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Aerosol-Cloud Interactions: Overcoming a Barrier to Projecting Near-Term Climate Evolution and Risk

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Key Points:

- Aerosol-cloud interactions (ACI) remain a barrier to provide precise and actionable advice to policy makers at global and regional levels
- We recommend improving satellite retrievals, expanding ground-based measurements, refining climate models, and advancing machine learning
- Collaboration across research communities will enhance understanding of ACI, the climate projections and policy recommendations

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Aerosol-cloud interactions (ACI) are a major source of uncertainty in climate science, critically affecting our ability to project near-term climate evolution and assess societal risks. These interactions influence effective radiative forcing, cloud dynamics, and precipitation patterns, yet remain insufficiently constrained due to limitations in observations, modeling, and process understanding. This uncertainty hampers robust policy advice across multiple domains—from estimating remaining carbon budgets and climate sensitivity, to anticipating regional extreme events and evaluating climate interventions such as solar radiation modification. In many cases, the influence of ACI is either underappreciated or excluded from decision-making frameworks due to its complexity and lack of quantification. This perspective outlines a path forward to overcome these barriers by leveraging emerging opportunities in satellite remote sensing, ground-based and airborne observations, high-resolution climate modeling, and machine learning. We identify key areas where rapid progress is feasible, including improved retrievals of cloud microphysical properties, better representation of natural aerosols in a warming world, and enhanced integration of observational and modeling communities. Even as anthropogenic aerosol and its impacts on clouds is reducing owing to emissions controls, addressing ACI uncertainties remains essential for refining climate projections, supporting effective mitigation and adaptation strategies, and delivering actionable science to policymakers in a rapidly changing climate system.

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Plain Language Summary Clouds have a big influence on Earth's climate. They affect how much sunlight is reflected or trapped, and how weather patterns form. But understanding clouds is very hard-especially how they interact with tiny particles in the air called aerosols. These particles come from human activities and sources like wildfires, volcanoes. The way aerosols and clouds affect each other is one of the most uncertain parts of climate science. Because of this uncertainty, it's difficult to make accurate predictions about climate change and to give clear advice to decision-makers. Scientists have made some progress in understanding aerosol-cloud interactions, but more work is needed. With better tools, observations, and computer models, we can learn more over the next decade. However, because the climate is changing quickly and impacts are getting worse, we need faster action now. This summary explains the current knowledge on how aerosols and clouds interact, and why it's important to reduce the uncertainty. It also highlights what steps can help improve our understanding-such as global collaboration and sharing knowledge between researchers, governments, and the public. Making faster progress in this area is key to better climate predictions, stronger climate policies, and lower risks for people and the planet.

1. Introduction

The atmosphere is laden with suspended liquid or solid aerosol particles of nano- to micron-sizes. Aerosols are either emitted directly into the atmosphere—primary aerosols (e.g., dust, sea salt, soot), or form through chemical reactions of precursor gases—secondary aerosols (e.g., sulfates, nitrates, organics). Aerosols impact the radiative balance directly by absorbing/scattering radiation (aerosol-radiation interactions: ARI) or indirectly through aerosol-cloud interactions (ACI).

The effective radiative forcing (ERF) from aerosol–radiation interactions is estimated to be -0.3 W m^{-2} (very likely range -0.6 to 0.0 W m^{-2}; medium confidence) according to IPCC AR6 (P. Forster et al., 2021), indicating a net cooling that partly offsets greenhouse gas warming. Uncertainty remains high due to variations in aerosol composition, vertical distribution, and regional emission patterns, though it has narrowed compared to AR5 as constraints from satellite and surface radiation data improved. Recent assessments give a total aerosol forcing around -0.85 W m^{-2} [-1.65 to -0.25] (P. M. Forster et al., 2025) with ARI contributing roughly one-quarter of the magnitude and the remaining uncertainty arising from ACI (Bellouin, Quaas, et al., 2020). Regionally, TOA ARI exerts up to -2 to -4 W m^{-2} (Kasoar et al., 2018; Szopa et al., 2021) over polluted areas in South and East Asia but is minimal elsewhere, producing hemispheric asymmetries (Loeb et al., 2025) that have affected monsoons and precipitation (Z. Li et al., 2016). Many studies have shown that the surface forcing can be much larger of opposite signs with that inside the atmospheric column due to the trade-off between surface cooling and atmospheric warming. Such a contrast has very significant implications for atmospheric dynamics and convection due to drastically altered temperature lapse rate. This is especially strong in Asia, for example, $-14/14$ W m^{-2} over the Indian Ocean (Ramanathan et al., 2001) and $-20/18$ W m^{-2} across China (Z. Li et al., 2010). Because ARI's cooling is short-lived, rapid aerosol emission reductions will unmask ∼0.1–0.3°C of near-term global warming unless accompanied by deep greenhouse-gas cuts (P. Forster et al., 2021), giving a total masking of ∼0.5 together with ACI. The remainder of this perspective will focus on ACI, which globally induces a larger cooling compared to ARI, and with a larger uncertainty (AR6).

Aerosols alter cloud properties by acting as cloud condensation nuclei (CCN), affecting cloud droplet concentrations (Köhler, 1936) and size (Twomey, 1959), or as ice nucleating particles (INPs: Murray et al., 2021), influencing ice production and cloud phase (liquid/ice amount). Clouds are highly efficient at scattering and absorbing radiation, playing a major role in Earth's energy budget. Anthropogenic ACI perturb the global radiation balance, termed Effective Radiative Forcing (ERF) of ACI (ERFaci). This includes changes in cloud albedo, water content, and cloud fraction CF. The IPCC's AR6 report (P. Forster et al., 2021) estimates ERFaci at -1.0 W m^{-2}, about half the ERF magnitude of CO2 increases over the industrial era (1.98 W m^{-2}; 1750–2014). However, the wide 90% confidence interval (-1.7 to -0.3 W m^{-2}) makes ERFaci the largest contributor to historical ERF uncertainty, and hence to anthropogenic surface temperature change (Figure 1). Despite decades of research, knowledge gaps in ACI remain (P. Forster et al., 2021; Seinfeld et al., 2016). Modeling and observational evidence in AR6 support the negative ERFaci estimate, suggesting aerosols mask a portion of greenhouse gas-driven warming. Progress since AR5 has improved scientific confidence from low to medium.

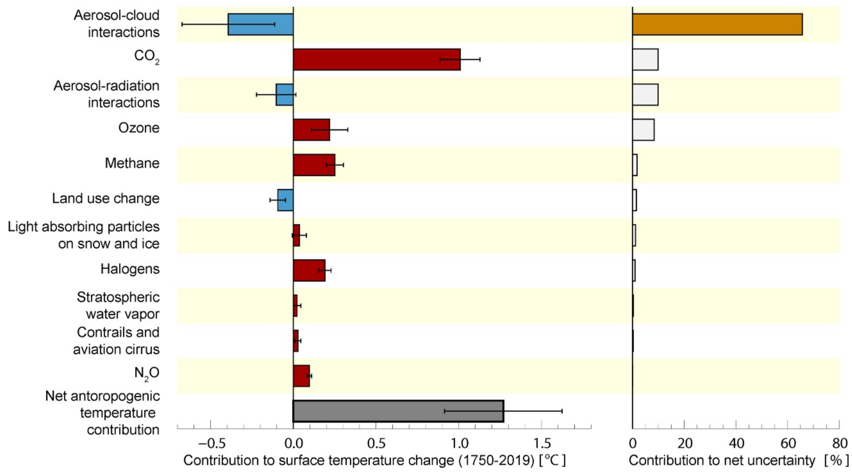

Figure 1. Aerosol-cloud interactions dominate the uncertainty on recent estimates of anthropogenic surface temperature change. Left: Contributions to global mean surface temperature (GSAT) change (1750–2019) from individual forcing components, including uncertainties as assessed by the IPCC AR6. Right: Relative contribution to the total uncertainty on historical GSAT change, estimated by re-calculating the uncertainty with one component excluded. Rows are ordered from high to low contributions to the total GSAT change uncertainty. All numbers from IPCC AR6 WG1 Chapter 7.

