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Multifaceted aerosol effects on precipitation

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Abstract

Aerosols have been proposed to influence precipitation rates and spatial patterns from scales of individual clouds to the globe. However, large uncertainty remains regarding the underlying mechanisms and importance of multiple effects across spatial and temporal scales. Here, we review the evidence and scientific consensus behind these effects, categorised into radiative effects via modification of radiative fluxes and the energy balance, and microphysical effects via modification of cloud droplets and ice crystals. Broad consensus and strong theoretical evidence exist that aerosol radiative effects (aerosol-radiation interactions (ARIs) and aerosol-cloud interactions (ACIs)) act as drivers of precipitation changes because global mean precipitation is constrained by energetics and surface evaporation. Likewise, aerosol radiative effects cause well-documented shifts of large-scale precipitation patterns, such as the Inter-Tropical Convergence Zone (ITCZ). The extent of aerosol effects on precipitation (APEs) at smaller scales is less clear. Although there is broad consensus and strong evidence that aerosol perturbations microphysically increase cloud droplet numbers and decrease droplet sizes, thereby slowing precipitation droplet formation, the overall aerosol effect on precipitation across scales remains highly uncertain. Global cloud resolving models (CRMs) provide opportunities to investigate mechanisms that are currently not well-represented in global climate models (GCMs) and to robustly connect local effects with larger scales. This will increase our confidence in predicted impacts of climate change.

Introduction

Less than three percent of water on Earth sustains life. Precipitation is the most important mechanism delivering fresh water from the atmosphere to the surface. Although climate change discussions are commonly framed in terms of global temperature change, precipitation changes significantly drive actual impacts of climate change on the planet[1,2].

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A substantial body of literature exists describing the impact of greenhouse gas (GHG) induced warming on precipitation, and the concepts are well understood[2,3]. In contrast, the uncertainty regarding aerosol (nano- to micrometre sized particles suspended in air of anthropogenic or natural origin) effects on precipitation (APEs) remains large. Many hypotheses describe APE based on radiative and cloud microphysical arguments. Some are included in current climate models, others are not (cf. Figure 1, Table 1). Large uncertainty remains regarding the underlying mechanisms and relative importance of proposed effects across spatial and temporal scales.

This article builds on the results of an expert workshop held under the auspices of the Global Energy and Water cycle Exchanges (GEWEX) Aerosol Precipitation (GAP) initiative[4]. It critically reviews the current evidence and scientific consensus (in the authors' view) for APEs and their proposed mechanisms. To facilitate this assessment, we categorise mechanisms according to their degree of scientific support: Category A: strong evidence / broad consensus; Category B: some evidence / limited consensus; Category C: hypothesised / no consensus.

THE PHYSICAL MECHANISMS OF AEROSOL EFFECTS ON PRECIPITATION

The physical drivers of APE can be categorised into **i) radiative effects** via modification of radiative fluxes and the energy balance, which occur due to aerosol scattering and absorption, and modification of cloud radiative properties by **ii) microphysical effects** via modification of cloud droplet and ice crystal number, size and morphology that can affect growth to precipitation-size particles, as well as latent heat from phase changes (enthalpy of vaporisation or fusion). All these effects can induce dynamical feedbacks across scales.

In addition to this mechanistic (bottom up) view, conservation laws provide a complementary (top down) perspective: conservation of energy constrains global mean precipitation[5-7], as changes in latent heat of condensation (L) associated with precipitation changes (dP) have to be compensated by opposite changes in net column integrated cooling (dQ) through adjustment of net surface or top-of-atmosphere fluxes, and vice versa. At smaller spatial scales, net latent heating associated with precipitation changes can also be balanced through divergence of dry static energy[5,8-10] ($\mathrm{d}\left(\nabla\cdot\underline{u}s\right)$) (column integrated, with $\underline{u}$ horizontal velocity, neglecting changes in energy and liquid or solid water storage and kinetic energy transport), as illustrated in Figure 2:

$$\boldsymbol{L}\,\mathbf{d}\boldsymbol{P} = \mathbf{d}\boldsymbol{Q} + \mathbf{d}(\boldsymbol{\nabla}\cdot\underline{\boldsymbol{us}}) \qquad 1$$

Conservation of water provides additional constraints. In the global mean and for sufficiently long time-scales, precipitation P must be balanced by evaporation E so *P-E=0.* On smaller spatial scales, moisture (q_v) flux convergence can compensate for imbalances in P-E so that:

$$\mathbf{d}\boldsymbol{P} - \mathbf{d}\boldsymbol{E} = -\,\mathbf{d}(\boldsymbol{\nabla}\cdot\underline{\boldsymbol{u}}\boldsymbol{q}_{\boldsymbol{v}}) \qquad 2$$

This implies the existence of *breakdown scales of budgetary constraints on precipitation* - a scale below which energy and water budget constraints on precipitation do not strictly apply due to efficient horizontal transport[11]. In the extra-tropics, this scale is expected to be related to the first baroclinic Rossby radius of deformation ($L = \frac{NH}{\pi f_0} \approx 1000km$, *where N is the Brunt–Väisälä frequency, H* is the scale height, and f_0 is the Coriolis parameter). This latitudinally dependent precipitation constraint on aerosol perturbations implies varying effects in the tropics and extra-tropics (Figure 3). Even for regional aerosol perturbations, energetic constraints apply to the global mean. Reductions in surface insolation and atmospheric heating by aerosol absorption decrease global mean precipitation in both simulations, with teleconnections in the tropical simulation.

Evidence from climate models shows that localised aerosol absorption could affect tropical precipitation over thousands of kilometres[12]. Similar scale arguments apply to the moisture budget, with limitations on moisture convergence constraining the susceptibility of regional APEs[13]. The combination of energy and water budget constraints (smallest closure scale) yields a characteristic scale for regional precipitation responses[11] of 3000 km to localized aerosol perturbations, similar to scales of weather systems[14].

It is important to note that this budgetary framework does not provide direct constraints on precipitation intensity distributions, despite constraints on its mean. APEs could invoke an additional feedback mechanism through the radiative effects of atmospheric humidity and clouds[15]. Combined, energy and moisture budget constraints can provide physical mechanisms underpinning the "*buffering*" of APEs[16] in equilibrium conditions, which is also related to radiative convective equilibrium concepts[17-19].

APEs can be decomposed into adjustments due to instantaneous atmospheric net diabatic heating, including rapid adjustments of the vertical structure of water vapour, temperature and clouds (hours to days), and a slower response mediated by surface temperature changes [6,20,21] defined as "hydrological sensitivity"[9,22]. Due to difficulties in separating fast surface temperature changes (days to months) from rapid adjustments in climate models, these are commonly considered jointly[20,21].

Finally, both radiative and microphysical effects and associated changes to the regional energy balance can lead to dynamical effects and regional circulation changes with concomitant changes in precipitation[23,24].

We now discuss each potential mechanism underlying APEs and assess their evidence and scientific consensus.

RADIATIVE EFFECTS

i. ***SURFACE ENERGY BUDGET*** ARIs and ACIs modulate radiative surface fluxes and, consequently, sensible and latent heat fluxes. These effects generally reduce surface insolation, decreasing surface evaporation which has been linked to a "spin down" of the hydrological cycle[25]. This is corroborated by the observed precipitation response to ARIs following major volcanic eruptions, showing substantial decreases in precipitation over land and river discharge into ocean[26,27]. (Near-surface absorbing aerosol can enhance precipitation through diabatic heating, even when surface sensible heat fluxes are reduced[28].) Energetically, the net-negative total ARIs[29] reduce the global mean temperature, atmospheric water vapour, and associated long-wave emission, which is compensated by reductions in precipitation and associated latent heat: climate models show that negative aerosol radiative forcing masks almost all temperature-driven GHG effects on precipitation over land up to present (with GHG effects dominating the future)[9,30,31]. However, such radiative arguments cannot be decoupled from dynamical feedbacks, as shown below.

That ARIs reduce global precipitation through changes in surface temperature and surface fluxes builds on our physical understanding of the energy budget, is supported by observational evidence[32] and reproduced by climate models. We assess this effect as Category A, supported by strong evidence and broad scientific consensus, although magnitudinal uncertainties remain.

The following two mechanisms could be combined as aerosol absorption effects, but we retain the mechanistic separation prevailing in existing literature.

ii. ***Atmospheric diabatic heating*** by aerosol absorption creates local energetic imbalances. To ensure energy conservation, this is compensated by reductions in latent heat release through precipitation, by rapid adjustments of net surface or top-of-atmosphere fluxes, or, on smaller scales or in the tropics[11,33], through divergence of dry static energy[8,34]. The energetic framework provides a useful tool to diagnose APEs[9,21,28,34,35] and can explain the contrasting behaviour of absorbing and non-absorbing aerosols[21,36].

That diabatic heating of absorbing aerosol reduces global mean precipitation is consistent with our physical understanding of the energy budget, is reproduced by climate models but builds on limited observational evidence. We therefore assess this effect as Category A, supported by strong evidence and broad scientific consensus but with remaining magnitudinal uncertainties.

iii. ***Semi-direct effects***[9,37-40] are rapid adjustments associated with aerosol absorption affecting the vertical temperature and humidity structure, with potential effects on clouds and precipitation. These effects are generally accompanied by corresponding surface flux changes (cf. ii). Elevated layers of absorbing aerosol can modify lower-tropospheric static stability and sub-tropical inversion strength[39,41], suppressing boundary layer deepening and concomitant entrainment[42]. Although the focus has been on shallow clouds[43], the impact on deep convection and associated precipitation has been demonstrated in CRMs, revealing a complex diurnal cycle[44], and climate models[28]. However, most prior research focused on semi-direct effects of shallow clouds in the context radiative forcing[43], not precipitation. Hence, the overall uncertainty remains large.

Semi-direct effects of absorbing aerosol on the thermodynamic structure of the atmosphere are based on a sound physical foundation and have been well documented. However, the sign and magnitude of the effect on clouds and subsequently precipitation are sensitive to the vertical collocation of clouds and aerosols as well as the cloud regime. Some consistency exists across CRM studies, however, the observational evidence remains limited. We therefore assess this effect as Category B, backed up by physical conceptual models, modelling studies and limited observational evidence and some scientific consensus, even if the magnitude and sign of the impact on precipitation remain unclear.

The following mechanisms iv) – vi) could be combined as aerosol effects on regional precipitation patterns but we retain the mechanistic separation prevailing in existing literature.

iv. ***Changes in regional-scale precipitation and monsoon dynamics*** have been attributed to regional patterns in ARI-induced surface cooling and atmospheric heating, both locally and remotely [12,34,45-49]. The precipitation response can be attributed to a combination of the modulation of surface fluxes over land, hence of the thermal gradient between land and sea[50,51], as well as aerosol absorption effects, driving thermally direct circulations[12,52] and moisture convergence[52] (linked to extreme precipitation [53,54]), the sea breeze circulation[55], and teleconnections[56].

