MULTIFACETED AEROSOL EFFECTS ON PRECIPITATION

Philip Stier[1], Susan C. van den Heever[2], Matthew W. Christensen[1,3], Edward Gryspeerdt[4], Guy Dagan[1,now at 20], Stephen M. Saleeby[2], Massimo Bollasina[5], Leo Donner[6], Kerry Emanuel[7], Annica M. L. Ekman[8], Graham Feingold[9], Paul Field[10,11], Piers Forster[12], Jim Haywood[13,11], Ralph Kahn[14], Ilan Koren[15], Christian Kummerow[2], Tristan L'Ecuyer[16] , Ulrike Lohmann[17], Yi Ming[6,now at 18,], Gunnar Myhre[19], Johannes Quaas[20], Daniel Rosenfeld[21], Bjorn Samset[19], Axel Seifert[22], Graeme Stephens[23], Wei-Kuo Tao[24]

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].

[1] Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, UK

[2] Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA

[3] Now at Pacific Northwest National Laboratory, Richland, WA 99354, United States.

[4] Space and Atmospheric Physics Group, Imperial College London, London SW7 2AZ, UK

[5] School of GeoSciences, The University of Edinburgh, Grant Institute, West Mains Road, Edinburgh EH9 3JW, UK

[6] NOAA/GFDL, Princeton University Forrestal Campus, 201 Forrestal Road, Princeton, New Jersey 08540, USA

[7] Lorenz Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[8] Department of Meteorology, and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

[9] National Oceanic and Atmospheric Administration, Chemical Sciences Laboratory, Boulder, CO 80305, USA

[10] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[11] Met Office, Fitzroy Rd, Exeter EX1 3PB, UK

[12] Priestley International Centre for Climate, University of Leeds, Leeds, LS2 9JT, UK

[13] CEMPS, University of Exeter, Exeter, UK

[14] NASA Goddard Space Flight Center, Greenbelt, MD, USA

[15] Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot, Israel

[16] Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, Wisconsin, USA

[17] ETH Zürich, Institute for Atmospheric and Climate Science, Zürich, Switzerland

[18] Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA

[19] Center for International Climate Research—Oslo (CICERO), Pb. 1129 Blindern, N-0318 Oslo, Norway

[20] Institute for Meteorology, Universität Leipzig, Leipzig, Germany

[21] Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel

[22] Deutscher Wetterdienst, Offenbach, Germany

[23] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

[24] Mesoscale Atmospheric Processes Laboratory, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

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

38 This article builds on the results of an expert workshop held under the auspices of the Global Energy
39 and Water cycle Exchanges (GEWEX) Aerosol Precipitation (GAP) initiative[4]. It critically reviews the
40 current evidence and scientific consensus (in the authors' view) for APEs and their proposed
41 mechanisms. To facilitate this assessment, we categorise mechanisms according to their degree of
42 scientific support: Category A: strong evidence / broad consensus; Category B: some evidence / limited
43 consensus; Category C: hypothesised / no consensus.
44

45 THE PHYSICAL MECHANISMS OF AEROSOL EFFECTS ON PRECIPITATION

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

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

60 $$L\, \mathrm{d}P = \mathrm{d}Q + \mathrm{d}(\nabla \cdot \underline{u}s) \qquad \qquad 1$$

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

64 $$\mathrm{d}P - \mathrm{d}E = -\,\mathrm{d}(\nabla \cdot \underline{u}q_v) \qquad \qquad 2$$

65 This implies the existence of *breakdown scales of budgetary constraints on precipitation* - a scale
66 below which energy and water budget constraints on precipitation do not strictly apply due to efficient
67 horizontal transport[11]. In the extra-tropics, this scale is expected to be related to the first baroclinic
68 Rossby radius of deformation ($L = \dfrac{NH}{\pi f_0} \approx 1000km$, *where N is the Brunt–Väisälä frequency, H is the*
69 *scale height, and f$_0$ is the Coriolis parameter*). This latitudinally dependent precipitation constraint on
70 aerosol perturbations implies varying effects in the tropics and extra-tropics (Figure 3). Even for
71 regional aerosol perturbations, energetic constraints apply to the global mean. Reductions in surface
72 insolation and atmospheric heating by aerosol absorption decrease global mean precipitation in both
73 simulations, with teleconnections in the tropical simulation.

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

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

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

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

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

96 RADIATIVE EFFECTS

97 i.   *SURFACE ENERGY BUDGET* ARIs and ACIs modulate radiative surface fluxes and, consequently, sensible
98   and latent heat fluxes. These effects generally reduce surface insolation, decreasing surface
99   evaporation which has been linked to a "spin down" of the hydrological cycle[25]. This is corroborated
100   by the observed precipitation response to ARIs following major volcanic eruptions, showing
101   substantial decreases in precipitation over land and river discharge into ocean[26,27]. (Near-surface
102   absorbing aerosol can enhance precipitation through diabatic heating, even when surface sensible
103   heat fluxes are reduced[28].) Energetically, the net-negative total ARIs[29] reduce the global mean
104   temperature, atmospheric water vapour, and associated long-wave emission, which is compensated
105   by reductions in precipitation and associated latent heat: climate models show that negative aerosol
106   radiative forcing masks almost all temperature-driven GHG effects on precipitation over land up to
107   present (with GHG effects dominating the future)[9,30,31]. However, such radiative arguments cannot
108   be decoupled from dynamical feedbacks, as shown below.
109   *That ARIs reduce global precipitation through changes in surface temperature and surface fluxes*
110   *builds on our physical understanding of the energy budget, is supported by observational evidence[32]*
111   *and reproduced by climate models. We assess this effect as Category A, supported by strong evidence*
112   *and broad scientific consensus, although magnitudinal uncertainties remain.*

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

115 ii. *Atmospheric diabatic heating* by aerosol absorption creates local energetic imbalances. To ensure
116   energy conservation, this is compensated by reductions in latent heat release through precipitation,
117   by rapid adjustments of net surface or top-of-atmosphere fluxes, or, on smaller scales or in the
118   tropics[11,33], through divergence of dry static energy[8,34]. The energetic framework provides a useful
119   tool to diagnose APEs[9,21,28,34,35] and can explain the contrasting behaviour of absorbing and non-
120   absorbing aerosols[21,36].
121   *That diabatic heating of absorbing aerosol reduces global mean precipitation is consistent with our*
122   *physical understanding of the energy budget, is reproduced by climate models but builds on limited*
123   *observational evidence. We therefore assess this effect as Category A, supported by strong evidence*
124   *and broad scientific consensus but with remaining magnitudinal uncertainties.*

125 iii. *Semi-direct effects*[9,37-40] are rapid adjustments associated with aerosol absorption affecting the
126   vertical temperature and humidity structure, with potential effects on clouds and precipitation.
127   These effects are generally accompanied by corresponding surface flux changes (cf. ii). Elevated
128   layers of absorbing aerosol can modify lower-tropospheric static stability and sub-tropical inversion
129   strength[39,41], suppressing boundary layer deepening and concomitant entrainment[42]. Although the
130   focus has been on shallow clouds[43], the impact on deep convection and associated precipitation has

131   been demonstrated in CRMs, revealing a complex diurnal cycle[44], and climate models[28]. However,
132   most prior research focused on semi-direct effects of shallow clouds in the context radiative
133   forcing[43], not precipitation. Hence, the overall uncertainty remains large.
134   *Semi-direct effects of absorbing aerosol on the thermodynamic structure of the atmosphere are*
135   *based on a sound physical foundation and have been well documented. However, the sign and*
136   *magnitude of the effect on clouds and subsequently precipitation are sensitive to the vertical*
137   *collocation of clouds and aerosols as well as the cloud regime. Some consistency exists across CRM*
138   *studies, however, the observational evidence remains limited. We therefore assess this effect as*
139   *Category B, backed up by physical conceptual models, modelling studies and limited observational*
140   *evidence and some scientific consensus, even if the magnitude and sign of the impact on*
141   *precipitation remain unclear.*
142   The following mechanisms iv) – vi) could be combined as aerosol effects on regional precipitation
143   patterns but we retain the mechanistic separation prevailing in existing literature.
144 iv. **Changes in regional-scale precipitation and monsoon dynamics** have been attributed to regional
145   patterns in ARI-induced surface cooling and atmospheric heating, both locally and remotely [12,34,45-
146   49]. The precipitation response can be attributed to a combination of the modulation of surface fluxes
147   over land, hence of the thermal gradient between land and sea[50,51], as well as aerosol absorption
148   effects, driving thermally direct circulations[12,52] and moisture convergence[52] (linked to extreme
149   precipitation [53,54]), the sea breeze circulation[55], and teleconnections[56].
150   *Aerosol effects on regional scale precipitation and monsoon dynamics have been shown to affect*
151   *precipitation patterns. This builds on climate model and CRM simulations and general physical*
152   *understanding, with some observational evidence. However, uncertainties remain regarding the*
153   *attribution of observed precipitation to aerosol effects and overall strength of the effects. We*
154   *therefore assess this effect as Category B, backed by some evidence and limited scientific consensus.*
155 v. **Aerosol radiative effects on sea surface temperature patterns** (SSTs) have been linked to observed
156   climatological trends[57,58]. Associated changes in multi-decadal SST variability[59] have previously been
157   linked to the Sahel drought[60-63]. In addition to the local effects on the SST distribution, aerosols may
158   also affect ocean dynamics and thereby SSTs. For example, aerosol forcing was shown to strengthen
159   the Atlantic Meridional Overturning Circulation (AMOC) thereby modulating SST patterns in the
160   Atlantic Ocean[64-67], and affecting the Northern Hemisphere climate and precipitation patterns[63,68].
161   SSTs also control hurricane activity[61,69-71], providing a mechanism for potential aerosol effects on
162   hurricanes[72,73]. Forcing trends associated with European sulfuremissions as aerosol precursor, have
163   been linked to a pronounced North Atlantic "hurricane drought" from the 1960s through early
164   1990s[74] during which hurricane power dissipation, a measure of storm damage[75], was strongly
165   inversely correlated with European sulfur emissions. Much of the direct SST forcing was from
166   Saharan mineral dust, which in turn was associated with reduced monsoonal flow resulting from
167   high sulfate aerosol concentrations[76].
168   *The SST mediated effect of aerosol on regional precipitation patterns and hurricane activity builds on*
169   *climate model simulations and general physical understanding, with limited observational evidence.*
170   *We therefore assess this effect as Category B, backed up by some evidence and limited scientific*
171   *consensus.*
172 vi. **Hemispheric asymmetry in aerosol radiative effects**[77] shifts the energy flux equator to where the
173   column-integrated meridional energy flux vanishes[78,79]. The position of the energy flux equator is
174   closely linked to the ITCZ position and associated precipitation. With anthropogenic aerosol
175   predominantly located in the northern hemisphere, associated negative/positive aerosol radiative
176   effects, e.g. from sulfate/black carbon, lead to a southward/northward ITCZ shift[62,78-87]. For sulfate,
177   this is a slow (SST mediated) response, whereas for black carbon adjustments in response to
178   absorption contribute[88]. Dynamical cloud feedbacks can further amplify the hemispheric
179   asymmetry[89] and ITCZ shifts can interact with local monsoon regimes[90].
180   *The effect of hemispherically asymmetric aerosol radiative effects on the energy flux equator and*
181   *ITCZ position builds on a robust theoretical foundation[79], agrees with observational evidence[83,91] and*