Human activities emit large amounts of aerosols and precursors, augmenting natural sources. Anthropogenic aerosols significantly modify cloud properties, as evident in ship (Conover, 1966) and aircraft tracks (Well, 1919), and downwind of industrial facilities (Hobbs et al., 1970; Toll et al., 2024), and settlements (Rosenfeld & Woodley, 2000). Natural sources of aerosols such as volcanoes are found to significantly modify cloud properties (Toll et al., 2017). Recent research highlights that decreasing anthropogenic aerosols reduces their masking effect on greenhouse gas-induced warming (Diamond, 2023; Quaas et al., 2022). Air quality regulations will likely further reduce primary aerosol emissions (Turnock et al., 2020), leading to changes in cloud properties under cleaner aerosol conditions. Natural aerosols (e.g., fire aerosols, dust, secondary organic aerosols) may thus play a greater role, creating heterogeneous climate forcing distinct from greenhouse gases (Persad et al., 2022). Regional and temporal heterogeneity in aerosol impacts necessitates understanding aerosol-cloud cycles across different regimes to improve projections.

ERF_{aci} uncertainty arises from its dependence on cloud type. Current assessments focus on large-scale clouds, while effects on convective clouds, which involve significant uncertainties, are not fully integrated into global climate models (Stier et al., 2024). AR6 acknowledges that the main part of the assessed ERF is for liquid-water clouds, and that ACI in ice/mixed-phase clouds are much less constrained (e.g., Mülmenstädt & Feingold, 2018). Small-scale observations and process models provide insights but are challenging to scale globally (Bellouin, Davies, et al., 2020). Long-term measurements of aerosols, CCN, and INPs remain sparse, especially over under sampled regions, like much of the Global South, and remote areas such as the Southern Ocean. While it is evident that the scarcity of aerosol in these remote regions strongly feeds back on cloud properties, the involved process chains are still debated on (He et al., 2025; Radenz et al., 2021). Major uncertainties persist in INP observations, modeling source strengths, the role of in-cloud turbulence, and ice formation processes at warmer subzero temperatures, where ice crystal concentrations often exceed INP concentrations by orders of magnitude (Georgakaki et al., 2022; Wieder et al., 2022). The sensitivity of clouds to warm-temperature INPs depends on secondary ice production processes, among the least understood areas of cloud microphysics due to observational challenges (Field et al., 2017).

Satellites play a crucial role in understanding ACI. However, satellite instruments have difficulty constraining ACI directly due to limitations on the data available (e.g., retrievals of aerosols and clouds have been mutually exclusive). While comparisons with aircraft data have shown that many cloud microphysical properties can be well retrieved in stratocumulus clouds (Gryspeerdt et al., 2022), the retrievals are less reliable in broken cloud regimes, where even retrievals of straightforward properties (e.g., cloud fraction) can be uncertain (Rosenfeld et al., 2023). This is a particular issue for studies of cloud adjustments, which may be stronger in regions of broken clouds where the cloud fraction can be modified (S. Chen et al., 2023).

For projecting future climate change, Earth System Models (ESMs) are still the only viable tools available to the community. However, clouds are heavily parametrized in ESMs, and their simulated ERFaci strongly depends on the details of the parametrizations. Past studies are heavily biased toward shallow liquid clouds to the detriment of mixed-phase clouds, deep convective clouds, and ice clouds. This bias happened despite evidence that all types of clouds potentially contribute to ERFaci, while several cloud types such as convective clouds are poorly or not at all treated in ESMs. Prominent issues, such as the Southern-Ocean shortwave radiation bias (Fiddes et al., 2022; Kay et al., 2016) clearly show that the current representation of aerosol and dynamics in model simulations is still far away from being able to accurately capture regional differences, even on large oceanic scales. The simulation of ice crystal concentrations in ESMs is affected by the representation of INP concentrations and their uncertainties, which leads to discrepancies in the modeled top-of-atmosphere radiative flux and, thereby, in the overall climate sensitivity of the models to greenhouse gases (Vergara-Temprado et al., 2018).

Aerosol effects on deep convective clouds influence precipitation and extreme events (Acosta Navarro et al., 2017; Fan & Li, 2022; Y. Li et al., 2017), yet these remain difficult to model due to coarse spatial resolution. Resolving mesoscale storms and extreme rainfall requires km-scale resolutions (Fosser et al., 2024), which are not feasible for routine long-term climate modeling (Schär et al., 2020). Current high-resolution climate ensembles and CORDEX models lack prognostic ACI (Haarsma et al., 2016), limiting their ability to investigate precipitation effects.

In summary, constraining ACI remains a significant challenge in climate science. ACI dominates the remaining uncertainty in human-induced warming over the industrial era, and induces major uncertainties also for precipitation, extreme events and other weather and climate factors. These uncertainties have strong implications for policymakers, limiting the robust assessment of the impacts of potential strategies to mitigate and adapt to climate change, which can ultimately evolve into policy.

2. Where ACI Uncertainties Are Currently Barriers to Good Policy Advice

Understanding ACI, and constraining their influence on anthropogenic climate change, are in themselves key scientific challenges. However, given the rapid rate of global warming and the urgency of implementing emissions mitigation and adaptation measures, the remaining large uncertainties associated with this set of processes are also hindrances for delivering solid and quantitative knowledge to policy makers and stakeholders. Critically the limitations posed by ACI may not even be fully acknowledged, possibly leading to overreliance on some conclusions. In other cases, the possibilities or explanations that lie in ACI may not be fully taken into consideration, because they are regarded as too uncertain. In this section, we outline some of these situations.

2.1. Explaining Recent Global Surface Temperature Trends and Records

An acceleration in energy accumulation in the global ocean since the 1990s has been documented by a range of studies (Cheng et al., 2024). Recently, an uptick has also been seen in the global top-of-atmosphere energy imbalance (Loeb et al., 2024), in the overall heating of the Earth System (Minière et al., 2023), and in global mean surface warming (P. M. Forster et al., 2025). The increase in energy imbalance over recent decades has been attributed partly to a global reduction in anthropogenic aerosol emissions (Hodnebrog et al., 2024). Notably, the year 2023 became the warmest on record, by a margin that surprised many. Throughout the year, record ocean surface temperatures were observed in multiple basins, including in the Central and East Pacific, where an El Nino event unfolded (Samset et al., 2024). Beyond the influence of ocean variability, however, several aerosol related mechanisms have been proposed. These include the strong, rapid and sustained reductions in Chinese SO_2 emissions (Samset et al., 2025), the 2020 International Maritime Organization regulations reducing SO_2 emissions from intercontinental shipping (Diamond, 2023; Yuan et al., 2022), and the low amounts of Saharan dust. Residual effects from the stratospheric water vapor injected by the January 2022 Hunga Tonga volcanic eruption has also been suggested as a contributing factor (Schoeberl et al., 2024).

While upcoming research will likely constrain the influences of each of these factors on recent temperature trends, ACI uncertainty remains a limiting factor. As an example, recent changes in shipping SO_2 emissions force the climate directly via sulfate aerosols, and indirectly via ship tracks, which occur when ship-emitted aerosols interact with low clouds. The 2020 International Maritime Organization fuel regulations contributed to reducing ship-track frequency to its lowest level in recent decades (Yuan et al., 2022). However, the influence of this change on the global and regional radiative balance or surface temperatures, is highly uncertain due to large internal variability (Watson-Parris et al., 2025).

