Paris Agreement’s Ambiguity About Aerosols Drives Uncertain Health and Climate Outcomes

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Abstract Anthropogenic aerosols are hazardous to human health but have helped offset warming from greenhouse gases (GHGs), creating a potential regulatory tradeoff. As countries implement their GHG reduction targets under the Paris climate agreement, the co-emissions of aerosols and their precursors will also change. Since these co-emissions vary by country and by economic sector, each country will face different tradeoffs between aerosol-driven health or temperature co-benefits. We combine simple parameterizations of physical processes and health outcomes to examine three idealized climate policy approaches that are consistent with the Paris Agreement targets, which (i) optimize for local air quality, (ii) reduce global temperature change, or (iii) reduce emissions equally from all domestic economic sectors. We evaluate aerosol impacts on premature mortality and global mean temperature change under these three policy approaches and find that by 2030 the three policies yield differences of over 1 million annual premature deaths and global temperature differences of the same magnitude as those from GHG reductions. We also show that implementing equal reductions between all economic sectors can actually result in less beneficial health and temperature outcomes than either of the other options, especially in less industrialized regions. We therefore conclude that aerosol-related co-benefits and aerosol accounting guidelines should be explicitly considered in setting international climate policy.

Plain Language Summary We develop a new analytical approach to climate decision-making that centers the implications of anthropogenic aerosol particulate emissions on climate and human health. Aerosol emissions occur in tandem with greenhouse gases (GHGs) and vary by type of economic activity, so concurrent changes to aerosols from GHG reduction depend on what activities are reduced. We show that, by 2030, the different policy priorities can differ by more than a million premature deaths annually and could cause a similar amount of cooling as from the reduced GHGs, indicating that there are substantial tradeoffs between global climate and local air quality objectives. We conclude that deliberate consideration of particle emissions as part of climate policy could provide additional benefits, especially in less industrialized regions.

1. Introduction

The Paris Agreement, a major international effort to limit global warming to 1.5 °C–2 °C, requires every participating country to submit a Nationally Determined Contribution (NDC), in which each country outlines the steps they believe are required to achieve the joint goal. The NDCs are non-binding, flexible, and vary substantially between different countries. NDCs differ in several important dimensions, including which greenhouse gases (GHGs) are considered, which economic sectors are expected to reduce emissions, which year’s emissions serve as the baseline, whether absolute emissions or emission intensity (i.e., emissions per gross domestic product [GDP] or population) will be reduced, or whether reductions are considered in absolutes or relative to a business as usual scenario. Many NDCs emphasize the importance of addressing climate change but do not state any concrete or quantifiable emissions reductions. The NDCs are largely unstructured text documents, and their phrasing is often ambiguous. This can leave substantial flexibility in their implementation (Denison et al., 2019). For example, several different emissions pathways (e.g., reductions in different sectors) could lead to the same stated outcome, or conversely, the same stated goal might correspond to very different changes in emissions, depending on the accounting details and assumptions (Seneviratne et al., 2018).
One confounding factor not addressed by the NDCs is the influence of atmospheric particulate matter (aerosols). Both anthropogenic emissions of "GHGs" and aerosols alter Earth's climate, but most countries only consider GHGs in their NDCs. However, GHG emissions are closely tied to aerosol emissions since many human activities simultaneously produce both (Rao et al., 2013; S. J. Smith & Mizrahi, 2013; Unger et al., 2010). As countries implement their GHG reduction commitments, aerosol emissions will also change (Fiore et al., 2015).

Joint consideration of GHGs and aerosols is critical because, while GHG emissions might be thought of as unambiguously harmful, from a climate change perspective, the influence of aerosols is complex and uncertain (Allen et al., 2020). Aerosols typically only have a lifetime of 5–10 days, but their impacts are pervasive due to their continuous emission. They can directly absorb and scatter radiation (direct effect), influence the formation and evolution of clouds as cloud condensation nuclei (indirect effects), alter vertical temperature profiles and thereby cloud dynamics (semi-direct effects), and modify surface albedo (e.g., darken snow). These effects can all change radiative transfer and thereby change radiative forcing, which is the net change in the energy balance of the Earth system due to some imposed perturbation (Myhre et al., 2013b). The impact on the energy budget depends on the aerosol chemical composition and size distribution, which vary in space and time (Fiore et al., 2012). In contrast to aerosols, the radiative forcing of greenhouse gases is substantially more spatially and temporally uniform due to longer lifetimes and simpler chemical properties. Radiative forcing leads to temperature changes, and in aggregate, anthropogenic aerosols have offset a third of warming from anthropogenic GHG emissions (Samset, 2018), though the aerosol impacts are much more uncertain than the GHG impacts (Bellouin et al., 2020). Despite net global cooling, some aerosols like black carbon have a net warming effect globally while others, like sulfates, cause cooling (Boucher et al., 2013; Stjern et al., 2016). The climate impacts of aerosols can have profound global implications (Zheng et al., 2020). However, in the context of policy, aerosols have historically been regulated in response to their impact on local air quality, rather than climate impacts, because air pollution has a host of negative health consequences that can lead to premature mortality (Burnett et al., 2018; Di et al., 2017; Heft-Neal et al., 2018).

