Modulation of Tropical Convection-circulation Interaction by Aerosol Indirect Effects in a Global Convection-permitting Model

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Abstract

Observations suggest tropical convection intensifies when aerosol concentrations enhance, but quantitative estimations of this effect remain highly uncertain. Leading theories for explaining the intensification are based on the dynamical response of convection to changes in cloud microphysics independently from possible changes in the environment. Here, we provide a new perspective on aerosol indirect effects on tropical convection by using a global convection-permitting model that realistically simulates convection-circulation interaction. Simulations of radiative-convective equilibrium show that pollution facilitates the development of deep convection in a drier environment, but cloud condensates are more likely to be exported from moist clusters to dry areas, impeding the large-scale moisture-convection feedback and limiting the intensity of maximum precipitation (30 vs. 47 mm h-1). Our results emphasize the importance of allowing atmospheric phenomena to evolve continuously across spatial and temporal scales in simulations when investigating the response of tropical convection to changes in cloud microphysics.





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Key Points:

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9	•	Simulations of the global convection-permitting model provide a new perspective
10		on aerosol indirect effects.
11	•	Pollution facilitates the development of deep convection in a drier environment.
12	•	The response of large-scale circulation to pollution limits the intensity of maxi-
13		mum precipitation.

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14 Abstract

Observations suggest tropical convection intensifies when aerosol concentrations enhance, 15 but quantitative estimations of this effect remain highly uncertain. Leading theories for 16 explaining the intensification are based on the dynamical response of convection to changes 17 in cloud microphysics independently from possible changes in the environment. Here, 18 we provide a new perspective on aerosol indirect effects on tropical convection by using 19 a global convection-permitting model that realistically simulates convection-circulation 20 interaction. Simulations of radiative-convective equilibrium show that pollution facili-21 tates the development of deep convection in a drier environment, but cloud condensates 22 are more likely to be exported from moist clusters to dry areas, impeding the large-scale 23 moisture-convection feedback and limiting the intensity of maximum precipitation (30 24 vs. 47 mm h⁻¹). Our results emphasize the importance of allowing atmospheric phenom-25 ena to evolve continuously across spatial and temporal scales in simulations when inves-26 tigating the response of tropical convection to changes in cloud microphysics. 27

²⁸ Plain Language Summary

How does air pollution affect thunderstorm intensity over the tropical ocean? Past 29 studies have proposed different opinions but generally neglect the interplay between the 30 development of thunderstorms and the long-range movement of air that redistributes the 31 Earth's thermal energy and moisture. Here, we address this question by investigating 32 33 results from numerical experiments in which the global domain is used to simulate the response of individual thunderstorms and large-scale air motion to pollution. Our results 34 show that tropical thunderstorms with given moisture are more vigorous under the pol-35 luted scenario. However, pollution makes the thunderstorms keep less moisture in their 36 surroundings, limiting the maximum intensity of thunderstorms and weakening the large-37 scale air motion that supplies moisture to thunderstorms. Our results suggest that the 38 interplay between the development of thunderstorms and the long-range movement of 39 air is crucial in determining the effects of pollution in the tropical atmosphere. 40

41 **1** Introduction

Deep convective clouds (DCCs) play a critical role in the global climate system via 42 their role in the Earth's energy budget (Arakawa, 2004; Hartmann et al., 2001). They 43 can aggregate into organized convective systems that span hundreds to a thousand kilo-44 meters (Houze, 2004) and contribute significantly to tropical rainfall (Chen et al., 2021; 45 Houze et al., 2015; Nesbitt et al., 2006; Tao & Chern, 2017; Yuan & Houze, 2010). Ob-46 servations suggest that updrafts of tropical DCCs can be invigorated by enhanced aerosol 47 concentrations that arise from human activities and natural sources (Andreae et al., 2004; 48 Koren et al., 2008; Niu & Li, 2012; Pan et al., 2021; Storer et al., 2014). By acting as 49 cloud condensate nuclei (CCN) or ice nuclei (IN), aerosols change cloud properties by 50 influencing cloud microphysics and dynamics, meanwhile influencing cloud-radiation feed-51 backs (i.e., aerosol indirect effects (AIEs); see reviews of Fan et al. (2016) and Tao et al. 52 (2012)). A deeper understanding of AIEs on tropical DCCs and organized convective sys-53 tems could improve the prediction of extreme precipitation events in global weather and 54 climate models. However, the underlying mechanisms of how the updrafts are invigo-55 rated remain elusive and are often debated (Fan et al., 2018; Fan & Khain, 2021; W. W. Grabowski 56 & Morrison, 2020, 2021; Igel & van den Heever, 2021). A particular challenge of under-57 standing AIEs using observations is that the observed aerosol concentrations in the en-58 vironments of DCCs often covary with other meteorological factors, such as convective 59 available potential energy and vertical wind shear (W. W. Grabowski, 2018; Nishant & 60 Sherwood, 2017; Varble, 2018), and the influences of meteorological and aerosol variabil-61 ity are difficult to disentangle from one another. Further, there is evidence from simu-62 lations that AIEs on DCCs vary as a function of meteorological conditions such as shear 63

and humidity (Fan et al., 2009; van den Heever & Cotton, 2007; Khain et al., 2008; Koren et al., 2010; Z. Lebo, 2018), which further complicates our ability to isolate the aerosol
effects from other meteorological processes. AIEs are underrepresented in global climate
models because of these knowledge gaps, which contributes to considerable uncertainty
in estimating human climate forcing (Forster et al., 2021).

