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Clean air policies are key for successfully mitigating Arctic warming

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A tighter integration of modeling frameworks for climate and air quality is urgently needed to assess the impacts of clean air policies on future Arctic and global climate. We combined a new model emulator and comprehensive emissions scenarios for air pollutants and greenhouse gases to assess climate and human health co-benefits of emissions reductions. Fossil fuel use is projected to rapidly decline in an increasingly sustainable world, resulting in far-reaching air quality benefits. Despite human health benefits, reductions in sulfur emissions in a more sustainable world could enhance Arctic warming by 0.8 °C in 2050 relative to the 1995–2014, thereby offsetting climate benefits of greenhouse gas reductions. Targeted and technically feasible emissions reduction opportunities exist for achieving simultaneous climate and human health co-benefits. It would be particularly beneficial to unlock a newly identified mitigation potential for carbon particulate matter, yielding Arctic climate benefits equivalent to those from carbon dioxide reductions by 2050.

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The Arctic annual mean surface temperature has warmed three times faster than the global average between 1971 and 2019, with consequences that reach far beyond the Arctic environment and people[1,2]. To limit Arctic warming and sea ice melt, and to mitigate risks associated with potential climate tipping points in the Arctic[3], reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases are urgently needed. Many countries have pledged to bring emissions of greenhouse gases to "net zero" by 2050, primarily targeting CO_2. Despite these commitments, the world is not currently on track to meet the goals of the Paris Agreement[4].

At the same time, strong national regulations and regional agreements are in place to reduce transboundary air pollution[5–7], which is a major health threat in many parts of the world[8]. Air pollutants such as particulate matter and tropospheric ozone (O_3) act as Short-Lived Climate Forcers (SLCFs). Although SLCFs, including methane (CH_4), are known to contribute to both air quality degradation and climate change, these are often dealt with as separate environmental concerns, despite scientific evidence indicating strong linkages between the two[9–15].

Since the atmospheric lifetimes of SLCFs range from a few hours to several years, their control has substantial potential for rapidly mitigating warming, in the Arctic and globally. However, the climate change mitigation potential of SLCFs is still poorly understood. SLCF mitigation actions to limit Arctic warming over the next few decades have not yet been robustly assessed or compared with greenhouse gas (GHG) mitigation actions. Climate modeling studies have consistently failed to meaningfully constrain the competing influences of scattering and absorbing particulate matter components on future Arctic climate[16]. Unsurprisingly, detailed modelling studies disagree on the magnitude of SLCF temperature impacts in the Arctic[15–18]. Although important information about process uncertainties has become available from multiple multi-model assessments, this information is not yet widely used in studies of SLCFs. Furthermore, highly idealized SLCF scenarios have been used, which are disconnected from greenhouse gas scenarios, or do not reflect technological changes in the real world.

Here we assess the climate impacts of a swift adoption of best available technologies to reduce key air pollutants (Table 1) and CH_4. In our analysis, we distinguish between different air pollutants, depending on whether their control leads to cooling or warming impacts. While regulation of sulfur dioxide (SO_2) and other chemically reactive sulfur compounds reduces particulate matter pollution and thereby yields far-reaching health benefits[19,20], influences of sulfur emissions on global climate are well documented[15,17,21–23]. In particular, sulfur emissions lead to the formation of sulfate (SO_4) particulate matter, which efficiently scatters short-wave radiation and enhances the cloud albedo. This has masked some of the past climate warming from increasing GHGs and light-absorbing black carbon (BC) particulate matter[24,25]. With globally declining levels of sulfate, this masking of global warming is diminishing, which enhances warming in the Arctic and globally.

Currently, the unmasking of warming from declining sulfur emissions cannot be observed with sufficient accuracy or continuity. Air quality and climate models remain as essential tools for assessing the efficacy of sulfur mitigation actions. Similar limitations exist for assessments of BC climate impacts. In addition to the observational constraints, previous climate modelling studies have often been limited to combined impacts of all emitted particulate matter components, without clearly distinguishing sulfur from BC emissions impacts. Here we compare the impacts of sulfur and BC emissions on radiatively forced temperature changes and use our results to identify scenarios for improving both climate and air quality in the near to mid-term using multiple emissions scenarios.

Future emissions scenarios. Given the uncertain nature of global socio-economic development trajectories, we consider eight alternative future GHG and air pollutant emissions scenarios. This includes a set of future emissions scenarios underpinning the 6th assessment report of the IPCC[4,26], the Shared Socioeconomic Pathways (SSPs), and a dedicated set of new scenarios specifically focusing on mitigation of tropospheric O_3 precursors, CH_4, and particulate matter. The new scenarios are subsequently referred to as "AMAP scenarios" because we recently used these to assess the impacts of SLCFs on Arctic climate and human health for the Arctic Monitoring and Assessment Programme (AMAP)[27], which provides the scientific basis of our analysis here (Supplementary Note 1).

Table 1 Key air pollutants which act as Short-Lived Climate Forcers, their sources, and trends.

Regulated air pollutant	Sources	Recent trends
Particulate matter with an aerodynamic diameter equal to or smaller than 2.5 μm ($PM_{2.5}$)	Contains sulfate (SO_4), nitrate, and carbonaceous aerosol compounds[45]. The former results from emissions of sulfur-containing gases and their oxidation. The latter consists of black carbon (BC) and organic carbon (OC). OC refers to compounds that contain carbon, hydrogen and oxygen, which are emitted from common combustion sources or form from oxidation of precursor gases. BC ("soot") represents the light-absorbing components of carbon particulate matter[33].	Owing to the introduction of air pollution control policies and technologies in highly industrialized countries, and more recently in China, sulfur emissions are declining in these countries and globally, which resulted in notable SO_4 reductions[46–49] (Fig. 1, Supplementary Figs. 1, 2). BC emissions are declining in the Arctic Council but have remained roughly constant globally (Fig. 1). In the Arctic, SO_4 and BC have generally decreased in the last few decades, primarily due to declining emissions at mid latitudes, whereby the strongest decrease occurred between 1990 and 2000. No significant concentration changes have been detectable since then[50] (Supplementary Figs. 5, 6).
Tropospheric ozone (O_3)	A secondary air pollutant that forms through photochemical reactions of emitted precursor gases, including the chemically reactive gases CH_4, nitrogen oxides (NO*x*), carbon monoxide (CO), and non-CH_4 volatile organic compounds (VOCs).	Surface O_3 has increased in several East, South and South-East Asian countries after about 2000 but no clear trends in global and Arctic surface ozone have recently been observed[51]. Relatively rapid increase in surface O_3 in Asia can be explained by globally increasing CH_4 and regionally varying trends in emissions of NO*x*, CO, and VOCs[52,53] (Supplementary Fig. 4).