Air quality improvements have short-term, local benefits, which can incentivize regulation (Bollen et al., 2009). Climate change mitigation on the other hand, is normally considered a short-term cost with long-term, global benefits, which lowers the incentive for domestic regulations. Including aerosols in economic analyses of climate regulation has been shown to make emissions reduction financially favorable in the short-term as well as the long-term (Scovronick et al., 2019). Aerosol regulation has historically come in the form of air quality regulations, but the cooling role of aerosols has led to concern that such regulation could amplify planetary warming (Chalmers et al., 2012). Meanwhile, others have argued that targeted reduction of warming aerosols could be leveraged for an additional cooling effect that would aid efforts to limit warming (Andreae & Ramanathan, 2013; Leelievd et al., 2019), though simultaneous changes to the emission of other species counter the intended cooling (Wang et al., 2015). Regardless of the sign of the effect, the use of climate-impact metrics that incorporate near-term climate forcers (NTCFs, which include gases and particles with short lifetimes that cause radiative forcing) can better predict climate outcomes, especially for ambitious emissions reduction pathways like those proposed in the Paris Agreement (Allen et al., 2018).

Here, we quantify aerosol-induced premature mortality and temperature effects in 2030 under different implementation strategies for meeting the targets associated with the Paris Agreement. We consider black carbon (BC), organic carbon (OC), sulfur dioxide (SO₂), and nitrogen oxides (NOₓ) using global gridded anthropogenic emissions data that specifies emissions by economic sector. OC, SO₂, and NOₓ are associated with negative radiative forcing (surface cooling) impacts, while BC is associated with positive radiative forcing, though all four lead to negative health outcomes. We simulate multiple operationalizations of the NDCs for each country using idealized physical assumptions and decision priorities that demonstrate the consequences of countries' ambiguous aerosol co-emissions in implementing their NDC target GHG reductions.
2. Methods

We examine outcomes under three country-level decision-making priorities: (1) minimization of global temperature change (climate priority), (2) minimizing local air pollution (air quality [AQ] priority), and (3) political expediency in the form of proportional cross-sectoral reductions, that is, no aerosol-specific policy (equal-by-sector). The underlying emissions rely on the no-climate-policy baseline shared socioeconomic pathway (no-policy SSP; Grant et al., 2020; Riahi et al., 2017). SSP3 is a nationalist, low-growth scenario with costly mitigation whose baseline corresponds to the Representative Concentration Pathway 7.0 (RCP7.0) (Fujimori et al., 2017); SSP5 is a scenario with high fossil fuel development whose baseline corresponds to RCP8.5 (Kriegler et al., 2017).

Some NDCs specify which greenhouse gases are covered by the agreement, while others do not. Unless otherwise specified, we assume that all targets refer to carbon dioxide equivalent (CO$_2$e), where CO$_2$e is emission rate of carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O) scaled by the global warming potential (GWP; CO$_2$: 1, CH$_4$: 28, N$_2$O: 265) (Myhre et al., 2013b). We limit the analysis to only CO$_2$ for countries that specify that targets are only for CO$_2$ (e.g., China). We define the notation, CO$_2$e, to refer to CO$_2$e or CO$_2$ emissions as specified by each country’s NDC. We do not consider additional gases (e.g., chlorofluorocarbons [CFCs], sulfur hexafluoride [SF$_6$]), even if they are specified, due to data availability; errors from omission are likely small since CO$_2$, CH$_4$, and N$_2$O constitute the vast majority of CO$_2$e emissions. We also consider four NTCFs: BC, OC, SO$_2$ (as the main precursor for sulfate aerosols), and NO$_x$ (as the main precursor for nitrate aerosols). All emissions are divided into eight economic sectors: agriculture, energy, industry, transportation, residential/commercial, solvents, waste, and shipping.