To investigate the aerosol indirect effects on DCCs that interact with their surround-69 ing environment, Abbott and Cronin (2021) carried out simulations using a small do-70 main (128x128 km²) three-dimension cloud-resolving model (3-D CRM) with parame-71 72 terized large-scale dynamics under the weak temperature gradient (WTG) approximation (Sobel et al., 2001). Abbott and Cronin (2021) suggested that enhanced CCN con-73 centrations produce clouds that mix more condensed water into the surrounding air. This 74 enhances the environment favorably for subsequent convection by moistening the free 75 troposphere and reducing the deleterious effects of entrainment. The humidity-entrainment 76 mechanism they proposed is distinct from past work, which linked stronger updrafts with 77 latent heat released by cloud condensation (Fan et al., 2018) or freezing (Rosenfeld et 78 al., 2008) independently from possible changes in the environment. Anber et al. (2019) 79 also used a small domain (192x192 km²) 3-D CRM with parameterized large-scale dy-80 namics to carry out simulations with different number concentrations of CCN but found 81 a contrasting result. In their simulations, convection and mean precipitation get weaker 82 when the CCN concentration increases. They suggested that the changes are associated 83 with the modulation of coupling between convective processes and large-scale motions 84 that overall reduces surface enthalpy fluxes. 85

Using a large domain (10000 km) two-dimension CRM configured in radiative-convective 86 equilibrium (RCE; Manabe & Strickler, 1964), van den Heever et al. (2011) found a weak 87 response of the large-scale organization of convection and the domain-averaged precip-88 itation to enhanced CCN concentrations. They suggested that AIEs on the three trop-89 ical cloud modes are opposite in sign, offsetting each other, thus producing a weak domain-90 wide response. In contrast, a more recent study by Beydoun and Hoose (2019) that used 91 a large channel-shaped domain (2000x120 km²) 3-D CRM found a comparatively large 92 decrease in domain-averaged precipitation in their RCE simulations with enhanced CCN 93 concentrations. They suggested that enhanced CCN concentrations lead to the weak-94 ened large-scale organization of convection, increased midlevel and upper-level clouds, 95 decreased radiative cooling, and decreased domain-averaged precipitation. 96

The difference in the above findings is likely influenced by the representation of large-97 scale dynamics and the geometry of the simulation domain, which could modulate convection-98 circulation interaction hence affect the overall AIEs. For example, a horizontal scale of 99 the model domain larger than 5000 km was suggested to be large enough to represent 100 the natural scale of large-scale organization of convection (Matsugishi & Satoh, 2022; 101 Patrizio & Randall, 2019; Yanase et al., 2022). Advances in computational resources have 102 allowed for global model simulations that explicitly simulate deep convection (Stevens 103 et al., 2019). These global convection-permitting models have been applied to investi-104 gate how clouds and convective processes couple to large-scale circulation and determine 105 cloud feedbacks and climate sensitivity (Wing et al., 2020). However, how is the coupling 106 of DCCs and large-scale circulations affected by enhanced aerosol concentrations has not 107 been fully understood. 108

This study aims to investigate the modulation of tropical convection-circulation interaction by AIEs in global simulations that simultaneously resolve the dynamical response of convection to changes in cloud microphysics and allow large-scale circulations to naturally develop since the horizontal scale is not artificially constrained by the domain size or shape. The modulation of tropical convection-circulation interaction by AIEs is demonstrated by analyzing the responses of moisture distribution, convection structures, and large-scale circulation to pollution. Section 2 introduces more details about the model and the experiment design. Section 3 describes the results, and the summary and discussion are presented in section 4.

¹¹⁸ 2 Model Description and Experiment Design

We use the Central Weather Bureau Global Forecast System (CWBGFS; Su et al., 119 2021a, 2021b; SU et al., 2022), which is a global convection-permitting model run at the 120 horizontal resolution of 15 km, to carry out our experiments. Deep convection in the CW-121 BGFS is represented by the unified relaxed Arakawa-Schubert scheme (URAS; Su et al., 122 2021b) in which the representation transitions from the parameterization to the explicit 123 simulation as the diagnosed convective updraft fraction increases (Arakawa & Wu, 2013; 124 Wu & Arakawa, 2014). Hence, the CWBGFS with the URAS can explicitly but efficiently 125 simulate deep convection and convection-circulation interaction on the global scale. This 126 model partially resolve circulations in organized convective systems and reproduce the 127 observed feature of convective systems that stronger extreme precipitation occurs in hor-128 izontally larger systems (Hamada et al., 2014; SU et al., 2022). 129

The CWBGFS uses the two-moment Predicted Particle Properties bulk microphysics 130 scheme (P3; Morrison & Milbrandt, 2015) to represent cloud microphysical processes, 131 including cloud-aerosol interaction. The aerosol concentration prescribed in P3 is fixed 132 throughout the integration and acts as CCN. Cloud-aerosol interaction is not included 133 in the URAS. In our simulations, the averaged percentage of precipitation produced by 134 explicitly simulated convection is more than 93~% over precipitation events stronger than 135 5 mm h^{-1} , indicating that most of the cloud-aerosol interactions associated with deep con-136 vection are resolved. The rest of the descriptions regarding physics suites and the dy-137 namic core of the CWBGFS can be found in Su et al. (2021a). 138

Two idealized non-rotating aqua-planet simulations configured in RCE are carried 139 out. Simulations in RCE have been extensively used to investigate feedback among clouds, 140 environmental moisture, radiation, and precipitation (Bretherton et al., 2005; Coppin 141 & Bony, 2015; Cronin & Wing, 2017; Emanuel et al., 2014; Holloway & Woolnough, 2016; 142 Pendergrass et al., 2016; Popke et al., 2013; Singh & O'Gorman, 2013, 2015; Wing & Emanuel, 143 2014; Wing et al., 2020), and therefore provide an ideal experimental setting to study 144 AIEs. Under certain circumstances, convection in RCE spontaneously self-organizes into 145 one or more moist ascending clusters surrounded by dry subsiding convection-free ar-146 eas in simulations configured in non-rotating RCE (convective self-aggregation (CSA); 147 C. Muller et al., 2022; Wing et al., 2017). We note that CSA occurs in the simulations 148 of van den Heever et al. (2011) and Beydoun and Hoose (2019). 149

The simulations are initialized with an analytic sounding (Wing et al., 2018) that 150 approximates the moist tropical sounding of Dunion (2011), and the initial horizontal 151 winds are set to zero. The initial surface pressure of all grid columns is 1014.8 hPa. The 152 incoming solar radiation (409.6 W m⁻²), the sea surface temperature (300 K), and the 153 surface albedo (0.07) are spatially uniform and constant in time. The simulations are 154 run for 120 days, and the random perturbation of temperature from 0.1 to 0.02 K is added 155 to the five lowest model levels in the first 20 days to speed up convection initiation. The 156 only difference between the two simulations is the prescribed spatially uniform aerosol 157 number mixing ratio set in P3. They are set at 3×10^8 kg⁻¹ and 3×10^{10} kg⁻¹, represent-158 ing the pristine and polluted scenarios, respectively. The scenarios here are referred to 159 the marine environment (Andreae, 2009) and the urban environment (Chang et al., 2021) 160 and are used to evaluate the upper bound of AIEs on convection-circulation interaction. 161 In the following section, 30 days of hourly output (days 90 to 120) are analyzed when 162 the simulation is in an RCE state. 163

The overall results of the pristine run are showcased in Fig. 1, demonstrating that our simulations resemble the global model simulations in the RCE model intercompar¹⁶⁶ ison project (Wing et al., 2018, 2020), in which convection self-organizing into multiple ¹⁶⁷ moist clusters (Fig. 1a). Fig. 1b shows the spatial distribution of column water vapor ¹⁶⁸ (CWV) of a moist cluster, indicating high heterogeneity that is coupled to spatial con-¹⁶⁹ vection structures. Precipitation stronger than 30 mm h⁻¹ (Fig. 1c) is found in a con-¹⁷⁰ vective system with intense resolved updrafts (>1 m s⁻¹) (Fig. 1d). Fig. 1 with more de-¹⁷¹ tail will be introduced in the following section.



