ENVIRONMENTAL RESEARCH
CLIMATE

TOPICAL REVIEW • OPEN ACCESS

Rapidly evolving aerosol emissions are a dangerous omission from near-term climate risk assessments

To cite this article: G Persad *et al* 2023 *Environ. Res.: Climate* **2** 032001

ENVIRONMENTAL RESEARCH
CLIMATE

OPEN ACCESS

RECEIVED
21 October 2022

REVISED
15 May 2023

ACCEPTED FOR PUBLICATION
18 May 2023

PUBLISHED
5 June 2023

TOPICAL REVIEW

Rapidly evolving aerosol emissions are a dangerous omission from near-term climate risk assessments

G Persad[1,18,*], B H Samset[2,18,*], L J Wilcox[3,18,*], Robert J Allen[4], Massimo A Bollasina[5], Ben B B Booth[6], Céline Bonfils[7], Tom Crocker[6], Manoj Joshi[8], Marianne T Lund[2], Kate Marvel[9,17], Joonas Merikanto[10], Kalle Nordling[2], Sabine Undorf[11,12], Detlef P van Vuuren[13,14], Daniel M Westervelt[15,16] and Alcide Zhao[3]

1 Jackson School of Geosciences, The University of Texas at Austin, Austin, TX, United States of America
2 CICERO, Center for International Climate Research, Oslo, Norway
3 National Centre for Atmospheric Science, University of Reading, Reading, United Kingdom
4 Department of Earth and Planetary Sciences, University of California Riverside, Riverside, CA, United States of America
5 School of GeoSciences, University of Edinburgh, Edinburgh, United Kingdom
6 Met Office Hadley Centre, Exeter, United Kingdom
7 Lawrence Livermore National Laboratory, Livermore, CA, United States of America
8 Climatic Research Institute, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
9 Center for Climate Systems Research, Columbia University, New York, NY, United States of America
10 Finnish Meteorological Institute, Helsinki, Finland
11 Research Department for Climate Resilience—Climate Impacts and Adaptation, Potsdam Institute for Climate Impact Research, Potsdam, Germany
12 Department of Meteorology and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
13 Department of Climate, Air and Energy, PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands
14 Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands
15 Lamont-Doherty Earth Observatory, Columbia University Climate School, New York, NY, United States of America
16 NASA Goddard Institute for Space Studies, New York, NY, United States of America
17 Project Drawdown, San Francisco, CA, United States of America
18 These authors contributed equally to this work.
* Authors to whom any correspondence should be addressed.

E-mail: geeta.persad@jsg.utexas.edu, b.h.samset@cicero.oslo.no and l.j.wilcox@reading.ac.uk

Keywords: anthropogenic aerosol, climate change, climate risk

Abstract

Anthropogenic aerosol emissions are expected to change rapidly over the coming decades, driving strong, spatially complex trends in temperature, hydroclimate, and extreme events both near and far from emission sources. Under-resourced, highly populated regions often bear the brunt of aerosols' climate and air quality effects, amplifying risk through heightened exposure and vulnerability. However, many policy-facing evaluations of near-term climate risk, including those in the latest Intergovernmental Panel on Climate Change assessment report, underrepresent aerosols' complex and regionally diverse climate effects, reducing them to a globally averaged offset to greenhouse gas warming. We argue that this constitutes a major missing element in society's ability to prepare for future climate change. We outline a pathway towards progress and call for greater interaction between the aerosol research, impact modeling, scenario development, and risk assessment communities.

1. Anthropogenic aerosols as a unique driver of climate change

Anthropogenic aerosols—the particulate air pollutants that make up a major component of atmospheric haze—play an important role in the evolution of both air quality and global climate change. Anthropogenic emissions of aerosols and their precursors have continuously changed through the historical era and are expected to continue to rapidly evolve over the coming decades (figure 1). Currently, the net effect of aerosols cools the Earth's surface by around 0.4° C, offsetting part of the global warming due to increased atmospheric concentrations of greenhouse gases (GHGs). Since the 1970s, however, the geographical

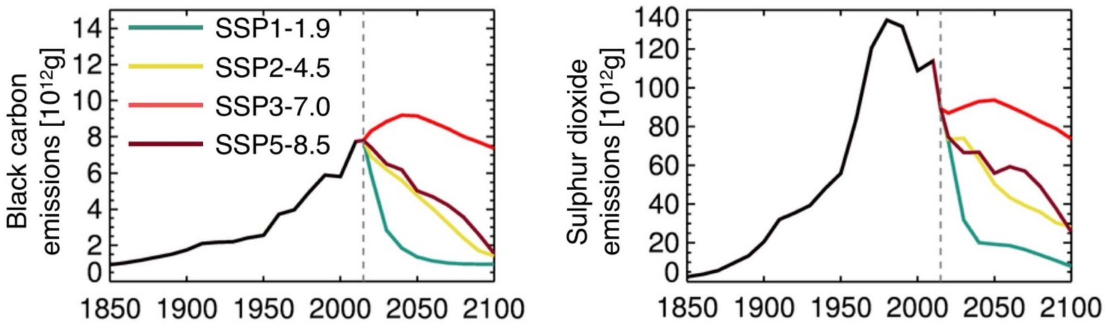

Figure 1. The range of expected near-term emissions changes in the shared socioeconomic pathways (SSPs) for the two main species of anthropogenic aerosol (colored lines) through mid-21st century is comparable in magnitude to total historical emissions growth (black line). The SSP future emissions scenarios are used in the sixth Climate Model Intercomparison Project, a key dataset for the IPCC's Sixth Assessment Report.

distribution of emissions has shifted substantially: transitioning from a locus over North America and Europe to one over Asia [1]. In the last decade, emissions from China have slowed markedly, bringing improvements in air quality and human health [2]. However, China and India both remain major emitters. Aerosol emissions in many low and middle-income countries, including much of Africa and Southeast Asia, are projected to increase with future industrialization, depending on socio-economic factors and technology choices [3]. The range of potential global trajectories of anthropogenic aerosol emissions by the mid-21st century, as captured by the shared socioeconomic pathways (SSPs) future emissions scenarios employed in the current generation of climate model projections, is comparable to the growth of emissions over the entire industrial era (figure 1). Future aerosol induced climate forcing, therefore, constitutes a major source of uncertainty in near-term climate change—globally and regionally.

The global and regional implications of anthropogenic aerosol changes are known to be distinct from those of GHGs. For instance, the global hydrological sensitivity—i.e. the precipitation change per unit of temperature change—to aerosol emissions (3%/K for sulfate and −3%/K for black carbon) is twice as large as the sensitivity to CO_2 (1.5%/K) [4, 5], due to their differing interactions with short- and longwave radiation and with clouds and circulation. Temperature and precipitation extremes have also recently been recognized to be more sensitive to changes in aerosol forcing than to an equivalent change in GHG forcing [6–8].

This builds on progress in our understanding of the interactions between anthropogenic aerosols, radiation, and clouds, and their effect on the climate at local, regional, and hemispheric scales [9–11]. Atmospheric concentrations and radiative effects of aerosols are highly heterogeneous in space and time [12] and influence the climate system via different mechanisms than do GHGs [13]. Anthropogenic aerosols have driven the sign of observed trends in global-mean temperature, monsoon rainfall, and the location of the tropical precipitation belt over substantial portions of the historical period. They have played a dominant role in many wet and dry extreme events, particularly since the 1950s [14–17] (figure 2). However, in contrast to monotonically increasing GHG forcing, the influences of spatially heterogeneous and decadally-varying short-lived aerosols are more difficult to separate from internal climate variability on decadal timescales and thus more difficult to distinguish in historical observations. The term 'aerosols' also encompasses many species (including black carbon, organic carbon, and sulfates, among others) that may have offsetting or compounding effects at the global and regional scale; intricacies that remain under-constrained in both models and observations. Additionally, recent work suggests that the climate response to concurrent regional aerosol emission changes is nonlinear; the sum of the responses to individual regional emissions changes is not equal to the response to total emissions changes across all regions, so that dedicated simulations may be required to fully understand their effects [18]. Finally, while GHGs are long-lived in the atmosphere, aerosols have lifetimes of days to weeks. This means that changes in aerosol emissions have more immediate climate effects than do changes in GHG emissions. These factors conspire to make anthropogenic aerosols a unique and important driver of regional climate change, as has now been widely identified in observations and earth system models (ESMs) [19, 20]. In short, the evolving emissions of anthropogenic aerosols—whether increasing, declining, or geographically redistributing—will remain a major driver of changes in the climate system for at least the next several decades [21–23].