2.1. Idealized Decision-Making

To minimize temperature change or air pollution, we identify each sector’s impact per CO$_2$e emission and sequentially reduce the most sectorally impactful emissions of CO$_2$e and NTCF co-emissions. These represent the extreme, unconstrained cases and therefore represent bounding cases under the assumption that countries meet their Paris Agreement goals.

In the case of no aerosol-specific policy (equal-by-sector), we alter each sector’s anthropogenic emissions equally to meet the GHG target. For example, a 20% reduction in GHGs between 2020 and 2030 would yield linearly decreasing emissions of all GHGs and NTCFs for each sector, and therefore also of the total. We include the equal-by-sector implementation because it could be seen as the simplest implementation, wherein every economic sector within a country is expected to contribute equally toward the common goal. We view this as a politically expedient implementation because all greenhouse gas emitting sectors would bear proportional burdens in meeting domestic emissions commitments. All the priorities assume that the country-level relationship between GHGs and each NTCF remains constant (at 2020 values) between 2020 and 2030, though this relationship changes in the unmodified SSP scenarios - particularly on longer time scales - because of technological developments.

For the climate priority and AQ priority, we calculate the aerosol impact per CO$_2$e emissions for each sector in each country (see Sections 2.4 and 2.5). These metrics allow us to identify the most impactful sectors to change. For the climate priority, we calculate global aerosol forcing per CO$_2$e and for the AQ priority we calculate population-weighted aerosol concentration per CO$_2$e. All emissions reductions are then made from the most impactful sector. If that sector has fewer CO$_2$e emissions than are required to meet the NDC target, that sector’s emissions are reduced to zero and the remainder is taken from the next most impactful sector, and so on. The operationalization of the three decision making priorities is illustrated in Figure 1. A few countries specify sectors in their NDC; in those cases, we limit the analysis to those sectors (see Section 2.2 for further discussion).

We assume that the country-level relationship between NTCFs and CO$_2$e emissions remains constant at the 2020 ratio for each sector. In some countries, emissions are anticipated to increase between 2020 and 2030 despite emissions reductions targets, because targets are relative to a business as usual (BAU) scenario (i.e., a country says they will emit a certain percent less than they would have in 2030 without climate policies). In those cases, emissions are added to the least damaging sector, but are not allowed to exceed...
the 2030 no-policy SSP sectoral emissions. For countries with no stated reduction targets, we use unaltered 2030 SSP emissions. This methodology results in bounding, idealized cases, not a realistic representation of future changes. The temporal evolution of global emissions for each priority and each species are shown in Figure S1.

2.2. NDC Quantification

We implement existing NDC tabulations with a few notable exceptions. Our estimates were based on the CD-LINKS protocol (CD-LINKS, 2018), which is very similar to the table provided by Vandyck et al. (2016). The NDC tabulation used for this study is publicly available (see Data Availability); all deviations from CD-LINKS are noted. For countries that specify emission reduction targets, these tables provide a baseline year and a percent reduction of emissions from that baseline by a target year. The target year is normally 2030. When target years are after 2030, we linearly interpolate to 2030 between the base year and target year. When target years are before 2030, we assume the country will take until 2030 to actually achieve their goal. Despite the current uncertain status of the United States (US) in the Paris Agreement, we implemented US targets from CD-LINKS as we did for other countries. Many countries provide conditional and unconditional targets, where the condition refers to foreign aid. When multiple options exist, we implement the most ambitious targets.

For NDC targets that are stated in CO$_2$[e] intensities (i.e., emissions per GDP or per capita), we use the country-level population and GDP projections provided on the SSP database (https://bit.ly/33nNwL7). When the use of GDP is required, the country’s SSP GDP time series is harmonized with historical World Bank (WB) GDP data by scaling SSP GDP projections by the ratio of 2018 WB GDP to linearly interpolated 2018 SSP GDP. WB GDP is converted to 2005 international dollars for consistency with the SSP GDP using the WB GDP deflator.