Figure 1. A snapshot of moist clusters smaller (light blue shaded) and larger (navy shaded) than 1000 km of horizontal scale, convective systems (orange shaded), and distance to the nearest convective system (green contours of 375, 1125, 1875 km) of the pristine run on day 106.5 (a). Column water vapor (mm) and convective systems (black contours) in a moist cluster (b), which the domain is demonstrated by the black dashed lines in (a). Precipitation intensity (mm h^{-1}) of a convective system (c), which the domain is demonstrated by the white dashed lines in (b). The vertical profiles of mixed-phase cloud condensates (shaded) and vertical velocity (green contours of 0.1, 0.5, 1 m s⁻¹) (d) along the red dashed line in (c). See the context for the definition of moist clusters and convective systems. The horizontal scale is determined by the square root of the cluster's horizontal area.

172 **3 Results**

We start from demonstrating the response of moisture probability distribution to
enhanced CCN concentrations. In both runs, the distribution of CWV is bimodal (Fig.
2). The bimodality suggests the presence of an aggregated state (Arnold & Randall, 2015;
Tsai & Wu, 2017) which is maintained by large-scale circulation. The difference between
the two local maxima of the bimodality is smaller in the polluted run, suggesting AIEs

drive columns away from both moist and dry equilibria in the pristine run. We use the 178 CWV value that corresponds to the smallest value along the curve in Fig. 2 between the 179 local maxima at dry and moist CWV values as the threshold to define moist clusters (i.e., 180 43 mm in both runs). The difference in area coverage percentage of moist clusters in the 181 global domain between the two runs is less than 3 %. The moist clusters in the polluted 182 run are notably drier than that in the pristine run. Further, the number of moist clus-183 ters in the polluted run is 23 % more than that in the pristine run. Sixty-five percent 184 of moist clusters are smaller than 1000 km of horizontal scale in the polluted run, and 185 there are 45 % of them in the pristine run. 186



Figure 2. Probability distribution of column water vapor (black) and distance to the nearest convective system conditional sampled by column water vapor (red) from days 90 to 120. The gray line labels 43 mm of column water vapor, which is set as the criteria for defining a moist cluster.

We evaluate AIEs by first identifying the updraft regions of convective systems as 187 laterally connected columns of vertical velocity $>0.1 \text{ m s}^{-1}$ in any level between 700 to 188 400 hPa (Fig. 1a-b). A critical characteristic of tropical deep moist convection is the rapid 189 intensification of precipitation once CWV has exceeded a critical value, which charac-190 terizes the effect of water vapor on the buoyancy of clouds through entrainment (Bretherton 191 et al., 2004; Neelin et al., 2009; Peters & Neelin, 2006). Hence, we investigate the influ-192 ence of pollution on this precipitation-CWV dependency. Analyses among all updraft 193 regions with a given CWV indicate that both of our simulations mimic the precipitation-194 CWV dependency seen in nature, with a rapid increase in mixed-phase cloud conden-195 sate, updraft intensity (Fig. 3a-b), and precipitation (Fig. 3c) occurring in both simu-196 lations above a certain threshold in CWV. However, a distinct difference of the polluted 197 run from the pristine one is that the threshold CWV which heralds the increase in con-198

vective intensity occurs at a lower CWV value (57 mm) than it does in the pristine run (62 mm).

Fig. 3a-b show that the vertical profiles to the right of the CWV thresholds resem-201 ble the convection structures of deep convection at the developing and mature stage, and 202 the profiles to the left resemble deep convection at the dissipating stage, in which mixed-203 phase cloud condensates concentrate at mid-level free atmosphere beneath which weak 204 downdrafts due to water loading take place. In the dissipating stage, moisture in the pol-205 luted run is more heavily distributed over the mid-to-low free atmosphere (Fig. 3d). The 206 water vapor mixing ratio there is 1.5 g kg^{-1} more than that in the pristine run. The dif-207 ference may be caused by the stronger evaporation of raindrops as we found there is more 208 mass but nearly the same number of falling raindrops beneath clouds in the polluted run 209 leading to two times stronger surface precipitation (figure not shown). These raindrops 210 could be from the melting of graupel and hail since the warm-rain process is suppressed 211 due to pollution. 212

Past studies have shown that humidity in the lower free atmosphere is critical to 213 the onset of tropical deep convection (Derbyshire et al., 2004; Holloway & Neelin, 2009, 214 2010; Schiro et al., 2016; Tompkins, 2001). The enhanced moisture in the lower free at-215 mosphere increases the buoyancy of entraining plumes, leading to an increased chance 216 of deep convection. The signal of the exceeding moisture in the mid-to-low free atmo-217 sphere in the polluted run extends to the CWV regimes of developing and mature con-218 vection (Fig. 3d), in which the increase in moisture in the mid-to-high atmosphere re-219 flects the prevalence of convection (Fig. 3a-b). The modulated moisture distribution, orig-220 inating from the response of dissipating stage of convection to changes in cloud micro-221 physics, enhances conditional instability, potentially contributing to the development of 222 subsequent convection. Further investigations on the mechanism will be carried out in 223 the future. 224



Figure 3. Mass mixing ratio of cloud water and cloud ice (shaded) and vertical velocity (contours at 0, 0.1, 0.2, 0.5, 1, 2 m s⁻¹) within the updraft regions of convective systems conditional sampled by column water vapor of the pristine (a) and the polluted (b) run from days 90 to 120. Precipitation intensity of the two runs (c) and the difference of water vapor mixing ratio (polluted run minus the pristine run) (d) sampled by the same method. The red dotted line in (d) shows the contour of 0 g kg⁻¹. The red sticks along the x-axis show the CWV value of 57 and 62 mm