182 *is reliably reproduced by GCMs. We therefore assess this effect as Category A, backed up by strong*
183 *evidence and broad scientific consensus.*

184 **MICROPHYSICAL EFFECTS**

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

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

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

217 *viii.* **CCN mediated effects on shallow convection:** for shallow (liquid) convective clouds, an aerosol
218 mediated increase in cloud droplet numbers has several effects: associated smaller droplet radii
219 enhance evaporation that increases the buoyancy gradient at the cloud edge, creating vorticity and
220 increasing associated entrainment/detrainment[116], which results in a reduction of cloud size, liquid
221 water path, buoyancy and precipitation. At the same time, suppression of rain production via the
222 droplet number effect on autoconversion can produce enhanced condensation and latent heat
223 release due to larger numbers of remaining cloud droplets and associated increase in surface area,
224 often referred to as *"warm phase or condensational invigoration"[118-120]*. It can also enhance cloud-
225 top detrainment; subsequent evaporative cooling can destabilize the environment[121]. Both
226 mechanisms could generate deeper clouds[122] with potentially enhanced precipitation. The net effect
227 on mean precipitation could therefore be small[16,17] or even positive, depending on environmental
228 conditions: high-resolution large-eddy simulations demonstrate a non-monotonic precipitation
229 response with increases at low aerosol concentrations up to an optimal aerosol concentration,
230 followed by a precipitation decrease[118-120,123-125]. For larger spatio-temporal scales, idealised
231 simulations of shallow convection approach a radiative-convective equilibrium state[17]. Although the
232 transient behaviour approaching equilibrium responds to increasing cloud droplet number

233 concentrations through deepening and delays precipitation onset[126], in the equilibrium state
234 associated decreases in relative humidity and faster evaporation of small clouds compensates for
235 much of the radiative effects with broader intensity precipitation distributions[19]. The overall effect
236 depends on the relative importance of transient and equilibrium states[17,93,127] with recent evidence
237 highlighting limitations of idealised simulations that unrealistically favour equilibrium states[128].
238 However, contrasting environmental factors, such as boundary layer development or humidity, can
239 influence the overall effects[123,129].
240 *CCN mediated effects on shallow convection have been shown to increase droplet numbers and slow*
241 *warm-phase precipitation formation. This is based on high-resolution CRMs and observational*
242 *evidence. It is important to note that convection parameterisations in most GCMs do not represent*
243 *any microphysical aerosol effects on convection. The overall effect on precipitation is less certain. We*
244 *assess this effect as Category B, backed up by some evidence and limited scientific consensus.*
245 ix. **CCN mediated effects on deep convection:** for deep (liquid & ice phase) convective clouds,
246 *"convective invigoration"* is widely discussed, generally referring to enhanced aerosol levels causing
247 stronger updrafts or higher clouds and an associated increase in precipitation[93,98,130-136]. Several
248 hypotheses about underlying mechanisms exist. Often overlooked, these share a common starting
249 point with shallow convection in the liquid base of clouds: the suppression of warm rain formation
250 from reduced autoconversion with enhanced CCN in the lower, liquid part of the cloud[137,138], with an
251 associated reduction in droplet size and resulting entrainment/detrainment feedbacks. Subsequent
252 invigoration hypotheses include: enhanced condensation and associated latent heat release (*"warm*
253 *phase invigoration", c.f. viii)*[118,119,139,140]; enhanced evaporation and downdraft formation affecting
254 cold pool strength and surface convergence[141,142]; delay of warm-phase precipitation increasing the
255 amount of cloud water reaching the freezing level, enhancing the release of latent heat of
256 freezing[93,98,132] although the importance of this *("cold phase invigoration")* is disputed[143]; the
257 hypothesis that depletion of cloud water through precipitation in low aerosol environments could
258 generate high supersaturations and subsequent activation of small aerosol particles into cloud
259 droplets, enhancing condensation and (warm phase) latent heat release[144] – a hypothesis shown to
260 be inconsistent with a limited set of observations[145]; and that enhanced CCN levels increase
261 environmental humidity through clouds mixing more condensed water into the surrounding air,
262 preconditioning the environment for invigorated convection[146]. The latter result is likely a
263 consequence of idealised equilibrium simulations as it is not observed in realistic simulations across
264 a wide range of environmental conditions[147]. Feedbacks between convective clouds and their
265 thermodynamic environment may modulate or buffer APEs. Overall, the strength and relative
266 importance of mechanisms underlying convective invigoration are disputed [143] – it is sensitive to
267 uncertain microphysical effects[148,149] and strongly dependent on environmental regimes[49,130,141,150-
268 152]. In addition, the excess buoyancy associated with the respective mechanisms can be partially
269 offset by negative buoyancy associated with condensate loading[153,154], with the net effect dependent
270 on condensate offloading through precipitation. The role of condensate loading has been explored
271 through theoretical calculations that show the potential of aerosol-induced invigoration is
272 significantly limited for cold-based storms, and that aerosol-induced cold-phase processes weaken,
273 rather than strengthen the updrafts in warm-based storms (referred to as aerosol enervation)[155].
274 The first systematic multi-model assessment of these competing aerosol effects on deep convective
275 updrafts[154] has been performed as part of a deep convection case study[137] over Houston, USA, under
276 the umbrella of the Aerosol, Cloud, Precipitation, and Climate initiative (Figure 4). This
277 intercomparison revealed updraft increases by 5%-15% in the mid-storm regions (4-7 km above
278 ground) with increased CCN, primarily driven by enhanced condensation, with waning and mixed
279 difference in levels above. Condensate loading contributions are generally limited. Despite this
280 apparent invigoration, 6 of 7 models produce precipitation decreases (of -10% to -80%), highlighting
281 the complexity of precipitation responses to aerosol perturbations. There are indications that
282 microphysical effects strengthen deep and weaken shallow clouds in convective cloud fields, thereby
283 broadening the precipitation intensity distribution[18,44]. Observations and modelling suggest a non-

284 monotonic effect, with precipitation peaking at an optimal aerosol concentration[156,157]. It should be
285 re-iterated that even high-resolution CRM simulations of aerosol effects on deep convection remain
286 subject to large uncertainty, particularly with mixed-phase and ice-cloud microphysics, affecting the
287 simulated base states as well as their response to aerosol perturbations[137,148,158] (Figure 4). Few
288 current climate models include aerosol aware convection parameterisations and their early results
289 indicate limited aerosol effects on convective precipitation on the global scale[159,160]. However, the
290 associated uncertainties remain large, providing challenges for the next generation of cloud
291 resolving climate models.

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

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

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

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

326 **DETECTABILITY AND ATTRIBUTION OF PRECIPITATION CHANGES**

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

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

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

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

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

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

368 ### CONCLUSIONS

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

381 Research on APEs has been limited by the fact that: locally to regionally, precipitation is controlled by
382 complex non-linear interactions with multiple microphysical, radiative and dynamical feedbacks; the
383 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).

436   8   Muller, C. J. & O'Gorman, P. A. An energetic perspective on the regional response of precipitation to climate
437   change. *Nat Clim Change* **1**, 266-271 (2011). https://doi.org/10.1038/Nclimate1169

438   9   Myhre, G. *et al.* PDRMIP A Precipitation Driver and Response Model Intercomparison Project-Protocol and
439   Preliminary Results. *B Am Meteorol Soc* **98**, 1185-1198 (2017). https://doi.org/10.1175/Bams-D-16-0019.1

440   10   Richardson, T. B. *et al.* Drivers of Precipitation Change: An Energetic Understanding. *J Climate* **31**, 9641-9657
441   (2018). https://doi.org/10.1175/Jcli-D-17-0240.1

442   11   Dagan, G. & Stier, P. Constraint on precipitation response to climate change by combination of atmospheric energy
443   and water budgets. *Npj Clim Atmos Sci* **3** (2020). https://doi.org/10.1038/s41612-020-00137-8

444   12   Roeckner, E. *et al.* Impact of carbonaceous aerosol forcing on regional climate change. *Clim. Dyn.* **27**, 553-571
445   (2006). https://doi.org/10.1007/s00382-006-0147-3

446   13   Dagan, G., Stier, P. & Watson-Parris, D. Analysis of the Atmospheric Water Budget for Elucidating the Spatial Scale
447   of Precipitation Changes Under Climate Change. *Geophys. Res. Lett.* **46** (2019).
448   https://doi.org/10.1029/2019GL084173