India and China both have intensity targets based on GDP. Based on our calculations, India is expected to meet its 2030 targets, even without climate policy implementation (Figure S2), which is consistent with
previous NDC quantification (Vandyck et al., 2016). We therefore use the unmodified, no-policy SSP emissions projections for India. For SSP5, China also exceeds its targets without additional policy. However, China also states that it will peak emissions by 2030, which is a more ambitious target. Therefore, we implement a smooth transition (linear derivative) from 2020 to 2030 so that the change of annual emissions is zero by 2030. For SSP3, China does not automatically meet the intensity target, so we implement the target as we would for other countries (Figure S2). Several countries specify economic sectors for their planned emissions reduction. We only reduce emissions from those economic sectors. Though it initially seems like an added level of specificity to include sectors specified in an NDC, it can actually introduce ambiguity. In our interpretation, some countries plan to reduce their total emissions from a subset of economic sectors, whereas some plan to reduce a percentage of the emissions from those sectors. The global impact of this difference is small, but this distinction does not appear to be included in CD-LINKS. Upon review we also identified a few sectors specified in NDCs that were not included in the CD-LINKS tabulation, which we have added and noted in the supplement.

For all countries that do not have explicit climate reduction goals, GHG and NTCF emissions are assumed to follow a no-policy scenario (SSP3 or SSP5); this applies to all three priorities and the unmodified case. For countries who state that their CO$_2$ e reductions will be relative to BAU rather than relative to a baseline year, we assume that the no-policy SSP represents BAU and we apply GHG reductions from 2030 SSP emissions (i.e., 2030 is both the baseline year and the target year).

After we calculate the intended 2030 CO$_2$ e emissions for each country (which are based entirely on the NDCs and are therefore the same for all three priorities), we assume that each country has followed the SSP until 2020 and will implement their Paris Agreement commitments between 2020 and 2030. For countries with BAU-based targets, this can result in an increase in CO$_2$ e emissions between 2020 and 2030, rather than a reduction, but emissions will still be lower in 2030 than they would have been in the unmodified no-policy SSP. In all cases, once the total CO$_2$ e emission changes have been calculated, those changes are implemented through modifications to specific sectors as described in Section 2.1.

2.3. Input Data

Historical (pre-2015) mean annual global gridded anthropogenic emissions of GHGs and NTCFs were primarily taken from the Community Emissions Data System (CEDS, Hoesly et al., 2018), available on the input4mips database. The only exception is N$_2$O, which was taken from the EDGAR emissions database (Janssens-Maenhout et al., 2012) since gridded CEDS N$_2$O emissions are not available. The EDGAR data set has more detailed sectors than the CEDS data set; the mapping used to aggregate EDGAR sectors to CEDS sectors is given in Table S1. These data do not include biomass burning, aircraft, or land use change emissions. The 0.5 $\times$ 0.5° gridded products were aggregated by country using population weighting at border grid cells. This aggregation excludes shipping emissions except those that occur within country borders, which are attributed to the country in which they occur. Population data were from NASA’s Socioeconomic Data and Applications Center (SEDAC) database and have 0.125° spatial resolution (CIESIN, 2005). All calculations are conducted on aggregated data, though we do produce an altered gridded product for the three priorities. Converting aggregated modifications to a grid can result in errors at the border grid cells. These errors are small for large countries and insignificant globally but can be substantial for small countries.

Future projections of emissions under the SSPs were also taken from the input4mips database (Feng et al., 2020; Gidden et al., 2019). Again, gridded N$_2$O emissions are not available. Therefore, we use global (non-gridded) N$_2$O projections from the SSP database and assume that each grid cell’s fraction of global N$_2$O emissions remains constant from the most recent EDGAR historical emissions (Janssens-Maenhout et al., 2012), and scale the most recent emissions accordingly into the future.

We included all economic sectors in the data set: agriculture, energy, industry, transportation, residential/commercial, solvents, waste, and shipping. The solvent sector has zero BC, OC, SO$_2$, and NO$_x$ emissions, so it has neither aerosol forcing nor health impacts. However, it does have associated GHG emissions. When maximizing health benefits, the solvent sector is therefore somewhat trivial and will only be targeted after all other options are depleted, since there is no air quality benefit from reducing zero aerosol emissions.
However, when minimizing temperature change, zero aerosol forcing is nontrivial since forcing can be positive or negative.