Similarly, the influence of recent strong East Asian SO2 emission reductions, where the observational evidence is clear (Xiang et al., 2023) and modeling estimates of the climate influences of regional aerosol emissions exist (Gao et al., 2023; Samset et al., 2025), the ACI uncertainties are generally acknowledged as limiting factors. Notably, the potential for a saturation of the ACI with high aerosol loadings is important, as is the heterogeneous dynamical response of the climate system to regional forcing (Jia & Quaas, 2023). In combination, they mean that even for a known change in global aerosol loading from East Asian sulfur emissions, the total, realized local radiative forcing is poorly constrained, as are the subsequent influences on local and remote surface temperature.

However, taken together with the earlier rise in anthropogenic aerosol emissions in East and South Asia, since around 1980, the industrialization and air quality policies in China and neighboring countries represents an ideal, if unintended, testbed for hypotheses concerning the broader impacts of anthropogenic activities on climate changes. As discussed below, this opportunity should be taken by the observational and modeling communities, as well as developers of climate model emulators and impact assessment frameworks (Persad et al., 2023).

2.2. Constraining the Equilibrium Climate Sensitivity and Transient Climate Response

The most recent assessment of equilibrium climate sensitivity (ECS), in the IPCC AR6 (P. Forster et al., 2021) was based on multiple lines of evidence; paleoclimate, feedback process understanding, emergent constraints, and historical observational record. Initially, aerosol ERF, and hence ACI, was only considered to be directly and strongly relevant for the last of these, the observational record. However, for transient climate response (TCR), the historical observational record is a more central line of evidence, and therefore aerosol ERF also becomes much more influential. Recent literature indicates that the overall aerosol forcing may be stronger than previously thought (Julsrud et al., 2022), partly due to not accounting for the coupling between clouds and the boundary layer (Su et al., 2025). Apart from forcing, the natural aerosols, and their changing profiles from the effects of climate change, modulate clouds and precipitation. This means that the climate sensitivity is also shifting and ACI plays a critical role that goes beyond the established concept of "anthropogenic aerosol forcing" (Gettelman et al., 2016). Estimates of ECS and TCR are influenced by uncertainties in climate effects of aerosols, which are—in turn—dominated by ACI uncertainties. Interestingly, recent studies that use aerosol/cloud-observations in combination with ESMs give higher ECS/TCR than the central estimate in the IPCC AR6 assessment (P. Forster et al., 2021), while methods utilizing rates and/or patterns of warming in combination with ESMs give central ECS/TCR estimates close to, or lower than, the IPCC AR6 assessment (Ricard et al., 2024)—but also do not rule out the higher values. Clearly, further work is required to resolve these apparent discrepancies in these different lines of evidence. Better constraints on ACI is a key component in this work, as it represents a dominating source of uncertainty for a core constraint on ECS and TCR.

2.3. Pinning Down the Remaining Carbon Budget

Estimates of the amount of carbon we may still emit while staying below 1.5°C, or any other strong mitigation target, are heavily influenced by the uncertainty in non-CO_2 forcing (P. Forster et al., 2021). The uncertainty in non-CO_2 ERF is, in turn, dominated by the uncertainty in ACI (P. Forster et al., 2021). Uncertainty in ERFaci relevant for carbon budgets includes both the geophysical uncertainty of how strong the present day ACI is (how much warming has been offset), and scenario uncertainty in how emissions trends will develop in the coming years. The majority of the more than 1000 emissions scenarios produced by integrated assessment models that are assessed by the IPCC show a decline in aerosol emissions in the coming decades (Riahi et al., 2022), due to an expected strengthening of clean air policies around the world (Rao et al., 2017), with large uncertainty in future natural emissions in a warming world. Rapid reductions in aerosols remove their temporary cooling, causing an earlier and higher peak warming that can influence the level and duration of any temperature overshoot of 1.5°C even if levels later fall below Paris targets. This is relevant, since climate risks depend on peak as well as long-term warming (Schleussner et al., 2024). Slower phase-outs delay this unmasking but prolong pollution. Because aerosols mainly affect near-term forcing, their earlier reduction tightens the remaining carbon budget—by roughly 100–200 Gt CO_2—making early, deep greenhouse-gas cuts essential to limit both overshoot and peak warming (IPCC, 2021). This gradual reduction in net cooling influence reduces the available space for CO_2 emissions and hence limits the remaining carbon budget (Shindell & Smith, 2019; Stjern et al., 2023). Revisions to how ERFaci and its uncertainty is assessed can therefore have significant impacts on the 1.5°C carbon budget, given the small amount of headroom left until this limit is exceeded (P. M. Forster et al., 2025; Lamboll et al., 2023). More generally, ACI is a strong determinant of the expected warming from any emissions pathway and can make the difference to whether a mitigation scenario is consistent with Paris Agreement temperature goals or not (Watson-Parris & Smith, 2022).

2.4. Projecting Regional Precipitation Change and Likelihood of Extreme Events

Understanding the rates and magnitudes of changes in precipitation and extreme weather events are among the most crucial topics for adaptation strategies. Here, ACI comes in because aerosols affect atmospheric radiation via different physical mechanisms to greenhouse gases, notably through changing clouds, and through scattering and absorbing shortwave radiation. Broad consensus and strong theoretical evidence exist that ACI is a contributing driver of global precipitation changes, mediated via affecting atmospheric energetics and surface evaporation. ACI is also causing well-documented shifts of large-scale precipitation patterns, such as the inter-tropical convergence zone. The extent of aerosol effects on precipitation at smaller scales is however less clear. Aerosol perturbations microphysically increase cloud droplet numbers and decrease droplet sizes, thereby slowing precipitation formation, however the overall aerosol effect on precipitation across scales remains highly uncertain (Stier et al., 2024). Therefore, a better understanding of ACI and their representation in climate models can lead to more robust science-based policy.

Aerosol forcing is much more localized than greenhouse gas forcing, has stronger seasonal and diurnal variations, and influences regions far from the emission sources via tropical (Dong et al., 2014) and midlatitude (Wilcox et al., 2019) teleconnections. Several studies have shown that the overall influence of aerosols on precipitation and extreme event rates is different to greenhouse gases (Stier et al., 2024). A recent review (Wang et al., 2022) also explored the specific influence of aerosols on meteorological extremes, noting the specific mechanisms affecting temperature, winds, humidity, turbulence and boundary layer conditions, and subsequent extreme conditions. Black carbon, which imposes strong heating aloft through shortwave absorption, is expected to have an outsized effect on precipitation, both directly, and indirectly via modifying clouds (ACI) (Samset et al., 2024). Additionally, studies demonstrate aerosol influences on monsoons, tropical cyclones, extreme heat waves, thunderstorms and more (Persad et al., 2023; Rosenfeld et al., 2007), including efforts exploiting the unintended experiment presented by the recent decadal scale changes in East Asian aerosol emissions (Z. Li et al., 2016, 2019). These regional impacts also have important implications on policy. Models that represent convection and cloud formation in any detail (convection resolving models, regional climate models) generally do not yet include aerosols treatment, or ACI, and those that have ACI included do not agree on the strength and sign of their effect (Marinescu et al., 2021).

In summary, the current uncertainty in ACI is hampering proper projections of both the frequency of extremes under present and future conditions, and the properties of individual events or compounds of multiple extremes.