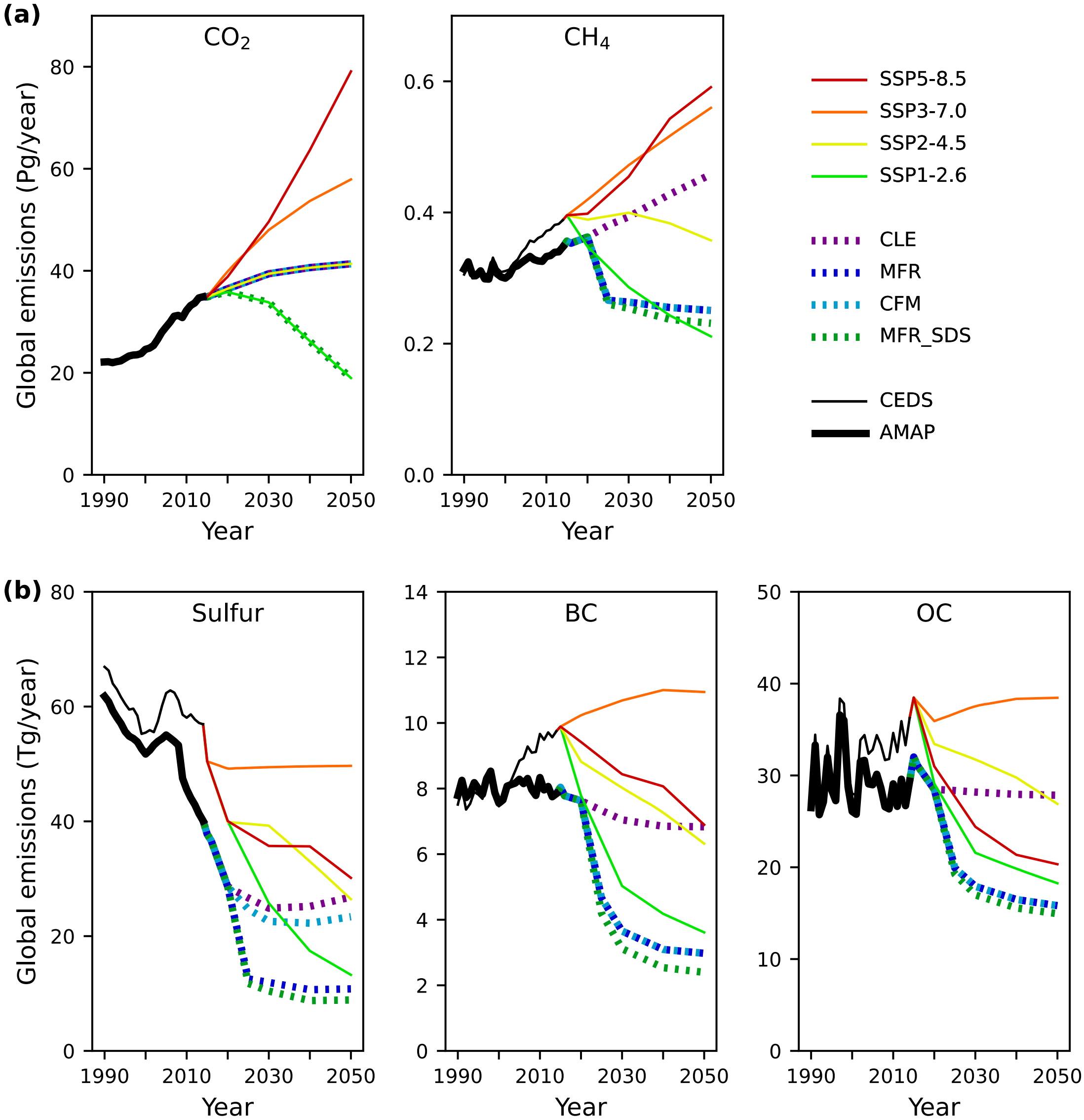

Fig. 1 Global and annual mean greenhouse gas and particulate matter component emissions for the recent historical time period and in future scenarios. a Historical carbon dioxide (CO_2) and methane (CH4) emissions in two inventories (as indicated in the legend; thin black line: Community Emission Data System, CEDS[56], thick black line: Arctic Monitoring and Assessment Programme, AMAP[27]) and 8 future scenarios[26,27] for 2015 to 2050 (colored lines and acronyms in legend); also see the section describing the future scenarios. **b** Corresponding emissions of sulfur, black carbon (BC), and organic carbon (OC). Note that some of the scenarios are overlapping for some emitted species. The inter-annual variability in the historical methane, BC, and OC emissions is largely due to wildfires. See Supplementary Figs. 1, 2 for regional contributions to global emissions.

We selected four SSP scenarios that capture a wide possible range of GHGs and other anthropogenic drivers of climate change. This includes emissions which depend, beyond consumption of fossil fuels, on SSP-specific assumptions about air quality and development policies[28,29]. Global emissions of SO_2 and carbon aerosol particles are projected to decline after 2015 in all SSP scenarios, except in the scenario depicting regional rivalry (SSP3-7.0), which is based on the narrative of material-intensive consumption, with low international priority for addressing environmental concerns[26] (Fig. 1). However, emissions from North America, Europe, and North-East Asia are still projected to decline in this scenario, which is of relevance for the Arctic (Supplementary Fig. 1). The emission reductions are even more rapid in the sustainability scenario (SSP1-2.6), with low challenges to climate mitigation and increasing shares of renewables, resulting in considerable reductions already before 2030. The remaining SSP scenarios describe narratives of continued socio-economic development, similar to historical patterns (SSP2-4.5), and fossil-fueled economic growth (SSP5-8.5).

In addition to the SSP scenarios, the four new AMAP scenarios (Table 2) were developed to explore the impacts of dedicated air quality and SLCF policies for two distinct socio-economic futures, broadly consistent with the SSP2-4.5 and SSP1-2.6 scenario CO_2 emissions trajectories, using the GAINS model[30]. We used these scenarios to assess SLCF mitigation options and to address health challenges from air pollution exceeding national standards and WHO air quality guidelines. The pace and degree of SLCF emission reductions in the AMAP Current LEgislation (CLE) scenario are comparable to the SSP2-4.5 scenario. The Maximum technically Feasible Reduction (MFR and MFR_SDS) scenarios assume strong mitigation of BC, CH_4, and other air pollutants beyond those in the CLE scenario. Neither the CLE nor MFR

Table 2 AMAP emissions scenarios.

Identifier	Descriptor	Key policy and innovations	Characteristics
CLE	Current LEgislation	Full implementation of current national and regional air pollution legislation as well as commitments under Nationally Determined Contributions[54] (NDC, as of 2018).	Moderate changes in emissions of sulfur and carbon particles after 2030 since there is no further strengthening of legislation. The pace of global particulate matter reductions is comparable to the SSP2-4.5 scenario. CO_2 emissions follow SSP2-4.5.
MFR	Maximum technically Feasible Reduction	Mitigation beyond CLE: introduction of lowest air pollutant emission technologies globally, without any constraints related to required investment costs, while accounting for the lifetime of currently installed equipment and the technical feasibility of implementing respective technologies.	Deeper and more rapid reductions of particulate matter species than any of the SSP scenarios; strong CH_4 mitigation measures. CO_2 emissions follow SSP2-4.5.
MFR_SDS	MFR + Sustainable Development	Implementation of MFR policies and Sustainable Development Scenario of the International Energy Agency[54] (IEA).	Strong SLCF mitigation, similar to MFR. CO_2 emissions follow the SSP1-2.6 scenario.
CFM	Climate Forcing Mitigation	Policy actions focusing on CH_4 and warming SLCFs, assuming CLE policies for other species.	Strong mitigation of BC and CH_4, similar to MFR. Reductions of cooling species (sulfur and nitrogen oxides) are similar to CLE, although some further reductions occur as a consequence of the introduction of low emission technologies for BC. CO_2 emissions follow SSP2-4.5.

scenario were developed from the perspective of addressing global or Arctic warming; thereby they result in strong reductions of both warming and cooling SLCFs. Therefore, the focus of policy actions in the Climate Forcing Mitigation (CFM) scenario is on only the warming SLCFs, assuming compliance with current air quality legislation.

