Broader research efforts and assessments needed to uncover the complex climate effects of regional changes in aerosol emissions

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OPINION

Broader research efforts and assessments needed to uncover the complex climate effects of regional changes in aerosol emissions

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Human activities are associated with two dominant drivers of global climate change: Greenhouse gases (GHGs), and atmospheric aerosols. Both are well studied and discussed in the scientific literature, and assessed in a series of reports from the Intergovernmental Panel on Climate Change (IPCC). For instance, the latest IPCC report, IPCC AR6, assessed a current global warming of about 1.5 ˚C from GHG emissions since 1850–1900, counteracted by 0.4 ˚C of cooling from aerosol emissions [1].

However, aerosols also drive strong, regionally heterogenous climate impacts, both near to and far from emission sources, that are distinct from those of GHGs, and also have a different time evolution. Further, aerosol emissions are rapidly changing, and will continue to do so over the coming decades; due to air quality policies and industrialization, but also from feedbacks to global warming in natural systems. The regional influences from these emission changes can be similar, if not larger, in magnitude as compared to the effects of GHGs on decadal time scales, in addition to their modulating effect on global mean GHG driven warming [2]. The IPCC AR6 report only briefly covered this complicating factor, mainly because there was very little literature to assess. The upcoming AR7 report may have an even more difficult time, as the most widely used underlying scenarios used by the climate modelling community (CMIP7) are likely to have far less diversity in future aerosol emissions than the previous generation (CMIP6) [3].

If the community is to be able to deliver the necessary information on climate hazard evolution over the coming decades, for impact and adaptation studies, there is therefore critical need for (i) a global research effort focusing on the regional influences of changes in aerosol emissions, (ii) diversity in future aerosol emission represented in commonly used global emission scenarios, notably those for CMIP7, and (iii) inclusion of aerosol-climate effects in high resolution tools such as regional models, downscaling approaches and dedicated impacts studies such as flooding or crop yield modelling, relevant for the Working Group 2 contribution to the upcoming IPCC 7^{th} Assessment Report.

Aerosols are key for understanding regional climate change

The influences of GHG and aerosol emissions on global mean temperatures over the historical era are well understood [1]. Beyond this, however, aerosols and GHGs differ markedly in their climate interactions. Aerosols have atmospheric lifetimes of only a few days, meaning that they exert their radiative forcing primarily close to the emission sources. However, through interactions with atmospheric and oceanic circulation, and through affecting global temperatures, they also affect the climate over long distances. Further, their radiative interactions are different to GHGs, predominantly acting to scatter incoming shortwave radiation, and having different absorption properties in both the long and shortwave spectra. One consequence of this is that they influence precipitation differently to aerosols, with recent model studies indicating that the balance between GHGs and aerosols is close to being equal over the historical era [4].

A last, key difference, related to the short atmospheric lifetimes of aerosols, is that when emissions change, the atmospheric concentrations rapidly respond, and therefore also their climate effects. This, indeed, is what is currently happening. Rapid air pollution cleanup is occurring in some regions, while others are seeing increases. Natural processes such as wildfires, dust and biogenic emissions, and wind induced sea spray are also altering the amounts of aerosols. Recent studies have shown that these changes have strong influences on regional climate phenomena. This includes magnitudes and rates of change of temperature and precipitation extremes [5], influences on monsoon circulations [6], and on wildfire risk [7]. As a result, the detailed evolution of both anthropogenic and natural species of atmospheric aerosols, and their climate interactions, are all key pieces of the puzzle of current and future climate hazards–and therefore, also, adaptation needs.

Current regional aerosol modelling efforts

To date, however, few coordinated efforts have been made to disentangle the climate influences of regional aerosol emissions in a multi-model setting. Globally, aerosols and GHGs have regularly been simulated separately over the historical era in detection and attribution settings, such as DAMIP [8]. The most recent coordinated aerosol specific modelling effort was AerChemMIP, designed to quantify the mid-century climate effects of a low aerosol emissions scenario [9]. Regional aerosol perturbations, however, were not employed. The global and regional effects of idealized perturbations were studied by the PDRMIP collaboration [10], and regional transport and radiative forcing has been quantified by the Task Force on Hemispheric Transport of Air Pollution (HTAP) [11]. Individual studies have also contributed critical knowledge on the regional dependence on emission region, albeit with differing setups making intercomparisons challenging. The Shared Socioeconomic Pathways used through the CMIP6 era also include a variety of assumptions on regional air quality policies, leading to starkly differing pathways in aerosol loading over the coming decades [12].