### 2.4. Calculating Temperature Change From Emissions

We convert country-level anthropogenic NCTF emissions to radiative forcing (W m$^{-2}$) using the same aerosol forcing coefficients as Scovronick et al. (2019), who provide a table for converting emission to global radiative forcing for SO$_2$, BC, and OC. These coefficients incorporate both the direct and indirect aerosol effects. Strong dependence of aerosol on emission location has recently been demonstrated in coupled earth system models (Persad & Caldeira, 2018). This variation is partially accounted for in the table via separate conversions for 12 global regions, though the variation in the table used here is significantly smaller than is shown in Persad and Caldeira (2018). For NOx emissions, we use the conversion rate used in the Finite Amplitude Impulse Response (FaIR) model (Millar et al., 2017; Smith et al., 2018). This coefficient does not account for any spatial heterogeneity and only parameterizes the direct effect (Myhre et al., 2013a). After converting emissions to radiative forcing, we convert radiative forcing to global mean surface temperature change using FaIR. As described in the FaIR documentation, we generate an ensemble of 100 combinations of climate parameters and proceed with only those that are constrained by the historical temperature observations provided in FaIR. Using those parameters, we simulate temperature with the RCP8.5 scenario for SSP5 and RCP6.0 for SSP3, but we modified CO$_2$, CH$_4$, and N$_2$O to match our calculated 2000–2030 emissions and add our NTCF forcing calculations as an external aerosol forcing (in lieu of NTCF emissions). We do this for the unmodified case and the three policy priorities. We align simulations with most recent observations (2016). We also conduct the same set simulations again with the NTCF forcing from the unmodified SSP and the GHG emissions from the different priorities; this demonstrates the influence of the GHGs alone (which by definition is nearly identical for the three priorities). This means that there are a total of seven FaIR simulations for each SSP: one with GHG emissions and NTCF forcing from the unmodified SSP, three with GHG emissions from the three priorities and NTCF forcing from the unmodified SSP, and three with GHG emissions and NTCF forcing from the three priorities.

### 2.5. Calculating Mortality From Emissions

We estimate a country-level conversion of emissions to aerosol concentrations using annual mean, historical (2000–2014) CMIP6 GISS-E2.1 output with one-moment aerosols as available on the MIP database (Kelley et al., 2020; Miller et al., 2020). This model was selected because it has all the desired variables. We use a linear regression between grid-level total emissions and surface-level (i.e., lowest vertical grid cell) concentrations for each country and the resulting slope defines the change in concentration to a change in emission. Our regressions for SO$_2$, OC, BC, and NOx emissions are with surface-level sulfate (SO$_4$), organic aerosol (OA), BC, and nitrate (NO$_3$) respectively. Applying the slope to annual average emissions therefore yields annual average surface concentrations. The coefficients for countries with poor fits ($r^2 < 0.3$) or negative slopes are replaced by the coefficients that result from using all land grid cells; this occurs for several small countries and countries with low emissions, causing the relationship to be poorly defined (regression coefficients available—see Data Availability Statement). We also assume that these aerosol species are not coarse mode and therefore that their mass directly corresponds to the concentration of particulate matter with diameter under 2.5 μm (PM2.5), a metric which is often used to calculate aerosol-induced health impacts.

Concentrations are converted to premature mortality using a relationship between exposure and the hazard ratio to obtain the attribution function (AF) as explained by Burnett et al. (2018). We calculate the slope of the AF at the country’s background PM2.5 concentration as determined by model output surface PM2.5. This slope describes the change in the AF with a change in the PM2.5 concentration. Uncertainties are calculated using the slope of the upper and lower bounds of the 95% confidence interval. The premature mortality is then calculated as the product of this slope with the crude death rate of that country, the total population of that country, and the population-weighted mean PM2.5 concentration from the four considered constituents. This methodology includes only the anthropogenic contribution to mortality from the four considered constituents, though it accounts for increased background from other sources. Under these simplifications, we consider the nonlinearity of the health impacts of PM2.5 but do not account for some
factors that an epidemiological study would incorporate, such as population age distribution and seasonal PM2.5 variation.

3. Results

3.1. Sectoral Heterogeneity of Aerosol Impacts

As a reference case and as a backbone for the modified cases, we use unmodified no-policy SSPs. We first look at the sectoral and spatial breakdown of aerosol impacts under these unmodified SSPs. Aerosol radiative forcing can be positive or negative. Therefore, from a global temperature perspective, aerosols can enhance or mask the warming caused by GHGs. Conversely, non-zero aerosol concentrations in populated areas will always produce undesirable health outcomes.