Aerosol effects on regional scale precipitation and monsoon dynamics have been shown to affect precipitation patterns. This builds on climate model and CRM simulations and general physical understanding, with some observational evidence. However, uncertainties remain regarding the attribution of observed precipitation to aerosol effects and overall strength of the effects. We therefore assess this effect as Category B, backed by some evidence and limited scientific consensus.

v. ***Aerosol radiative effects on sea surface temperature patterns*** (SSTs) have been linked to observed climatological trends[57,58]. Associated changes in multi-decadal SST variability[59] have previously been linked to the Sahel drought[60-63]. In addition to the local effects on the SST distribution, aerosols may also affect ocean dynamics and thereby SSTs. For example, aerosol forcing was shown to strengthen the Atlantic Meridional Overturning Circulation (AMOC) thereby modulating SST patterns in the Atlantic Ocean[64-67], and affecting the Northern Hemisphere climate and precipitation patterns[63,68]. SSTs also control hurricane activity[61,69-71], providing a mechanism for potential aerosol effects on hurricanes[72,73]. Forcing trends associated with European sulfuremissions as aerosol precursor, have been linked to a pronounced North Atlantic "hurricane drought" from the 1960s through early 1990s[74] during which hurricane power dissipation, a measure of storm damage[75], was strongly inversely correlated with European sulfur emissions. Much of the direct SST forcing was from Saharan mineral dust, which in turn was associated with reduced monsoonal flow resulting from high sulfate aerosol concentrations[76].

The SST mediated effect of aerosol on regional precipitation patterns and hurricane activity builds on climate model simulations and general physical understanding, with limited observational evidence. We therefore assess this effect as Category B, backed up by some evidence and limited scientific consensus.

vi. ***Hemispheric asymmetry in aerosol radiative effects***[77] shifts the energy flux equator to where the column-integrated meridional energy flux vanishes[78,79]. The position of the energy flux equator is closely linked to the ITCZ position and associated precipitation. With anthropogenic aerosol predominantly located in the northern hemisphere, associated negative/positive aerosol radiative effects, e.g. from sulfate/black carbon, lead to a southward/northward ITCZ shift[62,78-87]. For sulfate, this is a slow (SST mediated) response, whereas for black carbon adjustments in response to absorption contribute[88]. Dynamical cloud feedbacks can further amplify the hemispheric asymmetry[89] and ITCZ shifts can interact with local monsoon regimes[90].

The effect of hemispherically asymmetric aerosol radiative effects on the energy flux equator and ITCZ position builds on a robust theoretical foundation[79], agrees with observational evidence[83,91] and *is reliably reproduced by GCMs. We therefore assess this effect as Category A, backed up by strong evidence and broad scientific consensus.*

Microphysical effects

vii. ***CCN mediated effects on stratiform liquid clouds, including stratocumulus:*** enhanced loading of CCN (hygroscopic or wettable aerosols of sufficient size to facilitate droplet growth) can increase cloud droplet numbers and, at constant liquid water content, lead to smaller droplets. This effect saturates for high aerosol concentrations[92] and/or low updraft velocities due to the depletion of supersaturation by condensation. This pathway can slow droplet growth to the threshold size for precipitation[93-96], thereby supressing precipitation efficiency; this mechanism can also apply to warm phase of stratiform mixed-phase clouds[97]. The reduced removal of cloud water by precipitation has been hypothesized to increase cloud liquid water path (LWP) and lifetime[95]. There is clear observational evidence of an increase in cloud droplet numbers and associated decrease in droplet radii due to aerosol perturbations from aircraft data[98], ship-track observations[99-103] and satellite remote sensing[104-106]. This is reproduced in CRMs and qualitatively in climate models[105,107]. Analysis of satellite-retrieved CloudSat[108] radar reflectivity and MODIS[109] effective radius data provides observational evidence for droplet size dependence of precipitation onset, with enhanced (low) drizzle rates above effective radii of 15 (10) μm. Combined with the documented impact of CCN on effective radii, this indicates warm rain susceptibility to CCN perturbations[110]. These observations are limited to liquid-top shallow clouds, which represent a small fraction of global mean precipitation[111]. The observational evidence for an increase in liquid water paths via precipitation suppression due to increased aerosol concentrations is still disputed and cloud-regime dependent[101,112-114]. Many climate models simulatestrong LWP responses to aerosol perturbations[112,115], likely because their simplified representations of warm rain formation ("autoconversion") have built-in power-law dependences on cloud droplet number but lack small-scale feedbacks, such droplet size effects on evaporation and associated cloud entrainment feedbacks[16,116,117]. This uncertainty propagates into climate model assessments of APEs.

CCN mediated effects on stratiform liquid cloud, including stratocumulus, have been shown to increase droplet numbers and suppress warm rain formation. This is consistent with warm rain formation theory, supported by observational evidence from space-born cloud radars and reproduced by high-resolution CRMs. The expected effect is reduced light rain occurrence, possibly compensated by increasing occurrence of stronger rain events. However, the overall impact on large-scale precipitation remains unclear. We therefore assess this effect as Category B, backed up by some evidence and limited scientific consensus.

The following mechanisms viii) and ix) could be combined as aerosol effects on convection but we retain the mechanistic separation by cloud phase prevailing in existing literature.

viii. ***CCN mediated effects on shallow convection:*** for shallow (liquid) convective clouds, an aerosol mediated increase in cloud droplet numbers has several effects: associated smaller droplet radii enhance evaporation that increases the buoyancy gradient at the cloud edge, creating vorticity and increasing associated entrainment/detrainment[116], which results in a reduction of cloud size, liquid water path, buoyancy and precipitation. At the same time, suppression of rain production via the droplet number effect on autoconversion can produce enhanced condensation and latent heat release due to larger numbers of remaining cloud droplets and associated increase in surface area, often referred to as *"warm phase or condensational invigoration"*[118-120]. It can also enhance cloud-top detrainment; subsequent evaporative cooling can destabilize the environment[121]. Both mechanisms could generate deeper clouds[122] with potentially enhanced precipitation. The net effect on mean precipitation could therefore be small[16,17] or even positive, depending on environmental conditions: high-resolution large-eddy simulations demonstrate a non-monotonic precipitation response with increases at low aerosol concentrations up to an optimal aerosol concentration, followed by a precipitation decrease[118-120,123-125]. For larger spatio-temporal scales, idealised simulations of shallow convection approach a radiative-convective equilibrium state[17]. Although the transient behaviour approaching equilibrium responds to increasing cloud droplet number concentrations through deepening and delays precipitation onset[126], in the equilibrium state associated decreases in relative humidity and faster evaporation of small clouds compensates for much of the radiative effects with broader intensity precipitation distributions[19]. The overall effect depends on the relative importance of transient and equilibrium states[17,93,127] with recent evidence highlighting limitations of idealised simulations that unrealistically favour equilibrium states[128]. However, contrasting environmental factors, such as boundary layer development or humidity, can influence the overall effects[123,129].

CCN mediated effects on shallow convection have been shown to increase droplet numbers and slow warm-phase precipitation formation. This is based on high-resolution CRMs and observational evidence. It is important to note that convection parameterisations in most GCMs do not represent any microphysical aerosol effects on convection. The overall effect on precipitation is less certain. We assess this effect as Category B, backed up by some evidence and limited scientific consensus.

ix. ***CCN mediated effects on deep convection:*** for deep (liquid & ice phase) convective clouds, *"convective invigoration"* is widely discussed, generally referring to enhanced aerosol levels causing stronger updrafts or higher clouds and an associated increase in precipitation[93,98,130-136]. Several hypotheses about underlying mechanisms exist. Often overlooked, these share a common starting point with shallow convection in the liquid base of clouds: the suppression of warm rain formation from reduced autoconversion with enhanced CCN in the lower, liquid part of the cloud[137,138], with an associated reduction in droplet size and resulting entrainment/detrainment feedbacks. Subsequent invigoration hypotheses include: enhanced condensation and associated latent heat release (*"warm phase invigoration", c.f. viii)*[118,119,139,140]; enhanced evaporation and downdraft formation affecting cold pool strength and surface convergence[141,142]; delay of warm-phase precipitation increasing the amount of cloud water reaching the freezing level, enhancing the release of latent heat of freezing[93,98,132] although the importance of this *("cold phase invigoration"*) is disputed[143]; the hypothesis that depletion of cloud water through precipitation in low aerosol environments could generate high supersaturations and subsequent activation of small aerosol particles into cloud droplets, enhancing condensation and (warm phase) latent heat release[144] – a hypothesis shown to be inconsistent with a limited set of observations[145]; and that enhanced CCN levels increase environmental humidity through clouds mixing more condensed water into the surrounding air, preconditioning the environment for invigorated convection[146]. The latter result is likely a consequence of idealised equilibrium simulations as it is not observed in realistic simulations across a wide range of environmental conditions[147]. Feedbacks between convective clouds and their thermodynamic environment may modulate or buffer APEs. Overall, the strength and relative importance of mechanisms underlying convective invigoration are disputed [143] – it is sensitive to uncertain microphysical effects[148,149] and strongly dependent on environmental regimes[49,130,141,150-152]. In addition, the excess buoyancy associated with the respective mechanisms can be partially offset by negative buoyancy associated with condensate loading[153,154], with the net effect dependent on condensate offloading through precipitation. The role of condensate loading has been explored through theoretical calculations that show the potential of aerosol-induced invigoration is significantly limited for cold-based storms, and that aerosol-induced cold-phase processes weaken, rather than strengthen the updrafts in warm-based storms (referred to as aerosol enervation)[155]. The first systematic multi-model assessment of these competing aerosol effects on deep convective updrafts[154] has been performed as part of a deep convection case study[137] over Houston, USA, under the umbrella of the Aerosol, Cloud, Precipitation, and Climate initiative (Figure 4). This intercomparison revealed updraft increases by 5%-15% in the mid-storm regions (4-7 km above ground) with increased CCN, primarily driven by enhanced condensation, with waning and mixed difference in levels above. Condensate loading contributions are generally limited. Despite this apparent invigoration, 6 of 7 models produce precipitation decreases (of -10% to -80%), highlighting the complexity of precipitation responses to aerosol perturbations. There are indications that microphysical effects strengthen deep and weaken shallow clouds in convective cloud fields, thereby broadening the precipitation intensity distribution[18,44]. Observations and modelling suggest a non-monotonic effect, with precipitation peaking at an optimal aerosol concentration[156,157]. It should be re-iterated that even high-resolution CRM simulations of aerosol effects on deep convection remain subject to large uncertainty, particularly with mixed-phase and ice-cloud microphysics, affecting the simulated base states as well as their response to aerosol perturbations[137,148,158] (Figure 4). Few current climate models include aerosol aware convection parameterisations and their early results indicate limited aerosol effects on convective precipitation on the global scale[159,160]. However, the associated uncertainties remain large, providing challenges for the next generation of cloud resolving climate models.

CCN mediated effects on deep convection consistently show increased droplet numbers and reduced warm rain formation in the lower parts of the cloud. This builds on a robust theoretical foundation, is supported by limited observations and is consistently reproduced by CRMs. The propagation of these perturbations through the mixed- and ice-phase microphysics of clouds remains uncertain across models, with limited observational constraints. Severalhypotheses exist on associated changes in buoyancies leading to invigoration, with models consistently simulating an increase in latent heating of condensation due to the increased surface area of enhanced droplet numbers. However, their importance remains highly uncertain. The overall effect on aggregated precipitation remains highly uncertain. We therefore assess this effect as Category C, backed up by plausible hypotheses, but with limited evidence and limited scientific consensus.

x. ***INP mediated effects*** on clouds are likely to be significant, but still highly uncertain, given the unknown proportion of cloud ice between -38°C and 0°C that forms by INP-induced heterogeneous freezing or remains supercooled. Clouds glaciate below approximately -38°C, where droplets freeze homogeneously. Increased concentrations of INPs (generally solid or crystalline aerosols which provide a surface onto which water molecules are likely to adsorb, bond and form ice-like aggregates) have been proposed to enhance the glaciation of clouds[97,161,162] with an associated increase in precipitation efficiency and reduction of cloud lifetime[163]. Low INP concentrations in remote marine environments consistently inhibit precipitation[164]. However, the complexity of microphysical pathways in mixed- and ice-phase clouds is significant[149] with potential compensating pathways buffering the response, leading to low precipitation susceptibility[165]. Modification of precipitation through controlled INP emissions ("cloud seeding") has been extensively attempted in the weather modification community, with demonstrated impact on cloud microphysical processes[166]; however, limited evidence exists for its effectiveness in terms of large-scale precipitation modulation[167,168]. The role of INPs is further complicated by secondary ice production processes that are ill-constrained but can lead to rapid cloud glaciation[169].

