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

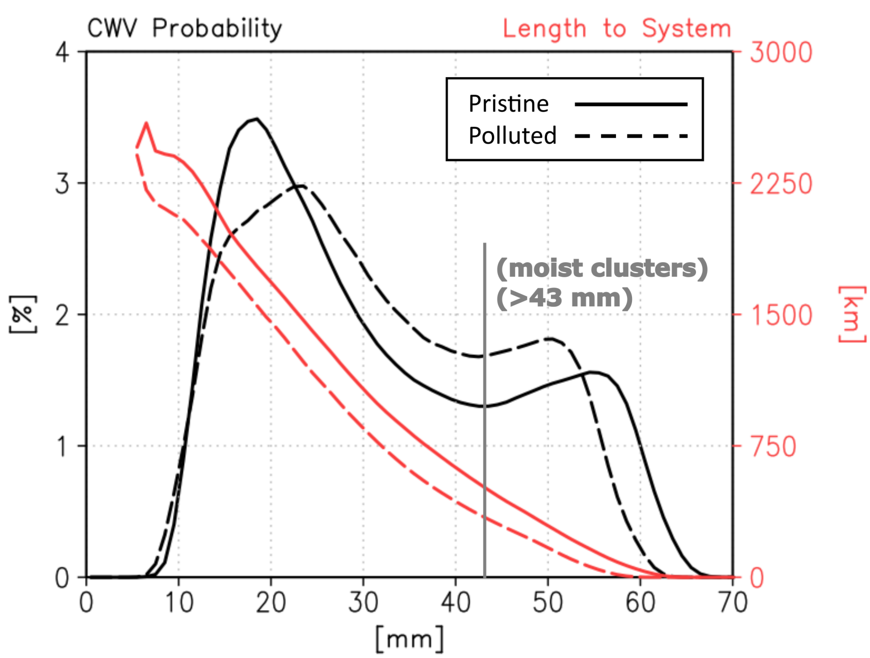
Chun-Yian Su[1], Chien-Ming Wu[2], Wei-Ting Chen[2], and john peters[3]

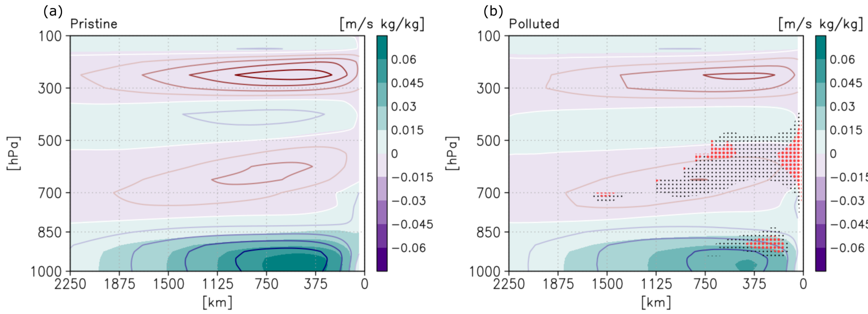
[1]Pennsylvania State University
[2]National Taiwan University
[3]Penn State

March 6, 2023

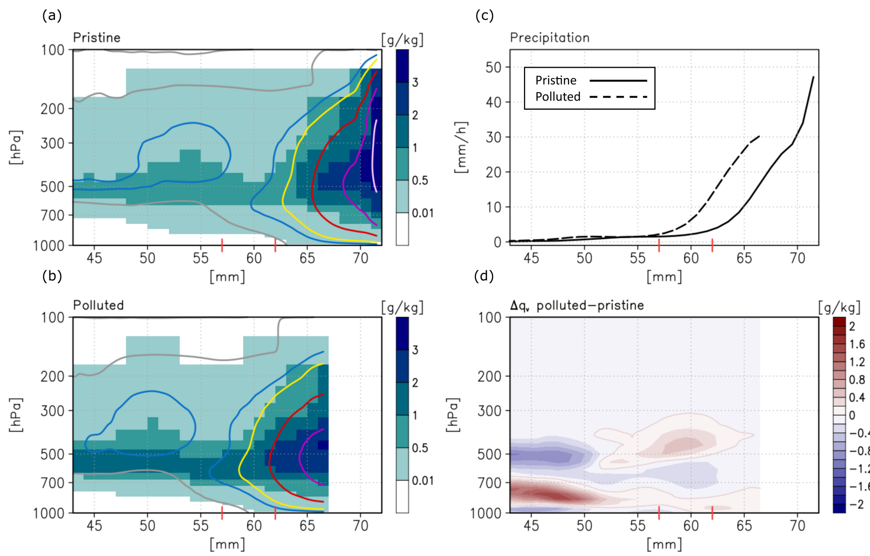
Abstract

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.

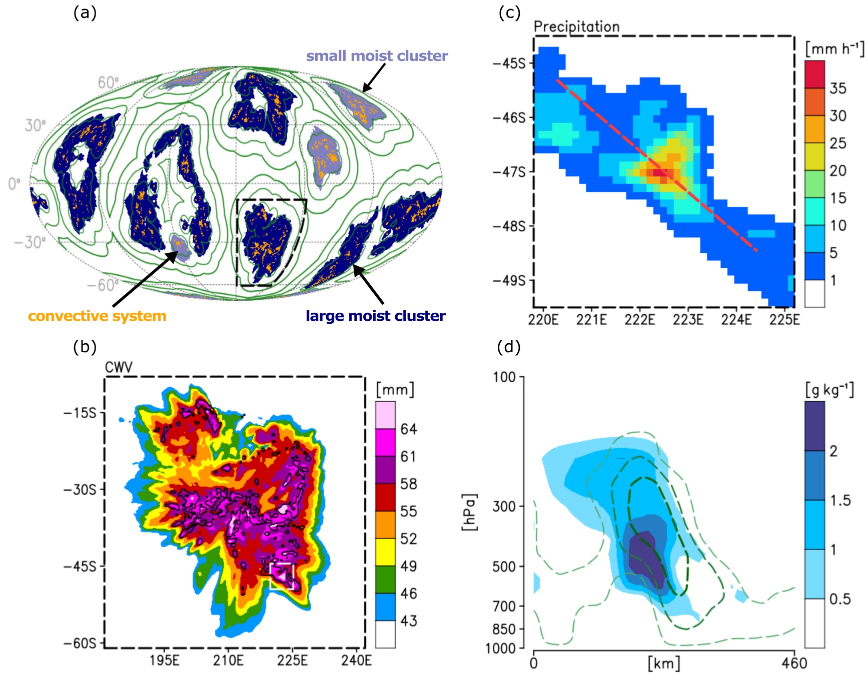




(a)
Pristine
[m/s kg/kg]
(b)
Polluted
[m/s kg/kg]
[hPa]
[km]



(a)
Pristine
[g/kg]
(b)
Polluted
[g/kg]
(c)
Precipitation
Pristine
Polluted
[mm/h]
(d)
Δq, polluted−pristine
[g/kg]
[hPa]
[mm]


(a)
small moist cluster
60°
30°
0°
−30°
−60°
convective system
large moist cluster
(c)
Precipitation
[mm h^{-1}]
−45S
−46S
−47S
−48S
−49S
220E 221E 222E 223E 224E 225E
35
30
25
20
15
10
5
1
(b)
CWV
[mm]
−15S
−30S
−45S
−60S
195E 210E 225E 240E
64
61
58
55
52
49
46
43
(d)
[hPa]
100
300
500
700
850
1000
0
[km]
460
[g kg^{-1}]
2
1.5
1
0.5

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

Chun-Yian Su[1,2], Chien-Ming Wu[2], Wei-Ting Chen[2], and John M. Peters[1]

[1]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA
[2]Department of Atmospheric Sciences, National Taiwan University, Taipei city, Taiwan

Key Points:

- Simulations of the global convection-permitting model provide a new perspective on aerosol indirect effects.
- Pollution facilitates the development of deep convection in a drier environment.
- The response of large-scale circulation to pollution limits the intensity of maximum precipitation.