There is substantial variation between sectors and countries of these aerosol climate and health impacts, which illustrates that different countries may require different approaches even if pursuing identical policy objectives for climate or health optimization (SSP3: Figure S3; SSP5: Figure S4). We find that residential/commercial emissions are often associated with positive radiative forcing, especially in less wealthy countries. Industry and energy sectors are consistently associated with negative radiative forcing. These two sectors also often comprise a disproportionately large fraction of GHG emissions, especially in wealthy countries. Per GHG emission, industry, residential/commercial, and sometimes waste emissions have the largest impact on aerosol exposure since their emissions tend to coincide with high population density. The solvent sector has no aerosol impact because there are no BC, OC, SO₂, or NOₓ emissions associated with that sector in the data set.

3.2. Spatial Variability of Aerosol Impacts

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Each country’s contribution to global radiative forcing from anthropogenic NTCFs and each country’s population-weighted surface aerosol concentrations from anthropogenic NTCFs are shown in Figure 2, averaged over 2030 under SSP3. They are shown once without normalization with a linear colorbar (a and b) and once normalized by greenhouse gas emissions with a quadratic colorbar (c and d).

We find negative aerosol forcing associated with most countries’ 2030 emissions, with the exception of many in Africa (Figure 2a). (Figure S4 shows the analogous figure for SSP5.) India has the greatest forcing
impact (−177 mWm⁻²), followed by China (−146 mWm⁻²), Russia (−53 mWm⁻²), and the United States (−33 mWm⁻²). In China, the negative forcing from SO₂ emissions slightly outweighs positive forcing from BC, with relatively small additional negative contributions from NOₓ and OC. Over half of the SO₂ emissions in China are from the industry sector and almost a quarter are from the energy sector. China’s BC emissions are approximately one third from energy and one third from residential and commercial sources. In India, the contribution from SO₂ dominates the forcing since two thirds of the positive BC forcing is already canceled out by the smaller negative forcing from NOₓ and OC. Two thirds of India’s SO₂ emissions are from the energy sector and a quarter are from the industry sector. The global PM2.5 burden is also dominated by India and China (Figure 2b). The largest contributor is NOₓ; in China the largest NOₓ sources are the industry and energy sectors, and in India the largest NOₓ sources are the transportation and energy sectors.

The normalized maps (Figures 2c and 2d) demonstrate the geographic distribution of aerosol impacts relative to each country’s GHG emissions. Highly industrialized countries with large GHG emissions, such as China and the USA therefore have a smaller aerosol impact than many less industrialized countries. Figure 2c demonstrates the difference in forcing for Africa compared to much of the rest of the world. For many African countries, BC emissions outweigh the other NTCFs, causing a net positive forcing, which is large relative to those countries’ CO₂[e] emissions. A large majority of the BC emissions in those African countries are from the residential and commercial sector. Although the pattern is less pronounced, we draw a similar conclusion from the normalized concentration; less industrialized economies tend to have more aerosol pollution per GHG emission. This representation is less relevant to global decision-making but gives insight into the potential air pollution impacts of changing country-level GHG emissions. The patterns from SSP5 are consistent with those from SSP3 (Figure S5).

3.3. Global Consequences of Ambiguity About Aerosols

When we implement our three decision priorities for emissions reductions under the Paris Agreement, we demonstrate the range of possible outcomes associated with aerosol ambiguity in the NDCs. These priorities each entail the same CO₂[e] reductions from the Paris Agreement, but prioritize reductions from different sectors, resulting in three different combinations of aerosol emissions for each country.

The net global impact of the three decision priorities is summarized in Figure 3. In 2030, we estimate global mean surface temperature increase from preindustrial to be about 1.19 °C for SSP3 (Figure 3a, gray) and 1.25 °C for SSP5 (Figure 3b, gray). The temperature change from GHGs alone are nearly identical under the three priorities (Figures 3a and 3b, dashed lines) because they are all implementations of the Paris Agreement CO₂[e] targets with no modifications to the aerosol emissions. Minor differences are due to some countries (notably China) specifying only CO₂ reductions, not other GHGs, resulting in minor ambiguity even before aerosols are considered. Despite both being implementations of the Paris Agreement, the resulting temperature change from GHGs differs between the SSPs (Figure 3a vs. Figure 3b, dashed lines), because some countries do not have reduction targets (and therefore follow the no-policy SSP) and some countries benchmark their reduction against “business as usual,” which we take to be the no-policy SSP.