Results and discussion

Unmasking of warming. We used state-of-the-art Earth System Models (ESMs, see Methods) to simulate the changes in global and Arctic climate in the future scenarios. For emissions following the SSP scenarios, the global Surface Air Temperature (SAT) is projected to increase between 1 °C (0.5–1.6 °C) and 1.7 °C (1–2.4 °C) from the 1995–2014 average to the 2046–2055 average, for SSP1-2.6 and SSP5-8.5, respectively (Fig. 2c). The corresponding increase in Arctic SAT ranges from 1.9 °C (0.2–4.3 °C) to 3.4 °C (1.6–6 °C), for SSP1-2.6 and SSP5-8.5, respectively (Fig. 2d). Note that we use 60°N as the boundary of the Arctic.

We further used a new Earth System model emulator (see Methods) to compare the Arctic warming contributions from global anthropogenic CO_2 emissions and the unmasking of warming from sulfate reductions, which are not available from the ESMs. The simulations show that these contributions could be nearly equal in magnitude until at least 2030 (Fig. 2 and Supplementary Fig. 9). The unmasking of warming would be particularly strong if the world shifted toward a more sustainable path of improved air quality following SSP1-2.6. This would result in reductions in global sulfate concentrations and could lead to enhanced warming in the Arctic by 0.8 °C (0.4–1.4 °C) and by 0.4 °C (0.3–0.8 °C) globally, from the 1995 – 2014 average to 2050. In comparison, this represents roughly 70% of the Arctic and 60% of the global warming from anthropogenic CO_2. This is larger than the contributions of the changes in other SLCFs emissions in this scenario. In broad agreement with our results, earlier ESM studies[31,32] showed that particulate matter reductions could increase temperatures in 2050 by up to 0.7 °C in the Arctic, (relative to 2010), and by about 0.4 °C globally (relative to 2000).

The unmasking of Arctic warming could also be considerable with less rapid reductions in sulfur emissions (0.4 °C, from 0 to 0.7 °C, for SSP3-7.0). Overall, a substantial Arctic warming commitment from sulfur emission reductions does not appear to be avoidable within the context of the available climate scenarios and considering the likelihood of near-term renewable energy technology and air quality advancements, which are essential for advancing global progress on the United Nations Sustainable Development Goals.

While the unmasking of warming by reductions in sulfate exacerbates the CO_2-induced Arctic warming in all of the available SSP scenarios, the warming is enhanced further by increasing CH_4 emissions in two of the scenarios (SSP3-7.0 and SSP5-8.5). Ultimately, the consequence of the changing emissions of these and other chemically reactive compounds is an enhancement of CO_2-induced Arctic warming, which is directly and indirectly associated with changes in air pollution, primarily from declining sulfate and increasing CH_4. The magnitude of the air pollution warming enhancement is uncertain, owing to uncertainties in aerosol radiative forcings and climate sensitivity (see Methods).

For the SSP2-4.5, SSP3-7.0, SSP5-8.5, and CLE scenarios we find that forced temperature increases could reach or exceed 2 °C globally and 4 °C in the Arctic during the time period 2046−2055, relative to 1880–1920 (Fig. 2). In comparison, the contribution of the CO_2-induced warming to the forced temperatures is less than 2 °C (global) and 4 °C (Arctic). Consequently, the rate of Arctic warming to 2050, and successful implementation of the Paris Agreement, may considerably depend upon changes in air quality, within the uncertainties of the emissions scenarios and emulator simulations. Note that physical process uncertainties affect the scenario simulations in a systematic manner; they either enhance or reduce the changes in all scenarios, permitting robust comparisons of different scenarios.

Arctic climate benefits of black carbon and methane mitigation. Historically, emissions of BC contributed to global warming by enhancing the atmospheric absorption of solar radiation and through impacts on clouds[4,18]. When deposited on Arctic snow and ice, BC also decreases the ability of the snow and ice to reflect solar radiation. The absorption of solar radiation by BC in the snow and ice results in a positive radiative forcing from interactions of BC with surface albedo[16,33]. Thereby interactions of BC with radiation, clouds, and surface albedo have warmed the Arctic in recent decades[10,15,16].