Corresponding author: Chien-Ming Wu, `mog@as.ntu.edu.tw`

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.

Plain Language Summary

How does air pollution affect thunderstorm intensity over the tropical ocean? Past studies have proposed different opinions but generally neglect the interplay between the development of thunderstorms and the long-range movement of air that redistributes the Earth's thermal energy and moisture. Here, we address this question by investigating 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 show that tropical thunderstorms with given moisture are more vigorous under the polluted scenario. However, pollution makes the thunderstorms keep less moisture in their surroundings, limiting the maximum intensity of thunderstorms and weakening the large-scale air motion that supplies moisture to thunderstorms. Our results suggest that the interplay between the development of thunderstorms and the long-range movement of air is crucial in determining the effects of pollution in the tropical atmosphere.

1 Introduction

Deep convective clouds (DCCs) play a critical role in the global climate system via their role in the Earth's energy budget (Arakawa, 2004; Hartmann et al., 2001). They can aggregate into organized convective systems that span hundreds to a thousand kilometers (Houze, 2004) and contribute significantly to tropical rainfall (Chen et al., 2021; Houze et al., 2015; Nesbitt et al., 2006; Tao & Chern, 2017; Yuan & Houze, 2010). Observations suggest that updrafts of tropical DCCs can be invigorated by enhanced aerosol concentrations that arise from human activities and natural sources (Andreae et al., 2004; Koren et al., 2008; Niu & Li, 2012; Pan et al., 2021; Storer et al., 2014). By acting as cloud condensate nuclei (CCN) or ice nuclei (IN), aerosols change cloud properties by influencing cloud microphysics and dynamics, meanwhile influencing cloud-radiation feedbacks (i.e., aerosol indirect effects (AIEs); see reviews of Fan et al. (2016) and Tao et al. (2012)). A deeper understanding of AIEs on tropical DCCs and organized convective systems could improve the prediction of extreme precipitation events in global weather and climate models. However, the underlying mechanisms of how the updrafts are invigorated remain elusive and are often debated (Fan et al., 2018; Fan & Khain, 2021; W. W. Grabowski & Morrison, 2020, 2021; Igel & van den Heever, 2021). A particular challenge of understanding AIEs using observations is that the observed aerosol concentrations in the environments of DCCs often covary with other meteorological factors, such as convective available potential energy and vertical wind shear (W. W. Grabowski, 2018; Nishant & Sherwood, 2017; Varble, 2018), and the influences of meteorological and aerosol variability are difficult to disentangle from one another. Further, there is evidence from simulations that AIEs on DCCs vary as a function of meteorological conditions such as shear 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 surrounding environment, Abbott and Cronin (2021) carried out simulations using a small domain (128x128 km^2) three-dimension cloud-resolving model (3-D CRM) with parameterized large-scale dynamics under the weak temperature gradient (WTG) approximation (Sobel et al., 2001). Abbott and Cronin (2021) suggested that enhanced CCN concentrations produce clouds that mix more condensed water into the surrounding air. This enhances the environment favorably for subsequent convection by moistening the free troposphere and reducing the deleterious effects of entrainment. The humidity-entrainment mechanism they proposed is distinct from past work, which linked stronger updrafts with latent heat released by cloud condensation (Fan et al., 2018) or freezing (Rosenfeld et al., 2008) independently from possible changes in the environment. Anber et al. (2019) also used a small domain (192x192 km^2) 3-D CRM with parameterized large-scale dynamics to carry out simulations with different number concentrations of CCN but found a contrasting result. In their simulations, convection and mean precipitation get weaker when the CCN concentration increases. They suggested that the changes are associated with the modulation of coupling between convective processes and large-scale motions that overall reduces surface enthalpy fluxes.

Using a large domain (10000 km) two-dimension CRM configured in radiative-convective equilibrium (RCE; Manabe & Strickler, 1964), van den Heever et al. (2011) found a weak response of the large-scale organization of convection and the domain-averaged precipitation to enhanced CCN concentrations. They suggested that AIEs on the three tropical cloud modes are opposite in sign, offsetting each other, thus producing a weak domain-wide response. In contrast, a more recent study by Beydoun and Hoose (2019) that used a large channel-shaped domain (2000x120 km^2) 3-D CRM found a comparatively large decrease in domain-averaged precipitation in their RCE simulations with enhanced CCN concentrations. They suggested that enhanced CCN concentrations lead to the weakened large-scale organization of convection, increased midlevel and upper-level clouds, decreased radiative cooling, and decreased domain-averaged precipitation.

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

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.

2 Model Description and Experiment Design

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

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

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

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

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 intercomparison project (Wing et al., 2018, 2020), in which convection self-organizing into multiple moist clusters (Fig. 1a). Fig. 1b shows the spatial distribution of column water vapor (CWV) of a moist cluster, indicating high heterogeneity that is coupled to spatial convection structures. Precipitation stronger than 30 mm h^{-1} (Fig. 1c) is found in a convective system with intense resolved updrafts (>1 m s^{-1}) (Fig. 1d). Fig. 1 with more detail will be introduced in the following section.

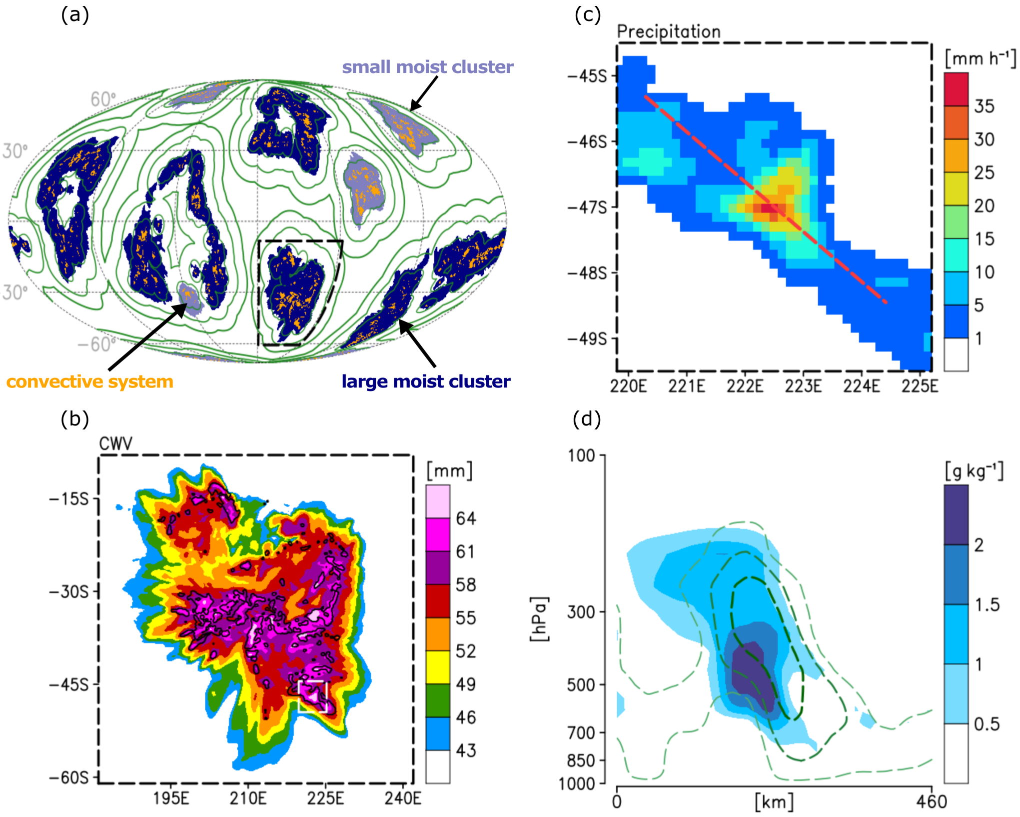


Figure 1. A snapshot of moist clusters smaller (light blue shaded) and larger (navy shaded) than 1000 km of horizontal scale, convective systems (orange shaded), and distance to the nearest convective system (green contours of 375, 1125, 1875 km) of the pristine run on day 106.5 (a). Column water vapor (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.