INP mediated effects have been shown to affect cloud phase and microphysics. A number of hypotheses exist on subsequent effects on precipitation. However, there is no complete theoretical framework, and evidence from modelling and observations is limited. We therefore assess this effect as Category C, backed up by plausible hypotheses, but only limited evidence and limited scientific consensus.

It is important to re-iterate that occurrence and strength, and spatiotemporal extent, of radiative and microphysical APEs are modulated by environmental conditions[49,142,150,170,171] as well as energy/water budget constraints[11,33,36], which complicates their detectability. Also, the potential exists for compensation between individual mechanisms, buffering the overall precipitation response[16].

Detectability and attribution of precipitation changes

In-situ observations provide the most detailed insights into processes underlying APEs and are invaluable for the development and evaluation of theories and models. However, due to the inhomogeneous and intermittent nature of precipitation it is generally impossible to measure areal average precipitation reliably. Representation errors[172] are likely to exceed the expected magnitude of aerosol effects.

Statistical analysis of satellite-retrieved aerosol radiative properties and precipitation shows higher precipitation rates with higher aerosol optical depth[134] with potentially non-monotonic behaviour[173].

Confounding factors (as aerosol extinction, cloud and precipitation are controlled by common factors, such as relative humidity[174], and precipitation is the predominant aerosol sink[175]) complicate the interpretation. More fundamentally, remotely sensed aerosol properties are not always representative of the relevant aerosol perturbations[176] and statistical analyses rely on assumptions of spatial representativeness of not co-located retrievals[177,178]. However, satellites provide the only source for global observational constraints and the abundance of data permits robust statistical relationships. When environmental conditions are controlled for[179], the apparent increase in precipitation with aerosol extinction is significantly reduced, although a positive relationship remains for cloud regimes[179-181] with tops colder than 0°C, suggesting a role of ice processes[180]. Furthermore, satellite data provide constraints on microphysical processes: TRMM and CloudSat observations show a systematic shift in the relationship between rain drop size distribution and liquid water path with enhanced aerosol concentrations off the coast of Asia[182].

Situations with well-characterised aerosol perturbations can serve as analogues for APEs[183]. Aerosols emitted from point sources, such as ships, volcanoes, industrial sites, or cities, can cause distinct tracks in clouds that can be analysed from satellite data[101,184,185], even when invisible[186]. The analysis of cloud droplet size in ship-track data shows a consistent effective radius reduction in the track[99,113], consistent with observed effective radii reductions in response to SO_2 emissions from a degassing volcano[187]. In general, cloud droplet effective radius is expected to be positively correlated with precipitation formation through warm rain formation[188]. However, the precipitation in ship-tracks reveals a differentiated response across cloud regimes[113]. Satellite observations of lightning enhancement over shipping lanes[189] also provide strong indications of aerosol effects on convective microphysics and potential aerosol-driven mesoscale circulations, although APEs itself remain more elusive[190] and contributions from dynamical factors cannot be ruled out.

The difficulty remains to consistently reconcile observations with modelling data: any shift in the precipitation intensity distribution also implies a shift in the fraction of rain detectable from radar or microwave data[191]. Also, the formation of detectable perturbations in clouds is limited to a sub-set of environmental conditions[102,186] with overall limited precipitation amounts, thereby limiting the global representativeness of such observations.

On larger scales, observational uncertainty and low signal-to-noise ratios complicate the attribution of observed changes of regional APEs[192]. Detection and attribution techniques[193] use GCMs to estimate spatio-temporal response patterns (*"fingerprints"*) of precipitation to aerosol perturbations, which then can be compared to observed precipitation changes. However, observational and modelling uncertainties still obscure unambiguous evidence of such fingerprints of aerosol on regional scale precipitation[194-196].

Conclusions

This article reviews the evidence and scientific consensus for APEs and the underlying set of physical mechanisms. Broad consensus and strong theoretical evidence exists that because global mean precipitation is constrained by conservation of energy[6] and water[11,13] as well as surface evaporation[25], aerosol radiative effects act as direct drivers of precipitation changes[8]. Likewise, aerosol radiative effects cause well-documented shifts of large-scale precipitation patterns, such as the ITCZ. The extent to which APEs are i) applicable to smaller scales and ii) driven or buffered by compensating microphysical and dynamical mechanisms and budgetary constraints is less clear. Despite broad consensus and strong evidence that suitable aerosols increase cloud droplet numbers and reduce warm rain formation efficiencies across cloud regimes, the overall aerosol effect on cloud microphysics and dynamics, as well as the subsequent impact on local, regional and global precipitation, is less constrained. Air-pollution control measures will reduce aerosol levels in the future, with an expected reversal of aerosol effects on regional precipitation patterns[197].

Research on APEs has been limited by the fact that: locally to regionally, precipitation is controlled by complex non-linear interactions with multiple microphysical, radiative and dynamical feedbacks; the expected aerosol-induced change in precipitation is potentially smaller than the internal variability[198] and uncertainty in current observations; current observations can only constrain some of the processes involved – satellite retrievals are often limited to proxies of the parameters involved and in-situ measurements are limited, in particular in convective updrafts; isolating causal effects of aerosol on precipitation in the presence of multiple confounding variables remains challenging – it is easier to identify a strong "effect" than to prove that it is the consequence of confounding; and finally, because the representation of clouds in current climate models is inadequate to represent key microphysical processes and, importantly, the coupling between microphysics and cloud dynamics. Consequently, significant uncertainty remains, limiting our ability to quantify and predict past and future precipitation changes.

It should be emphasised that, in terms of local impacts on humans and ecosystems, absolute precipitation changes are likely to be less important than relative precipitation changes in the mean and in the frequency of occurrence of extremes. To illustrate this point, the absolute precipitation changes over the Sahel region simulated by the CMIP6 multi-model intercomparison seem negligible – but constitute ~ 40% of the local precipitation (Figure 1). Likewise, local impacts may be dominated by regional shifts of precipitation patterns rather than precipitation process changes. These aspects have not been given sufficient attention.

New Frontiers

Out of ten mechanisms reviewed, only three have been assessed to be supported by strong evidence and broad consensus and two primarily based on hypotheses without consensus (Table 1). Future research should define critical tests for numerical models based on observations, in particular of convective updraft microphysics and thermodynamics, including observational simulators for comparability. Active remote sensing and systematic in-situ observations[199,200], including from un-crewed aerial vehicles, will provide novel constraints on particularly uncertain mixed-phase cloud microphysics and dynamics. Advanced geostationary satellites and cube-sat fleets will allow monitoring the full cloud life cycle. Idealised aqua-planet[33,201] or radiative convective equilibrium simulations[18,202], such as the GAP Radiative Convective Equilibrium aerosol perturbation model intercomparison[140], connect evidence from local scale effects to regional and global precipitation. The availability of global CRMs[203] and digital twin Earths[204] provides significant opportunities to overcome our reliance on climate models with parameterised local-scale processes and inadequate microphysics, that currently do not represent three of the ten mechanisms reviewed here (Table 1). However, even CRMs have large uncertainties in cloud microphysical processes that can obscure aerosol effects[148] and remain to be systematically constrained by observations. The shift to global CRMs, which will be a focus of the GAP initiative[4], will also allow for robust quantification of the connection between local ACIs and large-scale dynamical feedbacks and teleconnections.

References

1 Field, C. B. *et al.* in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 1-32 (Cambridge University Press, 2014).

2 Douville, H. *et al.* 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* Vol. In Press (eds V. Masson-Delmotte *et al.*) (Cambridge University Press, 2021).

3 Hartmann, D. L. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds T.F. Stocker *et al.*) (Cambridge University Press, 2013).

4 Stier, P., Heever, S. C. v. d. & Dagan, G. *The GEWEX Aerosol Precipitation initiative*, <https://www.gewex.org/GAP/> (2023).

5 Mitchell, J. F. B., Wilson, C. A. & Cunnington, W. M. On Co2 Climate Sensitivity and Model Dependence of Results. *Q J Roy Meteor Soc* **113**, 293-322 (1987). https://doi.org/DOI 10.1256/smsqj.47516

6 Allen, M. R. & Ingram, W. J. Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224-232 (2002). https://doi.org/10.1038/nature01092

7 Stephens, G. L. & Hu, Y. X. Are climate-related changes to the character of global-mean precipitation predictable? *Environ Res Lett* **5** (2010).

8 Muller, C. J. & O'Gorman, P. A. An energetic perspective on the regional response of precipitation to climate change. *Nat Clim Change* **1**, 266-271 (2011). https://doi.org/10.1038/Nclimate1169

9 Myhre, G. *et al.* PDRMIP A Precipitation Driver and Response Model Intercomparison Project-Protocol and Preliminary Results. *B Am Meteorol Soc* **98**, 1185-1198 (2017). https://doi.org/10.1175/Bams-D-16-0019.1

10 Richardson, T. B. *et al.* Drivers of Precipitation Change: An Energetic Understanding. *J Climate* **31**, 9641-9657 (2018). https://doi.org/10.1175/Jcli-D-17-0240.1

11 Dagan, G. & Stier, P. Constraint on precipitation response to climate change by combination of atmospheric energy and water budgets. *Npj Clim Atmos Sci* **3** (2020). https://doi.org/10.1038/s41612-020-00137-8

12 Roeckner, E. *et al.* Impact of carbonaceous aerosol forcing on regional climate change. *Clim. Dyn.* **27**, 553-571 (2006). https://doi.org/10.1007/s00382-006-0147-3

13 Dagan, G., Stier, P. & Watson-Parris, D. Analysis of the Atmospheric Water Budget for Elucidating the Spatial Scale of Precipitation Changes Under Climate Change. *Geophys. Res. Lett.* **46** (2019). https://doi.org/10.1029/2019GL084173

14 Trenberth, K. E., Dai, A., Rasmussen, R. M. & Parsons, D. B. The Changing Character of Precipitation. *B Am Meteorol Soc* **84**, 1205-1218 (2003). https://doi.org/10.1175/bams-84-9-1205

15 Hodnebrog, Ø. *et al.* Water vapour adjustments and responses differ between climate drivers. *Atmos Chem Phys* **19**, 12887-12899 (2019). https://doi.org/10.5194/acp-19-12887-2019

16 Stevens, B. & Feingold, G. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature* **461**, 607-613 (2009). https://doi.org/10.1038/Nature08281

17 Seifert, A., Heus, T., Pincus, R. & Stevens, B. Large-eddy simulation of the transient and near-equilibrium behavior of precipitating shallow convection. *J. Adv. Model. Earth Syst.* **7** (2015). https://doi.org/10.1002/ 2015MS000489