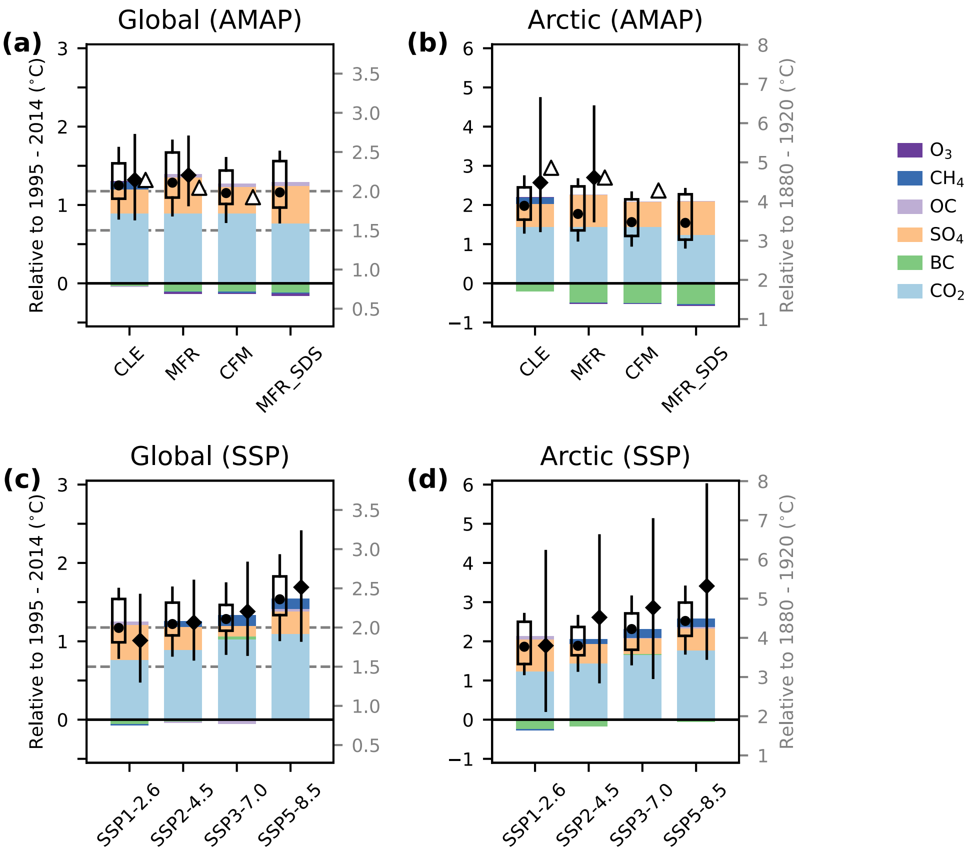

Fig. 2 Projected global and Arctic mean temperature changes in 2050. **a**, **b** are for Arctic Monitoring and Assessment Programme (AMAP) air pollution mitigation scenarios and **c**, **d** for Shared Socioeconomic Pathways (SSP) climate scenarios. Black diamonds refer to the multi-model median temperatures in Earth System Models (ESMs) for 2046–2055, relative to 1995–2014 (black font), where available. Warming relative to preindustrial conditions is also indicated (grey font, with 1.5 and 2 °C thresholds indicated by dashed lines in **a**, **c**). Color bars refer to the contributions from the individual changes in air pollutant and greenhouse gas emissions to forced temperature changes, based on emulator simulations (legend). Black bullets refer to the corresponding net changes. Results from the MRI-ESM2 are shown, the only ESM that ran the CFM scenario (triangles in **a**, **b**). Contributions from tropospheric ozone (O_3, less than 0.03 °C) and OC (less than 0.09 °C) are barely discernible but are included for the sake of completeness (AMAP scenarios only). 5–95% confidence intervals (± 1.64 σ), resulting from uncertainties in all simulated processes, are indicated by black vertical lines (error bars). Confidence ranges due to radiative forcing uncertainty in the emulator are indicated by transparent rectangles. The emulator does not account for unforced natural variability and so confidence ranges are typically smaller than ESM confidence ranges. See the Supplementary Note 4 for simulation details and Supplementary Fig. 9 for results for 2030.

As an encouraging step, the Arctic Council aims to reduce black carbon particulate matter emissions by 2025, which aligns with research showing that Arctic climate is sensitive to black carbon from sources at high latitudes in the Northern Hemisphere[15,16]. Our emulator simulations, using newly developed AMAP scenarios, show that deep reductions of BC and CH_4 emissions would help to mitigate the unmasking of warming from declining sulfur emissions (Fig. 2). Specifically, BC emissions reductions would reduce Arctic warming by 0.3 °C (0.1–0.4 °C) in the MFR scenario, compared to the CLE scenario, as a consequence of diminishing interactions of BC with radiation, clouds, and surface albedo (Fig. 3a). In addition, diminishing emissions and interactions of CH_4 with radiation would further reduce the Arctic warming by 0.2 °C (0.1–0.2 °C).

In the hypothetical case, where future sulfur emissions are driven by current legislation but BC and CH_4 emission reductions are prioritized, beyond those mandated by current legislation (the CFM scenario), it would be possible to notably reduce the air pollution-driven warming enhancement. This could lower the Arctic temperature by 0.4 °C in 2050 (Fig. 3b). In comparison, the avoided Arctic warming from global CO_2 emission reductions alone in the SSP1-2.6 versus the SSP5-8.5 scenario is 0.5 °C (0.4–0.7 °C), according to results shown in Fig. 2d. This indicates that ambitious global reductions of BC and CH_4 could lead to Arctic climate benefits by 2050, similar to those from global CO_2 reductions in a climate-focused mitigation strategy.

Climate benefits of global BC and CH_4 emission reductions are similar for the CFM, MFR, and MFR_SDS scenarios (Fig. 3). The combined global SLCF emission changes in the MFR or MFR_SDS scenarios could reduce the forced Arctic warming by 0.2 °C. This is still notable, considering the rapid sulfur emission reductions and associated warming impacts in these two scenarios. Overall, Arctic temperature is projected to increase less rapidly in the MFR_SDS than in the SSP1-2.6 scenario (1.5 vs. 1.9 °C), given the deeper SLCF emission reductions in that scenario.

With global BC emission reductions, Arctic warming would be reduced largely as a consequence of diminishing interactions of BC with surface albedo (0.2 °C, Fig. 3), relative to the CLE scenario. Consistent with earlier research[15,16], we find that policies targeting emissions of BC from sources in the Arctic Council countries would be particularly efficient at slowing Arctic warming, mainly due to reduced absorption of solar radiation by BC in snow and ice. Although roughly 40% of the Arctic warming reduction from BC is attributable to emissions in the Arctic Council countries, these account for only 6% of the global BC

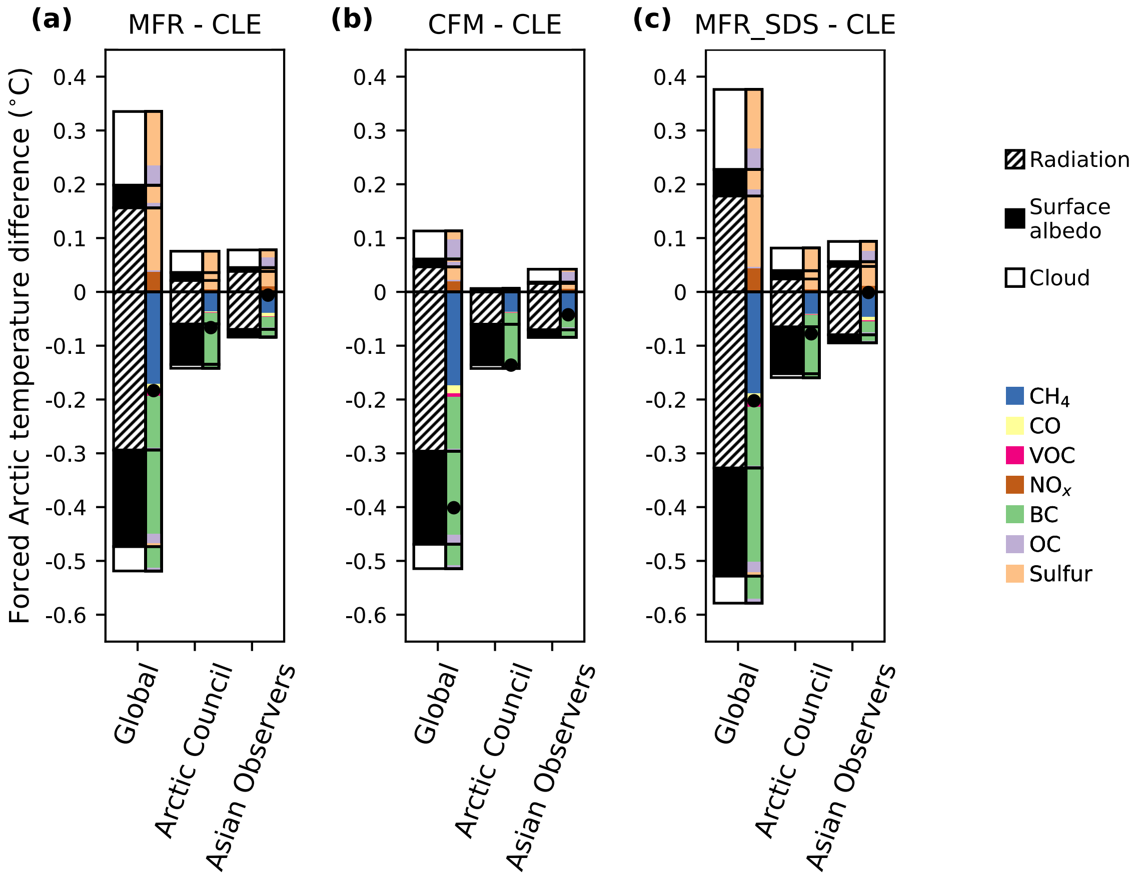

Fig. 3 Impacts of changes in air pollution on future Arctic climate. **a** Differences in forced Arctic temperatures in 2050 are shown between Maximum Feasible Reduction, **b** Climate Forcing Mitigation, Sustainable Development activity (**c**) scenarios and the Current LEgislation scenario. The differences are broken down into contributions of global and regional emissions of chemically reactive species and the radiative forcing processes that are associated with these emissions. 3 different radiative forcing processes are considered, indicated by wide bars (hatched, black, and white; for interactions of air pollutants and CH_4 with radiation, surface albedo, and clouds, respectively, see legend). Narrow colored bars refer to emissions of 7 reactive species (see legend) from global sources and two regions (Arctic Council, and Asian Arctic Council Observer countries: Japan, People's Republic of China, Republic of India, Republic of Korea, Republic of Singapore). Black bullets refer to the net temperature changes associated with global and regional emissions. Supplementary Fig. 10 provides the corresponding global temperature differences.