To date, most policy decisions targeting aerosol emissions, such as the U.S. and European Clean Air Acts and China's Air Pollution Prevention and Control plan, have been motivated by mitigating aerosols' chemical

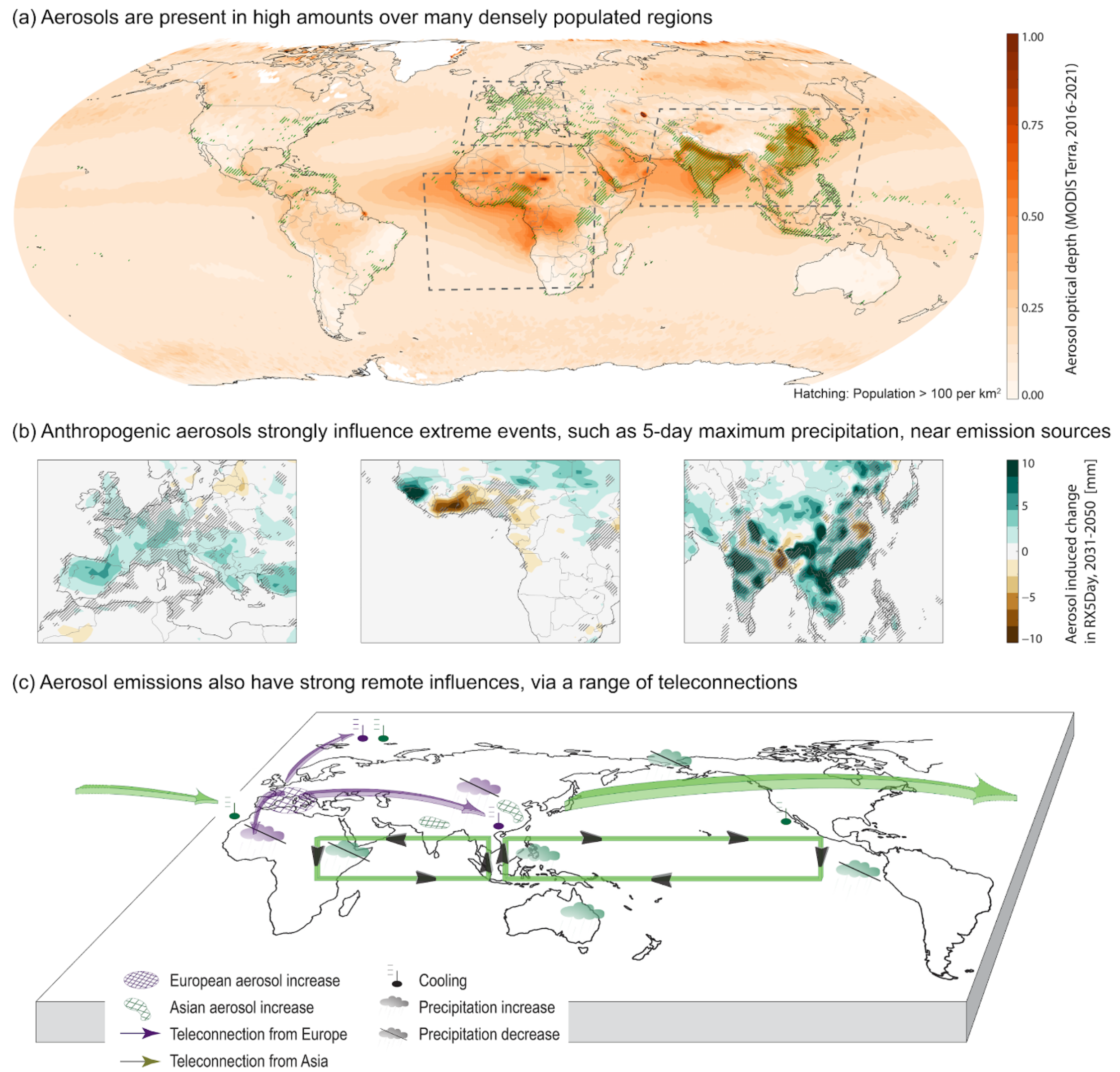

Figure 2. Aerosols are present in high amounts over many populated regions and currently influence weather and climate around the globe, both co-located with aerosol emissions and far afield. (a) Aerosol optical depth from MODIS (2016–2021). Green hatching shows grid cells with population >100 ppl km^{-2}. (b) Anomalies in maximum five-day precipitation amount (RX5day) due to anthropogenic aerosol reductions following RCP8.5 emissions, for 2031–2050 relative to 1986–2005, based on large ensemble simulations with and without the inclusion of time-evolving anthropogenic aerosol emissions in the NCAR CESM1 model. Gray hatching shows where the anomalies are significant at the 5% level. Based on Zhao *et al* [39]. (c) Documented remote impacts of Asian (green hatching, icons, and arrows, including depicted changed in Walker Circulation) and European (purple hatching, icons, and arrows) regional aerosol emissions on temperature and precipitation are schematically depicted based on results from recent studies [21, 40–48]).

and air quality impacts, rather than by concerns about their climate damages. Poor air quality due to aerosol emissions reduces life spans globally by an average of 20 months, rivaling the global impact of cigarette smoking [24]. Air pollution related health risk is also affected by climate change; co-exposure to poor air quality and extreme heat, for example, have a greater impact on mortality than does the sum of their individual effects [25]. This focus on aerosols' air quality-related risks, however, means that the current terminology of the climate science-policy interface is ill-suited for targeting aerosol-induced climate risks and motivates our focus here on aerosols' climate-mediated societal risks.

In current climate policy discussions, aerosols are typically put under the umbrella of short-lived climate forcers (SLCFs). This term is used to describe substances with a short atmospheric lifetime relative to CO_2 and other long-lived GHGs. It encompasses a wide variety of emissions and trace gases, of which aerosols are a key component. However, aerosols differ from gaseous SLCFs, such as methane and tropospheric ozone, because of their very short lifetimes (∼1 week), stronger regional heterogeneity, and distinct atmospheric thermodynamic and cloud microphysical effects. Another commonly used but challenging term appearing in discussions of synergies between climate and air quality is SLCPs or short-lived climate pollutants, which refers to the subgroup of SLCFs whose increased emissions have a warming climate effect (e.g. methane, ozone, and black carbon aerosol) [26]. However, the SLCP nomenclature neglects an important aerosol component, since the major anthropogenic aerosol emission type—sulfur dioxide, which forms sulfate aerosols via chemical reactions in the atmosphere—has a cooling effect.

Given the strong documented influence of aerosol emissions on regional climate change, uncertainties in future aerosol emissions and their impacts hamper robust prediction of decadal climate and near-term climate risks [27]. Even for global mean surface temperatures, estimates of the response to future aerosol reductions still span an order of magnitude, reaching a 1 K increase by 2050 in models with high sensitivity to aerosol changes [6, 22, 28–30]. In the future scenarios in which anthropogenic aerosol emissions decline rapidly, these reductions are typically found to account for 30% to 50% of the total warming over the coming 2–3 decades [22, 31, 32]. The highly heterogeneous nature of aerosol forcing and response means that regional effects can be even stronger [28].