Especially for the global temperature time series, the uncertainty bounds overlap between all priorities. This uncertainty reflects the scientific uncertainty of the climate system response to a change in radiative forcing. These uncertainties are therefore correlated, and we would expect differences between priorities despite the wide range of possible absolute temperature differences from preindustrial. The uncertainty range for premature mortality comes reflects only statistical uncertainty in the dose-response curves derived in epidemiological studies and therefore does not account for emissions uncertainties, model uncertainties, or parameterization errors. Therefore, the presented uncertainty range for premature mortality is also not random.

When countries optimize for their own air quality (purple, solid), global temperature is higher than it is under other priorities, though for both SSPs it is nearly identical to the outcome from the equal-by-sector priority. By definition, the climate priority has the lowest temperature in 2030 for both SSPs, and the magnitude of the difference is fairly large: −0.02 °C (SSP3, red dashed vs. solid) and −0.05 °C (SSP5, red dashed vs. solid). For comparison, the CO₂[e] reductions cause about −0.05 °C (SSP3, blue dashed vs. gray) and −0.04 °C (SSP5, blue dashed vs. gray). Therefore, the temperature change associated with the range
of potential aerosol emissions under the Paris Agreement may be as large as the temperature reduction from its associated greenhouse gas reductions. Lund et al. (2020) estimate changes to short-lived pollutants would cause $-0.03 \degree C$, which is somewhat lower than our estimates. This is unsurprising considering that the bounding priorities explored here are only constrained by CO$_2$ emissions, not by other economic and political factors.

Estimated global aerosol-induced premature deaths are shown in Figures 3c and 3d. In 2015, we calculate about 6.8 million premature deaths (SSP3 and SSP5), which is of a similar magnitude, but slightly slower than the 8.9 million calculated by Burnett et al. (2018), likely in part because our estimate does not include all sources of PM2.5. The AQ priority has the lowest mortality by definition and there are substantial differences between the three priorities. For both SSPs, the equal-by-sector priority results in more premature deaths from air pollution than either of the other priorities. The difference between equal-by-sector and AQ priority are 1.3 million (SSP3) and 0.9 million (SSP5) premature deaths in 2030. For SSP3 the equal-by-sector priority is less desirable from a global standpoint than the climate priority, since it contains neither the temperature nor the health benefits of aerosols. This result suggests that a politically expedient approach of reducing emissions from all economic sectors equally may come at a substantial cost to health and climate outcomes.

3.4. Tradeoffs Between Air Quality and Cooling

To better evaluate potential tradeoffs between air-quality-optimized and climate-optimized NDC implementations, we explored regional differences in outcomes for our three policy priorities. Figure 4a shows the tradeoffs between premature mortality from aerosol pollution and global temperature increase ($\Delta T$) as policy priorities shift (SSP5: Figure S5). (To obtain an approximate estimate of the regional contribution to global $\Delta T$, we assume linearity and scale the global $\Delta T$ with the country-level aerosol forcing.) The tradeoffs
between health and climate tend to be smaller in regions of the world with more existing pollution control like Oceania, North America, and Europe (Figure 4b; SSP5: Figure S6b).

The attractiveness of the equal-by-sector priority in terms of climate and health outcomes varies considerably by region. In some regions, such as Europe, North America and Asia (excluding China), it improves upon air quality outcomes relative to the climate priority, and it improves upon temperature outcomes relative to the AQ priority. Under these circumstances, whether such an option is attractive will depend on the perceived political or other benefits of a sectorally equitable climate policy approach. However, for some regions (i.e., Africa, Middle East, China), an equal-by-sector priority results in both climate and air quality outcomes that are inferior to those in one or both of the other prioritizations (a dominated option). In these regions, avoiding a climate policy approach which simply mandates equal cuts across all sectors would have clear health and climate benefits. In other words, a lack of a deliberate consideration of aerosol consequences in climate policy would be more consequential for African, South American, and Middle Eastern countries.