449   14   Trenberth, K. E., Dai, A., Rasmussen, R. M. & Parsons, D. B. The Changing Character of Precipitation. *B Am Meteorol
450   Soc* **84**, 1205-1218 (2003). https://doi.org/10.1175/bams-84-9-1205

451   15   Hodnebrog, Ø. *et al.* Water vapour adjustments and responses differ between climate drivers. *Atmos Chem Phys*
452   **19**, 12887-12899 (2019). https://doi.org/10.5194/acp-19-12887-2019

453   16   Stevens, B. & Feingold, G. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature* **461**,
454   607-613 (2009). https://doi.org/10.1038/Nature08281

455   17   Seifert, A., Heus, T., Pincus, R. & Stevens, B. Large-eddy simulation of the transient and near-equilibrium behavior
456   of precipitating shallow convection. *J. Adv. Model. Earth Syst.* **7** (2015). https://doi.org/10.1002/ 2015MS000489

457   18   van den Heever, S. C., Stephens, G. L. & Wood, N. B. Aerosol Indirect Effects on Tropical Convection Characteristics
458   under Conditions of Radiative-Convective Equilibrium. *J Atmos Sci* **68**, 699-718 (2011).
459   https://doi.org/10.1175/2010jas3603.1

460   19   Yamaguchi, T., Feingold, G. & Kazil, J. Aerosol-Cloud Interactions in Trade Wind Cumulus Clouds and the Role of
461   Vertical Wind shear. *J Geophys Res-Atmos* **124**, 12244-12261 (2019). https://doi.org/10.1029/2019jd031073

462   20   Richardson, T. B., Samset, B. H., Andrews, T., Myhre, G. & Forster, P. M. An assessment of precipitation adjustment
463   and feedback computation methods. *J Geophys Res-Atmos* **121**, 11608-11619 (2016).
464   https://doi.org/10.1002/2016jd025625

465   21   Samset, B. H. *et al.* Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study.
466   *Geophysical Research Letters* **43**, 2782-2791 (2016). https://doi.org/10.1002/2016gl068064

467   22   Flaschner, D., Mauritsen, T. & Stevens, B. Understanding the Intermodel Spread in Global-Mean Hydrological
468   Sensitivity. *J Climate* **29**, 801-817 (2016). https://doi.org/10.1175/Jcli-D-15-0351.1

469   23   Dagan, G., Yeheskel, N. & Williams, A. I. L. Radiative forcing from aerosol-cloud interactions enhanced by large-
470   scale circulation adjustments. *Nat Geosci* **16** (2023). https://doi.org/10.1038/s41561-023-01319-8

471   24   Williams, A. I. L., Watson-Parris, D., Dagan, G. & Stier, P. Dependence of Fast Changes in Global and Local
472   Precipitation on the Geographical Location of Absorbing Aerosol. *Journal of Climate* **36**, 6163-6176 (2023).
473   https://doi.org/10.1175/jcli-d-23-0022.1

474   25   Ramanathan, V., Crutzen, P. J., Kiehl, J. T. & Rosenfeld, D. Atmosphere - Aerosols, climate, and the hydrological
475   cycle. *Science* **294**, 2119-2124 (2001).

476   26   Trenberth, K. E. & Dai, A. Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of
477   geoengineering. *Geophysical Research Letters* **34** (2007). https://doi.org/L15702, doi:10.1029/2007GL030524

478   27   Oman, L., Robock, A., Stenchikov, G. L. & Thordarson, T. High-latitude eruptions cast shadow over the African
479   monsoon and the flow of the Nile. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2006gl027665

480   28   Ming, Y., Ramaswamy, V. & Persad, G. Two opposing effects of absorbing aerosols on global-mean precipitation.
481   *Geophysical Research Letters* **37** (2010). https://doi.org/Artn L13701, 10.1029/2010gl042895

482   29   Boucher, O. *et al.* in *Working Group I Contribution to the Intergovernmental Panel on Climate Change Firth
483   Assessment Report Climate Change 2013: The Physical Science Basis* (eds Sandro Fuzzi, Joyce Penner,
484   Venkatachalam Ramaswamy, & Claudia Stubenrauch) (Cambridge University Press, 2013).

485   30   Myhre, G. *et al.* Sensible heat has significantly affected the global hydrological cycle over the historical period. *Nat
486   Commun* **9** (2018). https://doi.org/10.1038/s41467-018-04307-4

487   31   Salzmann, M. Global warming without global mean precipitation increase? *Sci Adv* **2**, e1501572 (2016).
488   https://doi.org/10.1126/sciadv.1501572

489   32   Wu, P., Christidis, N. & Stott, P. Anthropogenic impact on Earth's hydrological cycle. *Nat Clim Change* **3**, 807-810
490   (2013). https://doi.org/10.1038/NCLIMATE1932

491   33   Dagan, G., Stier, P. & Watson-Parris, D. Contrasting Response of Precipitation to Aerosol Perturbation in the Tropics
492   and Extratropics Explained by Energy Budget Considerations. *Geophys Res Lett* **46**, 7828-7837 (2019).
493   https://doi.org/10.1029/2019GL083479

494   34   Hodnebrog, O., Myhre, G., Forster, P. M., Sillmann, J. & Samset, B. H. Local biomass burning is a dominant cause
495   of the observed precipitation reduction in southern Africa. *Nat Commun* **7** (2016).
496   https://doi.org/10.1038/ncomms11236

497   35   O'Gorman, P. A., Allan, R. P., Byrne, M. P. & Previdi, M. Energetic Constraints on Precipitation Under Climate
498   Change. *Surv Geophys* **33**, 585-608 (2012).

499 36 Dagan, G., Stier, P. & Watson-Parris, D. An Energetic View on the Geographical Dependence of the Fast Aerosol
500   Radiative Effects on Precipitation. *J Geophys Res-Atmos* **126** (2021). https://doi.org/10.1029/2020JD033045
501 37 Jiang, H. L. & Feingold, G. Effect of aerosol on warm convective clouds: Aerosol-cloud-surface flux feedbacks in a
502   new coupled large eddy model. *J Geophys Res-Atmos* **111** (2006). https://doi.org/D01202,
503   doi:10.1029/2005JD006138
504 38 Hansen, J., Sato, M. & Ruedy, R. Radiative forcing and climate response. *J Geophys Res-Atmos* **102**, 6831-6864
505   (1997). https://doi.org/10.1029/96jd03436
506 39 Ackerman, A. S. *et al.* Reduction of tropical cloudiness by soot. *Science* **288**, 1042-1047 (2000). https://doi.org/DOI
507   10.1126/science.288.5468.1042
508 40 Sand, M., Samset, B. H., Tsigaridis, K., Bauer, S. E. & Myhre, G. Black Carbon and Precipitation: An Energetics
509   Perspective. *J Geophys Res-Atmos* **125** (2020). https://doi.org/10.1029/2019JD032239
510 41 Johnson, B. T., Shine, K. P. & Forster, P. M. The semi-direct aerosol effect: Impact of absorbing aerosols on marine
511   stratocumulus. *Q J Roy Meteor Soc* **130**, 1407-1422 (2004). https://doi.org/10.1256/qj.03.61
512 42 Yamaguchi, T., Feingold, G., Kazil, J. & McComiskey, A. Stratocumulus to cumulus transition in the presence of
513   elevated smoke layers. *Geophysical Research Letters* **42**, 10478-10485 (2015).
514   https://doi.org/10.1002/2015gl066544
515 43 Redemann, J. *et al.* An overview of the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS)
516   project: aerosol-cloud-radiation interactions in the southeast Atlantic basin. *Atmospheric Chemistry and Physics*
517   **21**, 1507-1563 (2021). https://doi.org/10.5194/acp-21-1507-2021
518 44 Herbert, R., Stier, P. & Dagan, G. Isolating Large-Scale Smoke Impacts on Cloud and Precipitation Processes Over
519   the Amazon With Convection Permitting Resolution. *J Geophys Res-Atmos* **126** (2021).
520   https://doi.org/10.1029/2021JD034615
521 45 Menon, S., Hansen, J., Nazarenko, L. & Luo, Y. F. Climate effects of black carbon aerosols in China and India. *Science*
522   **297**, 2250-2253 (2002).
523 46 Bollasina, M. A., Ming, Y. & Ramaswamy, V. Anthropogenic Aerosols and the Weakening of the South Asian Summer
524   Monsoon. *Science* **334**, 502-505 (2011). https://doi.org/10.1126/science.1204994
525 47 Wang, C. A modeling study on the climate impacts of black carbon aerosols. *J Geophys Res-Atmos* **109** (2004).
526   https://doi.org/10.1029/2003jd004084
527 48 Leung, G. R. & van den Heever, S. C. Aerosol breezes drive cloud and precipitation increases. *Nat Commun* **14**
528   (2023). https://doi.org/10.1038/s41467-023-37722-3
529 49 Fan, J. W. *et al.* Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. *J
530   Geophys Res-Atmos* **114** (2009). https://doi.org/10.1029/2009jd012352
531 50 Li, X. Q. *et al.* South Asian Summer Monsoon Response to Aerosol-Forced Sea Surface Temperatures. *Geophysical
532   Research Letters* **47** (2020). https://doi.org/10.1029/2019GL085329
533 51 Zanis, P. *et al.* Fast responses on pre-industrial climate from present-day aerosols in a CMIP6 multi-model study.
534   *Atmos Chem Phys* **20**, 8381-8404 (2020).
535 52 Wang, C., Kim, D., Ekman, A. M. L., Barth, M. C. & Rasch, P. J. Impact of anthropogenic aerosols on Indian summer
536   monsoon. *Geophysical Research Letters* **36** (2009). https://doi.org/10.1029/2009gl040114
537 53 O'Gorman, P. A. & Schneider, T. The physical basis for increases in precipitation extremes in simulations of 21st-
538   century climate change. *P Natl Acad Sci USA* **106**, 14773-14777 (2009). https://doi.org/10.1073/pnas.0907610106
539 54 Singh, D., Bollasina, M., Ting, M. F. & Diffenbaugh, N. S. Disentangling the influence of local and remote
540   anthropogenic aerosols on South Asian monsoon daily rainfall characteristics. *Clim Dynam* **52**, 6301-6320 (2019).
541   https://doi.org/10.1007/s00382-018-4512-9
542 55 Grant, L. D. & van den Heever, S. C. Aerosol-cloud-land surface interactions within tropical sea breeze convection.
543   *J Geophys Res-Atmos* **119** (2014). https://doi.org/10.1002/2014jd021912
544 56 Bollasina, M. A., Ming, Y., Ramaswamy, V., Schwarzkopf, M. D. & Naik, V. Contribution of local and remote
545   anthropogenic aerosols to the twentieth century weakening of the South Asian Monsoon. *Geophysical Research
546   Letters* **41**, 680-687 (2014). https://doi.org/10.1002/2013gl058183
547 57 Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. & Bellouin, N. Aerosols implicated as a prime driver of
548   twentieth-century North Atlantic climate variability. *Nature* **484**, 228-U110 (2012).
549   https://doi.org/10.1038/nature10946
550 58 Undorf, S., Bollasina, M. A., Booth, B. B. B. & Hegerl, G. C. Contrasting the Effects of the 1850-1975 Increase in
551   Sulphate Aerosols from North America and Europe on the Atlantic in the CESM. *Geophysical Research Letters* **45**,
552   11930-11940 (2018). https://doi.org/10.1029/2018gl079970
553 59 Wilcox, L. J., Highwood, E. J. & Dunstone, N. J. The influence of anthropogenic aerosol on multi-decadal variations
554   of historical global climate. *Environ Res Lett* **8** (2013). https://doi.org/10.1088/1748-9326/8/2/024033
555 60 Folland, C. K., Palmer, T. N. & Parker, D. E. Sahel Rainfall and Worldwide Sea Temperatures, 1901-85. *Nature* **320**,
556   602-607 (1986). https://doi.org/DOI 10.1038/320602a0
557 61 Zhang, R. & Delworth, T. L. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic
558   hurricanes. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2006gl026267
559 62 Rotstayn, L. D. & Lohmann, U. Tropical rainfall trends and the indirect aerosol effect. *J Climate* **15**, 2103-2116
560   (2002). https://doi.org/Doi 10.1175/1520-0442(2002)015<2103:Trtati>2.0.Co;2