18 van den Heever, S. C., Stephens, G. L. & Wood, N. B. Aerosol Indirect Effects on Tropical Convection Characteristics under Conditions of Radiative-Convective Equilibrium. *J Atmos Sci* **68**, 699-718 (2011). https://doi.org/10.1175/2010jas3603.1

19 Yamaguchi, T., Feingold, G. & Kazil, J. Aerosol-Cloud Interactions in Trade Wind Cumulus Clouds and the Role of Vertical Wind shear. *J Geophys Res-Atmos* **124**, 12244-12261 (2019). https://doi.org/10.1029/2019jd031073

20 Richardson, T. B., Samset, B. H., Andrews, T., Myhre, G. & Forster, P. M. An assessment of precipitation adjustment and feedback computation methods. *J Geophys Res-Atmos* **121**, 11608-11619 (2016). https://doi.org/10.1002/2016jd025625

21 Samset, B. H. *et al.* Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophysical Research Letters* **43**, 2782-2791 (2016). https://doi.org/10.1002/2016gl068064

22 Flaschner, D., Mauritsen, T. & Stevens, B. Understanding the Intermodel Spread in Global-Mean Hydrological Sensitivity. *J Climate* **29**, 801-817 (2016). https://doi.org/10.1175/Jcli-D-15-0351.1

23 Dagan, G., Yeheskel, N. & Williams, A. I. L. Radiative forcing from aerosol-cloud interactions enhanced by large-scale circulation adjustments. *Nat Geosci* **16** (2023). https://doi.org/10.1038/s41561-023-01319-8

24 Williams, A. I. L., Watson-Parris, D., Dagan, G. & Stier, P. Dependence of Fast Changes in Global and Local Precipitation on the Geographical Location of Absorbing Aerosol. *Journal of Climate* **36**, 6163-6176 (2023). https://doi.org/10.1175/jcli-d-23-0022.1

25 Ramanathan, V., Crutzen, P. J., Kiehl, J. T. & Rosenfeld, D. Atmosphere - Aerosols, climate, and the hydrological cycle. *Science* **294**, 2119-2124 (2001).

26 Trenberth, K. E. & Dai, A. Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysical Research Letters* **34** (2007). https://doi.org/L15702, doi:10.1029/2007GL030524

27 Oman, L., Robock, A., Stenchikov, G. L. & Thordarson, T. High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2006gl027665

28 Ming, Y., Ramaswamy, V. & Persad, G. Two opposing effects of absorbing aerosols on global-mean precipitation. *Geophysical Research Letters* **37** (2010). https://doi.org/Artn L13701, 10.1029/2010gl042895

29 Boucher, O. *et al.* in *Working Group I Contribution to the Intergovernmental Panel on Climate Change Firth Assessment Report Climate Change 2013: The Physical Science Basis* (eds Sandro Fuzzi, Joyce Penner, Venkatachalam Ramaswamy, & Claudia Stubenrauch) (Cambridge University Press, 2013).

30 Myhre, G. *et al.* Sensible heat has significantly affected the global hydrological cycle over the historical period. *Nat Commun* **9** (2018). https://doi.org/10.1038/s41467-018-04307-4

31 Salzmann, M. Global warming without global mean precipitation increase? *Sci Adv* **2**, e1501572 (2016). https://doi.org/10.1126/sciadv.1501572

32 Wu, P., Christidis, N. & Stott, P. Anthropogenic impact on Earth's hydrological cycle. *Nat Clim Change* **3**, 807-810 (2013). https://doi.org/10.1038/NCLIMATE1932

33 Dagan, G., Stier, P. & Watson-Parris, D. Contrasting Response of Precipitation to Aerosol Perturbation in the Tropics and Extratropics Explained by Energy Budget Considerations. *Geophys Res Lett* **46**, 7828-7837 (2019). https://doi.org/10.1029/2019GL083479

34 Hodnebrog, O., Myhre, G., Forster, P. M., Sillmann, J. & Samset, B. H. Local biomass burning is a dominant cause of the observed precipitation reduction in southern Africa. *Nat Commun* **7** (2016). https://doi.org/10.1038/ncomms11236

35 O'Gorman, P. A., Allan, R. P., Byrne, M. P. & Previdi, M. Energetic Constraints on Precipitation Under Climate Change. *Surv Geophys* **33**, 585-608 (2012).

36 Dagan, G., Stier, P. & Watson-Parris, D. An Energetic View on the Geographical Dependence of the Fast Aerosol Radiative Effects on Precipitation. *J Geophys Res-Atmos* **126** (2021). https://doi.org/10.1029/2020JD033045

37 Jiang, H. L. & Feingold, G. Effect of aerosol on warm convective clouds: Aerosol-cloud-surface flux feedbacks in a new coupled large eddy model. *J Geophys Res-Atmos* **111** (2006). https://doi.org/D01202, doi:10.1029/2005JD006138

38 Hansen, J., Sato, M. & Ruedy, R. Radiative forcing and climate response. *J Geophys Res-Atmos* **102**, 6831-6864 (1997). https://doi.org/10.1029/96jd03436

39 Ackerman, A. S. *et al.* Reduction of tropical cloudiness by soot. *Science* **288**, 1042-1047 (2000). https://doi.org/DOI 10.1126/science.288.5468.1042

40 Sand, M., Samset, B. H., Tsigaridis, K., Bauer, S. E. & Myhre, G. Black Carbon and Precipitation: An Energetics Perspective. *J Geophys Res-Atmos* **125** (2020). https://doi.org/10.1029/2019JD032239

41 Johnson, B. T., Shine, K. P. & Forster, P. M. The semi-direct aerosol effect: Impact of absorbing aerosols on marine stratocumulus. *Q J Roy Meteor Soc* **130**, 1407-1422 (2004). https://doi.org/10.1256/qj.03.61

42 Yamaguchi, T., Feingold, G., Kazil, J. & McComiskey, A. Stratocumulus to cumulus transition in the presence of elevated smoke layers. *Geophysical Research Letters* **42**, 10478-10485 (2015). https://doi.org/10.1002/2015gl066544

43 Redemann, J. *et al.* An overview of the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) project: aerosol-cloud-radiation interactions in the southeast Atlantic basin. *Atmospheric Chemistry and Physics* **21**, 1507-1563 (2021). https://doi.org/10.5194/acp-21-1507-2021

44 Herbert, R., Stier, P. & Dagan, G. Isolating Large-Scale Smoke Impacts on Cloud and Precipitation Processes Over the Amazon With Convection Permitting Resolution. *J Geophys Res-Atmos* **126** (2021). https://doi.org/10.1029/2021JD034615

45 Menon, S., Hansen, J., Nazarenko, L. & Luo, Y. F. Climate effects of black carbon aerosols in China and India. *Science* **297**, 2250-2253 (2002).

46 Bollasina, M. A., Ming, Y. & Ramaswamy, V. Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon. *Science* **334**, 502-505 (2011). https://doi.org/10.1126/science.1204994

47 Wang, C. A modeling study on the climate impacts of black carbon aerosols. *J Geophys Res-Atmos* **109** (2004). https://doi.org/10.1029/2003jd004084

48 Leung, G. R. & van den Heever, S. C. Aerosol breezes drive cloud and precipitation increases. *Nat Commun* **14** (2023). https://doi.org/10.1038/s41467-023-37722-3

49 Fan, J. W. *et al.* Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. *J Geophys Res-Atmos* **114** (2009). https://doi.org/10.1029/2009jd012352

50 Li, X. Q. *et al.* South Asian Summer Monsoon Response to Aerosol-Forced Sea Surface Temperatures. *Geophysical Research Letters* **47** (2020). https://doi.org/10.1029/2019GL085329

51 Zanis, P. *et al.* Fast responses on pre-industrial climate from present-day aerosols in a CMIP6 multi-model study. *Atmos Chem Phys* **20**, 8381-8404 (2020).

52 Wang, C., Kim, D., Ekman, A. M. L., Barth, M. C. & Rasch, P. J. Impact of anthropogenic aerosols on Indian summer monsoon. *Geophysical Research Letters* **36** (2009). https://doi.org/10.1029/2009gl040114

53 O'Gorman, P. A. & Schneider, T. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *P Natl Acad Sci USA* **106**, 14773-14777 (2009). https://doi.org/10.1073/pnas.0907610106

54 Singh, D., Bollasina, M., Ting, M. F. & Diffenbaugh, N. S. Disentangling the influence of local and remote anthropogenic aerosols on South Asian monsoon daily rainfall characteristics. *Clim Dynam* **52**, 6301-6320 (2019). https://doi.org/10.1007/s00382-018-4512-9

55 Grant, L. D. & van den Heever, S. C. Aerosol-cloud-land surface interactions within tropical sea breeze convection. *J Geophys Res-Atmos* **119** (2014). https://doi.org/10.1002/2014jd021912

56 Bollasina, M. A., Ming, Y., Ramaswamy, V., Schwarzkopf, M. D. & Naik, V. Contribution of local and remote anthropogenic aerosols to the twentieth century weakening of the South Asian Monsoon. *Geophysical Research Letters* **41**, 680-687 (2014). https://doi.org/10.1002/2013gl058183

57 Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. & Bellouin, N. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature* **484**, 228-U110 (2012). https://doi.org/10.1038/nature10946

58 Undorf, S., Bollasina, M. A., Booth, B. B. B. & Hegerl, G. C. Contrasting the Effects of the 1850-1975 Increase in Sulphate Aerosols from North America and Europe on the Atlantic in the CESM. *Geophysical Research Letters* **45**, 11930-11940 (2018). https://doi.org/10.1029/2018gl079970

59 Wilcox, L. J., Highwood, E. J. & Dunstone, N. J. The influence of anthropogenic aerosol on multi-decadal variations of historical global climate. *Environ Res Lett* **8** (2013). https://doi.org/10.1088/1748-9326/8/2/024033

60 Folland, C. K., Palmer, T. N. & Parker, D. E. Sahel Rainfall and Worldwide Sea Temperatures, 1901-85. *Nature* **320**, 602-607 (1986). https://doi.org/DOI 10.1038/320602a0

61 Zhang, R. & Delworth, T. L. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2006gl026267

62 Rotstayn, L. D. & Lohmann, U. Tropical rainfall trends and the indirect aerosol effect. *J Climate* **15**, 2103-2116 (2002). https://doi.org/Doi 10.1175/1520-0442(2002)015<2103:Trtati>2.0.Co;2

63 Zhang, S., Stier, P., Dagan, G. & Wang, M. Anthropogenic aerosols modulated twentieth-century Sahel rainfall variability. *Geophys. Res. Lett.* (2021). https://doi.org/in press

64 Menary, M. B. *et al.* Aerosol-Forced AMOC Changes in CMIP6 Historical Simulations. *Geophysical Research Letters* **47** (2020). https://doi.org/10.1029/2020GL088166

65 Cai, W. *et al.* Pan-oceanic response to increasing anthropogenic aerosols: Impacts on the Southern Hemisphere oceanic circulation. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2006gl027513

66 Delworth, T. L. & Dixon, K. W. Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the North Atlantic thermohaline circulation? *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2005gl024980

67 Dagan, G., Stier, P. & Watson-Parris, D. Aerosol Forcing Masks and Delays the Formation of the North Atlantic Warming Hole by Three Decades. *Geophys Res Lett* **47**, e2020GL090778 (2020). https://doi.org/10.1029/2020GL090778

68 Haarsma, R. J., Selten, F. M. & Drijfhout, S. S. Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes. *Environ Res Lett* **10** (2015). https://doi.org/10.1088/1748-9326/10/9/094007

69 Goldenberg, S. B., Landsea, C. W., Mestas-Nunez, A. M. & Gray, W. M. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **293**, 474-479 (2001). https://doi.org/DOI 10.1126/science.1060040

70 Trenberth, K. Uncertainty in hurricanes and global warming. *Science* **308**, 1753-1754 (2005). https://doi.org/10.1126/science.1112551

71 Emanuel, K. & Sobel, A. Response of tropical sea surface temperature, precipitation, and tropical cyclone-related variables to changes in global and local forcing. *J Adv Model Earth Sy* **5**, 447-458 (2013). https://doi.org/10.1002/jame.20032

72 Chiacchio, M. *et al.* On the links between meteorological variables, aerosols, and tropical cyclone frequency in individual ocean basins. *J Geophys Res-Atmos* **122**, 802-822 (2017). https://doi.org/10.1002/2015jd024593

73 Jones, A. C. *et al.* Impacts of hemispheric solar geoengineering on tropical cyclone frequency. *Nat Commun* **8** (2017). https://doi.org/10.1038/s41467-017-01606-0

74 Mann, M. E. & Emanuel, K. A. Atlantic hurricane trends linked to climate change. *Eos Trans. AGU* **87**, 233-241 (2011). https://doi.org/10.1029/2006EO240001

75 Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**, 686-688 (2005). https://doi.org/10.1038/nature03906

76 Rousseau-Rizzi, R. *On the climate variability of tropical cyclone potential intensity and Atlantic hurricane activity*, Massachusetts Institute of Technology, Cambridge, MA., (2021).