These efforts have uncovered and quantified a substantial regional heterogeneity in aerosol influences on global quantities. A large number of regional studies have also quantified the climate and air quality effects of aerosols near emission sources [13].

What is needed for projecting near-term climate evolution is, however, a full inventory of near- and remote effects of realistic, transient evolutions of aerosol emission changes, in a multi-model setting, with multiple simulations per model (large initial condition ensembles) to separate the competing influences of internal variability for weak forcing strengths. This is the aim of the Regional Aerosol Model Intercomparison Project (RAMIP) [14], which will deliver its first results in 2024. RAMIP is part of the second generation of coordinated experiments using CMIP6 era global climate models. Its main methodology is to use a high-aerosol-emission pathway as baseline (SSP3-7.0), and switch out emissions to a low-emission pathway (SSP1-2.6) for one region at a time. In its initial phase, RAMIP covers the regions East Asia, South Asia, Africa and the Middle East, and Europe and the US. Future phases will include additional regions, and splits between absorbing and scattering aerosol species. The aim is to have a thorough understanding of the regional-to-regional influences of aerosol emissions, near to, and far from emissions sources, by the time of the IPCC AR7 assessment and its contributions to the UNFCCC Global Stocktake process. Examples of topics to be covered include the local, regional, and global influences of the recent strong cleanup of Chinese SO_2 emissions, and disentangling the influence on climate features in Sub-Saharan Africa from local emissions and those arising from teleconnections from remote sources.

Regional aerosols in the CMIP7 era

In CMIP6, and in ScenarioMIP, which provided the main scenario climate projection information for the IPCC AR6, the decision to use Shared Socioeconomic Pathways that differ in their assumptions on future air quality policy was hugely beneficial. However, even here only a subset of the possible combinations of regional changes was sampled, and key uncertainties were left unexplored. An example is the broad uncertainty in future aerosol emissions in Sub-Saharan Africa, depending critically on the rapid industrial, economic and political evolution of the region. For the upcoming CMIP7, however, it is likely that the main scenarios to be explored in global climate models will all assume a rapid reduction in global air pollution. Limits on computational capacity also contribute to reducing the number of ensemble members requested in planned global aerosol related simulations, such as the ones in AerChemMIP, which is a strongly limiting factor for determining regional responses. And finally, regional climate models such as the ones used in CORDEX still do not always have interactive treatment of aerosol processes, leading to challenges in reproducing local climate features [15]. This is acknowledged and being worked on e.g. in Euro-CORDEX, but so far has not been broadly discussed for the next generation of CORDEX experiments.

Hence, there is a critical need for supplementary efforts that detail not only the potential global influences of aerosols, but those from a given pattern of regional emissions. Without this information, for instance, developing statistical emulators capable of representing sub-annual climate features on a regional basis will not be possible. Such emulators are a natural extension of the workflow developed during the AR6 process, connecting IPCC Working Groups 1 and 3 to provide climate response information for a wider range of global emission scenarios. For AR7, there is an opportunity to make similar efforts to connect to the impact and vulnerability assessments of Working Group 2, provided that the relevant communities are given sufficient time to develop literature connecting to local knowledge and adaptation needs. Again, this speaks to the need for a rapid community effort to identify, disentangle and quantify the region-to-region influences of the current rapid changes in aerosol emissions, and how they interplay with greenhouse gas dominated global warming, feedbacks from natural aerosol processes, and internal variability in the climate system. Further, the physical science basis assessment of Working Group 1 can be substantially extended by including information on regional aerosol influence on precipitation, extreme events, sub-seasonal weather features, interactions with internal variability, and the timescales of responses after an emissions change. RAMIP will provide a dataset capable of answering some of these questions, but closing the full range of knowledge gaps requires a broader community effort.

Author Contributions

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