2.5. Providing Advice on the Efficiency and Side Effects of Solar Radiation Modification

Some types of solar radiation modification, notably cloud brightening and cirrus cloud thinning, rely on aerosol induced modification of cloud properties. It is noted that cloud brightening refers to both land and ocean—while often marine cloud brightening is considered since such clouds are more susceptible to aerosol perturbations, there may be reasons to focus on continental clouds as well (Quaas et al., 2016). We also note that some studies consider mixed-phase clouds in solar radiation modification schemes as well (Villanueva et al., 2022). Please note the inconsistency in the term "solar radiation modification" for cirrus and mixed-phase cloud thinning which in fact target mainly terrestrial radiation. ACI uncertainties therefore influence our ability to constrain the climate responses both directly, and indirectly, by also limiting our ability to interpret natural analogs such as volcanic eruptions. While climate models indicate that reducing global-mean temperatures via solar radiation modification techniques is feasible in principle, a wide range of side effects are to be expected, differing between the type of implementation (Stjern et al., 2018). Cloud brightening and cirrus and mixed-phase cloud thinning technologies are of interest since in principle they can be applied at a scale limited in space and time (Gruber et al., 2019; Hernandez-Jaramillo et al., 2025; Villanueva et al., 2022), for example, targeting only specific regions and/or targeting mitigation of specific climate extremes such as heatwaves (Afroz et al., 2023). However, it is unclear to which extent it is feasible to indeed limit effects, and modeling tools are not yet mature for reliable anticipation

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and attribution of the seeding outcomes (Quaas et al., 2016). Here, lack of ACI implementation and physical processes at high resolution is a critical shortcoming. Recently, marine cloud brightening has been considered to be effective based on the responses of cloud properties to volcanic eruptions (Y. Chen et al., 2024). However, since cloud brightening is proposed to be done using spraying of sea salt, processes related to spraying (e.g., evaporation of water) will have implications on cloud formation (Feingold et al., 2024) and is hence also limited by poor constraints on ACI. Better understanding and representation of ACI leads to better assessment of climate impacts of aerosol-based SRMs, as well as their possible adverse impacts on circulation and ecosystems, leading to more robust policy advice on the mitigation of climate change.

2.6. Quantifying the Link Between Extreme Weather Events, Air Quality and Global Health Issues

A well-known tradeoff in climate and air quality policy is that while reducing aerosol emissions leads to clear benefits for air quality and human and ecosystem health (Im et al., 2023; Wei et al., 2023), it also leads to a reduction in their masking of the warming induced by greenhouse gases (Yuan et al., 2024). Recent studies estimate that without this masking, global temperatures would already be close to 2°C above pre-industrial levels, rather than the ∼1.4°C currently observed (Hausfather, 2025). This "unmasking" effect has contributed approximately 0.14°C of the ∼0.5°C warming since 2007, with notable contributions from declining sulfur emissions in China (Samset et al., 2025) and maritime fuel regulations. The sulfur content regulation is a typical example of the trade-off between air quality and climate policy trade-offs. While no policy advocates weakening air quality standards to mitigate warming, the interplay between aerosol reductions, climate extremes, and health impacts must be better understood. Reductions in aerosols can exacerbate extreme weather events—such as heatwaves, floods, and droughts—by accelerating warming and altering precipitation patterns (Akinyoola et al., 2024; Persad et al., 2022). These events pose direct and indirect health risks, including respiratory and cardiovascular stress and mortality. A major barrier to quantifying these risks is the regional dependency of aerosols and their interactions with clouds and their sensitivity to cloud-surface coupling, diurnal cycles, and aerosol composition (Herbert et al., 2025; Su et al., 2025). The clouds also impact the incoming radiation, which drives formation of certain atmospheric species like O3, which impact air quality (Im et al., 2022), and therefore human health (Im et al., 2023), as well as ecosystems (Emberson, 2020). To move forward, it is essential to adopt a holistic approach to understanding aerosol and cloud life cycles across different regimes. Such efforts are critical not only for improving climate projections but also for developing robust risk assessments and early warning systems that can inform adaptation strategies under varying aerosol emission futures. 2.1 A descriptive heading about methods.

3. Next Steps for Advancing Aerosol-Cloud Interaction Research

Having highlighted the remaining knowledge gaps in our understanding of how ACI influences the current and future changes to the global climate, and the limitations they pose for the ability of the scientific community to deliver actionable policy advice, the next step is to outline a plan for closing the knowledge gaps in a timely manner. There are emerging opportunities in observations, modeling, analysis and computing techniques, and community efforts, that open for rapid progress if properly leveraged. These opportunities are summarized in Table 1, along with their timelines of when concrete results can be achieved in immediate, short (1–5 years), mid (5–10 years), and longer (10–20 years) terms.

3.1. Improving Satellite Data and Retrieval Accuracy

Satellite data are essential for providing global-scale insights into ACI, but are limited with respect to resolution, sensitivity and available observables. This together with limitations in current retrieval methods leads to difficulties in accurately determining cloud micro- and macrophysical properties such as droplet number concentration, cloud-top phase, liquid water path and cloud fraction, particularly in broken cloud regimes. Furthermore, retrievals of cloud condensation nuclei (CCN) concentrations are hampered by lack of information content or retrieval biases (Hasekamp, Gryspeerdt, & Quaas, 2019). These uncertainties in satellite-based retrievals hinder our understanding of ACI and its role in climate change. A holistic view of different measurement techniques and platforms is therefore essential to transfer knowledge gained on smaller scales (cloud to regional scale) to the larger scale (continental to global scale), and to define observables serving as indicators for different processes. Therefore, the next steps should focus on:

Table 1
Recommendations to Address Uncertainties and Knowledge Gaps in Aerosol-Cloud Interactions (ACI)

Recommendations	Timescale
Improving Satellite Data and Retrieval Accuracy	
Reassessing satellite constraints (Dubovik et al., 2021)	Next 5–10 years
Combining ground based in situ and remote sensing (Papagiannopoulos et al., 2016)	Next 1–5 years
Combining observations and models within data assimilation systems (Scheck et al., 2020)	Next 1–5 years
Enhancing Observational Campaigns and Ground-Based Measurements	
Expanding vertical profile measurements (Lopatin et al., 2021)	Next 10–20 years
Drones and balloons for in situ profiling (Kahn et al., 2017)	Next 10–20 years
Systematic aircraft measurements of key aerosol properties and ACI processes (Kahn et al., 2017, 2023)	Next 5–10 years
Refining Climate Models to Accurately Simulate ACI	
Developing aerosol-aware, high-resolution models (Fosser et al., 2024)	Next 5–10 years
Process-based model evaluation (Blichner et al., 2024; Virtanen et al., 2025)	Next 1–5 years
Improved representations of aerosol size distributions and updrafts (Burgos et al., 2020)	Next 1–5 years
Leveraging Upcoming Satellite Missions for ACI	
Maximizing data from EarthCARE and PACE (Wehr et al., 2023; Werdell et al., 2019)	Next 5–10 years
Utilizing new polarimetric instruments (Hasekamp, Fu, et al., 2019; Hasekamp, Gryspeerdt, & Quaas, 2019)	Next 5–10 years
Long-term monitoring via METOP-SG and CO2M (Dubovik et al., 2019)	Next 10–20 years
Focusing on Post-Fossil Natural Aerosols	
Improving understanding of natural aerosol (Schmale et al., 2021)	Next 1–5 years
Improving understanding of interactions within and between natural and post-fossil anthropogenic aerosols (Dada et al., 2022; Sharma et al., 2019)	Next 1–5 years
Investigating aerosol-cloud feedbacks (Gong et al., 2023; Yli-Juuti et al., 2021)	Next 1–5 years
Laboratory studies of cloud relevant properties for natural aerosol and cloud microphysical processes (NASEM, 2016)	Next 1–5 years
Exploiting the unintended experiment posed by strong decadal trends in East Asian and natural aerosols (Samset et al., 2025)	Next 1–5 years
Advancing Machine Learning Applications in ACI Research	
Incorporating physical constraints into ML models (Eyring et al., 2024)	Next 1–5 years
Developing climate model emulators (Watson-Parris, Christensen, et al., 2022; Watson-Parris, Rao, et al., 2022)	Next 5–10 years
ML for satellite retrieval algorithms (Kim et al., 2021)	Next 1–5 years
Improving Communication and Collaboration Across ACI Research Communities	
Fostering cross-disciplinary research (Kahn et al., 2023)	Immediate
Expanding data accessibility (Lopatin et al., 2021)	Immediate

Note. Timescale shows when the recommended actions can result in improving our understanding of ACI and/or their representation in weather and climate models.