77 Myhre, G. *et al.* Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmos Chem Phys* **13**, 1853-1877 (2013). https://doi.org/10.5194/acp-13-1853-2013

78 Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. The Response of the ITCZ to Extratropical Thermal Forcing: Idealized Slab-Ocean Experiments with a GCM. *J Climate* **21**, 3521-3532 (2008). https://doi.org/10.1175/2007jcli2146.1

79 Adam, O., Bischoff, T. & Schneider, T. Seasonal and Interannual Variations of the Energy Flux Equator and ITCZ. Part I: Zonally Averaged ITCZ Position. *J Climate* **29**, 3219-3230 (2016). https://doi.org/10.1175/Jcli-D-15-0512.1

80 Kristjansson, J. E., Iversen, T., Kirkevag, A., Seland, O. & Debernard, J. Response of the climate system to aerosol direct and indirect forcing: Role of cloud feedbacks. *J Geophys Res-Atmos* **110** (2005). https://doi.org/10.1029/2005jd006299

81 Broccoli, A. J., Dahl, K. A. & Stouffer, R. J. Response of the ITCZ to Northern Hemisphere cooling. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2005gl024546

82 Wang, C. The sensitivity of tropical convective precipitation to the direct radiative forcings of black carbon aerosols emitted from major regions. *Ann Geophys-Germany* **27**, 3705-3711 (2009).

83 Haywood, J. M., Jones, A., Bellouin, N. & Stephenson, D. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nat Clim Change* **3**, 660-665 (2013). https://doi.org/10.1038/Nclimate1857

84 Navarro, J. C. A. *et al.* Future Response of Temperature and Precipitation to Reduced Aerosol Emissions as Compared with Increased Greenhouse Gas Concentrations. *J Climate* **30**, 939-954 (2017). https://doi.org/10.1175/Jcli-D-16-0466.1

85 Voigt, A. *et al.* Fast and slow shifts of the zonal-mean intertropical convergence zone in response to an idealized anthropogenic aerosol. *J Adv Model Earth Sy* **9**, 870-892 (2017). https://doi.org/10.1002/2016ms000902

86 Hawcroft, M., Haywood, J. M., Collins, M. & Jones, A. The contrasting climate response to tropical and extratropical energy perturbations. *Clim Dynam* **51**, 3231-3249 (2018).

87 Zhao, S. Y. & Suzuki, K. Differing Impacts of Black Carbon and Sulfate Aerosols on Global Precipitation and the ITCZ Location via Atmosphere and Ocean Energy Perturbations. *J Climate* **32**, 5567-5582 (2019). https://doi.org/10.1175/Jcli-D-18-0616.1

88 Zhang, S. P., Stier, P. & Watson-Parris, D. On the contribution of fast and slow responses to precipitation changes caused by aerosol perturbations. *Atmos Chem Phys* **21**, 10179-10197 (2021). https://doi.org/10.5194/acp-21-10179-2021

89 Soden, B. & Chung, E. S. The Large-Scale Dynamical Response of Clouds to Aerosol Forcing. *J Climate* **30**, 8783-8794 (2017). https://doi.org/10.1175/Jcli-D-17-0050.1

90 Hari, V., Villarini, G., Karmakar, S., Wilcox, L. J. & Collins, M. Northward Propagation of the Intertropical Convergence Zone and Strengthening of Indian Summer Monsoon Rainfall. *Geophysical Research Letters* **47** (2020). https://doi.org/10.1029/2020GL089823

91 Allen, R. J., Evan, A. T. & Booth, B. B. B. Interhemispheric Aerosol Radiative Forcing and Tropical Precipitation Shifts during the Late Twentieth Century. *J Climate* **28**, 8219-8246 (2015). https://doi.org/10.1175/Jcli-D-15-0148.1

92 Reutter, P. *et al.* Aerosol- and updraft-limited regimes of cloud droplet formation: influence of particle number, size and hygroscopicity on the activation of cloud condensation nuclei (CCN). *Atmos Chem Phys* **9**, 7067-7080 (2009).

93 Williams, E. *et al.* Contrasting convective regimes over the Amazon: Implications for cloud electrification. *J Geophys Res-Atmos* **107** (2002). https://doi.org/10.1029/2001jd000380

94 L'Ecuyer, T. S., Berg, W., Haynes, J., Lebsock, M. & Takemura, T. Global observations of aerosol impacts on precipitation occurrence in warm maritime clouds. *J Geophys Res-Atmos* **114** (2009). https://doi.org/10.1029/2008jd011273

95 Albrecht, B. A. Aerosols, cloud microphysics, and fractional cloudiness. *Science* **245**, 1227-1230 (1989). https://doi.org/10.1126/science.245.4923.1227

96 Twomey, S. Pollution and the planetary albedo. *Atmospheric Environment* **8**, 1251-1256 (1974). https://doi.org/10.1016/0004-6981(74)90004-3

97 Possner, A., Ekman, A. M. L. & Lohmann, U. Cloud response and feedback processes in stratiform mixed-phase clouds perturbed by ship exhaust. *Geophysical Research Letters* **44**, 1964-1972 (2017). https://doi.org/10.1002/2016gl071358

98 Andreae, M. O. *et al.* Smoking rain clouds over the Amazon. *Science* **303**, 1337-1342 (2004). https://doi.org/10.1126/science.1092779

99 Durkee, P. A. *et al.* The impact of ship-produced aerosols on the microstructure and albedo of warm marine stratocumulus clouds: A test of MAST hypotheses 1i and 1ii. *J Atmos Sci* **57**, 2554-2569 (2000). https://doi.org/Doi 10.1175/1520-0469(2000)057<2554:Tiospa>2.0.Co;2

100 Christensen, M. W., Suzuki, K., Zambri, B. & Stephens, G. L. Ship track observations of a reduced shortwave aerosol indirect effect in mixed-phase clouds. *Geophysical Research Letters* **41**, 6970-6977 (2014). https://doi.org/10.1002/2014gl061320

101 Toll, V., Christensen, M., Gasso, S. & Bellouin, N. Volcano and Ship Tracks Indicate Excessive Aerosol-Induced Cloud Water Increases in a Climate Model. *Geophysical Research Letters* **44**, 12492-12500 (2017). https://doi.org/10.1002/2017gl075280

102 Gryspeerdt, E., Smith, T. W. P., O'Keeffe, E., Christensen, M. W. & Goldsworth, F. W. The Impact of Ship Emission Controls Recorded by Cloud Properties. *Geophysical Research Letters* **46**, 12547-12555 (2019). https://doi.org/10.1029/2019gl084700

103 Watson-Parris, D. *et al.* Shipping regulations lead to large reduction in cloud perturbations. *Proceedings of the National Academy of Sciences* **119**, e2206885119 (2022). https://doi.org/doi:10.1073/pnas.2206885119

104 Quaas, J., Boucher, O. & Lohmann, U. Constraining the total aerosol indirect effect in the LMDZ and ECHAM4 GCMs using MODIS satellite data. *Atmos Chem Phys* **6**, 947-955 (2006).

105 Quaas, J. *et al.* Aerosol indirect effects - general circulation model intercomparison and evaluation with satellite data. *Atmos Chem Phys* **9**, 8697-8717 (2009).

106 Rosenfeld, D. *et al.* Global observations of aerosol-cloud-precipitation-climate interactions. *Rev Geophys* **52**, 750-808 (2014). https://doi.org/10.1002/2013rg000441

107 Bellouin, N. *et al.* Bounding Global Aerosol Radiative Forcing of Climate Change. *Rev Geophys* **58**, e2019RG000660 (2020). https://doi.org/10.1029/2019RG000660

108 Stephens, G. *et al.* CLOUDSAT AND CALIPSO WITHIN THE A-TRAIN: Ten Years of Actively Observing the Earth System. *B Am Meteorol Soc* **99**, 569-581 (2018). https://doi.org/10.1175/Bams-D-16-0324.1

109 Platnick, S. *et al.* The MODIS Cloud Optical and Microphysical Products: Collection 6 Updates and Examples From Terra and Aqua. *Ieee T Geosci Remote* **55**, 502-525 (2017). https://doi.org/10.1109/Tgrs.2016.2610522

110 Suzuki, K., Nakajima, T. Y. & Stephens, G. L. Particle Growth and Drop Collection Efficiency of Warm Clouds as Inferred from Joint CloudSat and MODIS Observations. *J Atmos Sci* **67**, 3019-3032 (2010). https://doi.org/10.1175/2010jas3463.1

111 Mulmenstadt, J., Sourdeval, O., Delanoe, J. & Quaas, J. Frequency of occurrence of rain from liquid-, mixed-, and ice-phase clouds derived from A-Train satellite retrievals. *Geophysical Research Letters* **42**, 6502-6509 (2015). https://doi.org/10.1002/2015gl064604

112 Malavelle, F. F. *et al.* Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature* **546**, 485-491 (2017).

113 Christensen, M. W. & Stephens, G. L. Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: 2. Impacts of haze on precipitating clouds. *J Geophys Res-Atmos* **117** (2012).