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 CWV value that corresponds to the smallest value along the curve in Fig. 2 between the local maxima at dry and moist CWV values as the threshold to define moist clusters (i.e., 43 mm in both runs). The difference in area coverage percentage of moist clusters in the global domain between the two runs is less than 3 %. The moist clusters in the polluted run are notably drier than that in the pristine run. Further, the number of moist clusters in the polluted run is 23 % more than that in the pristine run. Sixty-five percent of moist clusters are smaller than 1000 km of horizontal scale in the polluted run, and there are 45 % of them in the pristine run.

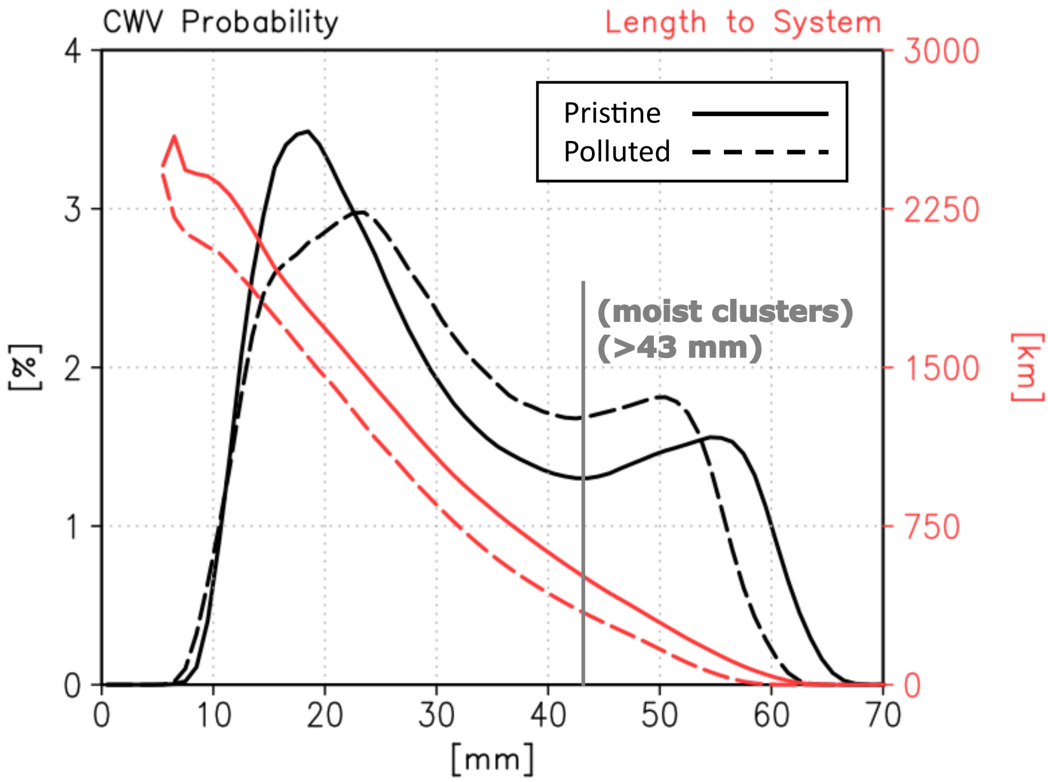


Figure 2. Probability distribution of column water vapor (black) and distance to the nearest convective system conditional sampled by column water vapor (red) from days 90 to 120. The gray line labels 43 mm of column water vapor, which is set as the criteria for defining a moist cluster.

We evaluate AIEs by first identifying the updraft regions of convective systems as laterally connected columns of vertical velocity >0.1 m s^{-1} in any level between 700 to 400 hPa (Fig. 1a-b). A critical characteristic of tropical deep moist convection is the rapid intensification of precipitation once CWV has exceeded a critical value, which characterizes the effect of water vapor on the buoyancy of clouds through entrainment (Bretherton et al., 2004; Neelin et al., 2009; Peters & Neelin, 2006). Hence, we investigate the influence of pollution on this precipitation-CWV dependency. Analyses among all updraft regions with a given CWV indicate that both of our simulations mimic the precipitation-CWV dependency seen in nature, with a rapid increase in mixed-phase cloud condensate, updraft intensity (Fig. 3a-b), and precipitation (Fig. 3c) occurring in both simulations above a certain threshold in CWV. However, a distinct difference of the polluted run from the pristine one is that the threshold CWV which heralds the increase in convective 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 resemble the convection structures of deep convection at the developing and mature stage, and the profiles to the left resemble deep convection at the dissipating stage, in which mixed-phase cloud condensates concentrate at mid-level free atmosphere beneath which weak downdrafts due to water loading take place. In the dissipating stage, moisture in the polluted run is more heavily distributed over the mid-to-low free atmosphere (Fig. 3d). The water vapor mixing ratio there is 1.5 g kg^{-1} more than that in the pristine run. The difference may be caused by the stronger evaporation of raindrops as we found there is more mass but nearly the same number of falling raindrops beneath clouds in the polluted run leading to two times stronger surface precipitation (figure not shown). These raindrops could be from the melting of graupel and hail since the warm-rain process is suppressed due to pollution.

Past studies have shown that humidity in the lower free atmosphere is critical to the onset of tropical deep convection (Derbyshire et al., 2004; Holloway & Neelin, 2009, 2010; Schiro et al., 2016; Tompkins, 2001). The enhanced moisture in the lower free atmosphere increases the buoyancy of entraining plumes, leading to an increased chance of deep convection. The signal of the exceeding moisture in the mid-to-low free atmosphere in the polluted run extends to the CWV regimes of developing and mature convection (Fig. 3d), in which the increase in moisture in the mid-to-high atmosphere reflects the prevalence of convection (Fig. 3a-b). The modulated moisture distribution, originating from the response of dissipating stage of convection to changes in cloud microphysics, enhances conditional instability, potentially contributing to the development of subsequent convection. Further investigations on the mechanism will be carried out in the future.