Differences in regional aerosol emission pathways have been linked to significant differences in how climate, both near to and far from emission changes, will evolve over the next several decades. This includes the Asian summer and winter monsoon [33, 34], temperature extremes over Europe and China [35], East and West African rainfall [36], and Arctic climate [37] (figure 2). While air quality concerns are projected to drive down emissions in many (but not all) regions (figure 1), potentially avoiding 2 million premature deaths per year [30], the rate at which these changes occur will be determined by diverse technological, economic, political, and social factors [38].

2. Aerosols and the standard climate risk framework

Despite a solid knowledge base and the recognized magnitude and diversity of potential effects, the regional climate implications of aerosol emissions are obscured in key steps of the standard framework that has been developed by the scientific community to evaluate near-term climate risk across applications, from the Intergovernmental Panel on Climate Change (IPCC) assessment reports to local decision-making (figure 3). The regional heterogeneity of aerosol emissions is represented in historical emission inventories and in the integrated assessment models (IAMs) that produce the future emission scenarios used in international climate modeling efforts. Aerosols' geographically resolved climate effects are also explicitly, albeit imperfectly, simulated by full-complexity climate and earth system models (ESMs). However, this geographic complexity in aerosols' climate effects is rapidly lost in translation when moving towards discussions of regional climate risk.

Initially, projected emissions are typically generated by IAMs without directly modeling air pollution levels or local climate implications. This means that the socio-economic impacts, and associated policy responses, do not feed back into the resulting scenario [49]. This may limit the sophistication, realism, and range of regional aerosol trajectories that are represented in the emissions scenarios used by ESMs.

Next, ESM projections of climate responses to changes in emissions are often either downscaled (increased in resolution) and/or bias-corrected for direct use in local to regional scale climate planning or impact models (e.g. [50, 51]) or used to train statistical emulators or simple climate models which produce a broader range of climate projections for use in impact models, damage functions, or cost-benefit analysis. In the latter case, statistical emulators and simple climate models frequently only consider global-mean temperature effects or simple linear scalings. These do not capture the prominent effects of aerosol changes on regional climate or the difference in their effects compared to GHGs'. In the former case, the regional climate models (RCMs) typically used to dynamically downscale ESM output often neglect aerosol processes altogether, introducing major biases ([52, 53] figure 4). While RCMs with fully interactive aerosols exist [54], they are typically not used in dynamical downscaling exercises due to the greater computational expense. Meanwhile, statistical approaches to downscaling and bias-correction assume that statistical relationships present in the historical period will persist in the future. This is an untested assumption for all forced climate signals but is particularly problematic for aerosol-driven climate signals, as regional aerosol-driven effects can change in sign depending on the pattern of emissions and do not increase monotonically with aerosol amount [12, 55].

Finally, these tools are used in the impact models and social cost calculations that inform investments and planning. If these impact and social cost estimates are not designed with aerosol-driven climate risk in mind, they may neglect the unique pathways via which aerosol emissions generate geographically diverse societal impacts [56]. This reliance of key parts of our risk modeling toolkit on simplified climate projections that neglect spatially heterogeneous effects of aerosols (as well as land use and other complex forcings) runs the risk of setting up a feedback loop in which regional aerosol emissions are not viewed as important and hence are not broadly considered in scenario design, impact model development and, ultimately, climate risk assessments.

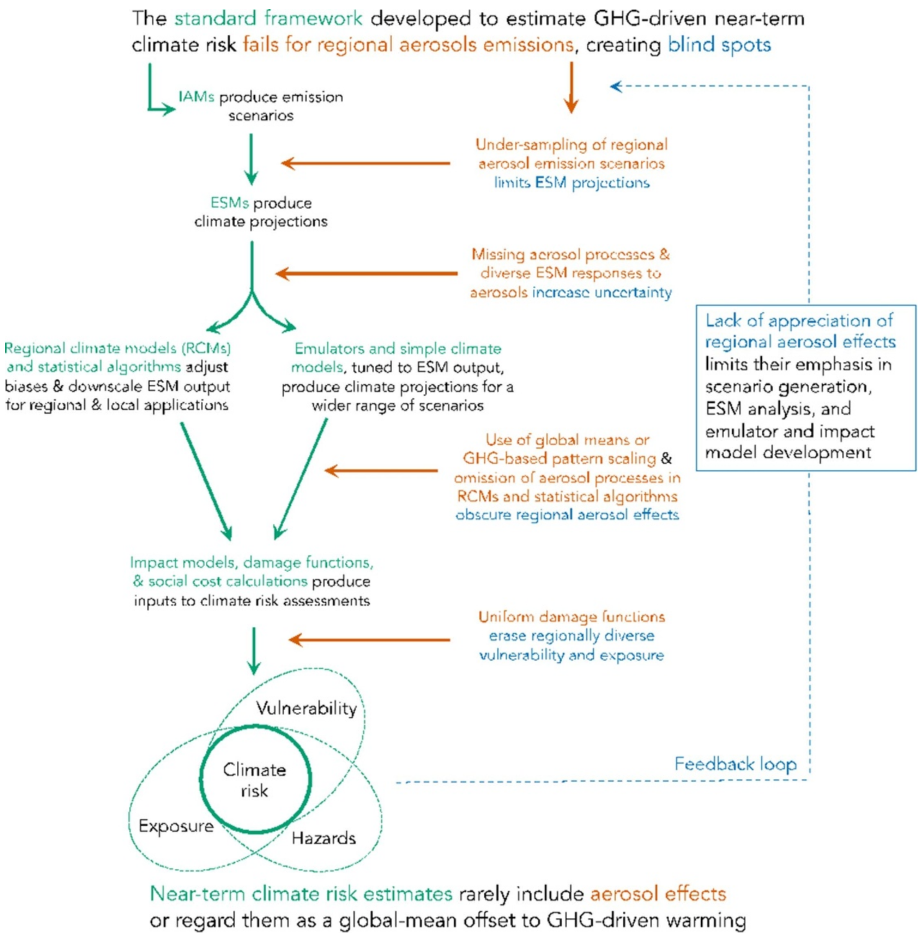

Figure 3. The standard framework via which earth system model climate projections are processed for use in near-term climate risk estimates fails to adequately capture the effects of regional aerosol emissions. Green text depicts the various tools that are used to translate climate projections into risk estimates, green arrows indicate the direction of information flow, and orange text and arrows illustrate how regional aerosol effects are obscured at each step in this translation, resulting in blind spots in our near-term climate risk estimates, highlighted in blue text.

3. Consequences of the omission of aerosols from climate risk assessments

A stark example of the challenges created by neglect of aerosol effects is seen in near-term projections from RCMs used for dynamical downscaling. While RCMs with interactive aerosols do exist [54], the RCMs used for downscaling efforts often neglect aerosol processes altogether, and therefore cannot downscale the full set of processes present in the ESMs. For example, over Europe, ESMs project an increase in surface solar radiation (SSR) or ‘brightening’. However, the lack of time varying aerosols in most RCMs lead them to project a decrease in SSR, causing local inconsistencies as large as 30 W m^{-2} and thus missing the ‘brightening’-driven enhanced warming [57]. Boe *et al* [52] estimate that RCMs are consequently 1.5–2 K cooler than ESMs by the end of the century and project a mean decrease in precipitation of only 5% compared to 20% in ESMs. This limitation is a wider RCM issue, beyond projections, leading to both climatological biases [58, 59] and underestimation of historical trends [60, 61].

Figure 4 shows that current-generation RCMs fail to capture the warmest, and therefore most potentially damaging, of recent ESM-based climate projections. RCM simulations conducted as part of the Euro-CORDEX (COordinated Regional climate Downscaling EXperiment) project consistently underestimate near-future temperatures over Europe compared to the parent ESMs used to drive the RCMs (figure 4, left panel). The RCMs either lack any representation of aerosol changes or represent only simplified changes compared with the complexity and magnitude of changes simulated within the parent ESMs. In contrast, pairs of ESM-RCM simulations with consistent aerosol changes and physics (figure 4; right panel) produce broadly equivalent temperature projections. Users of CORDEX regional projections, therefore, are generally not exposed to potential higher end warming due to the limited aerosol representation in these simulations. This means that they may provide an overly optimistic picture of projected changes if used to inform adaptation planning.