114 McCoy, D. T. *et al.* Aerosol midlatitude cyclone indirect effects in observations and high-resolution simulations. *Atmos Chem Phys* **18**, 5821-5846 (2018). https://doi.org/10.5194/acp-18-5821-2018

115 Gryspeerdt, E. *et al.* Surprising similarities in model and observational aerosol radiative forcing estimates. *Atmospheric Chemistry and Physics* **20**, 613-623 (2020). https://doi.org/10.5194/acp-20-613-2020

116 Jiang, H., Xue, H., Teller, A., Feingold, G. & Levin, Z. Aerosol effects on the lifetime of shallow cumulus. *Geophysical Research Letters* **33** (2006). https://doi.org/ L14806, doi:10.1029/2006GL026024

117 Zhou, C. & Penner, J. E. Why do general circulation models overestimate the aerosol cloud lifetime effect? A case study comparing CAM5 and a CRM. *Atmos Chem Phys* **17**, 21-29 (2017). https://doi.org/10.5194/acp-17-21-2017

118 Koren, I., Dagan, G. & Altaratz, O. From aerosol-limited to invigoration of warm convective clouds. *Science* **344**, 1143-1146 (2014). https://doi.org/10.1126/science.1252595

119 Seiki, T. & Nakajima, T. Aerosol Effects of the Condensation Process on a Convective Cloud Simulation. *J Atmos Sci* **71**, 833-853 (2014). https://doi.org/10.1175/Jas-D-12-0195.1

120 Sheffield, A. M., Saleeby, S. M. & van den Heever, S. C. Aerosol-induced mechanisms for cumulus congestus growth. *J Geophys Res-Atmos* **120**, 8941-8952 (2015). https://doi.org/10.1002/2015jd023743

121 Xue, H. & Feingold, G. Large-Eddy Simulations of Trade Wind Cumuli: Investigation of Aerosol Indirect Effects. *Journal of Atmospheric Science* **63**, 1605–1622 (2006).

122 Stevens, B. & Seifert, A. Understanding macrophysical outcomes of microphysical choices in simulations of shallow cumulus convection. *Journal of the Meteorological Society of Japan. Ser. II* **86A**, 143-162 (2008). https://doi.org/10.2151/jmsj.86A.143

123 Dagan, G., Koren, I. & Altaratz, O. Aerosol effects on the timing of warm rain processes. *Geophysical Research Letters* **42**, 4590-4598 (2015). https://doi.org/10.1002/2015gl063839

124 Dagan, G., Koren, I. & Altaratz, O. Competition between core and periphery-based processes in warm convective clouds - from invigoration to suppression. *Atmos Chem Phys* **15**, 2749-2760 (2015). https://doi.org/10.5194/acp-15-2749-2015

125 Kogan, Y. L. & Martin, W. J. Parameterization of Bulk Condensation in Numerical Cloud Models. *J Atmos Sci* **51**, 1728-1739 (1994). https://doi.org/Doi 10.1175/1520-0469(1994)051<1728:Pobcin>2.0.Co;2

126 Seifert, A. & Heus, T. Large-eddy simulation of organized precipitating trade wind cumulus clouds. *Atmos Chem Phys* **13**, 5631-5645 (2013). https://doi.org/10.5194/acp-13-5631-2013

127 Dagan, G., Koren, I., Altaratz, O. & Lehahn, Y. Shallow Convective Cloud Field Lifetime as a Key Factor for Evaluating Aerosol Effects. *Iscience* **10**, 192-+ (2018). https://doi.org/10.1016/j.isci.2018.11.032

128 Spill, G., Stier, P., Field, P. R. & Dagan, G. Effects of aerosol in simulations of realistic shallow cumulus cloud fields in a large domain. *Atmos Chem Phys* **19**, 13507-13517 (2019). https://doi.org/10.5194/acp-19-13507-2019

129 Chen, Y. C., Christensen, M. W., Stephens, G. L. & Seinfeld, J. H. Satellite-based estimate of global aerosol-cloud radiative forcing by marine warm clouds. *Nat Geosci* **7**, 643-646 (2014). https://doi.org/10.1038/Ngeo2214

130 Khain, A., Rosenfeld, D. & Pokrovsky, A. Aerosol impact on the dynamics and microphysics of deep convective clouds. *Q J Roy Meteor Soc* **131**, 2639–2663 (2005). https://doi.org/doi:10.1256/qj.04.62

131 van den Heever, S. C., Carrio, G. G., Cotton, W. R., DeMott, P. J. & Prenni, A. J. Impacts of nucleating aerosol on Florida storms. Part I: Mesoscale simulations. *J Atmos Sci* **63**, 1752-1775 (2006). https://doi.org/Doi 10.1175/Jas3713.1

132 Rosenfeld, D. *et al.* Flood or drought: How do aerosols affect precipitation? *Science* **321**, 1309-1313 (2008). https://doi.org/Doi 10.1126/Science.1160606

133 Tao, W. K., Chen, J. P., Li, Z. Q., Wang, C. & Zhang, C. D. Impact of Aerosols on Convective Clouds and Precipitation. *Rev Geophys* **50** (2012). https://doi.org/Artn Rg2001, 10.1029/2011rg000369

134 Koren, I. *et al.* Aerosol-induced intensification of rain from the tropics to the mid-latitudes. *Nat Geosci* **5**, 118-122 (2012). https://doi.org/Doi 10.1038/Ngeo1364

135 Koren, I., Kaufman, Y. J., Rosenfeld, D., Remer, L. A. & Rudich, Y. Aerosol invigoration and restructuring of Atlantic convective clouds. *Geophysical Research Letters* **32** (2005). https://doi.org/L14828, doi:10.1029/2005GL023187

136 Clavner, M., Cotton, W. R., van den Heever, S. C., Saleeby, S. M. & Pierce, J. R. The response of a simulated mesoscale convective system to increased aerosol pollution: Part I: Precipitation intensity, distribution, and efficiency. *Atmos Res* **199**, 193-208 (2018). https://doi.org/10.1016/j.atmosres.2017.08.010

137 van den Heever, S. C. *et al.* The Aerosol, Clouds, Precipitation and Climate (ACPC) inititiative multi-cloud-resolving-model intercomparison on aerosol-effects on deep convection. *Bulleting of the American Meteorological Society* **in preparation** (2024).

138 Storer, R. L. & Van den Heever, S. C. Microphysical Processes Evident in Aerosol Forcing of Tropical Deep Convective Clouds. *J Atmos Sci* **70**, 430-446 (2013).

139 Wang, C. A modeling study of the response of tropical deep convection to the increase of cloud condensation nuclei concentration: 1. Dynamics and microphysics. *J Geophys Res-Atmos* **110** (2005). https://doi.org/10.1029/2004jd005720

140 Chua, X. R. & Ming, Y. Convective Invigoration Traced to Warm-Rain Microphysics. *Geophysical Research Letters* **47** (2020). https://doi.org/10.1029/2020GL089134

141 Lee, S. S., Donner, L. J., Phillips, V. T. J. & Ming, Y. Examination of aerosol effects on precipitation in deep convective clouds during the 1997 ARM summer experiment. *Q J Roy Meteor Soc* **134**, 1201-1220 (2008). https://doi.org/Doi 10.1002/Qj.287

142 Grant, L. D. & van den Heever, S. C. Cold Pool and Precipitation Responses to Aerosol Loading: Modulation by Dry Layers. *J Atmos Sci* **72**, 1398-1408 (2015). https://doi.org/10.1175/Jas-D-14-0260.1

143 Varble, A. C., Igel, A. L., Morrison, H., Grabowski, W. W. & Lebo, Z. J. Opinion: A critical evaluation of the evidence for aerosol invigoration of deep convection. *Atmos Chem Phys* **23**, 13791-13808 (2023). https://doi.org/10.5194/acp-23-13791-2023
144 Fan, J. W. *et al.* Substantial convection and precipitation enhancements by ultrafine aerosol particles. *Science* **359**, 411-+ (2018). https://doi.org/10.1126/science.aan8461
145 Romps, D. M. *et al.* Air Pollution Unable to Intensify Storms via Warm-Phase Invigoration. *Geophysical Research Letters* **50** (2023). https://doi.org/10.1029/2022gl100409
146 Abbott, T. H. & Cronin, T. W. Aerosol invigoration of atmospheric convection through increases in humidity. *Science* **371**, 83-85 (2021). https://doi.org/10.1126/science.abc5181
147 Dagan, G. *et al.* Boundary conditions representation can determine simulated aerosol effects on convective cloud fields. *Commun Earth Environ* **3** (2022). https://doi.org/10.1038/s43247-022-00399-5
148 White, B. *et al.* Uncertainty from the choice of microphysics scheme in convection-permitting models significantly exceeds aerosol effects. *Atmospheric Chemistry and Physics* **17**, 12145-12175 (2017). https://doi.org/10.5194/acp-17-12145-2017
149 Heikenfeld, M., White, B., Labbouz, L. & Stier, P. Aerosol effects on deep convection: the propagation of aerosol perturbations through convective cloud microphysics. *Atmos Chem Phys* **19**, 2601-2627 (2019). https://doi.org/10.5194/acp-19-2601-2019
150 Storer, R. L., van den Heever, S. C. & Stephens, G. L. Modeling Aerosol Impacts on Convective Storms in Different Environments. *J Atmos Sci* **67**, 3904-3915 (2010). https://doi.org/10.1175/2010jas3363.1
151 Miltenberger, A. K. *et al.* Aerosol-cloud interactions in mixed-phase convective clouds - Part 1: Aerosol perturbations. *Atmos Chem Phys* **18**, 3119-3145 (2018). https://doi.org/10.5194/acp-18-3119-2018
152 Lee, S. S., Donner, L. J. & Penner, J. E. Thunderstorm and stratocumulus: how does their contrasting morphology affect their interactions with aerosols? *Atmos Chem Phys* **10**, 6819-6837 (2010). https://doi.org/10.5194/acp-10-6819-2010
153 Grabowski, W. W. Untangling Microphysical Impacts on Deep Convection Applying a Novel Modeling Methodology. *J Atmos Sci* **72**, 2446-2464 (2015). https://doi.org/10.1175/Jas-D-14-0307.1
154 Marinescu, P. J. *et al.* Impacts of Varying Concentrations of Cloud Condensation Nuclei on Deep Convective Cloud Updrafts-A Multimodel Assessment. *J Atmos Sci* **78**, 1147-1172 (2021). https://doi.org/10.1175/Jas-D-20-0200.1
155 Igel, A. L. & van den Heever, S. C. Invigoration or Enervation of Convective Clouds by Aerosols? *Geophysical Research Letters* **48** (2021).
156 Connolly, P. J. *et al.* Cloud-resolving simulations of intense tropical Hector thunderstorms: Implications for aerosol-cloud interactions. *Q J Roy Meteor Soc* **132**, 3079-3106 (2006). https://doi.org/DOI 10.1256/qj.05.86
157 Pan, Z. X. *et al.* Observational Quantification of Aerosol Invigoration for Deep Convective Cloud Lifecycle Properties Based on Geostationary Satellite. *J Geophys Res-Atmos* **126** (2021). https://doi.org/10.1029/2020JD034275
158 Heikenfeld, M., Marinescu, P. J., White, B., Heever, S. C. v. d. & Stier, P. A Lagrangian microphysical view of deep convection and aerosol effects for isolated deep convection over Houston, Texas. *Atmos. Chem. Phys.* **in prep.** (in prep.).
159 Kipling, Z., Labbouz, L. & Stier, P. Global response of parameterised convective cloud fields to anthropogenic aerosol forcing. *Atmos Chem Phys* **20**, 4445-4460 (2020). https://doi.org/10.5194/acp-20-4445-2020
160 Lohmann, U. Global anthropogenic aerosol effects on convective clouds in ECHAM5-HAM. *Atmos Chem Phys* **8**, 2115-2131 (2008).
161 Choi, Y. S., Lindzen, R. S., Ho, C. H. & Kim, J. Space observations of cold-cloud phase change. *P Natl Acad Sci USA* **107**, 11211-11216 (2010). https://doi.org/10.1073/pnas.1006241107
162 Stevens, R. G. *et al.* A model intercomparison of CCN-limited tenuous clouds in the high Arctic. *Atmos Chem Phys* **18**, 11041-11071 (2018). https://doi.org/10.5194/acp-18-11041-2018
163 Lohmann, U. A glaciation indirect aerosol effect caused by soot aerosols. *Geophysical Research Letters* **29** (2002). https://doi.org/10.1029/2001GL014357
164 Vergara-Temprado, J. *et al.* Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. *P Natl Acad Sci USA* **115**, 2687-2692 (2018). https://doi.org/10.1073/pnas.1721627115
165 Glassmeier, F. & Lohmann, U. Precipitation Susceptibility and Aerosol Buffering of Warm- and Mixed-Phase Orographic Clouds in Idealized Simulations. *J Atmos Sci* **75**, 1173-1194 (2018). https://doi.org/10.1175/Jas-D-17-0254.1
166 French, J. R. *et al.* Precipitation formation from orographic cloud seeding. *P Natl Acad Sci USA* **115**, 1168-1173 (2018). https://doi.org/10.1073/pnas.1716995115
167 National Research Council (U.S.). Committee on the Status of and Future Directions in U.S. Weather Modification Research and Operations. & National Research Council (U.S.). Board on Atmospheric Sciences and Climate. *Critical issues in weather modification research*. (National Academies Press, 2003).
168 Benjamini, Y. *et al.* The Israel 4 Cloud Seeding Experiment: Primary Results. *J Appl Meteorol Clim* **62**, 317-327 (2023). https://doi.org/10.1175/Jamc-D-22-0077.1
169 Korolev, A. & Leisner, T. Review of experimental studies of secondary ice production. *Atmos Chem Phys* **20**, 11767-11797 (2020).
170 Khain, A. P. Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review. *Environ Res Lett* **4** (2009). https://doi.org/015004, doi:10.1088/1748-9326/4/1/015004