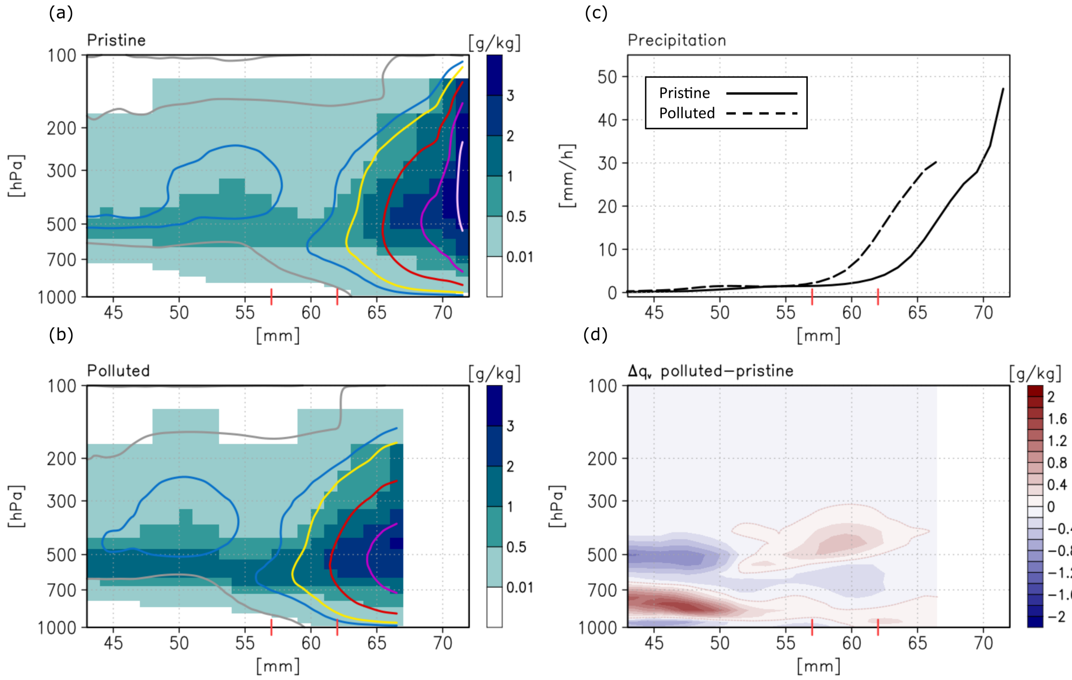


Figure 3. Mass mixing ratio of cloud water and cloud ice (shaded) and vertical velocity (contours at 0, 0.1, 0.2, 0.5, 1, 2 m s^{-1}) within the updraft regions of convective systems conditional sampled by column water vapor of the pristine (a) and the polluted (b) run from days 90 to 120. Precipitation 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 pristine run is absent in the polluted run (Fig. 3). The polluted run has notably drier moist clusters (Fig. 2), leading to the weaker maximum intensity of updraft and precipitation (30 vs. 47 mm h^{-1}). As the moisture distribution is maintained by large-scale circulation, we investigate the influence of pollution on large-scale circulation by sorting the distance to the nearest convective system and projecting horizontal winds in the direction pointing to the nearest system (green contours in Fig. 1a). Large-scale circulation has often been visualized with a streamfunction in moisture space when analyzing self-aggergated runs to RCE (Arnold & Putman, 2018; Bretherton et al., 2005; Holloway & Woolnough, 2016; C. Muller & Bony, 2015; C. J. Muller & Held, 2012). The streamfunction analyzed in past studies is designed to investigate the energy transport between dry areas and moist clusters but it does not represent circulation in physical space. It is natural to analyze large-scale circulation in physical space when using a global convection-permitting model with an appropriate choice of the source of momentum and energy transport. The result shows that both runs exhibit typical structures of tropical circulation, including low-level inflow, mid-level outflow, and deep convection outflow (Johnson et al., 1999), but every component of the circulation is weaker in the polluted run (Fig. 4).

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 from the edges of moist clusters to the nearest convective system in the pristine run is 1.5 times longer than that in the polluted run. Meanwhile, inhibiting the warm-rain process by pollution could increase the mid-level static stability as a result of a latent heating dipole associated with the freezing water and melting ice above and below the freezing level. Previous studies suggested that an increase in mid-level static stability promotes detrainment (Johnson et al., 1999; Patrizio & Randall, 2019; Posselt et al., 2008, 2012). Overall, cloud condensates in the polluted run are more likely to be exported from moist clusters to dry areas rather than stay in moist clusters and then re-evaporate. The export of clouds impedes the moisture-convection feedback in which moistening environment by convection plays a key role in favoring subsequent development of convection (W. Grabowski & Moncrieff, 2004; Holloway & Neelin, 2009). The above inference is supported by Fig. 4b, which shows that the exceeding cloud condensates in the polluted run coincide with the mid-level outflow of the large-scale circulation.

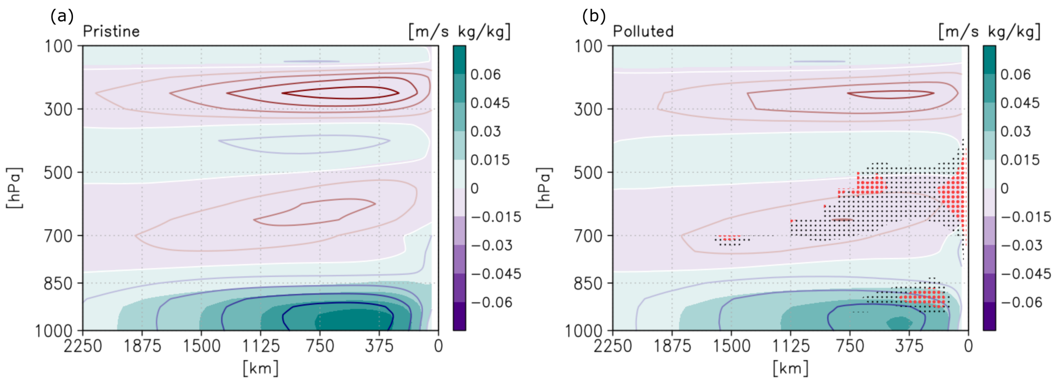


Figure 4. Water vapor flux (shaded) and horizontal winds (contours from -4 to 4 m s^{-1} with an interval of 1 m s^{-1} using a color scale from maroon to white to navy) projected to the direction of pointing to the nearest convective system in the pristine (a) and the polluted (b) run from days 90 to 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

4 Summary and Discussion

This study investigates the response of tropical convection-circulation interaction to enhanced CCN concentrations using non-rotating RCE simulations of a global convection-permitting model run at 15 km horizontal resolution. Deep convection in the model is represented in a way that the explicit simulation of convection seeds cloud-aerosol interaction and is responsible for strong precipitation events. The simulations allow for the large-scale organization of convection realistically inducing circulation without artificial constraints of scale separation assumption, domain size, or domain shape. The novel finding in this study is that pollution facilitates the development of deep convection in a drier environment, while the response of large-scale circulation limits the intensity of maximum precipitation. 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.

Connecting our result to the existing driving and maintaining mechanisms of CSA 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:

1. 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).
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 that the large-scale organization of convection (i.e., CSA) in non-rotating RCE simulations and MJO-like (i.e., Madden-Julian Oscillation; Madden & Julian, 1971) disturbance in rotating RCE simulations share the same driving mechanism (i.e., cloud-radiation feedbacks) in which AIEs can be critical. One of the characteristics of MJO propagation is that MJOs suffer from a barrier effect when it propagates over the Maritime Continent (MC) (Kim et al., 2014; Zhang & Ling, 2017). The development of convective systems over the water in the MC region plays a crucial role in carrying the MJO signal through the MC (Ling et al., 2019). Around the globe, MC is a major source of different types of aerosol (Reid et al., 2012; Salinas et al., 2013; Shpund et al., 2019). The modulation of the size of moist clusters and the geographical distribution of convective systems by enhanced CCN concentrations potentially provides a new perspective on the existing MJO theories (Jiang et al., 2020; Zhang, 2013). A possible approach for the investigation is to evaluate sub-seasonal hindcasts of an active MJO event with different aerosol emission scenarios.

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.

Acknowledgments

Chien-Ming Wu and Chun-Yian Su's efforts were supported by National Science and Technology Council (NSTC) in Taiwan grant 111-2111-M-002-012-NSTC. Wei-Ting Chen was supported by Ministry of Science and Technology (MOST) in Taiwan grant 109-2628-M-002-003-MY3. J. Peters was supported by National Science Foundation (NSF) grants AGS-1928666, AGS-1841674, and the Department of Energy Atmospheric System Research (DOE ASR) grant DE-SC0000246356. We thank Dr. Jen-Her Chen in Central Weather Bureau for his support of this work.