3.1.1. Reassessing Satellite Constraints

New advancements in satellite technology necessitate revisiting existing retrieval algorithms. Much of the current understanding of aerosol impacts on clouds is based on satellite retrievals of cloud properties like droplet concentration and liquid water path and their relationships. However, recent studies reveal that these cloud retrievals often carry significant biases due to assumptions made in the retrieval process (Arola et al., 2022), as in the case of cloud fraction in broken cloud regimes (Rosenfeld et al., 2023). Furthermore, retrieved aerosol products, such as spectral aerosol optical depth, are shown to be biased or poor proxies for CCN (Hasekamp, Gryspeerdt, &

Quaas, 2019). The cloud and aerosol microphysical retrieval schemes should be improved by refining the algorithms based on updated scattering models (Gasteiger & Wiegner, 2018) and by adding missing information from remote sensing (i.e., polarization, fluorescence: Dubovik et al., 2021; Grosvenor et al., 2018; Lv et al., 2018; Patel et al., 2024; Quaas et al., 2020). Updating these constraints by incorporating newer retrieval techniques will provide more reliable global estimates of ACI and reduce uncertainties in estimating the ERF_{aci}.

3.1.2. Multi-Instrument Synergy

The deep synergy approaches exploring complementarity of multi-instrument observations is another promising direction for improving accuracy of remote sensing products needed for ACI studies (Dubovik et al., 2021). Indeed, no single sensor provides comprehensive information about aerosol and cloud properties, especially in a complex environment. Therefore, there is always a need to inject the missing information from complementary observations, modeling or other sources of knowledge. Specifically, ACI investigations will clearly benefit from synergy of passive imagery with active vertical profiling (Ewald et al., 2021) of the atmosphere performed at different spectral ranges and at different time or spatial scales. In addition, once the instruments have been deployed, the quality of measurements cannot be radically improved, while the processing algorithms remain under constant improvement and the final product can be notably improved by fusion of information from the data sets based on the observations of different sensitivities. Furthermore, the combination of different techniques (e.g., in situ and remote sensing) allows us to transfer information about changes in the aerosol and cloud microphysical properties to observables in remote sensing measurements, which is essential to observe specific processes from space. Similarly, combining satellite observations with sub-orbital measurements and chemical transport model results is expected to be increasingly utilized for ACI analysis.

3.1.3. Combining Ground-Based and Aircraft Measurements, and Satellite Remote Sensing

Although satellite observations provide broad global coverage, they usually lack the detailed resolution and precision of ground-based and aircraft remote sensing and in situ measurements. Quality- assured suborbital measurements from ground and air are needed to validate the satellite products, improve the retrieval algorithms and advance the retrieved information by utilizing synergies from ground/air/space. Ground-based remote sensing measurements provide long-term, real-time, high-quality data on aerosol optical properties, which can be used to validate and refine satellite retrievals (Kanitz et al., 2014; Papagiannopoulos et al., 2016; Wandinger et al., 2010). Airborne measurements with similar instrumentation but higher precision, sensitivity and resolution allow for direct comparisons for validation, verification and algorithm test, assuring sufficient quality of satellite measurements for ACI studies. High resolution airborne measurements during dedicated campaigns are furthermore crucial to increase our knowledge on ACI processes but are limited in time and space. It is thus essential to combine these missions with long-term ground-based and satellite measurements to transfer this knowledge to a long-term and global scale. Combination of different measurement techniques are the backbone in defining observables retrieved from long-term and satellite missions that lead as indicators for ACI processes. European Research Infrastructures such as ACTRIS (Laj et al., 2024) and US facilities such as ARM are of paramount importance, to provide the quality assured aerosol and cloud remote sensing and in situ data from ground, while other infrastructures (e.g., IAGOS) can add airborne information from commercial aircraft worldwide (Thouret et al., 2022). In addition, dedicated field and flight experiments provide deep insights in ACI processes on a cloud to regional scale. Ground-based remote sensing techniques, such as LiDAR and radar, complemented by in situ aerosol and cloud microphysical measurements at high-altitude sites, offer the ability to observe cloud properties and aerosol profiles in three dimensions, providing a more comprehensive view of ACI processes (Wieder et al., 2022). Tailored experimental campaigns combining ground and airborne data sets during satellite overpasses are vital for addressing specific ACI objectives, by combining aircraft in situ, profiling and radiation measurements, and ground-based profiling from remote sensing techniques toward depicting a complete picture of ACI, helping to generalize detailed, localized measurements to the global scale. Integrating satellite, aircraft and ground-based data will enable more accurate retrievals of cloud properties in challenging conditions, such as regions with complex cloud dynamics. In addition, automations on adaptive cloud monitoring with scanning cloud radars and Doppler LiDARs will allow documenting the 3-D and 4-D cloud evolution, tracking of cloud elements to provide statistical representations of the evolution of the cloud structure and precipitation (Mason et al., 2023), and to improve retrievals of cloud microphysical properties (Heske et al., 2025).

3.1.4. Combining Observations and Models Within Data Assimilation Systems

Both traditional variational or ensemble-based and more recently ML-methods offer an ideal framework to combine observations and models to learn about ACI processes. In the data assimilation framework, it is possible to estimate atmospheric variables and model parameters that might be poorly observed (Scheck et al., 2020). For example, satellite data can be leveraged for global estimates of CCN by using the data assimilation as a sophisticated retrieval (Fielding & Janisková, 2020; Janisková & Fielding, 2020). The advantage of doing that is that dynamical, thermodynamical, and microphysical cloud and aerosol properties need to be consistent within the chosen assimilation system. Additionally, the data assimilation system can also exploit synergies between different observations (ground-based, space-borne, etc.), offering a unified framework for the treatment of model and observations.

3.2. Leveraging Upcoming Satellite Missions for ACI Insights

Several new satellite missions, such as ESA EarthCARE (Wehr et al., 2023), NASA PACE (Werdell et al., 2019), both launched in 2024, and ESA/EUMETSAT 3MI (Fougnie et al., 2018) are expected to provide groundbreaking data on ACI. These missions offer new opportunities to reduce uncertainties and improve constraints on climate models. Researchers should focus on maximizing the potential of these missions by integrating their data with existing observational and modeling frameworks, and to link them to ongoing or completed satellite missions for example, NASA's CALIPSO (Winker et al., 2010) and Cloudsat (Stephens et al., 2008) as well as their combined exploitation (Stephens et al., 2018). Key priorities include:

3.2.1. Maximizing Data From EarthCARE and PACE

The EarthCARE satellite provides unprecedented high-resolved correlative observations of aerosol, clouds, and radiation from space (Wehr et al., 2023). Its high-spectral-resolution LiDAR ATLID delivers, for the first time, global data sets of directly measured extinction profiles and thus invaluable information on aerosol properties at the altitudes where clouds reside and ACI takes place. Independent measurements of particle extinction-to-backscatter and depolarization ratios with ATLID allow for a dedicated aerosol classification (Wandinger et al., 2023), which is the precondition for CCN and INP concentration retrievals based on optical-to-microphysical conversion techniques (Ansmann et al., 2019).