561 63 Zhang, S., Stier, P., Dagan, G. & Wang, M. Anthropogenic aerosols modulated twentieth-century Sahel rainfall
562   variability. *Geophys. Res. Lett.* (2021). https://doi.org/in press

563 64 Menary, M. B. *et al.* Aerosol-Forced AMOC Changes in CMIP6 Historical Simulations. *Geophysical Research Letters*
564   **47** (2020). https://doi.org/10.1029/2020GL088166

565 65 Cai, W. *et al.* Pan-oceanic response to increasing anthropogenic aerosols: Impacts on the Southern Hemisphere
566   oceanic circulation. *Geophysical Research Letters* **33** (2006). https://doi.org/10.1029/2006gl027513

567 66 Delworth, T. L. & Dixon, K. W. Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the
568   North Atlantic thermohaline circulation? *Geophysical Research Letters* **33** (2006).
569   https://doi.org/10.1029/2005gl024980

570 67 Dagan, G., Stier, P. & Watson-Parris, D. Aerosol Forcing Masks and Delays the Formation of the North Atlantic
571   Warming Hole by Three Decades. *Geophys Res Lett* **47**, e2020GL090778 (2020).
572   https://doi.org/10.1029/2020GL090778

573 68 Haarsma, R. J., Selten, F. M. & Drijfhout, S. S. Decelerating Atlantic meridional overturning circulation main cause
574   of future west European summer atmospheric circulation changes. *Environ Res Lett* **10** (2015).
575   https://doi.org/10.1088/1748-9326/10/9/094007

576 69 Goldenberg, S. B., Landsea, C. W., Mestas-Nunez, A. M. & Gray, W. M. The recent increase in Atlantic hurricane
577   activity: Causes and implications. *Science* **293**, 474-479 (2001). https://doi.org/DOI 10.1126/science.1060040

578 70 Trenberth, K. Uncertainty in hurricanes and global warming. *Science* **308**, 1753-1754 (2005).
579   https://doi.org/10.1126/science.1112551

580 71 Emanuel, K. & Sobel, A. Response of tropical sea surface temperature, precipitation, and tropical cyclone-related
581   variables to changes in global and local forcing. *J Adv Model Earth Sy* **5**, 447-458 (2013).
582   https://doi.org/10.1002/jame.20032

583 72 Chiacchio, M. *et al.* On the links between meteorological variables, aerosols, and tropical cyclone frequency in
584   individual ocean basins. *J Geophys Res-Atmos* **122**, 802-822 (2017). https://doi.org/10.1002/2015jd024593

585 73 Jones, A. C. *et al.* Impacts of hemispheric solar geoengineering on tropical cyclone frequency. *Nat Commun* **8**
586   (2017). https://doi.org/10.1038/s41467-017-01606-0

587 74 Mann, M. E. & Emanuel, K. A. Atlantic hurricane trends linked to climate change. *Eos Trans. AGU* **87**, 233-241
588   (2011). https://doi.org/10.1029/2006EO240001

589 75 Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**, 686-688 (2005).
590   https://doi.org/10.1038/nature03906

591 76 Rousseau-Rizzi, R. *On the climate variability of tropical cyclone potential intensity and Atlantic hurricane activity*,
592   Massachusetts Institute of Technology, Cambridge, MA., (2021).

593 77 Myhre, G. *et al.* Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmos Chem Phys*
594   **13**, 1853-1877 (2013). https://doi.org/10.5194/acp-13-1853-2013

595 78 Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. The Response of the ITCZ to Extratropical Thermal Forcing:
596   Idealized Slab-Ocean Experiments with a GCM. *J Climate* **21**, 3521-3532 (2008).
597   https://doi.org/10.1175/2007jcli2146.1

598 79 Adam, O., Bischoff, T. & Schneider, T. Seasonal and Interannual Variations of the Energy Flux Equator and ITCZ.
599   Part I: Zonally Averaged ITCZ Position. *J Climate* **29**, 3219-3230 (2016). https://doi.org/10.1175/Jcli-D-15-0512.1

600 80 Kristjansson, J. E., Iversen, T., Kirkevag, A., Seland, O. & Debernard, J. Response of the climate system to aerosol
601   direct and indirect forcing: Role of cloud feedbacks. *J Geophys Res-Atmos* **110** (2005).
602   https://doi.org/10.1029/2005jd006299

603 81 Broccoli, A. J., Dahl, K. A. & Stouffer, R. J. Response of the ITCZ to Northern Hemisphere cooling. *Geophysical*
604   *Research Letters* **33** (2006). https://doi.org/10.1029/2005gl024546

605 82 Wang, C. The sensitivity of tropical convective precipitation to the direct radiative forcings of black carbon aerosols
606   emitted from major regions. *Ann Geophys-Germany* **27**, 3705-3711 (2009).

607 83 Haywood, J. M., Jones, A., Bellouin, N. & Stephenson, D. Asymmetric forcing from stratospheric aerosols impacts
608   Sahelian rainfall. *Nat Clim Change* **3**, 660-665 (2013). https://doi.org/10.1038/Nclimate1857

609 84 Navarro, J. C. A. *et al.* Future Response of Temperature and Precipitation to Reduced Aerosol Emissions as
610   Compared with Increased Greenhouse Gas Concentrations. *J Climate* **30**, 939-954 (2017).
611   https://doi.org/10.1175/Jcli-D-16-0466.1

612 85 Voigt, A. *et al.* Fast and slow shifts of the zonal-mean intertropical convergence zone in response to an idealized
613   anthropogenic aerosol. *J Adv Model Earth Sy* **9**, 870-892 (2017). https://doi.org/10.1002/2016ms000902

614 86 Hawcroft, M., Haywood, J. M., Collins, M. & Jones, A. The contrasting climate response to tropical and extratropical
615   energy perturbations. *Clim Dynam* **51**, 3231-3249 (2018).

616 87 Zhao, S. Y. & Suzuki, K. Differing Impacts of Black Carbon and Sulfate Aerosols on Global Precipitation and the ITCZ
617   Location via Atmosphere and Ocean Energy Perturbations. *J Climate* **32**, 5567-5582 (2019).
618   https://doi.org/10.1175/Jcli-D-18-0616.1

619 88 Zhang, S. P., Stier, P. & Watson-Parris, D. On the contribution of fast and slow responses to precipitation changes
620   caused by aerosol perturbations. *Atmos Chem Phys* **21**, 10179-10197 (2021). https://doi.org/10.5194/acp-21-
621   10179-2021

622 89 Soden, B. & Chung, E. S. The Large-Scale Dynamical Response of Clouds to Aerosol Forcing. *J Climate* **30**, 8783-8794
623   (2017). https://doi.org/10.1175/Jcli-D-17-0050.1

624   90   Hari, V., Villarini, G., Karmakar, S., Wilcox, L. J. & Collins, M. Northward Propagation of the Intertropical
625   Convergence Zone and Strengthening of Indian Summer Monsoon Rainfall. *Geophysical Research Letters* **47** (2020).
626   https://doi.org/10.1029/2020GL089823

627   91   Allen, R. J., Evan, A. T. & Booth, B. B. B. Interhemispheric Aerosol Radiative Forcing and Tropical Precipitation Shifts
628   during the Late Twentieth Century. *J Climate* **28**, 8219-8246 (2015). https://doi.org/10.1175/Jcli-D-15-0148.1

629   92   Reutter, P. *et al.* Aerosol- and updraft-limited regimes of cloud droplet formation: influence of particle number,
630   size and hygroscopicity on the activation of cloud condensation nuclei (CCN). *Atmos Chem Phys* **9**, 7067-7080
631   (2009).