171 Miltenberger, A. K., Field, P. R., Hill, A. A., Shipway, B. J. & Wilkinson, J. M. Aerosol-cloud interactions in mixed-phase convective clouds - Part 2: Meteorological ensemble. *Atmos Chem Phys* **18**, 10593-10613 (2018). https://doi.org/10.5194/acp-18-10593-2018

172 Schutgens, N. *et al.* On the spatio-temporal representativeness of observations. *Atmos Chem Phys* **17**, 9761-9780 (2017). https://doi.org/10.5194/acp-17-9761-2017

173 Liu, H. *et al.* Non-Monotonic Aerosol Effect on Precipitation in Convective Clouds over Tropical Oceans. *Sci Rep-Uk* **9** (2019). https://doi.org/10.1038/s41598-019-44284-2

174 Quaas, J., Stevens, B., Stier, P. & Lohmann, U. Interpreting the cloud cover – aerosol optical depth relationship found in satellite data using a general circulation model. *Atmos Chem Phys* **10**, 6129-6135 (2010). https://doi.org/10.5194/acp-10-6129-2010

175 Textor, C. *et al.* The effect of harmonized emissions on aerosol properties in global models – an AeroCom experiment. *Atmos Chem Phys* **7**, 4489-4501 (2007). https://doi.org/10.5194/acp-7-4489-2007

176 Stier, P. Limitations of passive satellite remote sensing to constrain global cloud condensation nuclei. *Atmos. Chem. Phys. Discuss.* **15**, 32607-32637 (2015). https://doi.org/10.5194/acpd-15-32607-2015

177 Grandey, B. S., Gururaj, A., Stier, P. & Wagner, T. M. Rainfall-aerosol relationships explained by wet scavenging and humidity. *Geophysical Research Letters* **41**, 5678-5684 (2014). https://doi.org/10.1002/2014gl060958

178 Gryspeerdt, E., Stier, P., White, B. A. & Kipling, Z. Wet scavenging limits the detection of aerosol effects on precipitation. *Atmos Chem Phys* **15**, 7557-7570 (2015). https://doi.org/10.5194/acp-15-7557-2015

179 Gryspeerdt, E. & Stier, P. Regime-based analysis of aerosol-cloud interactions. *Geophysical Research Letters* **39**, n/a-n/a (2012). https://doi.org/10.1029/2012gl053221

180 Gryspeerdt, E., Stier, P. & Partridge, D. G. Links between satellite-retrieved aerosol and precipitation. *Atmos Chem Phys* **14**, 9677-9694 (2014). https://doi.org/10.5194/acp-14-9677-2014

181 Storer, R. L., van den Heever, S. C. & L'Ecuyer, T. S. Observations of aerosol-induced convective invigoration in the tropical east Atlantic. *J Geophys Res-Atmos* **119**, 3963-3975 (2014). https://doi.org/10.1002/2013jd020272

182 Berg, W., L'Ecuyer, T. & van den Heever, S. Evidence for the impact of aerosols on the onset and microphysical properties of rainfall from a combination of satellite observations and cloud-resolving model simulations. *J Geophys Res-Atmos* **113** (2008).

183 Christensen, M. W. *et al.* Opportunistic experiments to constrain aerosol effective radiative forcing. *Atmos Chem Phys* **22**, 641-674 (2022). https://doi.org/10.5194/acp-22-641-2022

184 Coakley, J. A., Bernstein, R. L. & Durkee, P. A. Effect of Ship-Stack Effluents on Cloud Reflectivity. *Science* **237**, 1020-1022 (1987). https://doi.org/DOI 10.1126/science.237.4818.1020

185 Christensen, M. W., Coakley, J. A. & Tahnk, W. R. Morning-to-Afternoon Evolution of Marine Stratus Polluted by Underlying Ships: Implications for the Relative Lifetimes of Polluted and Unpolluted Clouds. *J Atmos Sci* **66**, 2097-2106 (2009).

186 Manshausen, P., Watson-Parris, D., Christensen, M. W., Jalkanen, J.-P. & Stier, P. Invisible ship tracks show large cloud sensitivity to aerosol. *Nature* **610**, 101-106 (2022). https://doi.org/10.1038/s41586-022-05122-0

187 Malavelle, F. F. *et al.* Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature* **551**, 256 (2017). https://doi.org/10.1038/nature24275

188 Suzuki, K., Stephens, G. L., Heever, S. C. v. d. & Nakajima, T. Y. Diagnosis of the Warm Rain Process in Cloud-Resolving Models Using Joint CloudSat and MODIS Observations. *J. Atmos. Sci.* **68**, 2655–2670 (2011). https://doi.org/10.1175/JAS-D-10-05026.1

189 Thornton, J. A., Virts, K. S., Holzworth, R. H. & Mitchell, T. P. Lightning enhancement over major oceanic shipping lanes. *Geophysical Research Letters* **44**, 9102-9111 (2017). https://doi.org/10.1002/2017gl074982

190 Blossey, P. N., Bretherton, C. S., Thornton, J. A. & Virts, K. S. Locally Enhanced Aerosols Over a Shipping Lane Produce Convective Invigoration but Weak Overall Indirect Effects in Cloud-Resolving Simulations. *Geophysical Research Letters* **45**, 9305-9313 (2018). https://doi.org/10.1029/2018gl078682

191 Berg, W., L'Ecuyer, T. & Kummerow, C. Rainfall climate regimes: The relationship of regional TRMM rainfall biases to the environment. *J Appl Meteorol Clim* **45**, 434-454 (2006). https://doi.org/Doi 10.1175/Jam2331.1

192 Hegerl, G. C. *et al.* Challenges in Quantifying Changes in the Global Water Cycle. *B Am Meteorol Soc* **96**, 1097-1115 (2015). https://doi.org/Doi 10.1175/Bams-D-13-00212.1

193 Polson, D., Bollasina, M., Hegerl, G. C. & Wilcox, L. J. Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols. *Geophysical Research Letters* **41**, 6023-6029 (2014). https://doi.org/10.1002/2014gl060811

194 Sarojini, B. B., Stott, P. A. & Black, E. Detection and attribution of human influence on regional precipitation. *Nat Clim Change* **6**, 669-675 (2016). https://doi.org/10.1038/Nclimate2976

195 Paik, S. *et al.* Determining the Anthropogenic Greenhouse Gas Contribution to the Observed Intensification of Extreme Precipitation. *Geophysical Research Letters* **47** (2020). https://doi.org/10.1029/2019GL086875

196 Wilcox, L. J., Dong, B., Sutton, R. T. & Highwood, E. J. The 2014 Hot, Dry Summer in Northeast Asia. *B Am Meteorol Soc* **96**, S105-S110 (2015). https://doi.org/10.1175/Bams-D-15-00123.1

197 Wilcox, L. J. *et al.* Accelerated increases in global and Asian summer monsoon precipitation from future aerosol reductions. *Atmos Chem Phys* **20**, 11955-11977 (2020). https://doi.org/10.5194/acp-20-11955-2020

198 Deser, C. *et al.* Isolating the Evolving Contributions of Anthropogenic Aerosols and Greenhouse Gases: A New CESM1 Large Ensemble Community Resource. *J Climate* **33**, 7835-7858 (2020). https://doi.org/10.1175/Jcli-D-20-0123.1

199 Reddington, C. *et al.* The Global Aerosol Synthesis and Science Project (GASSP): Observations and modelling to reduce uncertainty. *B Am Meteorol Soc* **in prep.** (2016).

200 Kahn, R. A. *et al.* SAM-CAAM: A Concept for Acquiring Systematic Aircraft Measurements to Characterize Aerosol Air Masses. *B Am Meteorol Soc* **98**, 2215-2228 (2017).

201 Medeiros, B. Aquaplanets as a Framework for Examination of Aerosol Effects. *J Adv Model Earth Sy* **12** (2020). https://doi.org/10.1029/2019MS001874

202 Dingley, B., Dagan, G. & Stier, P. Forcing convection to aggregate using diabatic heating perturbations. *J Adv Model Earth Sy* (2021). https://doi.org/submitted

203 Stevens, B. *et al.* DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. *Prog Earth Planet Sc* **6** (2019). https://doi.org/10.1186/s40645-019-0304-z

204 Bauer, P., Stevens, B. & Hazeleger, W. A digital twin of Earth for the green transition. *Nat Clim Change* **11**, 80-83 (2021). https://doi.org/10.1038/s41558-021-00986-y

205 Gillett, N. P. *et al.* The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6. *Geosci Model Dev* **9**, 3685-3697 (2016). https://doi.org/10.5194/gmd-9-3685-2016

206 Giorgetta, M. A. *et al.* ICON-A, the Atmosphere Component of the ICON Earth System Model: I. Model Description. *J Adv Model Earth Sy* **10**, 1613-1637 (2018). https://doi.org/10.1029/2017ms001242

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COMPETING INTERESTS DECLARATION

The authors declare no competing interests.

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AUTHOR CONTRIBUTION STATEMENTS

P.S. and S. vd H. developed the structure of the GEWEX Aerosol Preciptiation Initiative workshop programme providing the basis for this review paper. M. W.C and E. G. served as raporteurs provided detailed meeting notes. P.S. and S. vd H. drafted the first version of the manuscript that was extended upon with contributions from all authors to the literature review, the synthesis of the results and revising the manuscript. G.D. created the figures in Figure 1 and Figure 3. S.M.S created Figure 4.

TABLES & FIGURES

Table 1: Assessment of the effect of increasing aerosol on precipitation. Microphysical and radiative pathways are distinguished in the second column. Columns 3 and 4 indicate the expected effect on mean precipitation or the intensity distribution; column 5 indicates whether the effect is included in current generation (CMIP6) climate models. The scientific consensus (A strong evidence / broad consensus; B some evidence / limited consensus; C hypothesised / no consensus) is summarized in column 6.