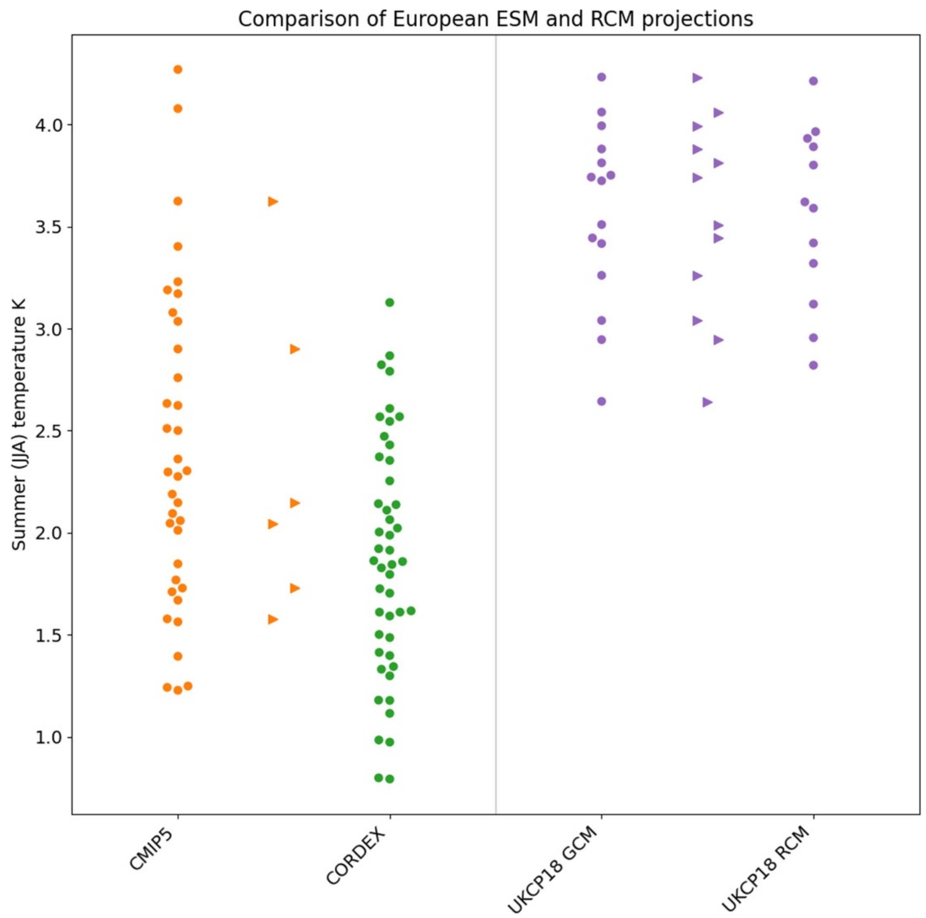

Figure 4. Comparison of regional projections of surface temperature change between RCMs and their driving ESMs shows the consequences of underrepresentation of aerosol processes in RCMs. Projected changes in summer temperature are shown for a central European domain (5 W to 30 E, 42–52 N) for 2041–2060 relative to 1996–2005 across a range of ESMs and RCMs. Euro-CORDEX RCM Projections are shown in green dots. Projections from fifth Climate Model Intercomparison Project (CMIP5) generation ESMs are shown in orange dots, and the subset of ESMs that provided boundary conditions to the Euro-CORDEX RCMs are shown in orange triangles. In contrast, pairs of ESM-RCM simulations with consistent aerosol changes and physics (UKCP18 GCM and RCMs; right panel) produce broadly equivalent temperature projections.

This documented lack of incorporation of the spatial heterogeneity of aerosol effects in commonly used tools and metrics has contributed to an underappreciation of the role of evolving aerosol emissions in near-term climate impacts, climate risk, and climate policy. A critical example is the IPCC Sixth Assessment Report (AR6), which is the primary conduit for scientific knowledge into international climate change negotiations and policy-making. AR6 does not broadly consider patterns of changes in anthropogenic aerosols or their unique effects relative to GHGs when quantifying climate impact drivers [62], despite the documented potential effects on near-term temperature and precipitation trends [63, 64]. While SSPs used in the most recent IPCC report sample a greater range of potential near-future aerosol emission pathways, both globally and regionally, than did the previous generation of scenarios [3, 38], they represent only a small fraction of the wider range of possibilities implied by current and potential technological and geopolitical trends [36, 65]. While the global climate influence of aerosol emissions is thoroughly discussed by Working Group 1 [64, 66, 67], including in the context of SLCFs [68], there is little to no assessment of aerosol literature in the chapters on regional climate change, hazards and extreme events. A positive example is a dedicated treatment of aerosol effects on regional precipitation and monsoon characteristics [63], which enabled high-level conclusions to be pulled through to the Summary for Policymakers and Technical Summary, but even here there is little connection to the regional assessments of climate risk. The Working Group 2 and 3 contributions to the AR6 only assess regional aerosol effects in terms of air quality [69, 70] and as a perturbation to the global carbon budget [71, 72]. Hence, specific aerosol-driven risks—for example, the potential for rapid acceleration of climate extremes in areas with aggressive near-term phasedown of aerosol emissions combined with high GHG-driven warming [73]—are not assessed and hence not passed on to stakeholders and policy makers.

Such under-appreciation of regional aerosol effects in near-term climate risks is particularly problematic, given the disproportionate impacts that aerosols have on the already vulnerable. The ability of developed countries to invest in improving air quality means that heavily polluting activities have been generally shifted into developing regions [74, 75]. As a result, currently under-resourced populations are disproportionately exposed to high aerosol concentrations and their attendant air quality and localized climate effects (figure 2). Additional effects of aerosols on climate can result from teleconnections that also disproportionately impact vulnerable regions in the tropics and subtropics. For example, the remote effect of Northern mid-latitude aerosols on tropical rainfall has been implicated in the late 20th century Sahel drought and concurrent weakening of the South Asian monsoon [44, 45, 76]. The regional climate effects of historical and present-day aerosol emissions already create societal impacts for vulnerable regions. Future aerosol reductions, though critical due to their air quality benefits, will also disproportionately exacerbate climate risks for these vulnerable communities.

4. The way forward

Groundbreaking work remains to be done to reduce uncertainties around aerosols' regional climate effects. ESMs have known biases in their simulation of how aerosols are distributed regionally compared with observations—observations which are themselves uncertain and limited in both space and time. There is a clear need for both a continuation of existing observational time series, such as optical depths from satellites [77] and optical properties estimated from surface stations [78], as well as new measurement programs to constrain abundances and chemical interactions and to facilitate the development of improved parameterizations. Examples of developments that would aid the field include systematic aircraft measurement campaigns [79] and remote sensing of aerosol shortwave absorption [80].

Another challenge is the incomplete knowledge of anthropogenic aerosol emissions. The quantification of aerosols' effect on climate relies critically on spatially and temporally resolved emission inventories. These are typically developed using bottom-up approaches and depend on national information about economic and industrial activity, fuel use, and associated emission factors. Such information can, in turn, be highly uncertain and difficult to compile. While there are ongoing efforts to develop air pollution inventories in many countries, no globally consistent framework for reporting currently exists [81], resulting in geographically variable data availability and quality. Consequently, there is a wide range in the existing gridded global emission inventories, in terms of both temporal trends and absolute magnitudes, which contributes to uncertainty in historical aerosol-driven climate effects [82–84]. Improving emissions inventories, especially in regions where they have known issues, such as sub-Saharan Africa and south Asia, would enhance the utility of ESMs for both air quality and climate modeling studies. As recently outlined by Smith *et al*, an important step towards the development of comparable, consistent, and transparent estimates of aerosol (and, more generally, SLCF) emissions is the establishment of a common methodology. Such work has been initialized through the IPCC Task Force on National GHG Inventories, which was recently tasked with producing a methodology report on SLCFs [85]. Considering this work in coordination with existing GHG reporting may offer additional benefits, e.g. for assessing synergies between air pollution and climate mitigation strategies [81]. Notably, natural aerosols—e.g. from biogenic sources, wildfire emissions, or mineral dust—remain an understudied and under-observed aspect of the climate system [86–89], though their sources may themselves have a non-negligible anthropogenic component [90, 91].