emission reductions in the AMAP scenarios. On the other hand, BC emission reductions in the Asian Arctic Council observer countries yield much smaller Arctic climate benefits (Fig. 3). Consequently, BC emissions at high latitudes have a disproportionately large impact on the Arctic climate, which may provide particularly interesting opportunities for climate policy development. For instance, ambitious BC and CO_2 emission reductions in Arctic Council countries could yield comparable Arctic climate benefits by 2050 (0.1 °C warming reductions for BC and CO_2), according to the available AMAP and SSP scenarios.

Air quality and human health co-benefits. Over the next few decades, maximum feasible reductions in air pollutant emissions (MFR and MFR_SDS scenarios) would lead to systematic reductions in annual mean $PM_{2.5}$ concentrations globally, in the Arctic Council, and in Asian Arctic Council observer countries, relative to the CLE scenario (Fig. 4). Changes in long-range transport of air pollutants between the regions contribute to the $PM_{2.5}$ reductions, but are less important than local emission reductions. Most of the $PM_{2.5}$ reductions are projected to occur before 2030 and are particularly large for the Asian countries, given the rapid reductions of the emissions in these scenarios (Fig. 4c). Here, reduced emissions of sulfur and carbon particles would contribute about equally to $PM_{2.5}$ reductions in the MFR and MFR_SDS scenarios, relative to the CLE scenario. Despite the rapidly declining emissions in these scenarios, the $PM_{2.5}$ concentration is projected to continue to exceed the World Health Organization's 2021 Air Quality Guideline[34] for annual average $PM_{2.5}$ of 5 μg/m^3. For the Arctic Council countries (Fig. 4b), reductions in sulfur emissions would contribute more strongly to reductions in $PM_{2.5}$ than reductions in emissions of carbon particulate matter (OC and BC).

$PM_{2.5}$- and ozone-attributable mortality are calculated using the TM5-FASST model (Supplementary Note 6). Air pollution-related mortality follows a different pattern from concentrations, due to simultaneously changing population, age structure, and disease rates. Despite relatively constant $PM_{2.5}$ concentrations in the CLE scenario, global $PM_{2.5}$ mortality is estimated to increase by approximately 300,000 (9%) annual deaths from 2015 to 2030, and further in 2050 (1.2 M deaths, 38%; Fig. 4). The increase from 2015 to 2050 is particularly large in the Asian countries (600,000 deaths, 36%), while $PM_{2.5}$ mortality decreases slightly under CLE in Arctic Council countries (−3,000 deaths, −2%). $PM_{2.5}$ mortality in 2050 is reduced under MFR compared with CLE globally (−1.2 M deaths, −28%), in Arctic Council countries (−100,000 deaths, −58%), and in the Asian countries (−700,000 deaths, −31%).

In the Climate Forcing Mitigation (CFM) scenario, global $PM_{2.5}$ concentrations would be reduced less strongly than in the

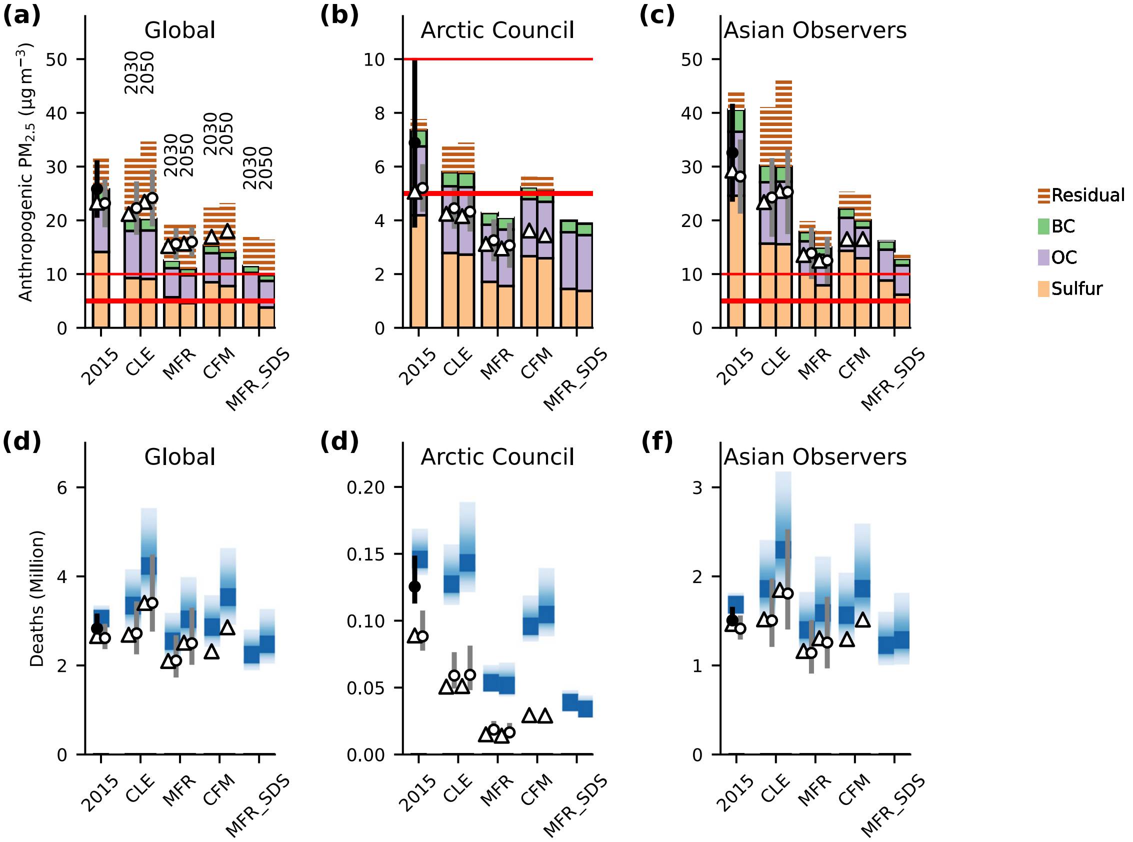

Fig. 4 Particulate matter impacts on human health. a–c show population-weighted $PM_{2.5}$ concentrations in three different regions for a 2015 baseline and 4 future AMAP scenarios. Anthropogenic and biomass $PM_{2.5}$ components from global emissions of sulfur, OC, and BC (color bars, legend) are based on emulator simulations. Additional residual $PM_{2.5}$ components (primarily sea salt, mineral dust, and nitrate) and total $PM_{2.5}$ from all components are based on simulations with the TM5-FASST model (full bars). Black bullets refer to corresponding multi-model mean population-weighted anthropogenic and biomass $PM_{2.5}$ from simulations with 10 global Earth System Models (ESMs) and Chemistry Transport Models (CTMs) for 2015. White circles are for a subset of 5 models which also provided results for years 2030 and 2050. White triangles refer to results from the MRI-ESM2, the only ESM simulating the CFM scenario. World Health Organization's Air Quality Guidelines from 2021 (5 μg/m^3) and 2005 (10 μg/m^3) are indicated by red lines. **d–f** show mean deaths in the same regions, based on simulations with the TM5-FASST model (blue squares). Additional mortality estimates from simulations with ESMs and CTMs are shown, too. Confidence intervals (error bars) are indicated by vertical lines for the full model ensemble (black), model subset (grey), and TM5-FASST (blue shading). See Supplementary Notes 5, 6 for model details.

