intensified action on pollution control and will need to be supported by adequate and coordinated institutional capacity. A key to developing a robust response to the challenge of air pollution robust implementation of integrated air quality management systems incorporating strengthening of institutional mechanisms, assessment of air quality (monitoring, emission inventories, source apportionment, air pollution exposure and damage), evaluation of control strategies, and the development of integrated strategies.

We identify a number of applications and future directions for the SSP scenarios:

Firstly, the current set of scenarios represents one set of internally consistent realizations of the SSP storylines. i,Alternative realizations of the pollution narratives with different IAMs could provide a richer basis for analysis in the future. Another important aspect is more sophisticated quantitative approaches to representing the narratives in IAMs, including for example, more direct use of emissions to concentration relationships and impacts, which would allow for endogenous estimation of pollutant concentration levels. We note that similar emission factors do not necessarily translate into similar concentrations across regions, and that there could be a need to adjust control policies to match the local circumstances in each region. This is particularly true as regions get wealthier and have more resources that could be allocated towards controlling pollution levels. Thus while the quantitative approach adopted here is relatively simplistic, as integration methodologies advance, greater consistency can be achieved in future work.

Within the current scenarios, we do not account for large changes in the direction or degree of pollution control. For example as sulfur dioxide emissions decrease, nitrogen species and secondary organic aerosols can become important determinants of particulate concentrations, which might change the focus of pollutant control efforts. Inclusion of such iterative effects could substantially alter the levels of such pollutants. We also note that we exclude in the current set, scenarios of absolute failure in planned pollution control, although historical evidence indicates that this could occur in times of economic or political instability. Inclusion of such scenarios in the future could be useful to isolate the impacts of pollution control policies. Further, the current set of SSP scenarios does not include a direct representation of pollutant control costs. although a few studies have also now begun to incorporate pollutant emission control costs into integrated assessment models (Wang et al., 2016). Ultimately, more advanced representations of pollution control costs, and technological changes over time would allow much greater consistency in long-term pollutant emission scenarios and improve their real-world applicability.

Secondly, while the SSP scenarios could be used as boundary conditions for regional studies on air pollution; downscaling and spatial interpretations of the scenarios will be vital to develop climate model projections as well as for detailed health and ecosystem analysis. This paper explores some initial projections on air quality but a detailed air quality assessment would require the use of a full chemical transport model which would significantly enhance the quality of assumptions in the current set of scenarios. This work is planned in subsequent phases of the scenario development. One next step for the SSP scenarios will be downscaling for use in global modeling studies, such as the Coupled Model Intercomparison Project phase 6 (CMIP6), which will include projections made by coupled chemistry-climate models. Current plans are to first downscale from native IAM resolution to the country level and then to a spatial grid, similar to previous efforts with global scenarios including the IPCC SRES and RCP scenarios (van Vuuren et al., 2007; Riahi et al., 2011). Data on air pollutant emissions will be made available in different source categories and in a geographically explicit manner. This could be particularly useful in terms of additional regional analyses, including a closer look at health and ecosystem implications.

To conclude, the SSP scenarios represent a new generation of scenarios that explicitly allow for inclusion of sustainability objectives including air pollution and assess their interactions with climate policy. In this paper, we have broadly examined some key trends and results. Future efforts can be expected to significantly enhance this endeavor.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.05.012.

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