Current ESMs also continue to produce strikingly different regional responses to aerosol emissions, though recent and planned community efforts are building greater consensus. Past and ongoing Model Intercomparison Projects (MIPs) and joint model-observation initiatives, such as the Precipitation Drivers and Response MIP (PDRMIP [92]), AeroCom initiative [93], Radiative Forcing MIP (RFMIP [94]), and Aerosol Chemistry MIP (AerChemMIP [95]) are helping build comprehensive understanding of the drivers of model differences and ways to leverage observations to improve model representation of aerosol processes. The recently initiated Regional Aerosol MIP [96] will apply this framework to quantify the contribution of regional aerosol emission changes to uncertainty in near-term climate change. The ESM development and regional aerosol-climate community must work together to continue improving the quantification of physical hazards associated with regional aerosol changes, including continued investment in aerosol process representation in ESMs and reduction of ESM biases.

The above uncertainties and knowledge gaps, however, do not reduce the imperative to incorporate the known regionally heterogeneous effects of aerosol emissions more comprehensively into policy facing toolkits. Inclusion of aerosols within these frameworks is critical to refining and extending current knowledge and to breaking the feedback loops (figure 3) that reduce investment in addressing knowledge gaps. As explicitly shown in the case of RCMs (figure 4), continuing to neglect aerosol effects, even if they introduce additional uncertainty, risks relying on overconfident, if not plainly biased, climate risk projections. This can in turn lead to short-sighted or poorly informed decision-making in policy [97]. Following best practices on communicating uncertainty will be particularly important in this context [98].

Integrating regional aerosol effects fully into our assessments of near-term climate risk will require concerted effort within, and stronger links between, the aerosol research, impact, risk, and scenario development communities, as well as related communities such as those working on air quality, health, and visibility. Building on recent efforts, we believe meaningful progress is both necessary and possible on a short time scale.

A key way forward, consistent with the evolution of IPCC methodology in the AR6, is the development of aerosol aware, computationally efficient emulators capable of reproduce regional climate features and variability. Emulators, statistical representations of the climate system trained on ESM simulations, are increasingly being used to circumvent the inevitable limit on the number of scenarios that can be run through full ESMs [99]. However, because current emulators are generally not capable of retaining the complexity of regional aerosol effects represented by ESMs, reliance on emulators will discount regional aerosol effects. Regionally resolving emulators capable of capturing heterogeneous climate responses to regional aerosol changes are already being developed, allowing the inclusion of regional aerosol effects in the simple climate models that translate ESM results for large parts of the climate impact and risk community [100, 101]. Here, the required functionality is an ability to represent diverse, yet realistic, evolutions of emissions of scattering and absorbing aerosols in different regions, beyond the combinations existing in widely studied pathways such as the main SSP realizations, in combination with a prescribed level of GHG-induced warming. The emulator should be able to rapidly produce a statistical sample of regional weather conditions, taking into account both local and remote effects of the resulting combined GHG and aerosol forcing [102–104]. The output of such emulators could be valuable in, for example, improving aerosol-specific statistical downscaling methodologies that account for the time-varying and pattern-dependent effects of aerosols and a range of other impact applications.

A valuable opportunity for linking aerosol studies to air quality and health impacts, and to joint influences with other SLCFs, is in chemical transport modeling (CTMs). CTMs are built around detailed representation of both aerosols and chemically active gases, have interactive atmospheric chemistry schemes, and are often used for studying air pollution distributions, long-range transport, and forecasting. In addition, they are generally driven by real meteorological data, taken from reanalysis, and are typically less resource-intensive to run than ESMs. A key drawback is that, when run in isolation, CTMs do not capture couplings and feedbacks from the simulated species on weather and climate. However, increasingly, CTMs are incorporated as atmospheric chemistry modules in ESMs, which may then be referred to as chemistry-climate models. Although computationally more costly, this, combined with methods such as nudging, offers new and improved opportunities to study air quality and climate in a more integrated framework. A recent example is the use of chemistry-climate ensemble simulations to study the role of natural variability in ozone concentration trends [105], though these efforts have been emerging for the last decade or more [106].

Increased implementation of aerosol processes in regional models will also be valuable, given their use across decision-making applications. While plans for downscaling of sixth Climate Model Intercomparison Project (CMIP6) are still being finalized, advances in RCM representation of aerosol and inclusion of their time evolved changes are still at their infancy and currently look likely to be incremental rather than transformational. Within the CORDEX context, open inclusion of diverse modeling groups has traditionally been a central part of how CORDEX works, as this allows ownership, production, and understanding of regional climate projections to accrue to groups geographically closer to where these RCM simulations are applied. A side effect of this, however, is that contributing groups may make use of modeling tools that are several generations behind state-of-the-art ESMs in their aerosol representation. Recently developed Regional ESMs present an opportunity to counteract this drawback [54, 107]. Adoption of these will need both community buy-in and wider dissemination of these new modeling tools to participating groups.

Finally, such novel, aerosol-aware modeling approaches will need to be operationalized and adopted by a wider community. Assumptions about the drivers of regional aerosol emissions in IAMs, which have confined the range of future aerosol emissions trajectories in the scenarios used in the IPCC reports, need to be interrogated, inter-compared, and refined. More comprehensive representation of regional aerosol emissions and their effects in the ESM-emulator-IAM ecosystem (figure 3) will enable quantification of a wider range of possible hazards from aerosol changes, which will need to be incorporated into the impact models used by various communities to translate physical hazards into regional climate risk. Aerosol-driven climate risks will then need to be integrated into policy and stakeholder discussions to ensure that scientific advances translate into improved societal outcomes. All of this will require the creation of new spaces for interaction among these communities and resources to facilitate knowledge transfer and co-creation of solutions. A timely opportunity is the current design and development of the CMIP7 ensemble and core simulation request. Here, aerosol differences can easily be given even better representation than in previous generations of CMIP, perhaps with a particular focus on aerosol effects on near-term climate change as is done in the Regional Model Intercomparison Project (RAMIP) [96]. Such a design would unlock subsequent opportunities for analyzing regional hazard evolution, conditioned on the chosen balance between regional aerosol emissions and global GHG forcing, and novel opportunities for tuning regionally resolved, aerosol-aware emulators for wider community usage.

Strong and rapid changes in regional aerosol emissions will continue to influence global and regional climate in the coming decades: accelerating GHG-driven warming in some regions, counteracting it in others, and interacting with natural variability to further stress human and ecological systems in a climate that is already outside previous experience [108]. The tools and processes we use to quantify climate risk, however, currently fail to fully capture the regionally heterogeneous and rapidly evolving climate effects of aerosols. Meaningful progress is possible through concerted interaction between the aerosol-climate, impact assessment, and policy communities, focusing on updating our modeling frameworks to enable climate risk estimates that incorporate the latest knowledge on regional aerosol-climate interactions. Achieving this goal is urgently needed if we are to avoid dangerous surprises in the coming decades of rapid climate change.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

The authors acknowledge graphical support by Jeffrey Horowitz. The work contribution of C B was performed under the auspices of the US Department of Energy (DOE) by Lawrence Livermore National Laboratory under Contract No. DE-AC52–07NA27344.