However, the highest CWV environment over the updraft regions (>67 mm) in the 225 pristine run is absent in the polluted run (Fig. 3). The polluted run has notably drier 226 moist clusters (Fig. 2), leading to the weaker maximum intensity of updraft and precip-227 itation (30 vs. 47 mm h^{-1}). As the moisture distribution is maintained by large-scale cir-228 culation, we investigate the influence of pollution on large-scale circulation by sorting 229 the distance to the nearest convective system and projecting horizontal winds in the di-230 rection pointing to the nearest system (green contours in Fig. 1a). Large-scale circula-231 tion has often been visualized with a streamfunction in moisture space when analyzing 232 self-aggergated runs to RCE (Arnold & Putman, 2018; Bretherton et al., 2005; Holloway 233 & Woolnough, 2016; C. Muller & Bony, 2015; C. J. Muller & Held, 2012). The stream-234 function analyzed in past studies is designed to investigate the energy transport between 235 dry areas and moist clusters but it does not represent circulation in physical space. It 236 is natural to analyze large-scale circulation in physical space when using a global convection-237 permitting model with an appropriate choice of the source of momentum and energy trans-238 port. The result shows that both runs exhibit typical structures of tropical circulation, 239 including low-level inflow, mid-level outflow, and deep convection outflow (Johnson et 240 al., 1999), but every component of the circulation is weaker in the polluted run (Fig. 4). 241

We trace the cause of the weaker large-scale circulation down to the influence of pollution on the geographical distribution of convective systems (i.e., updraft regions). In the polluted run, convective systems develop geographically closer to the meandering margin (i.e., 43 mm) of moist clusters, because CWV increases monotonically from dry areas toward moist clusters (Fig. 1b), and convection strength enhances more rapidly

as CWV increases in the polluted run (Fig. 3b). Fig. 2 shows that the average distance 247 from the edges of moist clusters to the nearest convective system in the pristine run is 248 1.5 times longer than that in the polluted run. Meanwhile, inhibiting the warm-rain pro-249 cess by pollution could increase the mid-level static stability as a result of a latent heat-250 ing dipole associated with the freezing water and melting ice above and below the freez-251 ing level. Previous studies suggested that an increase in mid-level static stability pro-252 motes detrainment (Johnson et al., 1999; Patrizio & Randall, 2019; Posselt et al., 2008, 253 2012). Overall, cloud condensates in the polluted run are more likely to be exported from 254 moist clusters to dry areas rather than stay in moist clusters and then re-evaporate. The 255 export of clouds impedes the moisture-convection feedback in which moistening environ-256 ment by convection plays a key role in favoring subsequent development of convection 257 (W. Grabowski & Moncrieff, 2004; Holloway & Neelin, 2009). The above inference is sup-258 ported by Fig. 4b, which shows that the exceeding cloud condensates in the polluted run 259 coincide with the mid-level outflow of the large-scale circulation. 260



Figure 4. Water vapor flux (shaded) and horizontal winds (contours from -4 to 4 m s⁻¹ with an interval of 1 m s⁻¹ using a color scale from maroon to white to navy) projected to the direction of pointing to the nearest convective system in the pristine (a) and the polluted (b) run from days 90 to 120. Positive values are vectors toward the system. The black and red dots in (b) show where the ratio of cloud water mixing ratio in the polluted run over the pristine one larger than 1 and 2, respectively

²⁶¹ 4 Summary and Discussion

This study investigates the response of tropical convection-circulation interaction 262 to enhanced CCN concentrations using non-rotating RCE simulations of a global convection-263 permitting model run at 15 km horizontal resolution. Deep convection in the model is 264 represented in a way that the explicit simulation of convection seeds cloud-aerosol in-265 teraction and is responsible for strong precipitation events. The simulations allow for the 266 large-scale organization of convection realistically inducing circulation without artificial 267 constraints of scale separation assumption, domain size, or domain shape. The novel find-268 ing in this study is that pollution facilitates the development of deep convection in a drier 269 environment, while the response of large-scale circulation limits the intensity of maxi-270 mum precipitation. Our results emphasize the importance of allowing atmospheric phe-271 nomena to evolve continuously across spatial and temporal scales in simulations when 272 investigating the response of tropical convection to changes in cloud microphysics. 273

274 Connecting our result to the existing driving and maintaining mechanisms of CSA 275 could inspire future investigation on the response of global warming to varied CCN concentrations since CSA is known to modulate climate sensitivity (Cronin & Wing, 2017).

- ²⁷⁷ The possible connections include:
- The export of mid-level cloud condensates could weaken the radiatively driven subsidence over the dry areas that drives CSA (Beydoun & Hoose, 2019; Bretherton et al., 2005; C. J. Muller & Held, 2012; Wing & Emanuel, 2014; Holloway & Woolnough, 2016).
- 282
 2. The response of cold pool dynamics to cloud microphysics has received considerable attention in the literature (Z. J. Lebo & Morrison, 2014; Seigel et al., 2013; Storer et al., 2014; Su et al., 2020; Tao et al., 2007; van den Heever & Cotton, 2007). Cold pools associated with the closer-to-edge convective systems in the polluted run could mix low-level dry areas and moist clusters more effectively, weakening the CSA (Jeevanjee & Romps, 2013; C. Muller & Bony, 2015).

Past studies (Arnold & Randall, 2015; Khairoutdinov & Emanuel, 2018) indicated 288 that the large-scale organization of convection (i.e., CSA) in non-rotating RCE simula-289 tions and MJO-like (i.e., Madden-Julian Oscillation; Madden & Julian, 1971) disturbance 290 in rotating RCE simulations share the same driving mechanism (i.e., cloud-radiation feed-291 backs) in which AIEs can be critical. One of the characteristics of MJO propagation is 292 that MJOs suffer from a barrier effect when it propagates over the Maritime Continent 293 (MC) (Kim et al., 2014; Zhang & Ling, 2017). The development of convective systems 294 over the water in the MC region plays a crucial role in carrying the MJO signal through 295 the MC (Ling et al., 2019). Around the globe, MC is a major source of different types 296 of aerosol (Reid et al., 2012; Salinas et al., 2013; Shpund et al., 2019). The modulation 297 of the size of moist clusters and the geographical distribution of convective systems by 298 enhanced CCN concentrations potentially provides a new perspective on the existing MJO 299 theories (Jiang et al., 2020; Zhang, 2013). A possible approach for the investigation is 300 to evaluate sub-seasonal hindcasts of an active MJO event with different aerosol emis-301 sion scenarios. 302

³⁰³ 5 Open Research

The model output data of a temporal snapshot, the Fortran program that computes vertical atmospheric profiles conditional sampled by column water vapor and the distance to the nearest convective system, and the GrADS plotting scripts in this study are available at https://doi.org/10.6084/m9.figshare.22149617.v1.