The cloud-profiling radar CPR with its novel Doppler capability contributes information on convective motions as well as ice precipitation and rainfall speeds, leading to improved drizzle, rainfall and snowfall rates. Synergistic retrieval products based on multi-instrument data allow direct access to EarthCARE's combined aerosol, cloud, and precipitation information (Mason et al., 2023). Similarly, PACE mission delivers advanced polarimetric measurements of aerosol and cloud properties, allowing for unprecedented retrievals of cloud droplet size distributions and concentrations (Werdell et al., 2019). Climate models should be constrained with these data sets, once they are calibrated and validated (Cal/Val) against other independent measurements, to improve the accuracy of ACI simulations and reduce uncertainties in cloud radiative forcing.

3.2.2. Utilizing New Polarimetric Instruments

Instruments like HARP-2 and SPEXone on PACE are designed to measure the particle size distribution PSD of liquid clouds using polarimetric techniques. These instruments provide a more accurate calibration error-free retrieval of cloud droplet sizes compared to traditional bi-spectral retrievals, particularly in regions with inhomogeneous cloud structures (Alexandrov et al., 2012). Combining these observations with data from EarthCARE's high-spectral-resolution LiDAR will offer a powerful tool for constraining cloud microphysical properties and understanding aerosol-induced cloud adjustments. Aerosol retrievals from accurate Multi-Angle Polarimeter (MAP) measurements have the capability to provide aerosol size distribution, column-integrated number concentration, and composition (Dubovik et al., 2019). These properties determine the suitability of aerosols to act as CCN and therefore can be used to derive CCN proxies which are more suited to quantify ACI than proxies based on aerosol optical properties (Hasekamp, Gryspeerdt, & Quaas, 2019). The SPEXone instrument on PACE (Hasekamp, Fu, et al., 2019) is designed to provide such retrievals also over land and for cleaner conditions (e.g., over oceans), which are of high importance for ACI (Gryspeerdt et al., 2023).

3.2.3. Exploiting Temporal Information to Constrain ACI

Clouds and cloud adjustment to aerosol are inherently time-dependent (Q. Li & Groß, 2022)—failing to consider this can lead to large biases in estimates of ACI from natural experiments such as ship tracks (Glassmeier et al., 2021) or to investigate impacts of anthropogenic aerosols, for example, the impact of aviation induced aerosols on ice clouds. Building on the success of SEVIRI for cloud retrievals, the new generation of geostationary satellites (GOES, MTG-I) will provide a highly detailed picture of cloud temporal evolution at scales previously only accessible to snapshot imagery from polar-orbiting instruments. Coupled to new methods to characterize cloud development and the response to aerosol perturbations (Gryspeerdt et al., 2021), this will move constraints on ACI toward the process timescales essential for constraining global model behavior and parameterizations.

3.2.4. Long-Term Satellite Monitoring Through METOP-SG and CO2M Missions

The METOP-SG and CO2M missions, scheduled for launch later this decade, will provide long-term monitoring of aerosol and cloud properties over multiple decades (Dubovik et al., 2019). The METOP-SG mission, developed jointly by ESA and EUMETSAT, is designed to extend and enhance the capabilities of the first-generation METOP satellites, which have been operational since 2006. METOP-SG will ensure continuity of polar-orbiting meteorological observations for weather forecasting and climate monitoring over the next two decades. Unlike its predecessor, METOP-SG consists of instruments to observe atmospheric temperature, humidity, aerosols, cloud properties, and trace gases with significantly improved spatial resolution and accuracy. This continuity is essential for maintaining long-term climate records and detecting subtle trends in atmospheric composition and ACI.

The CO2M mission, part of the Copernicus Sentinel Expansion program, represents a new observational initiative focused specifically on monitoring anthropogenic greenhouse gas emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (NO_2). CO2M will deploy a constellation of three satellites equipped with advanced instruments, including the Integrated CO_2 and NO_2 Imaging Spectrometer (CO2I), a Multi-Angular Polarimeter (MAP), and a Cloud Imager. These instruments will enable high-resolution measurements of greenhouse gases and aerosols, facilitating the quantification and verification of human-induced emissions at regional and national scales. This mission is not a continuation of previous satellite programs but rather a strategic expansion aimed at supporting climate policy and emission reduction efforts under frameworks like the Paris Agreement.

In summary, these missions will be particularly valuable for detecting trends in aerosol emissions and their impacts on cloud systems. The continuity of these data sets will be critical for understanding how ACI evolves in response to changes in both natural and anthropogenic aerosol emissions.

3.3. Enhancing Observational Campaigns and Long-Term Ground-Based Measurements

Ground-based observations, eventually combined with aircraft data, provide critical information that satellite data alone cannot capture, greatly supporting ACI processes understanding (Virtanen et al., 2025). The wealth of synergies which arise from multi-sensor deployments is essential for improving our understanding of ACI and validating satellite observations. Observational campaigns, such as those involving ground-based remote sensing networks, must be expanded to fill key data gaps. The next steps in this area include:

3.3.1. Expanding Ground-Based Long-Term Vertical Profile Measurements

Accurate monitoring of aerosol and clouds requires advanced vertical profiling techniques. Synergies, both by means of technical aspects as well as retrieval-wise, provide a wealth of opportunities for extended approaches. Combined cloud radar and multi-field-of view LiDAR observations enable the characterization of liquid and ice cloud microphysical properties simultaneously (Jimenez et al., 2025). Fixed-altitude in situ or column-integrated observations can be scaled to the vertical dimension by calibration against profiling remote sensing measurements as it is done in LiDAR-based INP and CCN retrievals (Mamouri & Ansmann, 2016) or multi-instrument mixed-phase cloud retrievals (Pasquier et al., 2022). Scanning cloud Doppler radars and LiDARs are in addition key for retrieving further insights into aerosol and cloud processes. Scanning polarimetry complements the classification of detected targets (Myagkov et al., 2016; Teisseire et al., 2024) while Doppler-velocity-resolved observations provide insights into the co-located presence of targets in a cloud volume including the presence of secondary ice formation or liquid droplets in deep mixed-phase clouds (Billault-Roux et al., 2023; Schimmel et al., 2022; Vogl et al., 2024). Scanning observations in general can document cloud evolution in three and four dimensions and are thus key technologies for understanding aerosol impacts on cloud formation and dissipation. These tools can track the time-dependent responses of clouds to aerosol perturbations (Lopatin et al., 2021). For instance, cloud adjustments to aerosol perturbations, including changes in cloud fraction and liquid water content in globally frequently occurring situations of broken clouds will become trackable using scanning observations for following the evolution of a targeted air mass. By automating the collection of vertical profiles, the cloud life cycle and the processes that drive aerosol-induced cloud adjustments can be better captured.

3.3.2. Deploying Drones and Balloons for In Situ Profiling

In addition to ground-based instruments, drones and tethered balloons equipped with aerosol and cloud sensors are emerging as valuable tools for capturing detailed in situ profiles of CCN and INPs. These platforms allow for high-resolution measurements directly within clouds (Henneberger et al., 2023), providing data that is otherwise challenging to obtain with conventional aircraft. In situ measurements from these and piloted aircraft are crucial for understanding cloud formation mechanisms, aerosol activation processes, ice nucleation (Miller et al., 2025) and the vertical structure of clouds, as well as for obtaining detailed aerosol microphysical and chemical properties, such as particle hygroscopicity, mass extinction efficiency, and CCN spectrum, that are needed to quantify ACI processes but are currently lacking (Kahn et al., 2017).