Funding

National Science Foundation Grant CNH-L 1715557 (G G P)

Research Council of Norway Grant 248834 (QUISARC) (B H S, M T L)

Research Council of Norway Grant 324182 (CATHY) (B H S, M T L, R J A, L J W)

OE Regional and Global Model Analysis Program, PCMDI ‘Earth System Model Evaluation Project’ Science Focus Area (C B).

Lamont Center for Climate and Life, Columbia University (D M W)

H2020 Societal Challenges Grant No. 101003826 (CRiceS) (J M)

Author contributions

All authors contributed to the conceptualization. Manuscript writing was led by G G P, B H S, and L J W with review and editing input from all authors. Visualizations were contributed by T C, G G P, M T L, B H S, L J W, and A Z.

Conflict of interest

Authors declare that they have no competing interests.

ORCID iDs

G Persad https://orcid.org/0000-0003-4690-0867
B H Samset https://orcid.org/0000-0001-8013-1833
Robert J Allen https://orcid.org/0000-0003-1616-9719
Ben B B Booth https://orcid.org/0000-0002-0715-2141
Tom Crocker https://orcid.org/0000-0001-7761-5546
Marianne T Lund https://orcid.org/0000-0001-9911-4160
Joonas Merikanto https://orcid.org/0000-0002-1145-2569
Daniel M Westervelt https://orcid.org/0000-0003-0806-9961
Alcide Zhao https://orcid.org/0000-0002-8300-5872

References

[1] Samset B H, Lund M T, Bollasina M, Myhre G and Wilcox L 2019 Emerging Asian aerosol patterns *Nat. Geosci.* **12** 582–4

[2] Zheng Y, Xue T, Zhang Q, Geng G, Tong D, Li X and He K 2017 Air quality improvements and health benefits from China's clean air action since 2013 *Environ. Res. Lett.* **12** 114020

[3] Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

[4] Samset B H *et al* 2018 Weak hydrological sensitivity to temperature change over land, independent of climate forcing *npj Clim. Atmos. Sci.* **1** 1–8

[5] Salzmann M 2016 Global warming without global mean precipitation increase? *Sci. Adv.* **2** e1501572

[6] Samset B H, Sand M, Smith C J, Bauer S E, Forster P M, Fuglestvedt J S, Osprey S and Schleussner C-F 2018 Climate impacts from a removal of anthropogenic aerosol emissions *Geophys. Res. Lett.* **45** 1020–9

[7] Zhao A, Bollasina M A and Stevenson D S 2019 Strong influence of aerosol reductions on future heatwaves *Geophys. Res. Lett.* **46** 4913–23

[8] Sillmann J, Pozzoli L, Vignati E, Kloster S and Feichter J 2013 Aerosol effect on climate extremes in Europe under different future scenarios *Geophys. Res. Lett.* **40** 2290–5

[9] Allen R J *et al* 2021 Significant climate benefits from near-term climate forcer mitigation in spite of aerosol reductions *Environ. Res. Lett.* **16** 034010

[10] Samset B H *et al* 2016 Fast and slow precipitation responses to individual climate forcers: a PDRMIP multimodel study *Geophys. Res. Lett.* **43** 2016GL068064

[11] Lewinschal A, Ekman A M L, Hansson H-C, Sand M, Berntsen T K and Langner J 2019 Local and remote temperature response of regional SO_2 emissions *Atmos. Chem. Phys.* **19** 2385–403

[12] Deser C, Phillips A S, Simpson I R, Rosenbloom N, Coleman D, Lehner F, Pendergrass A G, DiNezio P and Stevenson S 2020 Isolating the evolving contributions of anthropogenic aerosols and greenhouse gases: a new CESM1 large ensemble community resource *J. Clim.* **33** 7835–58

[13] Tian F, Dong B, Robson J and Sutton R 2018 Forced decadal changes in the East Asian summer monsoon: the roles of greenhouse gases and anthropogenic aerosols *Clim. Dyn.* **51** 3699–715

[14] Marvel K, Biasutti M and Bonfils C 2020 Fingerprints of external forcings on Sahel rainfall: aerosols, greenhouse gases, and model-observation discrepancies *Environ. Res. Lett.* **15** 084023

[15] Polson D, Bollasina M, Hegerl G C and Wilcox L J 2014 Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols *Geophys. Res. Lett.* **41** 6023–9

[16] Allen R J, Evan A T and Booth B B B 2015 Interhemispheric aerosol radiative forcing and tropical precipitation shifts during the late twentieth century *J. Clim.* **28** 8219–46

[17] Wilcox L J, Highwood E J and Dunstone N J 2013 The influence of anthropogenic aerosol on multi-decadal variations of historical global climate *Environ. Res. Lett.* **8** 024033

[18] Herbert R, Wilcox L J, Joshi M, Highwood E and Frame D 2021 Nonlinear response of Asian summer monsoon precipitation to emission reductions in South and East Asia *Environ. Res. Lett.* **17** 014005

[19] Marvel K, Cook B I, Bonfils C J W, Durack P J, Smerdon J E and Williams A P 2019 Twentieth-century hydroclimate changes consistent with human influence *Nature* **569** 59

[20] Hegerl G C, Brönnimann S, Cowan T, Friedman A R, Hawkins E, Iles C, Müller W, Schurer A and Undorf S 2019 Causes of climate change over the historical record *Environ. Res. Lett.* **14** 123006

[21] Acosta Navarro J C *et al* 2017 Future response of temperature and precipitation to reduced aerosol emissions as compared with increased greenhouse gas concentrations *J. Clim.* **30** 939–54

[22] Rotstayn L D, Collier M A, Chrastansky A, Jeffrey S J and Luo -J-J 2013 Projected effects of declining aerosols in RCP4.5: unmasking global warming? *Atmos. Chem. Phys.* **13** 10883–905

[23] Samset B H, Fuglestvedt J S and Lund M T 2020 Delayed emergence of a global temperature response after emission mitigation *Nat. Commun.* **11** 3261

[24] Health Effects Institute 2020 *State of Global Air 2020* Special Report Health Effects Institute, Boston, MA (available at: www.stateofglobalair.org/sites/default/files/documents/2022-09/soga-2020-report.pdf)

[25] Rahman M M *et al* 2022 The effects of coexposure to extremes of heat and particulate air pollution on mortality in California: implications for climate change *Am. J. Respir. Crit. Care Med.* **206** 1117–27

[26] IPCC 2021 Annex VII: glossary *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) pp 2215–56

[27] Wang Z, Lin L, Xu Y, Che H, Zhang X, Zhang H, Dong W, Wang C, Gui K and Xie B 2021 Incorrect Asian aerosols affecting the attribution and projection of regional climate change in CMIP6 models *npj Clim. Atmos. Sci.* **4** 1–8

[28] Westervelt D M, Horowitz L W, Naik V, Golaz J-C and Mauzerall D L 2015 Radiative forcing and climate response to projected 21st century aerosol decreases *Atmos. Chem. Phys.* **15** 12681–703

[29] Levy H, Horowitz L W, Schwarzkopf M D, Ming Y, Golaz J-C, Naik V and Ramaswamy V 2013 The roles of aerosol direct and indirect effects in past and future climate change *J. Geophys. Res. Atmos.* **118** 4521–32

[30] Partanen A-I, Landry J-S and Matthews H D 2018 Climate and health implications of future aerosol emission scenarios *Environ. Res. Lett.* **13** 024028

[31] Gillett N P and Salzen K V 2013 The role of reduced aerosol precursor emissions in driving near-term warming *Environ. Res. Lett.* **8** 034008

[32] Kloster S, Dentener F, Feichter J, Raes F, Lohmann U, Roeckner E and Fischer-Bruns I 2010 A GCM study of future climate response to aerosol pollution reductions *Clim. Dyn.* **34** 1177–94