MFR scenario, primarily because of the weak sulfur mitigation in the CFM scenario. $PM_{2.5}$ mortality is increased under CFM compared with MFR and is slightly lower for MFR_SDS compared with MFR.

For O_3, associated mortality increases steadily under CLE from 2015 to 2050 globally (by 72% from 400,000) and in both Arctic Council (by 11% from 30,000) and the Asian countries (by 77% from 300,000; Fig. 5). As for $PM_{2.5}$, ozone concentrations and mortality are lower under MFR and MFR_SDS compared with CLE and CFM. Since ozone mortality is an order of magnitude smaller than $PM_{2.5}$ mortality, total air pollution mortality impacts largely follow the patterns of $PM_{2.5}$ mortality.

Benefits and limits of maximum feasible emission reductions. Globally, air pollution is a major driver of climate change and the top environmental human health threat. Our results indicate that the understanding of future climate and health impacts of air pollutants can be advanced by using a combination of new emissions scenarios and an Earth System model emulator for simulating air pollutants and climate.

Cutting particulate carbon compounds and methane globally using best available technologies according to our AMAP scenarios would reduce particulate matter and tropospheric ozone pollution. More ambitious efforts than currently legislated emission reductions could prevent hundreds of thousands of premature deaths in Arctic Council Member and the Asian countries. This could be rapidly accomplished by increasing the use of best available technologies for reducing emissions of carbon particulate matter, particularly black carbon, according to the three AMAP mitigation scenarios that we considered here.

In addition to reduced mortality, the use of best available technologies would yield rapid benefits for Arctic and global climate. Deep reductions in emissions of particulate carbon compounds and methane will be required to compensate for the additional Arctic warming that is caused by globally reducing sulfur emissions and sulfate, which will be a major contributor to Arctic warming in the next few decades under any of the available future scenario. Addressing black carbon particulate matter and methane would be highly beneficial for Arctic climate over the next few decades, with climate benefits comparable to those from CO_2 reductions in a climate-focused mitigation strategy, according to the SSP scenarios. Reducing the black carbon component of particulate matter in Arctic nations would be particularly impactful. Arctic Council's goal of reducing black carbon emissions of 25-33 percent below 2013 levels by 2025 is a welcome step but still not ambitious enough in that regard.

In turn, without deep black carbon and methane future reductions, global society may need to prepare for enhanced near-

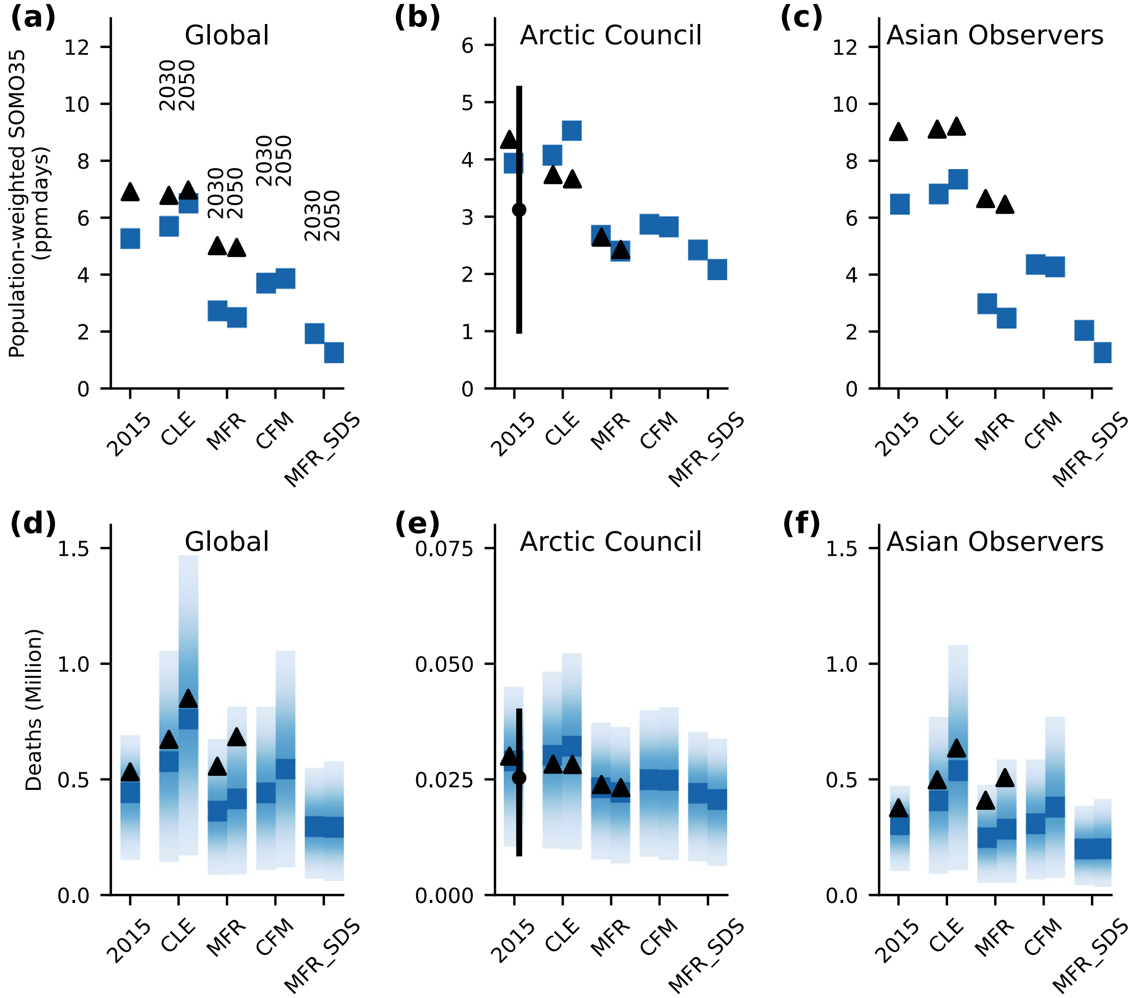

Fig. 5 Impact of ozone on human health. a–c show population-weighted Sum of Ozone Means Over 35 ppb (SOMO35) in three different regions, defined as the yearly sum of the daily maximum of 8-hour running average ozone abundance over 35 ppb (World Health Organization air quality standard), based on simulations with the TM5-FASST model (blue squares). For the Arctic Council, black bullets refer to 2015 multi-model mean results from simulations with 4 global Earth System Models (ESMs) and Chemistry Transport Models (CTMs, Supplementary Notes 5, 6). In addition, results from the EMEP-MSCW model are available for the CLE and MFR scenarios (black triangles). **d–f** show the corresponding deaths in the same regions, based on simulations with TM5-FASST (blue squares). Confidence intervals (error bars) are indicated by black vertical lines in **b**, **e**, and blue shading in **d–f**. Additional mortality estimates from simulations with ESMs and CTMs are shown.

term Arctic warming from declining sulfate particulate matter, well beyond the warming driven by carbon dioxide. Although the magnitude of the additional warming is subject to uncertainties in interactions of sulfate with radiative processes in the atmosphere, the climate consequences would be considerable, for all available scenarios and within plausible uncertainty ranges.