632   93   Williams, E. *et al.* Contrasting convective regimes over the Amazon: Implications for cloud electrification. *J Geophys*
633   *Res-Atmos* **107** (2002). https://doi.org/10.1029/2001jd000380

634   94   L'Ecuyer, T. S., Berg, W., Haynes, J., Lebsock, M. & Takemura, T. Global observations of aerosol impacts on
635   precipitation occurrence in warm maritime clouds. *J Geophys Res-Atmos* **114** (2009).
636   https://doi.org/10.1029/2008jd011273

637   95   Albrecht, B. A. Aerosols, cloud microphysics, and fractional cloudiness. *Science* **245**, 1227-1230 (1989).
638   https://doi.org/10.1126/science.245.4923.1227

639   96   Twomey, S. Pollution and the planetary albedo. *Atmospheric Environment* **8**, 1251-1256 (1974).
640   https://doi.org/10.1016/0004-6981(74)90004-3

641   97   Possner, A., Ekman, A. M. L. & Lohmann, U. Cloud response and feedback processes in stratiform mixed-phase
642   clouds perturbed by ship exhaust. *Geophysical Research Letters* **44**, 1964-1972 (2017).
643   https://doi.org/10.1002/2016gl071358

644   98   Andreae, M. O. *et al.* Smoking rain clouds over the Amazon. *Science* **303**, 1337-1342 (2004).
645   https://doi.org/10.1126/science.1092779

646   99   Durkee, P. A. *et al.* The impact of ship-produced aerosols on the microstructure and albedo of warm marine
647   stratocumulus clouds: A test of MAST hypotheses 1i and 1ii. *J Atmos Sci* **57**, 2554-2569 (2000). https://doi.org/Doi
648   10.1175/1520-0469(2000)057<2554:Tiospa>2.0.Co;2

649   100   Christensen, M. W., Suzuki, K., Zambri, B. & Stephens, G. L. Ship track observations of a reduced shortwave aerosol
650   indirect effect in mixed-phase clouds. *Geophysical Research Letters* **41**, 6970-6977 (2014).
651   https://doi.org/10.1002/2014gl061320

652   101   Toll, V., Christensen, M., Gasso, S. & Bellouin, N. Volcano and Ship Tracks Indicate Excessive Aerosol-Induced Cloud
653   Water Increases in a Climate Model. *Geophysical Research Letters* **44**, 12492-12500 (2017).
654   https://doi.org/10.1002/2017gl075280

655   102   Gryspeerdt, E., Smith, T. W. P., O'Keeffe, E., Christensen, M. W. & Goldsworth, F. W. The Impact of Ship Emission
656   Controls Recorded by Cloud Properties. *Geophysical Research Letters* **46**, 12547-12555 (2019).
657   https://doi.org/10.1029/2019gl084700

658   103   Watson-Parris, D. *et al.* Shipping regulations lead to large reduction in cloud perturbations. *Proceedings of the*
659   *National Academy of Sciences* **119**, e2206885119 (2022). https://doi.org/doi:10.1073/pnas.2206885119

660   104   Quaas, J., Boucher, O. & Lohmann, U. Constraining the total aerosol indirect effect in the LMDZ and ECHAM4 GCMs
661   using MODIS satellite data. *Atmos Chem Phys* **6**, 947-955 (2006).

662   105   Quaas, J. *et al.* Aerosol indirect effects - general circulation model intercomparison and evaluation with satellite
663   data. *Atmos Chem Phys* **9**, 8697-8717 (2009).

664   106   Rosenfeld, D. *et al.* Global observations of aerosol-cloud-precipitation-climate interactions. *Rev Geophys* **52**, 750-
665   808 (2014). https://doi.org/10.1002/2013rg000441

666   107   Bellouin, N. *et al.* Bounding Global Aerosol Radiative Forcing of Climate Change. *Rev Geophys* **58**, e2019RG000660
667   (2020). https://doi.org/10.1029/2019RG000660

668   108   Stephens, G. *et al.* CLOUDSAT AND CALIPSO WITHIN THE A-TRAIN: Ten Years of Actively Observing the Earth
669   System. *B Am Meteorol Soc* **99**, 569-581 (2018). https://doi.org/10.1175/Bams-D-16-0324.1

670   109   Platnick, S. *et al.* The MODIS Cloud Optical and Microphysical Products: Collection 6 Updates and Examples From
671   Terra and Aqua. *Ieee T Geosci Remote* **55**, 502-525 (2017). https://doi.org/10.1109/Tgrs.2016.2610522

672   110   Suzuki, K., Nakajima, T. Y. & Stephens, G. L. Particle Growth and Drop Collection Efficiency of Warm Clouds as
673   Inferred from Joint CloudSat and MODIS Observations. *J Atmos Sci* **67**, 3019-3032 (2010).
674   https://doi.org/10.1175/2010jas3463.1

675   111   Mulmenstadt, J., Sourdeval, O., Delanoe, J. & Quaas, J. Frequency of occurrence of rain from liquid-, mixed-, and
676   ice-phase clouds derived from A-Train satellite retrievals. *Geophysical Research Letters* **42**, 6502-6509 (2015).
677   https://doi.org/10.1002/2015gl064604

678   112   Malavelle, F. F. *et al.* Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature* **546**, 485-
679   491 (2017).

680   113   Christensen, M. W. & Stephens, G. L. Microphysical and macrophysical responses of marine stratocumulus polluted
681   by underlying ships: 2. Impacts of haze on precipitating clouds. *J Geophys Res-Atmos* **117** (2012).

682   114   McCoy, D. T. *et al.* Aerosol midlatitude cyclone indirect effects in observations and high-resolution simulations.
683   *Atmos Chem Phys* **18**, 5821-5846 (2018). https://doi.org/10.5194/acp-18-5821-2018

684   115   Gryspeerdt, E. *et al.* Surprising similarities in model and observational aerosol radiative forcing estimates.
685   *Atmospheric Chemistry and Physics* **20**, 613-623 (2020). https://doi.org/10.5194/acp-20-613-2020

686 116 Jiang, H., Xue, H., Teller, A., Feingold, G. & Levin, Z. Aerosol effects on the lifetime of shallow cumulus. *Geophysical*
687 *Research Letters* **33** (2006). https://doi.org/ L14806, doi:10.1029/2006GL026024

688 117 Zhou, C. & Penner, J. E. Why do general circulation models overestimate the aerosol cloud lifetime effect? A case
689 study comparing CAM5 and a CRM. *Atmos Chem Phys* **17**, 21-29 (2017). https://doi.org/10.5194/acp-17-21-2017

690 118 Koren, I., Dagan, G. & Altaratz, O. From aerosol-limited to invigoration of warm convective clouds. *Science* **344**,
691 1143-1146 (2014). https://doi.org/10.1126/science.1252595

692 119 Seiki, T. & Nakajima, T. Aerosol Effects of the Condensation Process on a Convective Cloud Simulation. *J Atmos Sci*
693 **71**, 833-853 (2014). https://doi.org/10.1175/Jas-D-12-0195.1

694 120 Sheffield, A. M., Saleeby, S. M. & van den Heever, S. C. Aerosol-induced mechanisms for cumulus congestus growth.
695 *J Geophys Res-Atmos* **120**, 8941-8952 (2015). https://doi.org/10.1002/2015jd023743

696 121 Xue, H. & Feingold, G. Large-Eddy Simulations of Trade Wind Cumuli: Investigation of Aerosol Indirect Effects.
697 *Journal of Atmospheric Science* **63**, 1605–1622 (2006).

698 122 Stevens, B. & Seifert, A. Understanding macrophysical outcomes of microphysical choices in simulations of shallow
699 cumulus convection. *Journal of the Meteorological Society of Japan. Ser. II* **86A**, 143-162 (2008).
700 https://doi.org/10.2151/jmsj.86A.143

701 123 Dagan, G., Koren, I. & Altaratz, O. Aerosol effects on the timing of warm rain processes. *Geophysical Research*
702 *Letters* **42**, 4590-4598 (2015). https://doi.org/10.1002/2015gl063839

703 124 Dagan, G., Koren, I. & Altaratz, O. Competition between core and periphery-based processes in warm convective
704 clouds - from invigoration to suppression. *Atmos Chem Phys* **15**, 2749-2760 (2015). https://doi.org/10.5194/acp-
705 15-2749-2015

706 125 Kogan, Y. L. & Martin, W. J. Parameterization of Bulk Condensation in Numerical Cloud Models. *J Atmos Sci* **51**,
707 1728-1739 (1994). https://doi.org/Doi 10.1175/1520-0469(1994)051<1728:Pobcin>2.0.Co;2

708 126 Seifert, A. & Heus, T. Large-eddy simulation of organized precipitating trade wind cumulus clouds. *Atmos Chem*
709 *Phys* **13**, 5631-5645 (2013). https://doi.org/10.5194/acp-13-5631-2013

710 127 Dagan, G., Koren, I., Altaratz, O. & Lehahn, Y. Shallow Convective Cloud Field Lifetime as a Key Factor for Evaluating
711 Aerosol Effects. *Iscience* **10**, 192-+ (2018). https://doi.org/10.1016/j.isci.2018.11.032

712 128 Spill, G., Stier, P., Field, P. R. & Dagan, G. Effects of aerosol in simulations of realistic shallow cumulus cloud fields
713 in a large domain. *Atmos Chem Phys* **19**, 13507-13517 (2019). https://doi.org/10.5194/acp-19-13507-2019

714 129 Chen, Y. C., Christensen, M. W., Stephens, G. L. & Seinfeld, J. H. Satellite-based estimate of global aerosol-cloud
715 radiative forcing by marine warm clouds. *Nat Geosci* **7**, 643-646 (2014). https://doi.org/10.1038/Ngeo2214

716 130 Khain, A., Rosenfeld, D. & Pokrovsky, A. Aerosol impact on the dynamics and microphysics of deep convective
717 clouds. *Q J Roy Meteor Soc* **131**, 2639–2663 (2005). https://doi.org/doi:10.1256/qj.04.62