3.4. Refining Climate Models to Accurately Simulate ACI

Climate models are the primary tools for predicting and projecting the future climate and how ACI will influence the Earth's radiative budget and broader climate in the future. However, these models are often limited by their coarse resolution and the incomplete representation of aerosol-cloud processes. Addressing these limitations will require significant improvements in model resolution, parameterization, and evaluation techniques. The next steps include:

3.4.1. Developing Aerosol-Aware, High-Resolution Models

Current global climate models and regional climate models typically run at resolutions that are too coarse to resolve cloud-scale processes. This limits the ability of models to accurately simulate extreme weather events and the influence of aerosols on cloud dynamics. Recent advances in high-resolution climate modeling, such as kilometer-scale models, offer the potential to resolve cloud dynamics more explicitly, improving the representation of ACI. These high-resolution models can simulate convection directly, providing more realistic simulations of mesoscale convective systems and extreme precipitation events (Fosser et al., 2024). Integrating interactive aerosols into these models will provide the first consistent assessments of ACI across different cloud types, although it is unclear what level of complexity is required to simulate ACI realistically in high-resolution models. The challenge in coupling ACI processes to high-resolution models will be the computational cost and the amount of data that will require simplification of aerosol-cloud modules. Machine learning will facilitate computational efficiency to account for complex ACI processes in climate models, e.g. through use of emulators that can replace some microphysical models or processes such as precipitation formation or vertical velocities (e.g., Ahola et al., 2022; Gettelman et al., 2021; Omanovic et al., 2025; Yuval & O'Gorman, 2020). They may also facilitate incorporation of previously computationally too demanding complexity, such as superdroplet parameterizations, through emulation (Sharma & Greenberg, 2025).

3.4.2. Process-Based Model Evaluation

Process-based model evaluation focuses on comparing modeled processes with observed processes rather than simply comparing bulk quantities. This approach allows for a more detailed understanding of how well models capture the physical processes and feedbacks underlying ACI (Omanovic et al., 2025). By integrating long-term observational data with satellite and in situ measurements, process-based evaluations can provide more robust constraints on model performance (Blichner et al., 2024; Virtanen et al., 2025). These evaluations are particularly valuable for understanding the complex interactions between aerosols, cloud microphysics, and atmospheric dynamics.

3.4.3. Improving Representations of Aerosol Size Distributions, Composition, and Updrafts

The ability of aerosols to influence cloud properties depends largely on aerosol size distribution and composition, and the strength of updrafts in the cloud. Current models often struggle to represent these factors sufficiently, leading to large uncertainties in estimates of cloud droplet number concentration and cloud albedo (Motos et al., 2023; Saponaro et al., 2020). Improvements in the representation of aerosol size distributions, aerosol composition, hygroscopicity, and updraft velocities are urgently needed to better capture the sensitivity of cloud properties to aerosols (e.g., Twomey effect, ice crystal formation, precipitation formation) (Burgos et al., 2020; Virtanen et al., 2025; Y. Zheng et al., 2015, 2021; F. Zheng et al., 2016). Global observations of updraft velocities at cloud base, where aerosol activation occurs, will be critical for improving model accuracy. While high-resolution climate models can better capture small-scale processes, the description of sub-grid scale processes such as cloud activation updrafts will remain a challenge. Finally, natural aerosols, such as dust and biological particles, which contribute to INPs and therefore ice production, should be included in models (Chatziparaschos et al., 2025; Fiedler et al., 2024; Gao et al., 2024).

3.5. Focusing on Natural Aerosols in a Post-Fossil Regime and Warming World

As the world transitions to cleaner energy sources, natural aerosols such as dust, sea salt, biogenic particles, and biomass burning aerosols will become increasingly important for determining future climate. In addition, climate change and human activity can lead to changes in emission strengths and locations, as well as in atmospheric processes associated with natural aerosols (Dall'Osto et al., 2018; Schmale et al., 2021). Understanding these dynamic natural aerosol sources and their interactions with clouds is essential for future climate projections. Future research must prioritize:

3.5.1. Improving Understanding and Modeling of Natural Aerosol Emissions

Natural aerosols, including sea salt, dust, fire, and biogenic aerosols from vegetation and the oceans, are expected to play a more significant role in the climate system as anthropogenic aerosols decrease (Toll et al., 2017). However, these sources remain poorly understood, with significant uncertainties surrounding how their emissions will respond to climate change (Galí et al., 2019; Kok et al., 2023; Mahowald et al., 2024; Pernov et al., 2024, 2025), adding to existing uncertainties in ACI and other aerosol effects. To improve future projections, studies must enhance baseline knowledge of natural aerosol emissions and their trends. Leveraging paleo data for components like dust and wildfire emissions could improve model constraints and sensitivity to climate and human impacts. Future studies must focus on improving the baseline understanding of natural aerosol emissions and their potential future trends.

3.5.2. Improving Understanding of Interactions Within and Between Natural and Post-Fossil Anthropogenic Aerosols

Altered emissions shift the ionic balance in particles and as a result their composition does not reflect directly the emission changes due to anthropogenic and natural aerosol interactions. For example, it has been observed that with less availability of sulfuric acid, due to cleaner air quality policies, the nitrate component in aerosols has increased, even though nitrogen dioxide emissions have been reduced simultaneously (Sharma et al., 2019). Another example is the enhanced presence of ammonium in particles, which allows natural acids such as methanesulfonic acid to preferentially enter the particle phase, while if ammonium were absent methanesulfonic acid would preferentially stay in the gas phase (Dada et al., 2022). As both anthropogenic and natural particle and precursor emissions change, we expect the composition of particles to change, however involving more complex chemical and thermodynamic processes. These processes need to be observed, understood, and modeling skill built.

3.5.3. Investigating Natural Aerosol-Cloud Feedback

Natural aerosols, such as dust, biomass-burning and biogenic particles, can act as CCN and INPs, influencing cloud formation and radiative forcing (Chatziparaschos et al., 2025; Gao et al., 2024; He et al., 2025). Research into how these aerosols contribute to cloud reflectivity and feedback mechanisms will be critical for improving estimates of cloud radiative forcing and constraining climate sensitivity (Yli-Juuti et al., 2021). Similarly, the influence of some natural aerosol sources on cloud properties, such as blowing snow in the polar regions, has only recently been addressed, because observations were not available for a quantitative assessment (Gong et al., 2023). Studies should also explore how changes in natural aerosol emissions due to climate change will affect cloud properties in different regions, such as how changes in the biogeochemistry of the oceans or continental vegetation will impact aerosol emissions and in turn may impact cloud properties in the coupled climate system.

3.5.4. Laboratory Studies of Cloud Relevant Properties for Natural Aerosol and Cloud Microphysical Processes

The aging of natural aerosols will result in an evolution of their CCN and INP properties, which carries important implications for the clouds and their impacts in future climate. There is a need for focused laboratory experiments (NASEM, 2016) to study these processes and their impact on cloud microphysics, leveraging existing infrastructures such as the ACTRIS. There is also a need for focused laboratory studies to probe cloud microphysical processes that are poorly understood (e.g., supersaturation distributions in warm and mixed phase clouds, secondary ice production, secondary activation, collision-coalescence and aggregation, aerosol scavenging in clouds). For these, established cloud chamber facilities such as PI (University of Michigan) and AIDA (Karlsruhe Institute of Technology) should be leveraged from. These experiments could form the basis for development of parameterizations that are critical for describing missing knowledge and processes in models. Such experiments can be deployed in the laboratory or under hybrid laboratory/field conditions and can provide targeted insight into interactions between anthropogenic and natural atmospheric constituents and their importance for ACI under post-fossil conditions.