To achieve the 2021 World Health Organization Air Quality Guidelines for more of the global population, and to stabilize Arctic climate in the longer term, sharp and immediate reductions of fossil fuel emissions of carbon dioxide and all other climate and air pollutants are needed. This requires an integrated approach addressing air quality, development, and climate policies, including a major shift away from fossil fuels as well as fundamental behavioral changes that go beyond the scenarios that we considered.

Methods

Earth system and air quality models. To assess changes in climate due to the AMAP emissions scenarios we used five Earth System Models[35] (ESMs; NorESM-happi, CESM2, MRI-ESM2, GISS-E2.1, and UKESM1; Supplementary Note 2, Supplementary Data 1) and simulated changes in global and Arctic temperatures from 2015 to 2050. For the SSP scenarios, we used ESM multi-model ensemble results from the Coupled Model Intercomparison Project Phase 6 (CMIP6; Supplementary Data 2)[36,37], which includes the same five ESMs. We included results from all available models in the analysis, regardless of the fact that some of the models are known to project global climate warming in response to carbon dioxide emissions that is larger than expected, based on various lines of evidence[38].

In addition to temperature, we assessed changes in air quality using results from 10 global models, including four of the ESMs (CESM2, MRI-ESM2, GISS-E2.1, and UKESM1) and additional models (CanAM5-PAM, CIESM-MAM7, ECHAM6-SALSA, EMEP MSC-W, GEOS-Chem, Oslo CTM).

Emulator. We employed an Earth System model emulator to assess the impacts of regional emissions of different air pollutants on radiative forcings, global and Arctic temperature, and $PM_{2.5}$ trends. These were not provided by the ESMs, given that the computational demands to compute these would have been prohibitive. Simple climate models, which are comparable to our emulator, have previously been used to analyze radiatively forced changes in temperatures and have been shown to match ESM simulations well, globally[39] and regionally[10].

Emulator simulations of $PM_{2.5}$ concentrations are based on pre-calculated equilibrium concentration pattern responses to specified regional emission perturbations. These were derived from simulations with CanAM5-PAM, CESM, MRI-ESM2, and UKESM1, for emissions from the Western Arctic Council (Canada and United States), Eastern Arctic Council (Kingdom of Denmark, Finland, Iceland, Norway, the Russian Federation, and Sweden), Rest of Europe, Arctic Council Asian observer countries (Japan, People's Republic of China, Republic of India, Republic of Korea, Republic of Singapore), and the Rest of the World. To reproduce concentration gradients for the analysis of health impacts, we

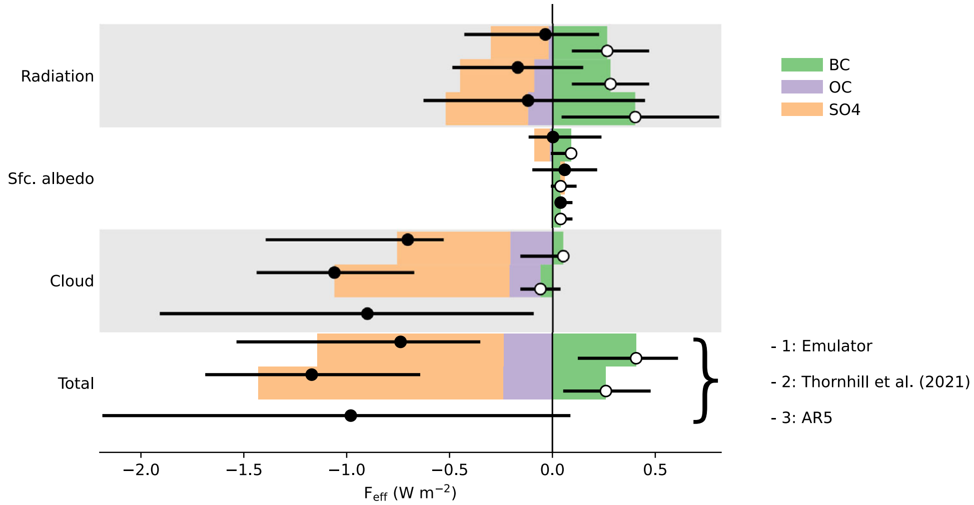

Fig. 6 Comparison of global mean aerosol effective radiative forcings in the emulator with results from the 5th and 6th IPCC assessment report. The estimates from this study (bar 1), 6th IPCC assessment[4,55] (bar 2), and 5th IPCC assessment[57] (bar 3) refer to a different reference year for present-day: 2015 (bar 1), 2014 (bar 2), and 2005 (bar 3), relative to pre-industrial conditions in 1850. Black bullets refer to net radiative forcings for each emitted species (see the section on methods for details). White circles refer to the contributions of black carbon (BC) to the net radiative forcings. Contributions of different aerosol species (sulfate, organic and black carbon) are shown, where available (colors indicated in the legend). Global sulfur emissions in the AMAP inventory used in the emulator are low compared to emissions used for the IPCC assessments (Fig. 1), which partly explains differences in sulfate radiative forcings. Confidence intervals (error bars) are indicated by black horizontal lines.

first downscale the $PM_{2.5}$ concentrations that are simulated in the 3D models using satellite-based data. This allows us to conduct the emulator simulations at a resolution of 0.5° latitude and longitude. The downscaled concentrations from the models are averaged and scaled linearly by the specified regional emission changes to obtain gridded and annual mean concentrations. The rigorous linearization of complex physical and chemical atmospheric processes in the emulator can limit the accuracy of simulated concentration responses involving non-linear processes. However, the emulator reproduces the simulated $PM_{2.5}$ trends in the ESMs during the simulation time period of interest.

The climate component of the emulator is based on simplified models of the heat, carbon and air pollutant cycles in the global Earth System. The simplicity of the emulator allows us to compare the climate influences of anthropogenic emissions of CO_2, CH_4, CO, NO_x, VOC, sulfur, BC, and OC. No other chemical species are represented in the emulator. On the other hand, ESM simulations usually account for more species and emission sources than we consider here, which limits comparisons between the simulated total warming trends in the emulator and ESMs. However, the focus of our study is on comparisons for SLCFs and CO_2 climate impacts, which can be approximated to be independent of other species. It is possible to add other chemical species to the emulator, as needed.

The model parameterizations are constrained by effective radiative forcing sensitivities from a series of equilibrium simulations with regionally perturbed emissions in CanAM5-PAM, CESM2, MRI-ESM2, and UKESM1. The emulator simulates global and Arctic temperature changes, assuming a linear relationship between the emissions and effective radiative forcings for the different regions, similar to the simulation of $PM_{2.5}$ concentrations. Separate effective radiative forcing sensitivities were obtained for each emitted species, region, and forcing process, for interactions of aerosols with radiation, clouds, and the surface albedo (snow and ice). For global effective radiative forcings of CO_2 and CH_4, global atmospheric greenhouse gas mass budgets are simulated which account for key physical and chemical loss processes. A more detailed description of the emulator is available[40].