References

Abbott, T. H., & Cronin, T. W. (2021, January). Aerosol invigoration of atmospheric convection through increases in humidity. *Science*, *371*(6524), 83–85. Retrieved from `https://doi.org/10.1126/science.abc5181` doi: 10.1126/science.abc5181

Anber, U. M., Wang, S., Gentine, P., & Jensen, M. P. (2019, September). Probing the response of tropical deep convection to aerosol perturbations using idealized cloud-resolving simulations with parameterized large-scale dynamics. *Journal of the Atmospheric Sciences*, *76*(9), 2885–2897. Retrieved from https://doi.org/10.1175/jas-d-18-0351.1 doi: 10.1175/jas-d-18-0351.1

Andreae, M. O. (2009, January). Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions. *Atmospheric Chemistry and Physics*, *9*(2), 543–556. Retrieved from https://doi.org/10.5194/acp-9-543-2009 doi: 10.5194/acp-9-543-2009

Andreae, M. O., Rosenfeld, D., Artaxo, P., Costa, A. A., Frank, G. P., Longo, K. M., & Silva-Dias, M. A. F. (2004, February). Smoking rain clouds over the amazon. *Science*, *303*(5662), 1337–1342. Retrieved from https://doi.org/10.1126/science.1092779 doi: 10.1126/science.1092779

Arakawa, A. (2004, July). The cumulus parameterization problem: Past, present, and future. *Journal of Climate*, *17*(13), 2493–2525. Retrieved from https://doi.org/10.1175/1520-0442(2004)017<2493:ratcpp>2.0.co;2 doi: 10.1175/1520-0442(2004)017⟨2493:ratcpp⟩2.0.co;2

Arakawa, A., & Wu, C.-M. (2013, July). A unified representation of deep moist convection in numerical modeling of the atmosphere. part i. *Journal of the Atmospheric Sciences*, *70*(7), 1977–1992. Retrieved from https://doi.org/10.1175/jas-d-12-0330.1 doi: 10.1175/jas-d-12-0330.1

Arnold, N. P., & Putman, W. M. (2018, April). Nonrotating convective self-aggregation in a limited area AGCM. *Journal of Advances in Modeling Earth Systems*, *10*(4), 1029–1046. Retrieved from https://doi.org/10.1002/2017ms001218 doi: 10.1002/2017ms001218

Arnold, N. P., & Randall, D. A. (2015, October). Global-scale convective aggregation: Implications for the madden-julian oscillation. *Journal of Advances in Modeling Earth Systems*, *7*(4), 1499–1518. Retrieved from https://doi.org/10.1002/2015ms000498 doi: 10.1002/2015ms000498

Beydoun, H., & Hoose, C. (2019, April). Aerosol-cloud-precipitation interactions in the context of convective self-aggregation. *Journal of Advances in Modeling Earth Systems*, *11*(4), 1066–1087. Retrieved from https://doi.org/10.1029/2018ms001523 doi: 10.1029/2018ms001523

Bretherton, C. S., Blossey, P. N., & Khairoutdinov, M. (2005, December). An energy-balance analysis of deep convective self-aggregation above uniform SST. *Journal of the Atmospheric Sciences*, *62*(12), 4273–4292. Retrieved from https://doi.org/10.1175/jas3614.1 doi: 10.1175/jas3614.1

Bretherton, C. S., Peters, M. E., & Back, L. E. (2004, April). Relationships between water vapor path and precipitation over the tropical oceans. *Journal of Climate*, *17*(7), 1517–1528. Retrieved from https://doi.org/10.1175/1520-0442(2004)017<1517:rbwvpa>2.0.co;2 doi: 10.1175/1520-0442(2004)017⟨1517:rbwvpa⟩2.0.co;2

Chang, Y.-H., Chen, W.-T., Wu, C.-M., Moseley, C., & Wu, C.-C. (2021, November). Tracking the influence of cloud condensation nuclei on summer diurnal precipitating systems over complex topography in taiwan. *Atmospheric Chemistry and Physics*, *21*(22), 16709–16725. Retrieved from https://doi.org/10.5194/acp-21-16709-2021 doi: 10.5194/acp-21-16709-2021

Chen, P.-J., Chen, W.-T., Wu, C.-M., & Yo, T.-S. (2021, May). Convective cloud regimes from a classification of object-based CloudSat observations over asian-australian monsoon areas. *Geophysical Research Letters*, *48*(10). Retrieved from https://doi.org/10.1029/2021gl092733 doi: 10.1029/2021gl092733

Coppin, D., & Bony, S. (2015, December). Physical mechanisms controlling the initiation of convective self-aggregation in a general circulation model. *Journal of Advances in Modeling Earth Systems*, *7*(4), 2060–2078. Retrieved from https://doi.org/10.1002/2015ms000571 doi: 10.1002/2015ms000571

Cronin, T. W., & Wing, A. A. (2017, December). Clouds, circulation, and climate sensitivity in a radiative-convective equilibrium channel model. *Journal of Ad-*

vances in Modeling Earth Systems, *9*(8), 2883–2905. Retrieved from https://doi.org/10.1002/2017ms001111 doi: 10.1002/2017ms001111

Derbyshire, S., Beau, I., Bechtold, P., Grandpeix, J.-Y., Piriou, J.-M., Redelsperger, J.-L., & Soares, P. (2004, October). Sensitivity of moist convection to environmental humidity. *Quarterly Journal of the Royal Meteorological Society*, *130*(604), 3055–3079. Retrieved from https://doi.org/10.1256/qj.03.130 doi: 10.1256/qj.03.130

Dunion, J. P. (2011, February). Rewriting the climatology of the tropical north atlantic and caribbean sea atmosphere. *Journal of Climate*, *24*(3), 893–908. Retrieved from https://doi.org/10.1175/2010jcli3496.1 doi: 10.1175/2010jcli3496.1

Emanuel, K., Wing, A. A., & Vincent, E. M. (2014, February). Radiative-convective instability. *Journal of Advances in Modeling Earth Systems*, *6*(1), 75–90. Retrieved from https://doi.org/10.1002/2013ms000270 doi: 10.1002/2013ms000270

Fan, J., & Khain, A. (2021, January). Comments on "do ultrafine cloud condensation nuclei invigorate deep convection?". *Journal of the Atmospheric Sciences*, *78*(1), 329–339. Retrieved from https://doi.org/10.1175/jas-d-20-0218.1 doi: 10.1175/jas-d-20-0218.1

Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A. T., … de Souza, R. A. F. (2018, January). Substantial convection and precipitation enhancements by ultrafineaerosol particles. *Science*, *359*(6374), 411–418. Retrieved from https://doi.org/10.1126/science.aan8461 doi: 10.1126/science.aan8461

Fan, J., Wang, Y., Rosenfeld, D., & Liu, X. (2016, October). Review of aerosol–cloud interactions: Mechanisms, significance, and challenges. *Journal of the Atmospheric Sciences*, *73*(11), 4221–4252. Retrieved from https://doi.org/10.1175/jas-d-16-0037.1 doi: 10.1175/jas-d-16-0037.1

Fan, J., Yuan, T., Comstock, J. M., Ghan, S., Khain, A., Leung, L. R., … Ovchinnikov, M. (2009, November). Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. *Journal of Geophysical Research*, *114*(D22). Retrieved from https://doi.org/10.1029/2009jd012352 doi: 10.1029/2009jd012352

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., … Zhang, H. (2021). The earth's energy budget, climate feedbacks, and climate sensitivity [Book Section]. In V. Masson-Delmotte et al. (Eds.), *Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change* (p. 923–1054). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi: 10.1017/9781009157896.009