4. Discussion and Conclusion

Having made GHG emissions reductions commitments under the Paris Agreement, countries are now faced with numerous pathways to meet self-imposed targets. We estimate outcomes associated with three imagined policy priorities that are all consistent with the NDCs. Incorporating co-emissions into an NDC assessment framework introduces the possibility of both co-benefits and negative side effects in meeting the temperature targets specified in the Paris Agreement. On short time scales, the global temperature ambiguity from the aerosol co-emissions is of a similar magnitude to the temperature changes from GHG emissions reductions commitments. Metrics like GWP*, which uses cumulative CO$_2$ emissions and current emissions of short-lived pollutants to quantify temperature impacts, could be a practical way to include the temperature impact of non-GHG emissions in NDCs (Allen et al., 2016, 2018), but may obscure substantial tradeoffs between additional marginal decreases in temperature and reductions in health impacts.
While previous work has highlighted opportunities for co-benefits in decarbonization (Harmsen et al., 2020; Li et al., 2018; Scovronick et al., 2019), our analysis does indicate some considerable tradeoffs between temperature and health outcomes will need to be contended with in meeting near-term emissions reductions goals. For some regions, it is unclear which of the presented priorities are preferable. Finding an acceptable solution would require value judgments about the relative benefits of local avoided PM2.5 mortality, global temperature change and political expediency. However, the tradeoff varies by several orders of magnitude (Figure 4b), so it would be surprising if all countries had the same priorities for weighing temperature versus health when making aerosol policy decisions. A simple policy of requiring equal emissions reductions from all economic sectors is in some cases not a compromise between the two criteria, but rather could lead to an objectively less beneficial outcome than a more targeted prioritization of either health or temperature co-benefits. We believe that this is a strong case for explicitly considering aerosols when constructing climate policy.

The presented methodology requires many simplifications of the complexities of aerosols. We use simple parameterizations of aerosol chemistry, physics, and transport, in addition to simple relationships between exposure and premature mortality. We also examine extreme policy priorities that are only constrained by the Paris Agreement NDCs and not other economic and technological factors. Importantly, our analysis does not include any cost optimization—a dominant consideration in many climate policy discussions.

We consider four NTCFs (BC, OC, SO\(_2\), NO\(_x\)); other NTCFs like ozone were not considered in our analysis, and ozone presents its own set of complexities (Unger et al., 2020). We also do not consider the impacts of changes to pollution transport between countries or altered dynamics that can arise from local differences in radiative forcing if countries pursue different policies (Liu et al., 2019; Luo et al., 2020). Assuming a continued global trend of reductions in NTCFs, the impact of aerosols would diminish in longer term projections due to air quality regulation and technology changes (Harmsen et al., 2019; Hienola et al., 2018). Projections tend to agree that NTCFs will decline over time, but here are many uncertain factors that will determine their future emissions pathways, even in the absence of climate policy.

Other sources of uncertainty that are not considered as part of this analysis include, but are not limited to, uncertainty in the magnitude of aerosol forcing and uncertainty in emissions inventories. Multiple estimates of radiative forcing per emission exist (Table S2), and the choice of these estimates does have some impact on our analysis (Figures S7 and S8). Choice of forcings alters the temperature change estimates provided here, but not the fundamental character of tradeoffs. For all the above reasons, we do not interpret the absolute magnitude of our results as a precise estimate of future aerosol impacts of the NDCs. Instead, we believe that this study better demonstrates relative impacts and the importance of policy priorities and tradeoffs for co-emissions in international climate policy.

We illustrate the range of global temperature and mortality impacts associated with anthropogenic aerosol changes that result from countries meeting their Paris Agreement greenhouse gas targets by 2030. In a world with fully implemented NDCs, ambiguity about the associated aerosol emissions contributes to uncertainty about global mean temperature in 2030 of the same magnitude as the expected temperature reductions from decreased greenhouse gas emissions. The differences in mortality between the different pathways to meeting the NDCs are substantial and premature deaths due to PM2.5 could differ by more than a million people annually, illustrating the potential dangers of not considering aerosol-driven outcomes when setting climate policy.

**Data Availability Statement**

Four data sets have been made available on Harvard Dataverse (https://doi.org/10.7910/DVN/FP0QTX):

1. The modified version of the CD-LINKS NDC target quantification.
2. The data required to make Figures S2 and S3.
3. The regression coefficients used to convert emissions to concentrations.
4. Modified gridded SSP emissions for the three decision priorities for SSP3 and SSP5, for CO\(_2\), CH\(_4\), N\(_2\)O, SO\(_2\), BC, OC, for 2020–2030.
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