[33] Wilcox L J *et al* 2020 Accelerated increases in global and Asian summer monsoon precipitation from future aerosol reductions *Atmos. Chem. Phys.* **20** 11955–77

[34] Zhang L, Wilcox L J, Dunstone N J, Paynter D J, Hu S, Bollasina M, Li D, Shonk J K P and Zou L 2021 Future changes in Beijing haze events under different anthropogenic aerosol emission scenarios *Atmos. Chem. Phys.* **21** 7499–514

[35] Luo F, Wilcox L, Dong B, Su Q, Chen W, Dunstone N, Li S and Gao Y 2020 Projected near-term changes of temperature extremes in Europe and China under different aerosol emissions *Environ. Res. Lett.* **15** 034013

[36] Scannell C *et al* 2019 The influence of remote aerosol forcing from industrialized economies on the future evolution of East and West African rainfall *J. Clim.* **32** 8335–54

[37] Schmale J, Zieger P and Ekman A M L 2021 Aerosols in current and future Arctic climate *Nat. Clim. Change* **11** 95–105
[38] Rao S *et al* 2017 Future air pollution in the shared socio-economic pathways *Glob. Environ. Change* **42** 346–58
[39] Zhao A D, Stevenson D S and Bollasina M A 2019 The role of anthropogenic aerosols in future precipitation extremes over the Asian Monsoon region *Clim. Dyn.* **52** 6257–78
[40] Krishnan S, Ekman A M L, Hansson H-C, Riipinen I, Lewinschal A, Wilcox L J and Dallafior T 2020 *Geophys. Res. Lett.* **47** e2019GL086681
[41] Wilcox L J, Dunstone N, Lewinschal A, Bollasina M, Ekman A M L and Highwood E J 2019 Mechanisms for a remote response to Asian anthropogenic aerosol in boreal winter *Atmos. Chem. Phys.* **19** 9081–95
[42] Dow W J, Maycock A C, Lofverstrom M and Smith C J 2021 The effect of anthropogenic aerosols on the aleutian low *J. Clim.* **34** 1725–41
[43] Dong B, Sutton R T, Highwood E J and Wilcox L J 2015 Preferred response of the East Asian summer monsoon to local and non-local anthropogenic sulphur dioxide emissions *Clim. Dyn.* **46** 1733–51
[44] Dong B, Sutton R T, Highwood E and Wilcox L 2014 The impacts of European and Asian anthropogenic sulfur dioxide emissions on Sahel rainfall *J. Clim.* **27** 7000–17
[45] Undorf S, Polson D, Bollasina M A, Ming Y, Schurer A and Hegerl G C 2018 Detectable impact of local and remote anthropogenic aerosols on the 20th century changes of West African and South Asian monsoon precipitation *J. Geophys. Res. Atmos.* **123** 4871–89
[46] Westervelt D M, Conley A J, Fiore A M, Lamarque J-F, Shindell D T, Previdi M, Mascioli N R, Faluvegi G, Correa G and Horowitz L W 2018 Connecting regional aerosol emissions reductions to local and remote precipitation responses *Atmos. Chem. Phys.* **18** 12461–75
[47] Westervelt D M, Mascioli N R, Fiore A M, Conley A J, Lamarque J-F, Shindell D T, Faluvegi G, Previdi M, Correa G and Horowitz L W 2020 Local and remote mean and extreme temperature response to regional aerosol emissions reductions *Atmos. Chem. Phys.* **20** 3009–27
[48] Persad G G and Caldeira K 2018 Divergent global-scale temperature effects from identical aerosols emitted in different regions *Nat. Commun.* **9** 1–9
[49] van Vuuren D P, Batlle Bayer L, Chuwah C, Ganzeveld L, Hazeleger W, van den Hurk B, van Noije T, O'Neill B and Strengers B J 2012 A comprehensive view on climate change: coupling of earth system and integrated assessment models *Environ. Res. Lett.* **7** 024012
[50] Jägermeyr J *et al* 2021 Climate impacts on global agriculture emerge earlier in new generation of climate and crop models *Nat. Food* **2** 873–85
[51] Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O and Schewe J 2014 The inter-sectoral impact model intercomparison project (ISI–MIP): project framework *Proc. Natl Acad. Sci.* **111** 3228–32
[52] Boé J, Somot S, Corre L and Nabat P 2020 Large discrepancies in summer climate change over Europe as projected by global and regional climate models: causes and consequences *Clim. Dyn.* **54** 2981–3002
[53] Pavlidis V, Katragkou E, Prein A, Georgoulias A K, Kartsios S, Zanis P and Karacostas T 2020 Investigating the sensitivity to resolving aerosol interactions in downscaling regional model experiments with WRFv3.8.1 over Europe *Geosci. Model Dev.* **13** 2511–32
[54] Wong D C, Pleim J, Mathur R, Binkowski F, Otte T, Gilliam R, Pouliot G, Xiu A, Young J O and Kang D 2012 WRF-CMAQ two-way coupled system with aerosol feedback: software development and preliminary results *Geosci. Model Dev.* **5** 299–312
[55] Fiedler S and Putrasahan D *Geophys. Res. Lett.* **48** e2020GL092142 accepted
[56] Burney J, Persad G, Proctor J, Bendavid E, Burke M and Heft-Neal S 2022 Geographically resolved social cost of anthropogenic emissions accounting for both direct and climate-mediated effects *Sci. Adv.* **8** eabn7307
[57] Taranu I S, Somot S, Alias A, Boé J and Delire C 2022 Mechanisms behind large-scale inconsistencies between regional and global climate model-based projections over Europe *Clim. Dyn.* 1–26
[58] Nabat P, Somot S, Mallet M, Sevault F, Chiacchio M and Wild M 2015 Direct and semi-direct aerosol radiative effect on the Mediterranean climate variability using a coupled regional climate system model *Clim. Dyn.* **44** 1127–55
[59] Nabat P, Solmon F, Mallet M, Kok J F and Somot S 2012 Dust emission size distribution impact on aerosol budget and radiative forcing over the Mediterranean region: a regional climate model approach *Atmos. Chem. Phys.* **12** 10545–67
[60] Bartók B, Wild M, Folini D, Lüthi D, Kotlarski S, Schär C, Vautard R, Jerez S and Imecs Z 2017 Projected changes in surface solar radiation in CMIP5 global climate models and in EURO-CORDEX regional climate models for Europe *Clim. Dyn.* **49** 2665–83
[61] Nabat P, Somot S, Mallet M, Sanchez-Lorenzo A and Wild M 2014 Contribution of anthropogenic sulfate aerosols to the changing Euro-Mediterranean climate since 1980 *Geophys. Res. Lett.* **41** 5605–11
[62] Seneviratne S *et al* 2021 Weather and climate extreme events in a changing climate *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Integovernmental Panel on Climate Change* ed V Masson-Delmotte, P Zhai, A Pirani, S L Connors, C Pean and S Berger (Cambridge: Cambridge University Press) pp 1513–766
[63] Douville H *et al* 2021 Water cycle changes *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Integovernmental Panel on Climate Change* (Cambridge University Press)
[64] Lee J-Y *et al* Future global climate: scenario-based projections and near-term information *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Integovernmental Panel on Climate Change* (Cambridge University Press) (available at: www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_04.pdf)
[65] Stohl A *et al* 2015 Evaluating the climate and air quality impacts of short-lived pollutants *Atmos. Chem. Phys.* **15** 10529–66
[66] Gulev S K *et al* 2021 Changing state of the climate system
[67] Eyring V *et al* 2021 Human influence on the climate system. In climate change 2021: the physical science basis. Contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change *IPCC Sixth Assess. Rep.*
[68] Szopa S *et al* 2021 Short-lived climate forcers *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (https://doi.org/10.1017/9781009157896.008)
[69] Sharma S and Dodman D 2022 Cities, settlements and key infrastructure (Intergovernmental Panel on Climate Change (IPCC))
[70] Riahi K, Schaeffer R, Arango J, Calvin K, Guivarch C, Hasegawa T, Jiang K, Kriegler E, Matthews R and Peters G P 2022 Mitigation pathways compatible with long-term goals
[71] Dhakal S, Minx J C, Toth F L, Abdel-Aziz A, Figueroa M J, Hubacek K, Jonckheere I G, Yong-gun K, Nemet G and Pachauri S 2022 Emissions trends and drivers *Climate Change 2022: Mitigation of Climate Change* (IPCC: Intergovernmental Panel on Climate Change)
[72] Costa M H, Cotrim da Cunha L, Cox P M, Eliseev A V, Hensen S, Ishii M, Jaccard S, Koven C, Lohila A and Patra P K 2021 Global carbon and other biogeochemical cycles and feedbacks(IPCC)