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Figure 1.



Figure 2.



Figure 3.



Figure 4.



Modulation of Tropical Convection-circulation Interaction by Aerosol Indirect Effects in a Global Convection-permitting Model

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Key Points:

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9	•	Simulations of the global convection-permitting model provide a new perspective
10		on aerosol indirect effects.
11	•	Pollution facilitates the development of deep convection in a drier environment.
12	•	The response of large-scale circulation to pollution limits the intensity of maxi-
13		mum precipitation.

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14 Abstract

Observations suggest tropical convection intensifies when aerosol concentrations enhance, 15 but quantitative estimations of this effect remain highly uncertain. Leading theories for 16 explaining the intensification are based on the dynamical response of convection to changes 17 in cloud microphysics independently from possible changes in the environment. Here, 18 we provide a new perspective on aerosol indirect effects on tropical convection by using 19 a global convection-permitting model that realistically simulates convection-circulation 20 interaction. Simulations of radiative-convective equilibrium show that pollution facili-21 tates the development of deep convection in a drier environment, but cloud condensates 22 are more likely to be exported from moist clusters to dry areas, impeding the large-scale 23 moisture-convection feedback and limiting the intensity of maximum precipitation (30 24 vs. 47 mm h⁻¹). Our results emphasize the importance of allowing atmospheric phenom-25 ena to evolve continuously across spatial and temporal scales in simulations when inves-26 tigating the response of tropical convection to changes in cloud microphysics. 27

²⁸ Plain Language Summary

How does air pollution affect thunderstorm intensity over the tropical ocean? Past 29 studies have proposed different opinions but generally neglect the interplay between the 30 development of thunderstorms and the long-range movement of air that redistributes the 31 Earth's thermal energy and moisture. Here, we address this question by investigating 32 33 results from numerical experiments in which the global domain is used to simulate the response of individual thunderstorms and large-scale air motion to pollution. Our results 34 show that tropical thunderstorms with given moisture are more vigorous under the pol-35 luted scenario. However, pollution makes the thunderstorms keep less moisture in their 36 surroundings, limiting the maximum intensity of thunderstorms and weakening the large-37 scale air motion that supplies moisture to thunderstorms. Our results suggest that the 38 interplay between the development of thunderstorms and the long-range movement of 39 air is crucial in determining the effects of pollution in the tropical atmosphere. 40

41 **1** Introduction

Deep convective clouds (DCCs) play a critical role in the global climate system via 42 their role in the Earth's energy budget (Arakawa, 2004; Hartmann et al., 2001). They 43 can aggregate into organized convective systems that span hundreds to a thousand kilo-44 meters (Houze, 2004) and contribute significantly to tropical rainfall (Chen et al., 2021; 45 Houze et al., 2015; Nesbitt et al., 2006; Tao & Chern, 2017; Yuan & Houze, 2010). Ob-46 servations suggest that updrafts of tropical DCCs can be invigorated by enhanced aerosol 47 concentrations that arise from human activities and natural sources (Andreae et al., 2004; 48 Koren et al., 2008; Niu & Li, 2012; Pan et al., 2021; Storer et al., 2014). By acting as 49 cloud condensate nuclei (CCN) or ice nuclei (IN), aerosols change cloud properties by 50 influencing cloud microphysics and dynamics, meanwhile influencing cloud-radiation feed-51 backs (i.e., aerosol indirect effects (AIEs); see reviews of Fan et al. (2016) and Tao et al. 52 (2012)). A deeper understanding of AIEs on tropical DCCs and organized convective sys-53 tems could improve the prediction of extreme precipitation events in global weather and 54 climate models. However, the underlying mechanisms of how the updrafts are invigo-55 rated remain elusive and are often debated (Fan et al., 2018; Fan & Khain, 2021; W. W. Grabowski 56 & Morrison, 2020, 2021; Igel & van den Heever, 2021). A particular challenge of under-57 standing AIEs using observations is that the observed aerosol concentrations in the en-58 vironments of DCCs often covary with other meteorological factors, such as convective 59 available potential energy and vertical wind shear (W. W. Grabowski, 2018; Nishant & 60 Sherwood, 2017; Varble, 2018), and the influences of meteorological and aerosol variabil-61 ity are difficult to disentangle from one another. Further, there is evidence from simu-62 lations that AIEs on DCCs vary as a function of meteorological conditions such as shear 63

and humidity (Fan et al., 2009; van den Heever & Cotton, 2007; Khain et al., 2008; Koren et al., 2010; Z. Lebo, 2018), which further complicates our ability to isolate the aerosol
effects from other meteorological processes. AIEs are underrepresented in global climate
models because of these knowledge gaps, which contributes to considerable uncertainty
in estimating human climate forcing (Forster et al., 2021).

To investigate the aerosol indirect effects on DCCs that interact with their surround-69 ing environment, Abbott and Cronin (2021) carried out simulations using a small do-70 main (128x128 km²) three-dimension cloud-resolving model (3-D CRM) with parame-71 72 terized large-scale dynamics under the weak temperature gradient (WTG) approximation (Sobel et al., 2001). Abbott and Cronin (2021) suggested that enhanced CCN con-73 centrations produce clouds that mix more condensed water into the surrounding air. This 74 enhances the environment favorably for subsequent convection by moistening the free 75 troposphere and reducing the deleterious effects of entrainment. The humidity-entrainment 76 mechanism they proposed is distinct from past work, which linked stronger updrafts with 77 latent heat released by cloud condensation (Fan et al., 2018) or freezing (Rosenfeld et 78 al., 2008) independently from possible changes in the environment. Anber et al. (2019) 79 also used a small domain (192x192 km²) 3-D CRM with parameterized large-scale dy-80 namics to carry out simulations with different number concentrations of CCN but found 81 a contrasting result. In their simulations, convection and mean precipitation get weaker 82 when the CCN concentration increases. They suggested that the changes are associated 83 with the modulation of coupling between convective processes and large-scale motions 84 that overall reduces surface enthalpy fluxes. 85