Grabowski, W., & Moncrieff, M. (2004, October). Moisture–convection feedback in the tropics. *Quarterly Journal of the Royal Meteorological Society*, *130*(604), 3081–3104. Retrieved from https://doi.org/10.1256/qj.03.135 doi: 10.1256/qj.03.135

Grabowski, W. W. (2018, October). Can the impact of aerosols on deep convection be isolated from meteorological effects in atmospheric observations? *Journal of the Atmospheric Sciences*, *75*(10), 3347–3363. Retrieved from https://doi.org/10.1175/jas-d-18-0105.1 doi: 10.1175/jas-d-18-0105.1

Grabowski, W. W., & Morrison, H. (2020, July). Do ultrafine cloud condensation nuclei invigorate deep convection? *Journal of the Atmospheric Sciences*, *77*(7), 2567–2583. Retrieved from https://doi.org/10.1175/jas-d-20-0012.1 doi: 10.1175/jas-d-20-0012.1

Grabowski, W. W., & Morrison, H. (2021, January). Reply to "comments on 'do ultrafine cloud condensation nuclei invigorate deep convection?'". *Journal of the Atmospheric Sciences*, *78*(1), 341–350. Retrieved from https://doi.org/10

.1175/jas-d-20-0315.1 doi: 10.1175/jas-d-20-0315.1

Hamada, A., Murayama, Y., & Takayabu, Y. N. (2014, October). Regional characteristics of extreme rainfall extracted from TRMM PR measurements. *Journal of Climate*, *27*(21), 8151–8169. Retrieved from https://doi.org/10.1175/jcli-d-14-00107.1 doi: 10.1175/jcli-d-14-00107.1

Hartmann, D. L., Moy, L. A., & Fu, Q. (2001, December). Tropical convection and the energy balance at the top of the atmosphere. *Journal of Climate*, *14*(24), 4495–4511. Retrieved from https://doi.org/10.1175/1520-0442(2001)014<4495:tcateb>2.0.co;2 doi: 10.1175/1520-0442(2001)014⟨4495:tcateb⟩2.0.co;2

Holloway, C. E., & Neelin, J. D. (2009, June). Moisture vertical structure, column water vapor, and tropical deep convection. *Journal of the Atmospheric Sciences*, *66*(6), 1665–1683. Retrieved from https://doi.org/10.1175/2008jas2806.1 doi: 10.1175/2008jas2806.1

Holloway, C. E., & Neelin, J. D. (2010, April). Temporal relations of column water vapor and tropical precipitation. *Journal of the Atmospheric Sciences*, *67*(4), 1091–1105. Retrieved from https://doi.org/10.1175/2009jas3284.1 doi: 10.1175/2009jas3284.1

Holloway, C. E., & Woolnough, S. J. (2016, February). The sensitivity of convective aggregation to diabatic processes in idealized radiative-convective equilibrium simulations. *Journal of Advances in Modeling Earth Systems*, *8*(1), 166–195. Retrieved from https://doi.org/10.1002/2015ms000511 doi: 10.1002/2015ms000511

Houze, R. A. (2004, December). Mesoscale convective systems. *Reviews of Geophysics*, *42*(4). Retrieved from https://doi.org/10.1029/2004rg000150 doi: 10.1029/2004rg000150

Houze, R. A., Rasmussen, K. L., Zuluaga, M. D., & Brodzik, S. R. (2015, September). The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the tropical rainfall measuring mission satellite. *Reviews of Geophysics*, *53*(3), 994–1021. Retrieved from https://doi.org/10.1002/2015rg000488 doi: 10.1002/2015rg000488

Igel, A. L., & van den Heever, S. C. (2021, August). Invigoration or enervation of convective clouds by aerosols? *Geophysical Research Letters*, *48*(16). Retrieved from https://doi.org/10.1029/2021gl093804 doi: 10.1029/2021gl093804

Jeevanjee, N., & Romps, D. M. (2013, March). Convective self-aggregation, cold pools, and domain size. *Geophysical Research Letters*, *40*(5), 994–998. Retrieved from https://doi.org/10.1002/grl.50204 doi: 10.1002/grl.50204

Jiang, X., Adames, Á. F., Kim, D., Maloney, E. D., Lin, H., Kim, H., … Klingaman, N. P. (2020, August). Fifty years of research on the madden-julian oscillation: Recent progress, challenges, and perspectives. *Journal of Geophysical Research: Atmospheres*, *125*(17). Retrieved from https://doi.org/10.1029/2019jd030911 doi: 10.1029/2019jd030911

Johnson, R. H., Rickenbach, T. M., Rutledge, S. A., Ciesielski, P. E., & Schubert, W. H. (1999, August). Trimodal characteristics of tropical convection. *Journal of Climate*, *12*(8), 2397–2418. Retrieved from https://doi.org/10.1175/1520-0442(1999)012<2397:tcotc>2.0.co;2 doi: 10.1175/1520-0442(1999)012⟨2397:tcotc⟩2.0.co;2

Khain, A. P., BenMoshe, N., & Pokrovsky, A. (2008, June). Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification. *Journal of the Atmospheric Sciences*, *65*(6), 1721–1748. Retrieved from https://doi.org/10.1175/2007jas2515.1 doi: 10.1175/2007jas2515.1

Khairoutdinov, M. F., & Emanuel, K. (2018, December). Intraseasonal variability in a cloud-permitting near-global equatorial aquaplanet model. *Journal of the Atmospheric Sciences*, *75*(12), 4337–4355. Retrieved from https://doi.org/10.1175/jas-d-18-0152.1 doi: 10.1175/jas-d-18-0152.1

Kim, D., Kug, J.-S., & Sobel, A. H. (2014, January). Propagating versus non-propagating madden–julian oscillation events. *Journal of Climate*, *27*(1), 111–125. Retrieved from `https://doi.org/10.1175/jcli-d-13-00084.1` doi: 10.1175/jcli-d-13-00084.1

Koren, I., Feingold, G., & Remer, L. A. (2010, September). The invigoration of deep convective clouds over the atlantic: aerosol effect, meteorology or retrieval artifact? *Atmospheric Chemistry and Physics*, *10*(18), 8855–8872. Retrieved from `https://doi.org/10.5194/acp-10-8855-2010` doi: 10.5194/acp-10-8855-2010

Koren, I., Martins, J. V., Remer, L. A., & Afargan, H. (2008, August). Smoke invigoration versus inhibition of clouds over the amazon. *Science*, *321*(5891), 946–949. Retrieved from `https://doi.org/10.1126/science.1159185` doi: 10.1126/science.1159185

Lebo, Z. (2018, February). A numerical investigation of the potential effects of aerosol-induced warming and updraft width and slope on updraft intensity in deep convective clouds. *Journal of the Atmospheric Sciences*, *75*(2), 535–554. Retrieved from `https://doi.org/10.1175/jas-d-16-0368.1` doi: 10.1175/jas-d-16-0368.1

Lebo, Z. J., & Morrison, H. (2014, March). Dynamical effects of aerosol perturbations on simulated idealized squall lines. *Monthly Weather Review*, *142*(3), 991–1009. Retrieved from `https://doi.org/10.1175/mwr-d-13-00156.1` doi: 10.1175/mwr-d-13-00156.1

Ling, J., Zhang, C., Joyce, R., ping Xie, P., & Chen, G. (2019, March). Possible role of the diurnal cycle in land convection in the barrier effect on the MJO by the maritime continent. *Geophysical Research Letters*, *46*(5), 3001–3011. Retrieved from `https://doi.org/10.1029/2019gl081962` doi: 10.1029/2019gl081962