[73] Xu Y, Lamarque J-F and Sanderson B M 2018 The importance of aerosol scenarios in projections of future heat extremes *Clim. Change* **146** 393–406
[74] Lin J, Pan D, Davis S J, Zhang Q, He K, Wang C, Streets D G, Wuebbles D J and Guan D 2014 China's international trade and air pollution in the United States *Proc. Natl Acad. Sci.* **111** 1736–41
[75] Peters G P, Minx J C, Weber C L and Edenhofer O 2011 Growth in emission transfers via international trade from 1990 to 2008 *Proc. Natl Acad. Sci.* **108** 8903–8
[76] Bollasina M A, Ming Y and Ramaswamy V 2011 Anthropogenic aerosols and the weakening of the South Asian summer monsoon *Science* **334** 502–5
[77] Schutgens N *et al* 2020 An AeroCom–AeroSat study: intercomparison of satellite AOD datasets for aerosol model evaluation *Atmos. Chem. Phys.* **20** 12431–57
[78] Gliß J *et al* 2021 AeroCom phase III multi-model evaluation of the aerosol life cycle and optical properties using ground- and space-based remote sensing as well as surface *in situ* observations *Atmos. Chem. Phys.* **21** 87–128
[79] Kahn R A *et al* 2017 SAM-CAAM: a concept for acquiring systematic aircraft measurements to characterize aerosol air masses *Bull. Am. Meteorol. Soc.* **98** 2215–28
[80] Li J *et al* 2022 Scattering and absorbing aerosols in the climate system *Nat. Rev. Earth Environ.* **3** 363–79
[81] Smith S J, McDuffie E E and Charles M 2022 Opinion: coordinated development of emission inventories for climate forcers and air pollutants *Atmos. Chem. Phys.* **22** 13201–18
[82] Elguindi N *et al* 2020 Intercomparison of magnitudes and trends in anthropogenic surface emissions from bottom-up inventories, top-down estimates, and emission scenarios *Earths Future* **8** e2020EF001520
[83] Lund M T, Myhre G, Skeie R B, Samset B H and Klimont Z 2022 Differences between recent emission inventories strongly affect anthropogenic aerosol evolution from 1990 to 2019 preprint, Aerosols/Atmospheric Modelling/Troposphere/Chemistry (chemical composition and reactions) (https://doi.org/10.5194/acp-2022-639)
[84] Saikawa E *et al* 2017 Comparison of emissions inventories of anthropogenic air pollutants and greenhouse gases in China *Atmos. Chem. Phys.* **17** 6393–421
[85] IPCC Methodology report on short-lived climate forcers— (available at: www.ipcc.ch/report/methodology-report-on-short-lived-climate-forcers/)
[86] Carslaw K S *et al* 2013 Large contribution of natural aerosols to uncertainty in indirect forcing *Nature* **503** 67–71
[87] Carslaw K S, Gordon H, Hamilton D S, Johnson J S, Regayre L A, Yoshioka M and Pringle K J 2017 Aerosols in the pre-industrial atmosphere *Curr. Clim. Change Rep.* **3** 1–15
[88] Gomez J, Allen R J, Turnock S T, Horowitz L W, Tsigaridis K, Bauer S E, Olivié D, Thomson E S and Ginoux P 2023 The projected future degradation in air quality is caused by more abundant natural aerosols in a warmer world *Commun. Earth Environ.* **4** 1–11
[89] Zhao X, Allen R J and Thomson E S 2021 An implicit air quality bias due to the state of pristine aerosol *Earths Future* **9** e2021EF001979
[90] Ginoux P, Prospero J M, Gill T E, Hsu N C and Zhao M 2012 Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS deep blue aerosol products *Rev. Geophys.* **50** RG3005
[91] Hoyle C R *et al* 2011 A review of the anthropogenic influence on biogenic secondary organic aerosol *Atmos. Chem. Phys.* **11** 321–43
[92] Myhre G *et al* 2016 PDRMIP: a precipitation driver and response model intercomparison project—protocol and preliminary results *Bull. Am. Meteorol. Soc.* **98** 1185–98
[93] Kinne S *et al* 2006 An AeroCom initial assessment—optical properties in aerosol component modules of global models *Atmos. Chem. Phys.* **6** 1815–34
[94] Pincus R, Forster P M and Stevens B 2016 The radiative forcing model intercomparison project (RFMIP): experimental protocol for CMIP6 *Geosci. Model Dev.* **9** 3447–60
[95] Collins W J *et al* 2017 AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6 *Geosci. Model Dev.* **10** 585–607
[96] Wilcox L J *et al* 2022 The regional aerosol model intercomparison project (RAMIP) *Geosci. Model Dev. Discuss.* 1–40
[97] Parker W S and Risbey J S 2015 False precision, surprise and improved uncertainty assessment *Phil. Trans. R. Soc.* A **373** 20140453
[98] Kause A, de Bruin W B, Domingos S, Mittal N, Lowe J and Fung F 2021 Communications about uncertainty in scientific climate-related findings: a qualitative systematic review *Environ. Res. Lett.* **16** 053005
[99] Nicholls Z *et al* 2021 Reduced complexity model intercomparison project phase 2: synthesizing earth system knowledge for probabilistic climate projections *Earths Future* **9** e2020EF001900
[100] Tebaldi C and Arblaster J M 2014 Pattern scaling: its strengths and limitations, and an update on the latest model simulations *Clim. Change* **122** 459–71
[101] Herger N, Sanderson B M and Knutti R 2015 Improved pattern scaling approaches for the use in climate impact studies *Geophys. Res. Lett.* **42** 3486–94
[102] Watson-Parris D *et al* 2022 ClimateBench v1.0: a benchmark for data-driven climate projections *J. Adv. Model. Earth Syst.* **14** e2021MS002954
[103] Beusch L, Nicholls Z, Gudmundsson L, Hauser M, Meinshausen M and Seneviratne S I 2022 From emission scenarios to spatially resolved projections with a chain of computationally efficient emulators: coupling of MAGICC (v7.5.1) and MESMER (v0.8.3) *Geosci. Model Dev.* **15** 2085–103
[104] Tebaldi C, Snyder A and Dorheim K 2022 STITCHES: creating new scenarios of climate model output by stitching together pieces of existing simulations *Earth Syst. Dyn.* **13** 1557–609
[105] Fiore A M *et al* 2022 Understanding recent tropospheric ozone trends in the context of large internal variability: a new perspective from chemistry-climate model ensembles *Environ. Res. Clim.* **1** 025008
[106] Marsh D R, Mills M J, Kinnison D E, Lamarque J-F, Calvo N and Polvani L M 2013 Climate change from 1850 to 2005 simulated in CESM1(WACCM) *J. Clim.* **26** 7372–91
[107] Giorgi F 2019 Thirty years of regional climate modeling: where are we and where are we going next? *J. Geophys. Res. Atmos.* **124** 5696–723
[108] Hawkins E, Frame D, Harrington L, Joshi M, King A, Rojas M and Sutton R 2020 Observed emergence of the climate change signal: from the familiar to the unknown *Geophys. Res. Lett.* **47** e2019GL086259