Using a large domain (10000 km) two-dimension CRM configured in radiative-convective 86 equilibrium (RCE; Manabe & Strickler, 1964), van den Heever et al. (2011) found a weak 87 response of the large-scale organization of convection and the domain-averaged precip-88 itation to enhanced CCN concentrations. They suggested that AIEs on the three trop-89 ical cloud modes are opposite in sign, offsetting each other, thus producing a weak domain-90 wide response. In contrast, a more recent study by Beydoun and Hoose (2019) that used 91 a large channel-shaped domain (2000x120 km²) 3-D CRM found a comparatively large 92 decrease in domain-averaged precipitation in their RCE simulations with enhanced CCN 93 concentrations. They suggested that enhanced CCN concentrations lead to the weak-94 ened large-scale organization of convection, increased midlevel and upper-level clouds, 95 decreased radiative cooling, and decreased domain-averaged precipitation. 96

The difference in the above findings is likely influenced by the representation of large-97 scale dynamics and the geometry of the simulation domain, which could modulate convection-98 circulation interaction hence affect the overall AIEs. For example, a horizontal scale of 99 the model domain larger than 5000 km was suggested to be large enough to represent 100 the natural scale of large-scale organization of convection (Matsugishi & Satoh, 2022; 101 Patrizio & Randall, 2019; Yanase et al., 2022). Advances in computational resources have 102 allowed for global model simulations that explicitly simulate deep convection (Stevens 103 et al., 2019). These global convection-permitting models have been applied to investi-104 gate how clouds and convective processes couple to large-scale circulation and determine 105 cloud feedbacks and climate sensitivity (Wing et al., 2020). However, how is the coupling 106 of DCCs and large-scale circulations affected by enhanced aerosol concentrations has not 107 been fully understood. 108

This study aims to investigate the modulation of tropical convection-circulation interaction by AIEs in global simulations that simultaneously resolve the dynamical response of convection to changes in cloud microphysics and allow large-scale circulations to naturally develop since the horizontal scale is not artificially constrained by the domain size or shape. The modulation of tropical convection-circulation interaction by AIEs is demonstrated by analyzing the responses of moisture distribution, convection structures, and large-scale circulation to pollution. Section 2 introduces more details about the model and the experiment design. Section 3 describes the results, and the summary and discussion are presented in section 4.

¹¹⁸ 2 Model Description and Experiment Design

We use the Central Weather Bureau Global Forecast System (CWBGFS; Su et al., 119 2021a, 2021b; SU et al., 2022), which is a global convection-permitting model run at the 120 horizontal resolution of 15 km, to carry out our experiments. Deep convection in the CW-121 BGFS is represented by the unified relaxed Arakawa-Schubert scheme (URAS; Su et al., 122 2021b) in which the representation transitions from the parameterization to the explicit 123 simulation as the diagnosed convective updraft fraction increases (Arakawa & Wu, 2013; 124 Wu & Arakawa, 2014). Hence, the CWBGFS with the URAS can explicitly but efficiently 125 simulate deep convection and convection-circulation interaction on the global scale. This 126 model partially resolve circulations in organized convective systems and reproduce the 127 observed feature of convective systems that stronger extreme precipitation occurs in hor-128 izontally larger systems (Hamada et al., 2014; SU et al., 2022). 129

The CWBGFS uses the two-moment Predicted Particle Properties bulk microphysics 130 scheme (P3; Morrison & Milbrandt, 2015) to represent cloud microphysical processes, 131 including cloud-aerosol interaction. The aerosol concentration prescribed in P3 is fixed 132 throughout the integration and acts as CCN. Cloud-aerosol interaction is not included 133 in the URAS. In our simulations, the averaged percentage of precipitation produced by 134 explicitly simulated convection is more than 93~% over precipitation events stronger than 135 5 mm h^{-1} , indicating that most of the cloud-aerosol interactions associated with deep con-136 vection are resolved. The rest of the descriptions regarding physics suites and the dy-137 namic core of the CWBGFS can be found in Su et al. (2021a). 138

Two idealized non-rotating aqua-planet simulations configured in RCE are carried 139 out. Simulations in RCE have been extensively used to investigate feedback among clouds, 140 environmental moisture, radiation, and precipitation (Bretherton et al., 2005; Coppin 141 & Bony, 2015; Cronin & Wing, 2017; Emanuel et al., 2014; Holloway & Woolnough, 2016; 142 Pendergrass et al., 2016; Popke et al., 2013; Singh & O'Gorman, 2013, 2015; Wing & Emanuel, 143 2014; Wing et al., 2020), and therefore provide an ideal experimental setting to study 144 AIEs. Under certain circumstances, convection in RCE spontaneously self-organizes into 145 one or more moist ascending clusters surrounded by dry subsiding convection-free ar-146 eas in simulations configured in non-rotating RCE (convective self-aggregation (CSA); 147 C. Muller et al., 2022; Wing et al., 2017). We note that CSA occurs in the simulations 148 of van den Heever et al. (2011) and Beydoun and Hoose (2019). 149

The simulations are initialized with an analytic sounding (Wing et al., 2018) that 150 approximates the moist tropical sounding of Dunion (2011), and the initial horizontal 151 winds are set to zero. The initial surface pressure of all grid columns is 1014.8 hPa. The 152 incoming solar radiation (409.6 W m^{-2}), the sea surface temperature (300 K), and the 153 surface albedo (0.07) are spatially uniform and constant in time. The simulations are 154 run for 120 days, and the random perturbation of temperature from 0.1 to 0.02 K is added 155 to the five lowest model levels in the first 20 days to speed up convection initiation. The 156 only difference between the two simulations is the prescribed spatially uniform aerosol 157 number mixing ratio set in P3. They are set at 3×10^8 kg⁻¹ and 3×10^{10} kg⁻¹, represent-158 ing the pristine and polluted scenarios, respectively. The scenarios here are referred to 159 the marine environment (Andreae, 2009) and the urban environment (Chang et al., 2021) 160 and are used to evaluate the upper bound of AIEs on convection-circulation interaction. 161 In the following section, 30 days of hourly output (days 90 to 120) are analyzed when 162 the simulation is in an RCE state. 163

The overall results of the pristine run are showcased in Fig. 1, demonstrating that our simulations resemble the global model simulations in the RCE model intercompar¹⁶⁶ ison project (Wing et al., 2018, 2020), in which convection self-organizing into multiple ¹⁶⁷ moist clusters (Fig. 1a). Fig. 1b shows the spatial distribution of column water vapor ¹⁶⁸ (CWV) of a moist cluster, indicating high heterogeneity that is coupled to spatial con-¹⁶⁹ vection structures. Precipitation stronger than 30 mm h⁻¹ (Fig. 1c) is found in a con-¹⁷⁰ vective system with intense resolved updrafts (>1 m s⁻¹) (Fig. 1d). Fig. 1 with more de-¹⁷¹ tail will be introduced in the following section.