Madden, R. A., & Julian, P. R. (1971, July). Detection of a 40–50 day oscillation in the zonal wind in the tropical pacific. *Journal of the Atmospheric Sciences*, *28*(5), 702–708. Retrieved from `https://doi.org/10.1175/1520-0469(1971)028<0702:doadoi>2.0.co;2` doi: 10.1175/1520-0469(1971)028⟨0702:doadoi⟩2.0.co;2

Manabe, S., & Strickler, R. F. (1964, July). Thermal equilibrium of the atmosphere with a convective adjustment. *Journal of the Atmospheric Sciences*, *21*(4), 361–385. Retrieved from `https://doi.org/10.1175/1520-0469(1964)021<0361:teotaw>2.0.co;2` doi: 10.1175/1520-0469(1964)021⟨0361:teotaw⟩2.0.co;2

Matsugishi, S., & Satoh, M. (2022, May). Sensitivity of the horizontal scale of convective self-aggregation to sea surface temperature in radiative convective equilibrium experiments using a global nonhydrostatic model. *Journal of Advances in Modeling Earth Systems*, *14*(5). Retrieved from `https://doi.org/10.1029/2021ms002636` doi: 10.1029/2021ms002636

Morrison, H., & Milbrandt, J. A. (2015, January). Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. part i: Scheme description and idealized tests. *Journal of the Atmospheric Sciences*, *72*(1), 287–311. Retrieved from `https://doi.org/10.1175/jas-d-14-0065.1` doi: 10.1175/jas-d-14-0065.1

Muller, C., & Bony, S. (2015, July). What favors convective aggregation and why? *Geophysical Research Letters*, *42*(13), 5626–5634. Retrieved from `https://doi.org/10.1002/2015gl064260` doi: 10.1002/2015gl064260

Muller, C., Yang, D., Craig, G., Cronin, T., Fildier, B., Haerter, J. O., … Sherwood, S. C. (2022, January). Spontaneous aggregation of convective storms. *Annual Review of Fluid Mechanics*, *54*(1), 133–157. Retrieved from `https://doi.org/10.1146/annurev-fluid-022421-011319` doi: 10.1146/annurev-fluid-022421-011319

Muller, C. J., & Held, I. M. (2012, August). Detailed investigation of the self-aggregation of convection in cloud-resolving simulations. *Journal of the Atmospheric Sciences*, *69*(8), 2551–2565. Retrieved from https://doi.org/10.1175/jas-d-11-0257.1 doi: 10.1175/jas-d-11-0257.1

Neelin, J. D., Peters, O., & Hales, K. (2009, August). The transition to strong convection. *Journal of the Atmospheric Sciences*, *66*(8), 2367–2384. Retrieved from https://doi.org/10.1175/2009jas2962.1 doi: 10.1175/2009jas2962.1

Nesbitt, S. W., Cifelli, R., & Rutledge, S. A. (2006, October). Storm morphology and rainfall characteristics of TRMM precipitation features. *Monthly Weather Review*, *134*(10), 2702–2721. Retrieved from https://doi.org/10.1175/mwr3200.1 doi: 10.1175/mwr3200.1

Nishant, N., & Sherwood, S. C. (2017, June). A cloud-resolving model study of aerosol-cloud correlation in a pristine maritime environment. *Geophysical Research Letters*, *44*(11), 5774–5781. Retrieved from https://doi.org/10.1002/2017gl073267 doi: 10.1002/2017gl073267

Niu, F., & Li, Z. (2012, September). Systematic variations of cloud top temperature and precipitation rate with aerosols over the global tropics. *Atmospheric Chemistry and Physics*, *12*(18), 8491–8498. Retrieved from https://doi.org/10.5194/acp-12-8491-2012 doi: 10.5194/acp-12-8491-2012

Pan, Z., Rosenfeld, D., Zhu, Y., Mao, F., Gong, W., Zang, L., & Lu, X. (2021, May). Observational quantification of aerosol invigoration for deep convective cloud lifecycle properties based on geostationary satellite. *Journal of Geophysical Research: Atmospheres*, *126*(9). Retrieved from https://doi.org/10.1029/2020jd034275 doi: 10.1029/2020jd034275

Patrizio, C. R., & Randall, D. A. (2019, July). Sensitivity of convective self-aggregation to domain size. *Journal of Advances in Modeling Earth Systems*, *11*(7), 1995–2019. Retrieved from https://doi.org/10.1029/2019ms001672 doi: 10.1029/2019ms001672

Pendergrass, A. G., Reed, K. A., & Medeiros, B. (2016, November). The link between extreme precipitation and convective organization in a warming climate: Global radiative-convective equilibrium simulations. *Geophysical Research Letters*, *43*(21). Retrieved from https://doi.org/10.1002/2016gl071285 doi: 10.1002/2016gl071285

Peters, O., & Neelin, J. D. (2006, May). Critical phenomena in atmospheric precipitation. *Nature Physics*, *2*(6), 393–396. Retrieved from https://doi.org/10.1038/nphys314 doi: 10.1038/nphys314

Popke, D., Stevens, B., & Voigt, A. (2013, January). Climate and climate change in a radiative-convective equilibrium version of ECHAM6. *Journal of Advances in Modeling Earth Systems*, *5*(1), 1–14. Retrieved from https://doi.org/10.1029/2012ms000191 doi: 10.1029/2012ms000191

Posselt, D. J., van den Heever, S., Stephens, G., & Igel, M. R. (2012, January). Changes in the interaction between tropical convection, radiation, and the large-scale circulation in a warming environment. *Journal of Climate*, *25*(2), 557–571. Retrieved from https://doi.org/10.1175/2011jcli4167.1 doi: 10.1175/2011jcli4167.1

Posselt, D. J., van den Heever, S. C., & Stephens, G. L. (2008, April). Trimodal cloudiness and tropical stable layers in simulations of radiative convective equilibrium. *Geophysical Research Letters*, *35*(8). Retrieved from https://doi.org/10.1029/2007gl033029 doi: 10.1029/2007gl033029

Reid, J. S., Xian, P., Hyer, E. J., Flatau, M. K., Ramirez, E. M., Turk, F. J., ... Maloney, E. D. (2012, February). Multi-scale meteorological conceptual analysis of observed active fire hotspot activity and smoke optical depth in the maritime continent. *Atmospheric Chemistry and Physics*, *12*(4), 2117–2147. Retrieved from https://doi.org/10.5194/acp-12-2117-2012 doi: 10.5194/acp-12-2117-2012

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., ... Andreae, M. O. (2008, September). Flood or drought: How do aerosols affect precipitation? *Science*, *321*(5894), 1309–1313. Retrieved from https://doi.org/10.1126/science.1160606 doi: 10.1126/science.1160606

Salinas, S. V., Chew, B. N., Miettinen, J., Campbell, J. R., Welton, E. J., Reid, J. S., ... Liew, S. C. (2013, March). Physical and optical characteristics of the october 2010 haze event over singapore: A photometric and lidar analysis. *Atmospheric Research*, *122*, 555–570. Retrieved from https://doi.org/10.1016/j.atmosres.2012.05.021 doi: 10.1016/j.atmosres.2012.05.021

Schiro, K. A., Neelin, J. D., Adams, D. K., & Lintner, B. R. (2016, September). Deep convection and column water vapor over tropical land versus tropical ocean: A comparison between the amazon and the tropical western pacific. *Journal of the Atmospheric Sciences*, *73*(10), 4043–4063. Retrieved from https://doi.org/10.1175/jas-d-16-0119.1 doi: 10.1175/jas-d-16-0119.1

Seigel, R. B., van den Heever, S. C., & Saleeby, S. M. (2013, April). Mineral dust indirect effects and cloud radiative feedbacks of a simulated idealized nocturnal squall line. *Atmospheric Chemistry and Physics*, *13*(8), 4467–4485. Retrieved from https://doi.org/10.5194/acp-13-4467-2013 doi: 10.5194/acp-13-4467-2013