718 131 van den Heever, S. C., Carrio, G. G., Cotton, W. R., DeMott, P. J. & Prenni, A. J. Impacts of nucleating aerosol on
719 Florida storms. Part I: Mesoscale simulations. *J Atmos Sci* **63**, 1752-1775 (2006). https://doi.org/Doi
720 10.1175/Jas3713.1

721 132 Rosenfeld, D. *et al.* Flood or drought: How do aerosols affect precipitation? *Science* **321**, 1309-1313 (2008).
722 https://doi.org/Doi 10.1126/Science.1160606

723 133 Tao, W. K., Chen, J. P., Li, Z. Q., Wang, C. & Zhang, C. D. Impact of Aerosols on Convective Clouds and Precipitation.
724 *Rev Geophys* **50** (2012). https://doi.org/Artn Rg2001, 10.1029/2011rg000369

725 134 Koren, I. *et al.* Aerosol-induced intensification of rain from the tropics to the mid-latitudes. *Nat Geosci* **5**, 118-122
726 (2012). https://doi.org/Doi 10.1038/Ngeo1364

727 135 Koren, I., Kaufman, Y. J., Rosenfeld, D., Remer, L. A. & Rudich, Y. Aerosol invigoration and restructuring of Atlantic
728 convective clouds. *Geophysical Research Letters* **32** (2005). https://doi.org/L14828, doi:10.1029/2005GL023187

729 136 Clavner, M., Cotton, W. R., van den Heever, S. C., Saleeby, S. M. & Pierce, J. R. The response of a simulated
730 mesoscale convective system to increased aerosol pollution: Part I: Precipitation intensity, distribution, and
731 efficiency. *Atmos Res* **199**, 193-208 (2018). https://doi.org/10.1016/j.atmosres.2017.08.010

732 137 van den Heever, S. C. *et al.* The Aerosol, Clouds, Precipitation and Climate (ACPC) inititiative multi-cloud-resolving-
733 model intercomparison on aerosol-effects on deep convection. *Bulleting of the American Meteorological Society*
734 **in preparation** (2024).

735 138 Storer, R. L. & Van den Heever, S. C. Microphysical Processes Evident in Aerosol Forcing of Tropical Deep Convective
736 Clouds. *J Atmos Sci* **70**, 430-446 (2013).

737 139 Wang, C. A modeling study of the response of tropical deep convection to the increase of cloud condensation
738 nuclei concentration: 1. Dynamics and microphysics. *J Geophys Res-Atmos* **110** (2005).
739 https://doi.org/10.1029/2004jd005720

740 140 Chua, X. R. & Ming, Y. Convective Invigoration Traced to Warm-Rain Microphysics. *Geophysical Research Letters* **47**
741 (2020). https://doi.org/10.1029/2020GL089134

742 141 Lee, S. S., Donner, L. J., Phillips, V. T. J. & Ming, Y. Examination of aerosol effects on precipitation in deep convective
743 clouds during the 1997 ARM summer experiment. *Q J Roy Meteor Soc* **134**, 1201-1220 (2008). https://doi.org/Doi
744 10.1002/Qj.287

745 142 Grant, L. D. & van den Heever, S. C. Cold Pool and Precipitation Responses to Aerosol Loading: Modulation by Dry
746 Layers. *J Atmos Sci* **72**, 1398-1408 (2015). https://doi.org/10.1175/Jas-D-14-0260.1

747 143 Varble, A. C., Igel, A. L., Morrison, H., Grabowski, W. W. & Lebo, Z. J. Opinion: A critical evaluation of the evidence
748 for aerosol invigoration of deep convection. *Atmos Chem Phys* **23**, 13791-13808 (2023).
749 https://doi.org/10.5194/acp-23-13791-2023

750 144 Fan, J. W. *et al.* Substantial convection and precipitation enhancements by ultrafine aerosol particles. *Science* **359**,
751 411-+ (2018). https://doi.org/10.1126/science.aan8461

752 145 Romps, D. M. *et al.* Air Pollution Unable to Intensify Storms via Warm-Phase Invigoration. *Geophysical Research*
753 *Letters* **50** (2023). https://doi.org/10.1029/2022gl100409

754 146 Abbott, T. H. & Cronin, T. W. Aerosol invigoration of atmospheric convection through increases in humidity. *Science*
755 **371**, 83-85 (2021). https://doi.org/10.1126/science.abc5181

756 147 Dagan, G. *et al.* Boundary conditions representation can determine simulated aerosol effects on convective cloud
757 fields. *Commun Earth Environ* **3** (2022). https://doi.org/10.1038/s43247-022-00399-5

758 148 White, B. *et al.* Uncertainty from the choice of microphysics scheme in convection-permitting models significantly
759 exceeds aerosol effects. *Atmospheric Chemistry and Physics* **17**, 12145-12175 (2017). https://doi.org/10.5194/acp-
760 17-12145-2017

761 149 Heikenfeld, M., White, B., Labbouz, L. & Stier, P. Aerosol effects on deep convection: the propagation of aerosol
762 perturbations through convective cloud microphysics. *Atmos Chem Phys* **19**, 2601-2627 (2019).
763 https://doi.org/10.5194/acp-19-2601-2019

764 150 Storer, R. L., van den Heever, S. C. & Stephens, G. L. Modeling Aerosol Impacts on Convective Storms in Different
765 Environments. *J Atmos Sci* **67**, 3904-3915 (2010). https://doi.org/10.1175/2010jas3363.1

766 151 Miltenberger, A. K. *et al.* Aerosol-cloud interactions in mixed-phase convective clouds - Part 1: Aerosol
767 perturbations. *Atmos Chem Phys* **18**, 3119-3145 (2018). https://doi.org/10.5194/acp-18-3119-2018

768 152 Lee, S. S., Donner, L. J. & Penner, J. E. Thunderstorm and stratocumulus: how does their contrasting morphology
769 affect their interactions with aerosols? *Atmos Chem Phys* **10**, 6819-6837 (2010). https://doi.org/10.5194/acp-10-
770 6819-2010

771 153 Grabowski, W. W. Untangling Microphysical Impacts on Deep Convection Applying a Novel Modeling Methodology.
772 *J Atmos Sci* **72**, 2446-2464 (2015). https://doi.org/10.1175/Jas-D-14-0307.1

773 154 Marinescu, P. J. *et al.* Impacts of Varying Concentrations of Cloud Condensation Nuclei on Deep Convective Cloud
774 Updrafts-A Multimodel Assessment. *J Atmos Sci* **78**, 1147-1172 (2021). https://doi.org/10.1175/Jas-D-20-0200.1

775 155 Igel, A. L. & van den Heever, S. C. Invigoration or Enervation of Convective Clouds by Aerosols? *Geophysical*
776 *Research Letters* **48** (2021).

777 156 Connolly, P. J. *et al.* Cloud-resolving simulations of intense tropical Hector thunderstorms: Implications for aerosol-
778 cloud interactions. *Q J Roy Meteor Soc* **132**, 3079-3106 (2006). https://doi.org/DOI 10.1256/qj.05.86

779 157 Pan, Z. X. *et al.* Observational Quantification of Aerosol Invigoration for Deep Convective Cloud Lifecycle Properties
780 Based on Geostationary Satellite. *J Geophys Res-Atmos* **126** (2021). https://doi.org/10.1029/2020JD034275

781 158 Heikenfeld, M., Marinescu, P. J., White, B., Heever, S. C. v. d. & Stier, P. A Lagrangian microphysical view of deep
782 convection and aerosol effects for isolated deep convection over Houston, Texas. *Atmos. Chem. Phys.* **in prep.** (in
783 prep.).

784 159 Kipling, Z., Labbouz, L. & Stier, P. Global response of parameterised convective cloud fields to anthropogenic
785 aerosol forcing. *Atmos Chem Phys* **20**, 4445-4460 (2020). https://doi.org/10.5194/acp-20-4445-2020

786 160 Lohmann, U. Global anthropogenic aerosol effects on convective clouds in ECHAM5-HAM. *Atmos Chem Phys* **8**,
787 2115-2131 (2008).

788 161 Choi, Y. S., Lindzen, R. S., Ho, C. H. & Kim, J. Space observations of cold-cloud phase change. *P Natl Acad Sci USA*
789 **107**, 11211-11216 (2010). https://doi.org/10.1073/pnas.1006241107

790 162 Stevens, R. G. *et al.* A model intercomparison of CCN-limited tenuous clouds in the high Arctic. *Atmos Chem Phys*
791 **18**, 11041-11071 (2018). https://doi.org/10.5194/acp-18-11041-2018

792 163 Lohmann, U. A glaciation indirect aerosol effect caused by soot aerosols. *Geophysical Research Letters* **29** (2002).
793 https://doi.org/10.1029/2001GL014357

794 164 Vergara-Temprado, J. *et al.* Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. *P Natl*
795 *Acad Sci USA* **115**, 2687-2692 (2018). https://doi.org/10.1073/pnas.1721627115

796 165 Glassmeier, F. & Lohmann, U. Precipitation Susceptibility and Aerosol Buffering of Warm- and Mixed-Phase
797 Orographic Clouds in Idealized Simulations. *J Atmos Sci* **75**, 1173-1194 (2018). https://doi.org/10.1175/Jas-D-17-
798 0254.1

799 166 French, J. R. *et al.* Precipitation formation from orographic cloud seeding. *P Natl Acad Sci USA* **115**, 1168-1173
800 (2018). https://doi.org/10.1073/pnas.1716995115

801 167 National Research Council (U.S.). Committee on the Status of and Future Directions in U.S. Weather Modification
802 Research and Operations. & National Research Council (U.S.). Board on Atmospheric Sciences and Climate. *Critical*
803 *issues in weather modification research*. (National Academies Press, 2003).

804 168 Benjamini, Y. *et al.* The Israel 4 Cloud Seeding Experiment: Primary Results. *J Appl Meteorol Clim* **62**, 317-327
805 (2023). https://doi.org/10.1175/Jamc-D-22-0077.1

806 169 Korolev, A. & Leisner, T. Review of experimental studies of secondary ice production. *Atmos Chem Phys* **20**, 11767-
807 11797 (2020).