Figure 1. A snapshot of moist clusters smaller (light blue shaded) and larger (navy shaded) than 1000 km of horizontal scale, convective systems (orange shaded), and distance to the nearest convective system (green contours of 375, 1125, 1875 km) of the pristine run on day 106.5 (a). Column water vapor (mm) and convective systems (black contours) in a moist cluster (b), which the domain is demonstrated by the black dashed lines in (a). Precipitation intensity (mm h^{-1}) of a convective system (c), which the domain is demonstrated by the white dashed lines in (b). The vertical profiles of mixed-phase cloud condensates (shaded) and vertical velocity (green contours of 0.1, 0.5, 1 m s⁻¹) (d) along the red dashed line in (c). See the context for the definition of moist clusters and convective systems. The horizontal scale is determined by the square root of the cluster's horizontal area.

172 **3 Results**

We start from demonstrating the response of moisture probability distribution to
enhanced CCN concentrations. In both runs, the distribution of CWV is bimodal (Fig.
2). The bimodality suggests the presence of an aggregated state (Arnold & Randall, 2015;
Tsai & Wu, 2017) which is maintained by large-scale circulation. The difference between
the two local maxima of the bimodality is smaller in the polluted run, suggesting AIEs

drive columns away from both moist and dry equilibria in the pristine run. We use the 178 CWV value that corresponds to the smallest value along the curve in Fig. 2 between the 179 local maxima at dry and moist CWV values as the threshold to define moist clusters (i.e., 180 43 mm in both runs). The difference in area coverage percentage of moist clusters in the 181 global domain between the two runs is less than 3 %. The moist clusters in the polluted 182 run are notably drier than that in the pristine run. Further, the number of moist clus-183 ters in the polluted run is 23 % more than that in the pristine run. Sixty-five percent 184 of moist clusters are smaller than 1000 km of horizontal scale in the polluted run, and 185 there are 45 % of them in the pristine run. 186



Figure 2. Probability distribution of column water vapor (black) and distance to the nearest convective system conditional sampled by column water vapor (red) from days 90 to 120. The gray line labels 43 mm of column water vapor, which is set as the criteria for defining a moist cluster.

We evaluate AIEs by first identifying the updraft regions of convective systems as 187 laterally connected columns of vertical velocity $>0.1 \text{ m s}^{-1}$ in any level between 700 to 188 400 hPa (Fig. 1a-b). A critical characteristic of tropical deep moist convection is the rapid 189 intensification of precipitation once CWV has exceeded a critical value, which charac-190 terizes the effect of water vapor on the buoyancy of clouds through entrainment (Bretherton 191 et al., 2004; Neelin et al., 2009; Peters & Neelin, 2006). Hence, we investigate the influ-192 ence of pollution on this precipitation-CWV dependency. Analyses among all updraft 193 regions with a given CWV indicate that both of our simulations mimic the precipitation-194 CWV dependency seen in nature, with a rapid increase in mixed-phase cloud conden-195 sate, updraft intensity (Fig. 3a-b), and precipitation (Fig. 3c) occurring in both simu-196 lations above a certain threshold in CWV. However, a distinct difference of the polluted 197 run from the pristine one is that the threshold CWV which heralds the increase in con-198

vective intensity occurs at a lower CWV value (57 mm) than it does in the pristine run (62 mm).

Fig. 3a-b show that the vertical profiles to the right of the CWV thresholds resem-201 ble the convection structures of deep convection at the developing and mature stage, and 202 the profiles to the left resemble deep convection at the dissipating stage, in which mixed-203 phase cloud condensates concentrate at mid-level free atmosphere beneath which weak 204 downdrafts due to water loading take place. In the dissipating stage, moisture in the pol-205 luted run is more heavily distributed over the mid-to-low free atmosphere (Fig. 3d). The 206 water vapor mixing ratio there is 1.5 g kg^{-1} more than that in the pristine run. The dif-207 ference may be caused by the stronger evaporation of raindrops as we found there is more 208 mass but nearly the same number of falling raindrops beneath clouds in the polluted run 209 leading to two times stronger surface precipitation (figure not shown). These raindrops 210 could be from the melting of graupel and hail since the warm-rain process is suppressed 211 due to pollution. 212

Past studies have shown that humidity in the lower free atmosphere is critical to 213 the onset of tropical deep convection (Derbyshire et al., 2004; Holloway & Neelin, 2009, 214 2010; Schiro et al., 2016; Tompkins, 2001). The enhanced moisture in the lower free at-215 mosphere increases the buoyancy of entraining plumes, leading to an increased chance 216 of deep convection. The signal of the exceeding moisture in the mid-to-low free atmo-217 sphere in the polluted run extends to the CWV regimes of developing and mature con-218 vection (Fig. 3d), in which the increase in moisture in the mid-to-high atmosphere re-219 flects the prevalence of convection (Fig. 3a-b). The modulated moisture distribution, orig-220 inating from the response of dissipating stage of convection to changes in cloud micro-221 physics, enhances conditional instability, potentially contributing to the development of 222 subsequent convection. Further investigations on the mechanism will be carried out in 223 the future. 224



Figure 3. Mass mixing ratio of cloud water and cloud ice (shaded) and vertical velocity (contours at 0, 0.1, 0.2, 0.5, 1, 2 m s⁻¹) within the updraft regions of convective systems conditional sampled by column water vapor of the pristine (a) and the polluted (b) run from days 90 to 120. Precipitation intensity of the two runs (c) and the difference of water vapor mixing ratio (polluted run minus the pristine run) (d) sampled by the same method. The red dotted line in (d) shows the contour of 0 g kg⁻¹. The red sticks along the x-axis show the CWV value of 57 and 62 mm