Physical driver of aerosol effect on precipitation	Pathway	Effect on mean	Effect on intensity distribution	Included in CMIP6 climate models	Scientific consensus
(i) Surface energy budget	Radiative	Decrease	Uncertain	Yes	A
(ii) Diabatic heating	Radiative	Decrease	Uncertain	Yes	A
(iii) Semi-direct effects	Radiative	Uncertain	Uncertain	Yes	B
(iv) Regional scale and monsoon dynamics	Radiative	Regional shifts	Uncertain	Yes	B
(v) Sea surface temperature patterns	Radiative	Regional shifts	Uncertain	Yes	B
(vi) Hemispheric asymmetry	Radiative	Regional shifts	Neutral	Yes	A
(vii) CCN effects on stratiform liquid clouds	Microphysical	Neutral	Uncertain	Yes (significant uncertainties)	B
(viii) CCN effects on shallow convection	Microphysical	Uncertain	Broaden	No	B
(ix) CCN effects on deep convection	Microphysical	Uncertain	Broaden	No	C
(x) INP effects	Microphysical	Uncertain	Uncertain	No (in most models)	C

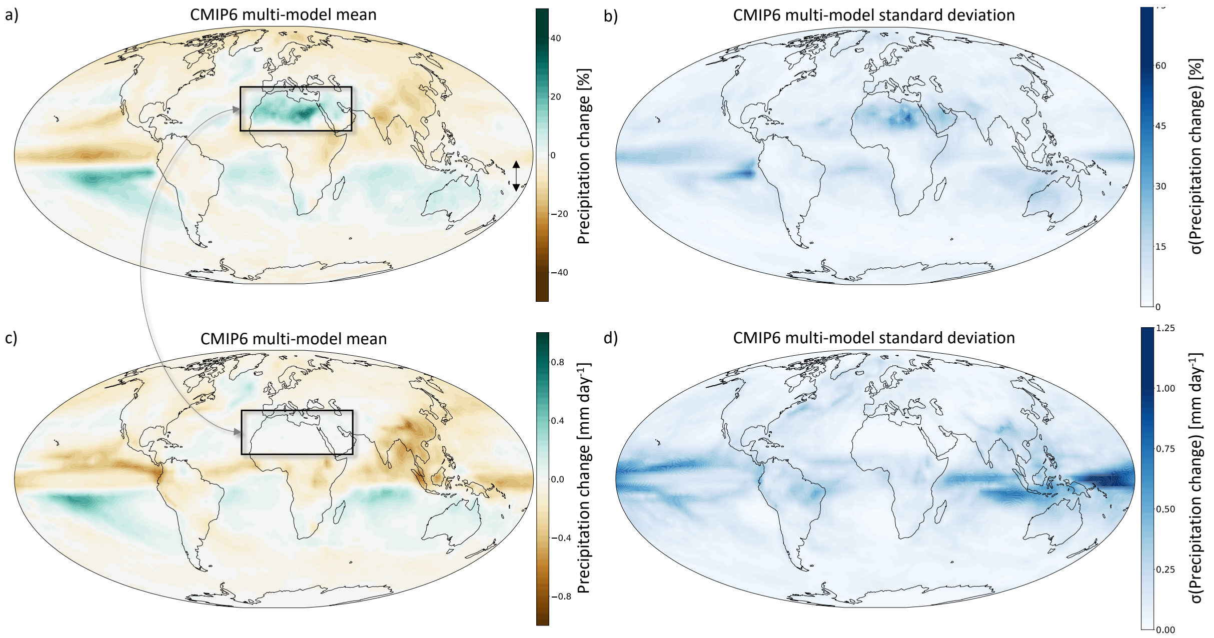

Figure 1: Climate model simulated a) relative and c) absolute precipitation changes [%] due to anthropogenic aerosol from the coupled model intercomparison project phase 6 (CMIP6) Detection and Attribution Model Intercomparison Project (DAMIP[205], difference between last 30 years of present-day DAMIP *hist-aer* minus pre-industrial *picontrol* control simulations) and the corresponding multi-model standard deviations b), d), respectively. Note the significant differences between relative (a) and absolute (b) precipitation changes, highlighted in the box over northern Africa and the Middle-East.

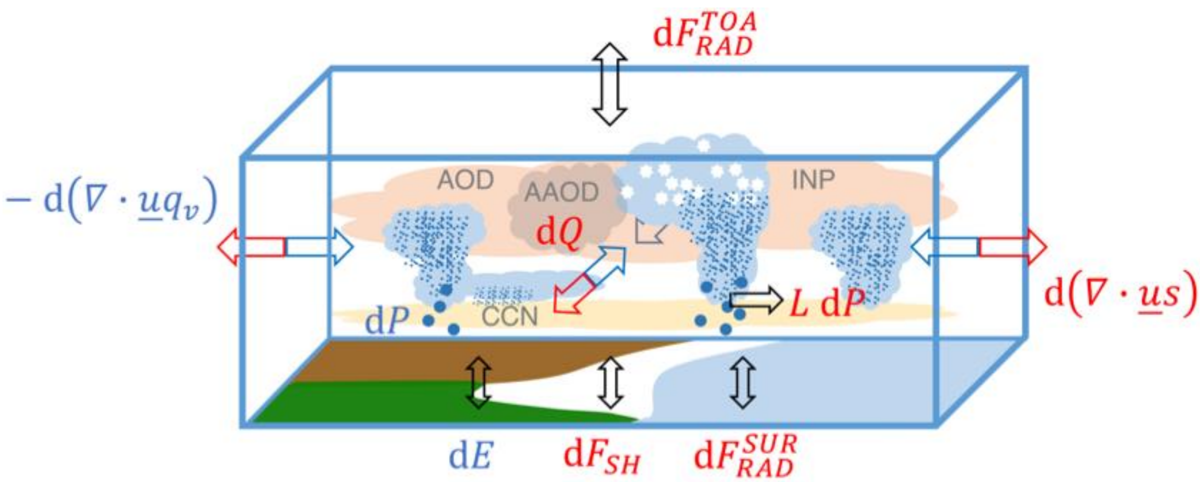

Figure 2: Illustration of mechanisms of aerosol effects on precipitation and their constraints from an energy (red) and water (blue) budget perspective. Radiative and microphysical effects are mediated by variations in Aerosol Optical Depth (AOD), Aerosol Absorption Optical Depth (AAOD) and Cloud Condensation Nuclei (CCN) as well as Ice Nucleating Particles (INP), respectively.

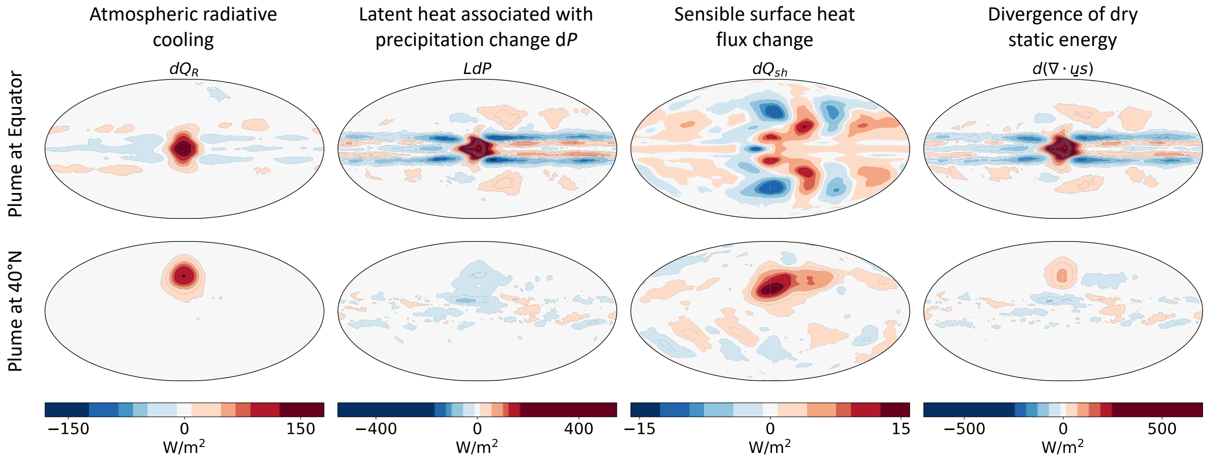

Figure 3: Idealised aqua-planet ICON[206] general circulation model simulations of changes of precipitation and the atmospheric energy balance in response to idealised circular absorbing aerosol radiative plumes (of 10° size and identical aerosol radiative properties with peak aerosol optical depth of 2.4 and single scattering albedo of 0.8)[33]. Top row: plume located on the equator. Bottom row: plume located at 40°N. dQ_R: atmospheric radiative cooling; LdP: latent heat associated with precipitation change dP ; dQ_{SH}: sensible surface heat flux; $\mathbf{d}(\nabla\cdot\underline{\boldsymbol{us}})$: divergence of dry static-energy.

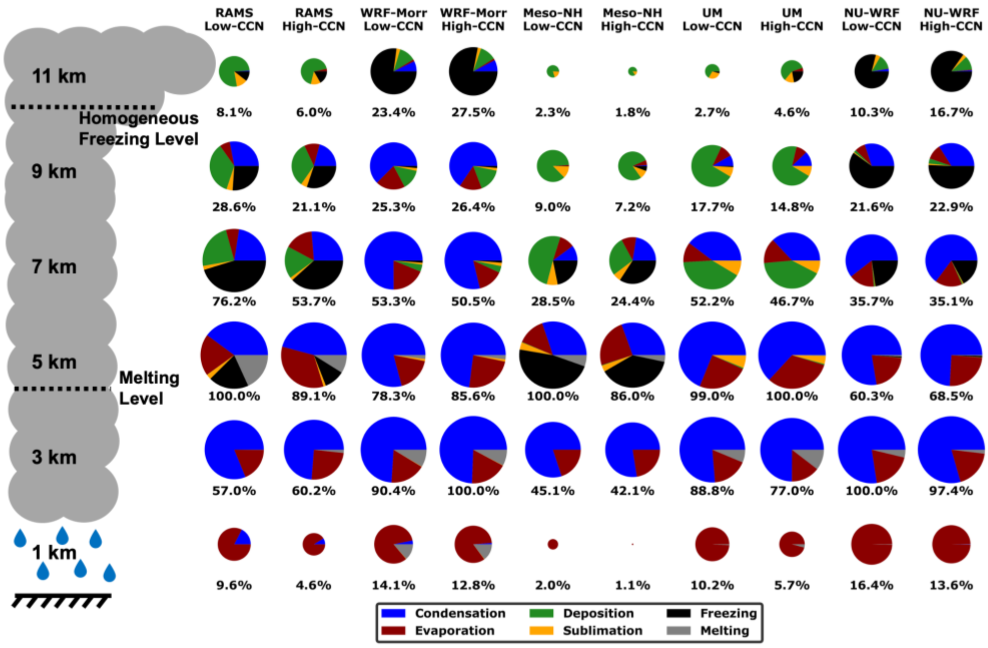

Figure 4: Cloud-resolving model intercomparison of CCN mediated effects on deep convection from the Aerosol, Clouds, Precipitation and Climate deep convection study[137,154]: fractional mass process rates for tracked deep convective systems for low and high CCN conditions as a function of height. Results for each model, named in the top row, are shown for low and high CCN conditions in individual columns. The size of the pies is scaled logarithmically by the largest mass production rate of the model. Significant differences in the model base state and the response to cloud condensation nuclei perturbations illustrate associated large uncertainties.