3.5.5. Exploiting the Unintended Experiment Posed by Strong Decadal Trends in East Asian and Natural Aerosols

During the satellite era, East Asia has undergone rapid industrialization and economic growth, and their associated anthropogenic aerosol emissions from fossil fuel usage, followed by a highly successful cleanup effort, especially in China, since around 2010 (Samset et al., 2025). These strong, decadal scale emission trends have been well monitored, especially in later decades, and form a natural testbed for hypotheses regarding the local and remote climate effects of anthropogenic aerosol emissions (Z. Li, 2020; Persad et al., 2023). On top, Eastern North American emission declines as well as the IMO 2020 regulations have also been a useful cases. Concurrently, global warming has increased rates of natural aerosol emissions, including for example, wildfire and sea spray emissions in the same regions (Galí et al., 2019; Kok et al., 2023; Mahowald et al., 2024; Pernov et al., 2024). This conjunction represents a golden opportunity for probing cloud microphysics, atmospheric energetics, aerosol-precipitation processes, and more. While the community is already broadly exploiting this unintended experiment, there are still broad opportunities here when combined with the other avenues for advancement listed in this section.

3.6. Advancing Machine Learning Applications in ACI Research

Machine learning offers new opportunities for advancing ACI research by enabling more efficient analysis of satellite and climate model data, improving model parameterizations, and exploring previously unexplored scenarios. However, challenges remain in integrating machine learning models with physical climate models. Future steps should focus on:

3.6.1. Improving Satellite Retrievals

ML has the potential to revolutionize satellite data processing by addressing the limitations of traditional retrieval methods (Pelucchi et al., 2025; Yang et al., 2022). Machine learning techniques can be used to develop new retrieval algorithms that account for non-linear relationships between observed satellite radiances and cloud properties. For instance, machine-learned retrievals could improve the accuracy of cloud property estimates, especially in regions with broken clouds, where standard retrieval techniques often fail (Gryspeerdt et al., 2022), also utilizing ground-based data for more accurate algorithms (Kim et al., 2021). They may also facilitate retrieval of previously inaccessible properties, such as CCN by training on extensive aircraft campaign data (Redemann & Gao, 2024). Further development of machine learning models for satellite data processing will be critical for refining global ACI estimates and reducing uncertainties in climate models.

3.6.2. Advancing the Analysis of Earth Observations and Models

Applications of computer vision transforms previously highly labor intensive studies, such as detection and labeling of ship-tracks in satellite data (Watson-Parris, Christensen, et al., 2022; Watson-Parris, Rao, et al., 2022; Yuan et al., 2022), from case studies to global monitoring across the entire satellite record. Causal approaches facilitate disentangling of causal relationships from confounding factors in studies of ACI in models (Fons et al., 2024) and observations (Jesson et al., 2022).

3.6.3. Incorporating Physical Constraints Into Machine Learning Models

While machine learning models are useful for improving satellite data retrievals and improving model parameterizations, they must incorporate physical constraints to ensure their validity for long-term climate projections. Machine learning tools that include physical constraints are emerging as a promising solution (Eyring et al., 2024). Hybrid modeling systems that combine climate models with machine learning can simulate aerosol effects, including ACI, with greater accuracy and efficiency, helping to reduce uncertainties in climate predictions.

3.6.4. Developing Climate Model Emulators

Machine learning tools called emulators that are trained on climate model data can significantly speed up climate modeling by predicting global distributions of climate variables, such as temperature and precipitation, for given aerosol emission scenarios. These emulators can efficiently probe previously unexplored scenarios, allowing researchers to explore the impacts of different levels of anthropogenic and natural aerosol emissions on cloud properties and climate (Watson-Parris, Christensen, et al., 2022; ; Watson-Parris, Rao, et al., 2022).

3.7. Improving Communication and Collaboration Across ACI Research Communities

Improved collaboration between satellite data analysts, climate modelers, and ground based observational data experts and scientists, and hence training of the next-generation atmospheric and climate scientists, is essential for advancing ACI research. Future efforts should focus on building cross-disciplinary teams and enhancing data sharing to bridge existing gaps in ACI knowledge. Key actions include:

3.7.1. Fostering Cross-Disciplinary Research

ACI research requires collaboration across multiple disciplines, including satellite observations, which can provide frequent measurements with broad coverage, ground based and aircraft measurements, which can offer much greater detail, and on spatial and temporal scales unobtainable from space, and climate modeling, which can embed the measurements in a theoretical framework that represents current understanding, and can calculate and extrapolate derived quantities. Efforts to foster communication between these communities will ensure that insights from one area inform the others (Kahn et al., 2023). For example, ground based remote sensing and in situ measurements will be required to constrain many physical and chemical processes involved in ACI, and satellite data can then be used to map out in space and time the distribution of regimes where these processes occur, thus placing the global occurrence of ACI processes on more solid ground. Models are needed to help interpret satellite data and to generate predictions about future climate responses to aerosol emissions.

3.7.2. Expanding Data Accessibility

Initiatives like AERONET and ACTRIS provide high-quality, real-time data on aerosol optical properties and other key ACI variables (Lopatin et al., 2021). Expanding the amount and accessibility of these data sets to a broader scientific community and providing the key documentation to support its proper use for scientific investigation, will enable more researchers to contribute to ACI studies, enhancing the collective understanding of ACI. Efforts should continue to streamline data-sharing processes.

4. Conclusions

The global climate is rapidly changing, in response to a wide range of anthropogenic emissions and other influences, with wide reaching consequences for society and nature. Projecting and communicating the responses of the climate to past and future emissions, and the efforts to mitigate them, is therefore among the most crucial tasks of the climate science community today. We have shown how ACI remain a stubborn barrier to providing precise and actionable advice to policy makers, at global, country, and local levels. This includes current and future rates of global warming, regional changes to temperature, precipitation and extreme events, constraining the carbon budgets remaining before breaching the temperature limits set out in the Paris Agreement and the Glasgow Pact, providing information on the risks and potential benefits of Solar Radiation Modification, and linking climate evolution to regional health issues.

Reducing uncertainties in ACI and therefore enabling the scientific community and assessment bodies such as the IPCC, to give improved advice on these and other topics, will require a multifaceted approach involving several subfields and leveraging a range of emerging opportunities. We propose advances in all of these recommendations summarized in Table 1, prioritizing those with immediate actions possible. These include improving satellite data retrievals, expanding ground-based measurements, refining high-resolution climate models, and advancing machine learning. Although some of these suggestions align with existing efforts carried out from the global community, they need to focus on natural and other aerosol sources that are emerging or anticipated to emerge in the next decades (e.g., dust sources in polar regions, biomass burning aerosol and intensified biological aerosol from the warming biosphere and new bioaerosol sources from areas previously covered by ice)—as they will modulate clouds and cloud systems and contribute to the structure of type of extreme events and impacts. Collaboration across research communities and the strategic use of upcoming satellite missions will further enhance our understanding of ACI processes, leading to better climate projections and more informed policy recommendations.

In conclusion, we see the reduction of uncertainties on global and regional ACI—and translating this knowledge into messaging of societal, stakeholder and policy maker relevance—as a grand challenge for current climate science. Reductions in anthropogenic aerosol emissions anticipated for the future do not imply that ACI will be less important, but rather that its characteristics will change fundamentally in ways that need to be constrained for reliable predictions and attributions with models. The coming years can see major developments and breakthroughs, but only if ACI is kept at the forefront of the global research agenda.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Figure 1 is produced using numbers from the IPCC AR6 WG1 Chapter 7 (P. Forster et al., 2021).

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