808 170 Khain, A. P. Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review. *Environ*
809 *Res Lett* **4** (2009). https://doi.org/015004, doi:10.1088/1748-9326/4/1/015004

810 171 Miltenberger, A. K., Field, P. R., Hill, A. A., Shipway, B. J. & Wilkinson, J. M. Aerosol-cloud interactions in mixed-
811   phase convective clouds - Part 2: Meteorological ensemble. *Atmos Chem Phys* **18**, 10593-10613 (2018).
812   https://doi.org/10.5194/acp-18-10593-2018

813 172 Schutgens, N. *et al.* On the spatio-temporal representativeness of observations. *Atmos Chem Phys* **17**, 9761-9780
814   (2017). https://doi.org/10.5194/acp-17-9761-2017

815 173 Liu, H. *et al.* Non-Monotonic Aerosol Effect on Precipitation in Convective Clouds over Tropical Oceans. *Sci Rep-Uk*
816   **9** (2019). https://doi.org/10.1038/s41598-019-44284-2

817 174 Quaas, J., Stevens, B., Stier, P. & Lohmann, U. Interpreting the cloud cover – aerosol optical depth relationship
818   found in satellite data using a general circulation model. *Atmos Chem Phys* **10**, 6129-6135 (2010).
819   https://doi.org/10.5194/acp-10-6129-2010

820 175 Textor, C. *et al.* The effect of harmonized emissions on aerosol properties in global models – an AeroCom
821   experiment. *Atmos Chem Phys* **7**, 4489-4501 (2007). https://doi.org/10.5194/acp-7-4489-2007

822 176 Stier, P. Limitations of passive satellite remote sensing to constrain global cloud condensation nuclei. *Atmos. Chem.
823   Phys. Discuss.* **15**, 32607-32637 (2015). https://doi.org/10.5194/acpd-15-32607-2015

824 177 Grandey, B. S., Gururaj, A., Stier, P. & Wagner, T. M. Rainfall-aerosol relationships explained by wet scavenging and
825   humidity. *Geophysical Research Letters* **41**, 5678-5684 (2014). https://doi.org/10.1002/2014gl060958

826 178 Gryspeerdt, E., Stier, P., White, B. A. & Kipling, Z. Wet scavenging limits the detection of aerosol effects on
827   precipitation. *Atmos Chem Phys* **15**, 7557-7570 (2015). https://doi.org/10.5194/acp-15-7557-2015

828 179 Gryspeerdt, E. & Stier, P. Regime-based analysis of aerosol-cloud interactions. *Geophysical Research Letters* **39**,
829   n/a-n/a (2012). https://doi.org/10.1029/2012gl053221

830 180 Gryspeerdt, E., Stier, P. & Partridge, D. G. Links between satellite-retrieved aerosol and precipitation. *Atmos Chem
831   Phys* **14**, 9677-9694 (2014). https://doi.org/10.5194/acp-14-9677-2014

832 181 Storer, R. L., van den Heever, S. C. & L'Ecuyer, T. S. Observations of aerosol-induced convective invigoration in the
833   tropical east Atlantic. *J Geophys Res-Atmos* **119**, 3963-3975 (2014). https://doi.org/10.1002/2013jd020272

834 182 Berg, W., L'Ecuyer, T. & van den Heever, S. Evidence for the impact of aerosols on the onset and microphysical
835   properties of rainfall from a combination of satellite observations and cloud-resolving model simulations. *J
836   Geophys Res-Atmos* **113** (2008).

837 183 Christensen, M. W. *et al.* Opportunistic experiments to constrain aerosol effective radiative forcing. *Atmos Chem
838   Phys* **22**, 641-674 (2022). https://doi.org/10.5194/acp-22-641-2022

839 184 Coakley, J. A., Bernstein, R. L. & Durkee, P. A. Effect of Ship-Stack Effluents on Cloud Reflectivity. *Science* **237**, 1020-
840   1022 (1987). https://doi.org/DOI 10.1126/science.237.4818.1020

841 185 Christensen, M. W., Coakley, J. A. & Tahnk, W. R. Morning-to-Afternoon Evolution of Marine Stratus Polluted by
842   Underlying Ships: Implications for the Relative Lifetimes of Polluted and Unpolluted Clouds. *J Atmos Sci* **66**, 2097-
843   2106 (2009).

844 186 Manshausen, P., Watson-Parris, D., Christensen, M. W., Jalkanen, J.-P. & Stier, P. Invisible ship tracks show large
845   cloud sensitivity to aerosol. *Nature* **610**, 101-106 (2022). https://doi.org/10.1038/s41586-022-05122-0

846 187 Malavelle, F. F. *et al.* Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature* **551**, 256
847   (2017). https://doi.org/10.1038/nature24275

848 188 Suzuki, K., Stephens, G. L., Heever, S. C. v. d. & Nakajima, T. Y. Diagnosis of the Warm Rain Process in Cloud-
849   Resolving Models Using Joint CloudSat and MODIS Observations. *J. Atmos. Sci.* **68**, 2655–2670 (2011).
850   https://doi.org/10.1175/JAS-D-10-05026.1

851 189 Thornton, J. A., Virts, K. S., Holzworth, R. H. & Mitchell, T. P. Lightning enhancement over major oceanic shipping
852   lanes. *Geophysical Research Letters* **44**, 9102-9111 (2017). https://doi.org/10.1002/2017gl074982

853 190 Blossey, P. N., Bretherton, C. S., Thornton, J. A. & Virts, K. S. Locally Enhanced Aerosols Over a Shipping Lane
854   Produce Convective Invigoration but Weak Overall Indirect Effects in Cloud-Resolving Simulations. *Geophysical
855   Research Letters* **45**, 9305-9313 (2018). https://doi.org/10.1029/2018gl078682

856 191 Berg, W., L'Ecuyer, T. & Kummerow, C. Rainfall climate regimes: The relationship of regional TRMM rainfall biases
857   to the environment. *J Appl Meteorol Clim* **45**, 434-454 (2006). https://doi.org/Doi 10.1175/Jam2331.1

858 192 Hegerl, G. C. *et al.* Challenges in Quantifying Changes in the Global Water Cycle. *B Am Meteorol Soc* **96**, 1097-1115
859   (2015). https://doi.org/Doi 10.1175/Bams-D-13-00212.1

860 193 Polson, D., Bollasina, M., Hegerl, G. C. & Wilcox, L. J. Decreased monsoon precipitation in the Northern Hemisphere
861   due to anthropogenic aerosols. *Geophysical Research Letters* **41**, 6023-6029 (2014).
862   https://doi.org/10.1002/2014gl060811

863 194 Sarojini, B. B., Stott, P. A. & Black, E. Detection and attribution of human influence on regional precipitation. *Nat
864   Clim Change* **6**, 669-675 (2016). https://doi.org/10.1038/Nclimate2976

865 195 Paik, S. *et al.* Determining the Anthropogenic Greenhouse Gas Contribution to the Observed Intensification of
866   Extreme Precipitation. *Geophysical Research Letters* **47** (2020). https://doi.org/10.1029/2019GL086875

867 196 Wilcox, L. J., Dong, B., Sutton, R. T. & Highwood, E. J. The 2014 Hot, Dry Summer in Northeast Asia. *B Am Meteorol
868   Soc* **96**, S105-S110 (2015). https://doi.org/10.1175/Bams-D-15-00123.1

869 197 Wilcox, L. J. *et al.* Accelerated increases in global and Asian summer monsoon precipitation from future aerosol
870   reductions. *Atmos Chem Phys* **20**, 11955-11977 (2020). https://doi.org/10.5194/acp-20-11955-2020

871 198 Deser, C. *et al.* Isolating the Evolving Contributions of Anthropogenic Aerosols and Greenhouse Gases: A New
872   CESM1 Large Ensemble Community Resource. *J Climate* **33**, 7835-7858 (2020). https://doi.org/10.1175/Jcli-D-20-
873   0123.1
874 199 Reddington, C. *et al.* The Global Aerosol Synthesis and Science Project (GASSP): Observations and modelling to
875   reduce uncertainty. *B Am Meteorol Soc* **in prep.** (2016).
876 200 Kahn, R. A. *et al.* SAM-CAAM: A Concept for Acquiring Systematic Aircraft Measurements to Characterize Aerosol
877   Air Masses. *B Am Meteorol Soc* **98**, 2215-2228 (2017).
878 201 Medeiros, B. Aquaplanets as a Framework for Examination of Aerosol Effects. *J Adv Model Earth Sy* **12** (2020).
879   https://doi.org/10.1029/2019MS001874
880 202 Dingley, B., Dagan, G. & Stier, P. Forcing convection to aggregate using diabatic heating perturbations. *J Adv Model
881   Earth Sy* (2021). https://doi.org/submitted
882 203 Stevens, B. *et al.* DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic
883   Domains. *Prog Earth Planet Sc* **6** (2019). https://doi.org/10.1186/s40645-019-0304-z
884 204 Bauer, P., Stevens, B. & Hazeleger, W. A digital twin of Earth for the green transition. *Nat Clim Change* **11**, 80-83
885   (2021). https://doi.org/10.1038/s41558-021-00986-y
886 205 Gillett, N. P. *et al.* The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to
887   CMIP6. *Geosci Model Dev* **9**, 3685-3697 (2016). https://doi.org/10.5194/gmd-9-3685-2016
888 206 Giorgetta, M. A. *et al.* ICON-A, the Atmosphere Component of the ICON Earth System Model: I. Model Description.
889   *J Adv Model Earth Sy* **10**, 1613-1637 (2018). https://doi.org/10.1029/2017ms001242

890

CORRESPONDING AUTHORS

892 Philip Stier (philip.stier@physics.ox.ac.uk) & Susan C. van den Heever (Sue.vandenHeever@colostate.edu)

COMPETING INTERESTS DECLARATION

894 The authors declare no competing interests.

ACKNOWLEDGEMENTS

AUTHOR CONTRIBUTION STATEMENTS

911 P.S. and S. vd H. developed the structure of the GEWEX Aerosol Preciptiation Initiative workshop programme providing the
912 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
913 the first version of the manuscript that was extended upon with contributions from all authors to the literature review, the
914 synthesis of the results and revising the manuscript. G.D. created the figures in Figure 1 and Figure 3. S.M.S created Figure
915 4.