However, the highest CWV environment over the updraft regions (>67 mm) in the 225 pristine run is absent in the polluted run (Fig. 3). The polluted run has notably drier 226 moist clusters (Fig. 2), leading to the weaker maximum intensity of updraft and precip-227 itation (30 vs. 47 mm h⁻¹). As the moisture distribution is maintained by large-scale cir-228 culation, we investigate the influence of pollution on large-scale circulation by sorting 229 the distance to the nearest convective system and projecting horizontal winds in the di-230 rection pointing to the nearest system (green contours in Fig. 1a). Large-scale circula-231 tion has often been visualized with a streamfunction in moisture space when analyzing 232 self-aggergated runs to RCE (Arnold & Putman, 2018; Bretherton et al., 2005; Holloway 233 & Woolnough, 2016; C. Muller & Bony, 2015; C. J. Muller & Held, 2012). The stream-234 function analyzed in past studies is designed to investigate the energy transport between 235 dry areas and moist clusters but it does not represent circulation in physical space. It 236 is natural to analyze large-scale circulation in physical space when using a global convection-237 permitting model with an appropriate choice of the source of momentum and energy trans-238 port. The result shows that both runs exhibit typical structures of tropical circulation, 239 including low-level inflow, mid-level outflow, and deep convection outflow (Johnson et 240 al., 1999), but every component of the circulation is weaker in the polluted run (Fig. 4). 241

We trace the cause of the weaker large-scale circulation down to the influence of pollution on the geographical distribution of convective systems (i.e., updraft regions). In the polluted run, convective systems develop geographically closer to the meandering margin (i.e., 43 mm) of moist clusters, because CWV increases monotonically from dry areas toward moist clusters (Fig. 1b), and convection strength enhances more rapidly

as CWV increases in the polluted run (Fig. 3b). Fig. 2 shows that the average distance 247 from the edges of moist clusters to the nearest convective system in the pristine run is 248 1.5 times longer than that in the polluted run. Meanwhile, inhibiting the warm-rain pro-249 cess by pollution could increase the mid-level static stability as a result of a latent heat-250 ing dipole associated with the freezing water and melting ice above and below the freez-251 ing level. Previous studies suggested that an increase in mid-level static stability pro-252 motes detrainment (Johnson et al., 1999; Patrizio & Randall, 2019; Posselt et al., 2008, 253 2012). Overall, cloud condensates in the polluted run are more likely to be exported from 254 moist clusters to dry areas rather than stay in moist clusters and then re-evaporate. The 255 export of clouds impedes the moisture-convection feedback in which moistening environ-256 ment by convection plays a key role in favoring subsequent development of convection 257 (W. Grabowski & Moncrieff, 2004; Holloway & Neelin, 2009). The above inference is sup-258 ported by Fig. 4b, which shows that the exceeding cloud condensates in the polluted run 259 coincide with the mid-level outflow of the large-scale circulation. 260



Figure 4. Water vapor flux (shaded) and horizontal winds (contours from -4 to 4 m s⁻¹ with an interval of 1 m s⁻¹ using a color scale from maroon to white to navy) projected to the direction of pointing to the nearest convective system in the pristine (a) and the polluted (b) run from days 90 to 120. Positive values are vectors toward the system. The black and red dots in (b) show where the ratio of cloud water mixing ratio in the polluted run over the pristine one larger than 1 and 2, respectively

²⁶¹ 4 Summary and Discussion

This study investigates the response of tropical convection-circulation interaction 262 to enhanced CCN concentrations using non-rotating RCE simulations of a global convection-263 permitting model run at 15 km horizontal resolution. Deep convection in the model is 264 represented in a way that the explicit simulation of convection seeds cloud-aerosol in-265 teraction and is responsible for strong precipitation events. The simulations allow for the 266 large-scale organization of convection realistically inducing circulation without artificial 267 constraints of scale separation assumption, domain size, or domain shape. The novel find-268 ing in this study is that pollution facilitates the development of deep convection in a drier 269 environment, while the response of large-scale circulation limits the intensity of maxi-270 mum precipitation. Our results emphasize the importance of allowing atmospheric phe-271 nomena to evolve continuously across spatial and temporal scales in simulations when 272 investigating the response of tropical convection to changes in cloud microphysics. 273

274 Connecting our result to the existing driving and maintaining mechanisms of CSA 275 could inspire future investigation on the response of global warming to varied CCN concentrations since CSA is known to modulate climate sensitivity (Cronin & Wing, 2017).

- The possible connections include:
- The export of mid-level cloud condensates could weaken the radiatively driven subsidence over the dry areas that drives CSA (Beydoun & Hoose, 2019; Bretherton et al., 2005; C. J. Muller & Held, 2012; Wing & Emanuel, 2014; Holloway & Woolnough, 2016).
- 282
 2. The response of cold pool dynamics to cloud microphysics has received considerable attention in the literature (Z. J. Lebo & Morrison, 2014; Seigel et al., 2013; Storer et al., 2014; Su et al., 2020; Tao et al., 2007; van den Heever & Cotton, 2007). Cold pools associated with the closer-to-edge convective systems in the polluted run could mix low-level dry areas and moist clusters more effectively, weakening the CSA (Jeevanjee & Romps, 2013; C. Muller & Bony, 2015).

Past studies (Arnold & Randall, 2015; Khairoutdinov & Emanuel, 2018) indicated 288 that the large-scale organization of convection (i.e., CSA) in non-rotating RCE simula-289 tions and MJO-like (i.e., Madden-Julian Oscillation; Madden & Julian, 1971) disturbance 290 in rotating RCE simulations share the same driving mechanism (i.e., cloud-radiation feed-291 backs) in which AIEs can be critical. One of the characteristics of MJO propagation is 292 that MJOs suffer from a barrier effect when it propagates over the Maritime Continent 293 (MC) (Kim et al., 2014; Zhang & Ling, 2017). The development of convective systems 294 over the water in the MC region plays a crucial role in carrying the MJO signal through 295 the MC (Ling et al., 2019). Around the globe, MC is a major source of different types 296 of aerosol (Reid et al., 2012; Salinas et al., 2013; Shpund et al., 2019). The modulation 297 of the size of moist clusters and the geographical distribution of convective systems by 298 enhanced CCN concentrations potentially provides a new perspective on the existing MJO 299 theories (Jiang et al., 2020; Zhang, 2013). A possible approach for the investigation is 300 to evaluate sub-seasonal hindcasts of an active MJO event with different aerosol emis-301 sion scenarios. 302

³⁰³ 5 Open Research

The model output data of a temporal snapshot, the Fortran program that computes vertical atmospheric profiles conditional sampled by column water vapor and the distance to the nearest convective system, and the GrADS plotting scripts in this study are available at https://doi.org/10.6084/m9.figshare.22149617.v1.

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