Simulated global aerosol effective radiative forcings in the emulator are comparable to results from previous multi-model based assessments (Fig. 6). Compared to an earlier assessment of Arctic climate by AMAP[41], differences in simulated forcings are due to a combination of differences in regional emissions, time periods, and changes in the climate models that were used to generate the radiative forcing sensitivities. The ESMs that we used to calculate effective radiative forcing sensitivities tend to produce concentrations of BC that are too low, especially in the Arctic (Supplementary Note 3), which indicates that BC effective radiative forcings in the emulator may also be low. Given the concentration biases and the tendency of the ESMs to underestimate absorption aerosol optical depth, we cannot rule out larger impacts of BC on effective radiative forcings and temperatures than our best estimates provided here.

The Arctic temperature responses to radiative forcing changes are simulated accounting for transport of heat to the Arctic but omitting natural climate variability, changes in natural air pollutants, and land-use. Specifically, the emulator simulates the forced response of the global and Arctic mean surface air temperatures to a series of annual emission pulses. The temporal evolution of the regional mean temperature in response to the pulse emissions is approximated using a specified Equilibrium Climate Sensitivity (ECS), time scales of heat dissipation, and other parameters derived from simulations with climate and other models. Global surface air temperature responses following an emission pulse are simulated by employing the Absolute Global Temperature-Change Potential[42] (AGTP). For simulation of Arctic temperatures, the AGTP is linearly decomposed into an Absolute Regional Temperature-Change Potential (ARTP), using Regional Temperature-Change Potentials (RTPs). This builds on the approach used by AMAP[15,41] to simulate the responses of Arctic and global temperatures to mean SLCF radiative forcings in 4 latitude bands. Some improvements were made, including updated linear relationships between regional emission perturbations, vertically distributed Arctic black carbon, and aerosol effective radiative forcing responses.

The RTP originally used by AMAP produces an ECS of 2.7 °C, which is low compared than that derived[43] from results of ESM simulations in Phase 6 of the Coupled Model Intercomparison Project, CMIP6. In order to match ESM simulations, the ARTP is scaled so that the emulator simulations are conducted for an ECS of 3.7 °C instead. However, the scaling does not affect the warming patterns. It seems possible that the simulated impacts of BC on Arctic temperature are underestimated in the emulator simulations. We note that Arctic warming rates are lower in the emulator than in ESMs simulations (Fig. 2). This seems plausible given that the original RTPs were derived from simulations with an ESM with a low ECS and weak Arctic sea ice response to temperature changes[15,44].

Assessment of uncertainties. Physical climate process uncertainties, particularly including climate feedbacks and aerosol radiative forcings, are a major source of uncertainty in climate model simulations and climate assessments[4]. An ESM assessment of uncertainties in Arctic SLCFs and climate would require very large ensembles of multiple ESMs, which are not available. Here we used the emulator to analyze the impacts of key climate process uncertainties on global and Arctic mean temperatures confidence ranges (Fig. 2). First, we estimated model confidence ranges for global radiative forcings, based on recent results from the CMIP6 multi-model ensemble. Second, the radiative forcings in the emulator were scaled to match the end points of these ranges (Table 3). Third, the ECS in the emulator was varied by 30%, corresponding to an ECS range[43] from 2.6 to 4.8 °C. Subsequently, emulator simulations were conducted with the scaled forcings and ECS to infer corresponding temperature confidence ranges for the different processes.

Finally, confidence ranges for global and Arctic mean temperatures, from the combination of all forcing and ECS uncertainties, were determined assuming statistical independence of all forcing process and ECS uncertainties. We tested the robustness of this approach by applying different combinations of forcing and ECS choices in Monte Carlo simulations with the emulator. These tests provide evidence for a highly systematic warming effect from reduced sulfur emissions for any scenario, global radiative forcing, or equilibrium climate sensitivity, within the specified physical process uncertainty ranges. Similarly, the sign of the cooling impact of reducing black carbon and methane emissions in all of the AMAP mitigation scenarios (MFR, MFR_SDS, and CFM) is highly robust.

Table 3 Global effective radiative forcings from aerosol interactions with radiation, surface albedo, and clouds for global emissions of sulfur, black carbon, and organic carbon in 2015, relative to a preindustrial atmosphere with no anthropogenic aerosol emissions.

Emitted SLCF species	Global effective radiative forcing (W m^{-2}) from aerosol interactions		
	radiation	surface albedo	clouds
Sulfur	−0.28 (−0.6 to −0.12)	−0.08 (−0.11 to 0.14)	−0.55 (−1.2 to −0.5)
Black carbon	0.26 (0.1 to 0.46)	0.09 (0 to 0.11)	0.05 (−0.15 to 0.06)
Organic carbon	−0.02 (−0.16 to −0.02)	−0.01 (−0.06 to 0.06)	−0.21 (−0.24 to −0.05)

Mean values in the emulator are based on multi-model simulations conducted for this study, based on a series of simulations with regionally perturbed emissions. Confidence ranges (in brackets) are constrained by results from simulations with a CMIP6 multi-model ensemble[55], with 30-year long simulations with globally specified emission changes for 2014.

Given that several ESMs are known to project global climate warming in response to carbon dioxide emissions that is larger than expected[38], we also specifically assessed the impacts of using a lower ECS of 3 °C in the emulator and removing ESMs that have an equilibrium climate sensitivity outside of a range from 2.5 to 4 °C from the analysis. This yields results that are similar to the original results (Supplementary Fig. 11 and Fig. 2). With the reduced ECS in the emulator, all the SLCF impacts on Arctic temperatures in 2050 are reduced by about 20%, whereas the CO_2 impacts are reduced by about 10–20%, which is well within the uncertainty of the analysis.

Data availability

Model data sets used here are publicly available: AMAP emissions and data from AMAP models (https://doi.org/10.18164/e0a0ac5c-d851-45b9-b6d9-4abc29d7d419, https://iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv6b.html), CEDS and SSP emissions (https://esgf-node.llnl.gov/projects/input4mips/), and the CMIP6 ESM data (https://esgf-node.llnl.gov/projects/cmip6/). See the Supplementary Data 1, 2 for specific model and data references.

Code availability

The AMAP emulator code and input files for all scenarios are available at https://zenodo.org/record/5555173 (https://doi.org/10.5281/zenodo.5555173).

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Author contributions

The study was initiated and conceptualized by K.v.S., C.H.W., S.C.A., R.V.D., Z.K., M.G.F., S.R.A., S.E., A.M.L.E., K.K., K.S.L., D.O., N.O., S.R., M.Sa., J.S., and S.T.T.; K.v.S. wrote the initial draft of the main manuscript and conducted much of the analysis, with major contributions from C.H.W., S.C.A., R.V.D., Z.K., R.M., A.M.L.E., G.F., N.O., M.Si., and S.T.T.; Key model data sets were generated and analyzed by K.v.S., R.V.D., Z.K., M.G.F., R.M., S.B., R.Y.C., J.H.C., N.E., J.S.F., M.G., W.G., J.L.H., U.I., S.K., T.K., J.L., L.M., D.O., T.O., N.O., V.V.P., Y.P., D.P., L.P., J.C.R., M.Sa., M.Si., M.A.T., K.T., S.T., S.T.T., M.W., B.W.; All authors discussed the analysis at all stages of writing.

Competing interests

The authors declare no competing interests.

Additional information

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