916

917

TABLES & FIGURES

919

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

925

926
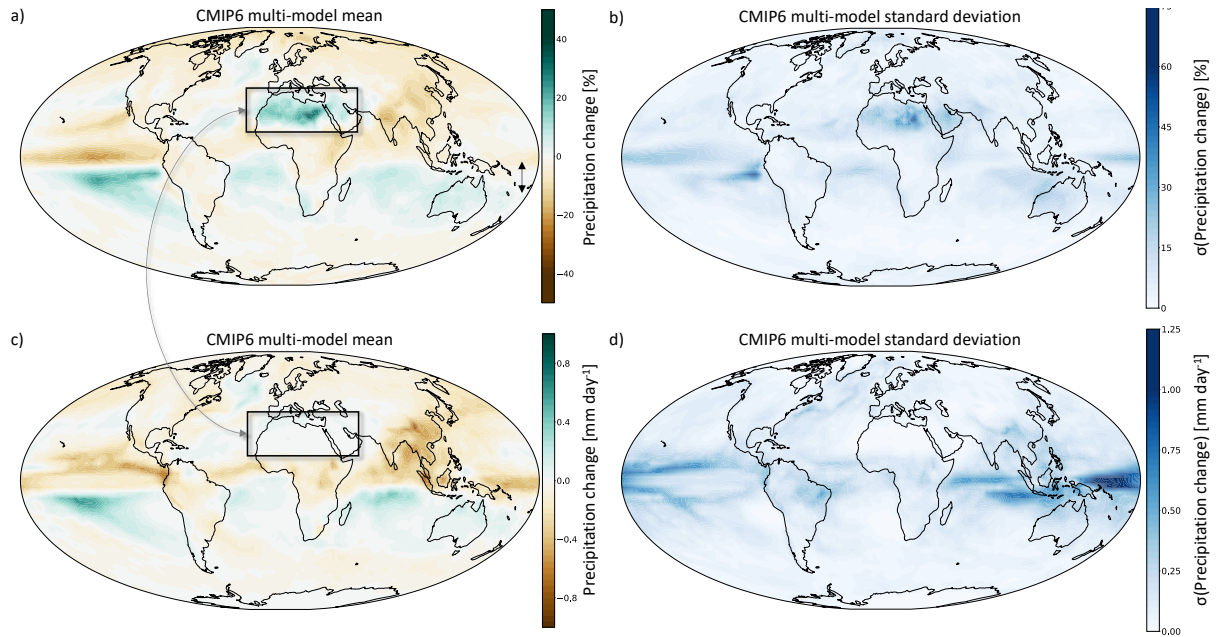
Figure 1: Climate model simulated a) relative and c) absolute precipitation changes [%] due to anthropogenic aerosol from the coupled model intercomparison project phase 6 (CMIP6) Detection and Attribution Model Intercomparison Project (DAMIP[205], difference between last 30 years of present-day DAMIP *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.
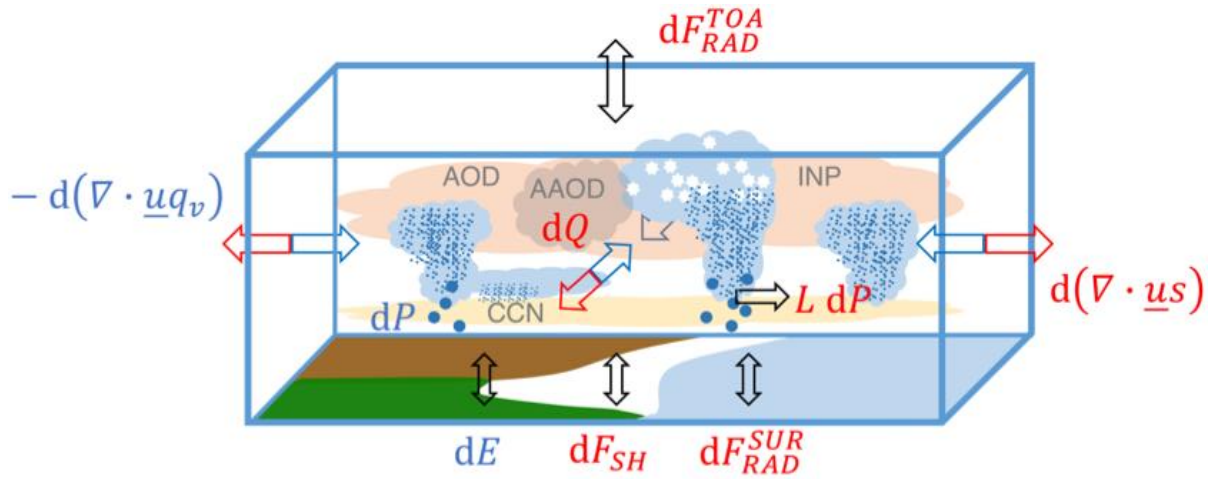
930
931
932
933
934
935
936
937
938

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.
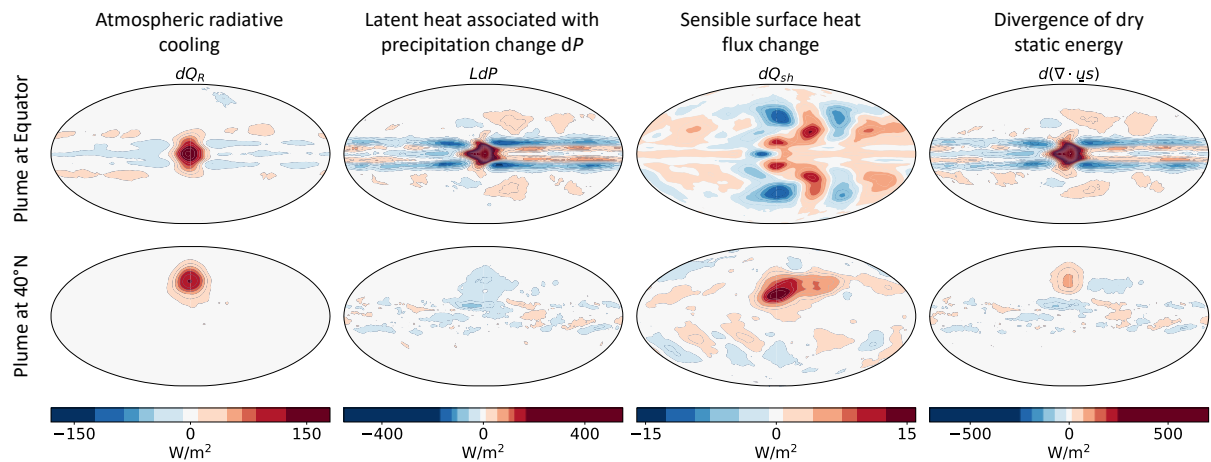
Figure 3: Idealised aqua-planet ICON[206] general circulation model simulations of changes of precipitation and the atmospheric energy balance in response to idealised circular absorbing aerosol radiative plumes (of 10° size and identical aerosol radiative properties with peak aerosol optical depth of 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; $\mathbf{d}(\nabla \cdot \underline{u}s)$: divergence of dry static-energy.
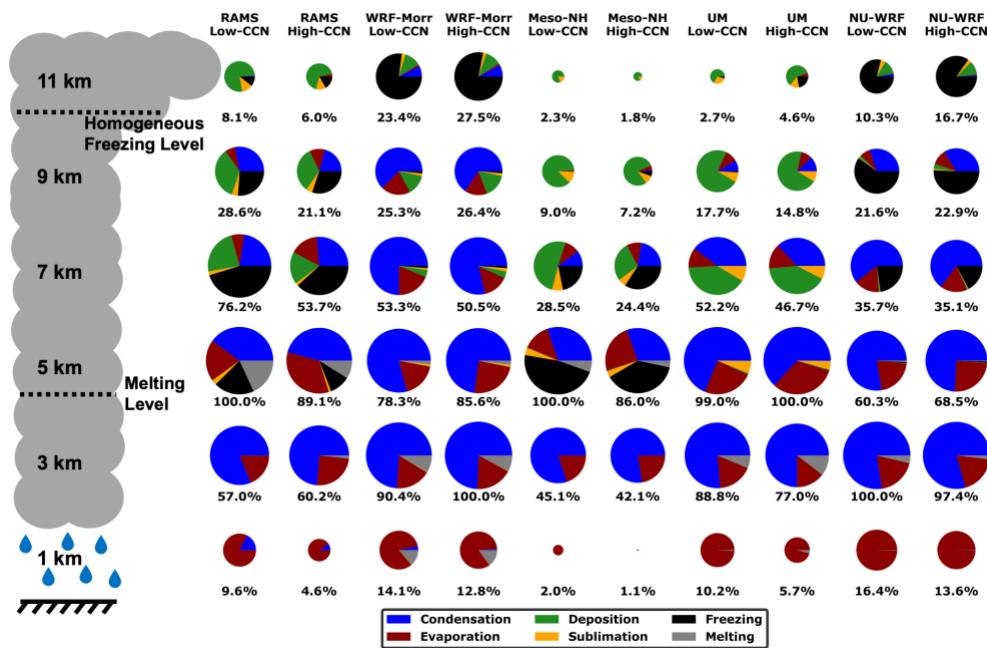

Figure 4: Cloud-resolving model intercomparison of CCN mediated effects on deep convection from the Aerosol, Clouds, Precipitation and Climate deep convection study[137,154]: fractional mass process rates for tracked deep convective systems for low and high CCN conditions as a function of height. Results 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.