Shpund, J., Khain, A., & Rosenfeld, D. (2019, August). Effects of sea spray on microphysics and intensity of deep convective clouds under strong winds. *Journal of Geophysical Research: Atmospheres*, *124*(16), 9484–9509. Retrieved from https://doi.org/10.1029/2018jd029893 doi: 10.1029/2018jd029893

Singh, M. S., & O'Gorman, P. A. (2013, August). Influence of entrainment on the thermal stratification in simulations of radiative-convective equilibrium. *Geophysical Research Letters*, *40*(16), 4398–4403. Retrieved from https://doi.org/10.1002/grl.50796 doi: 10.1002/grl.50796

Singh, M. S., & O'Gorman, P. A. (2015, June). Increases in moist-convective updraught velocities with warming in radiative-convective equilibrium. *Quarterly Journal of the Royal Meteorological Society*, *141*(692), 2828–2838. Retrieved from https://doi.org/10.1002/qj.2567 doi: 10.1002/qj.2567

Sobel, A. H., Nilsson, J., & Polvani, L. M. (2001, December). The weak temperature gradient approximation and balanced tropical moisture waves. *Journal of the Atmospheric Sciences*, *58*(23), 3650–3665. Retrieved from https://doi.org/10.1175/1520-0469(2001)058<3650:twtgaa>2.0.co;2 doi: 10.1175/1520-0469(2001)058⟨3650:twtgaa⟩2.0.co;2

Stevens, B., Satoh, M., Auger, L., Biercamp, J., Bretherton, C. S., Chen, X., ... Zhou, L. (2019, September). DYAMOND: the DYnamics of the atmospheric general circulation modeled on non-hydrostatic domains. *Progress in Earth and Planetary Science*, *6*(1). Retrieved from https://doi.org/10.1186/s40645-019-0304-z doi: 10.1186/s40645-019-0304-z

Storer, R. L., van den Heever, S. C., & L'Ecuyer, T. S. (2014, April). Observations of aerosol-induced convective invigoration in the tropical east atlantic. *Journal of Geophysical Research: Atmospheres*, *119*(7), 3963–3975. Retrieved from https://doi.org/10.1002/2013jd020272 doi: 10.1002/2013jd020272

Su, C.-Y., Chen, W.-T., Chen, J.-P., Chang, W.-Y., & Jou, B. J.-D. (2020). The impacts of cloud condensation nuclei on the extreme precipitation of a monsoon coastal mesoscale convection system. *Terrestrial, Atmospheric and Oceanic Sciences*, *31*(2), 131–139. Retrieved from https://doi.org/10.3319/tao.2019.11.29.01 doi: 10.3319/tao.2019.11.29.01

SU, C.-Y., CHEN, W.-T., WU, C.-M., & MA, H.-Y. (2022). Object-based evaluation of tropical precipitation systems in DYAMOND simulations over the maritime continent. *Journal of the Meteorological Society of Japan. Ser. II*, *100*(4), 647–659. Retrieved from https://doi.org/10.2151/jmsj.2022-033 doi: 10.2151/jmsj.2022-033

Su, C.-Y., Wu, C.-M., Chen, W.-T., & Chen, J.-H. (2021a, July). The effects of the unified parameterization in the CWBGFS: the diurnal cycle of precipitation over land in the maritime continent. *Climate Dynamics*, *58*(1-2), 223–233. Retrieved from `https://doi.org/10.1007/s00382-021-05899-2` doi: 10.1007/s00382-021-05899-2

Su, C.-Y., Wu, C.-M., Chen, W.-T., & Chen, J.-H. (2021b, October). Implementation of the unified representation of deep moist convection in the CWBGFS. *Monthly Weather Review*, *149*(10), 3525–3539. Retrieved from `https://doi.org/10.1175/mwr-d-21-0067.1` doi: 10.1175/mwr-d-21-0067.1

Tao, W.-K., Chen, J.-P., Li, Z., Wang, C., & Zhang, C. (2012, April). Impact of aerosols on convective clouds and precipitation. *Reviews of Geophysics*, *50*(2). Retrieved from `https://doi.org/10.1029/2011rg000369` doi: 10.1029/2011rg000369

Tao, W.-K., & Chern, J.-D. (2017, April). The impact of simulated mesoscale convective systems on global precipitation: A multiscale modeling study. *Journal of Advances in Modeling Earth Systems*, *9*(2), 790–809. Retrieved from `https://doi.org/10.1002/2016ms000836` doi: 10.1002/2016ms000836

Tao, W.-K., Li, X., Khain, A., Matsui, T., Lang, S., & Simpson, J. (2007, December). Role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations. *Journal of Geophysical Research*, *112*(D24). Retrieved from `https://doi.org/10.1029/2007jd008728` doi: 10.1029/2007jd008728

Tompkins, A. M. (2001, March). Organization of tropical convection in low vertical wind shears: The role of water vapor. *Journal of the Atmospheric Sciences*, *58*(6), 529–545. Retrieved from `https://doi.org/10.1175/1520-0469(2001)058<0529:ootcil>2.0.co;2` doi: 10.1175/1520-0469(2001)058⟨0529:ootcil⟩2.0.co;2

Tsai, W.-M., & Wu, C.-M. (2017, September). The environment of aggregated deep convection. *Journal of Advances in Modeling Earth Systems*, *9*(5), 2061–2078. Retrieved from `https://doi.org/10.1002/2017ms000967` doi: 10.1002/2017ms000967

van den Heever, S. C., & Cotton, W. R. (2007, June). Urban aerosol impacts on downwind convective storms. *Journal of Applied Meteorology and Climatology*, *46*(6), 828–850. Retrieved from `https://doi.org/10.1175/jam2492.1` doi: 10.1175/jam2492.1

van den Heever, S. C., Stephens, G. L., & Wood, N. B. (2011, April). Aerosol indirect effects on tropical convection characteristics under conditions of radiative–convective equilibrium. *Journal of the Atmospheric Sciences*, *68*(4), 699–718. Retrieved from `https://doi.org/10.1175/2010jas3603.1` doi: 10.1175/2010jas3603.1

Varble, A. (2018, April). Erroneous attribution of deep convective invigoration to aerosol concentration. *Journal of the Atmospheric Sciences*, *75*(4), 1351–1368. Retrieved from `https://doi.org/10.1175/jas-d-17-0217.1` doi: 10.1175/jas-d-17-0217.1

Wing, A. A., Emanuel, K., Holloway, C. E., & Muller, C. (2017, February). Convective self-aggregation in numerical simulations: A review. *Surveys in Geophysics*, *38*(6), 1173–1197. Retrieved from `https://doi.org/10.1007/s10712-017-9408-4` doi: 10.1007/s10712-017-9408-4

Wing, A. A., & Emanuel, K. A. (2014, February). Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations. *Journal of Advances in Modeling Earth Systems*, *6*(1), 59–74. Retrieved from `https://doi.org/10.1002/2013ms000269` doi: 10.1002/2013ms000269

Wing, A. A., Reed, K. A., Satoh, M., Stevens, B., Bony, S., & Ohno, T. (2018, March). Radiative–convective equilibrium model intercomparison project. *Geoscientific Model Development*, *11*(2), 793–813. Retrieved from `https://`

doi.org/10.5194/gmd-11-793-2018 doi: 10.5194/gmd-11-793-2018

Wing, A. A., Stauffer, C. L., Becker, T., Reed, K. A., Ahn, M.-S., Arnold, N. P., … Zhao, M. (2020, September). Clouds and convective self-aggregation in a multimodel ensemble of radiative-convective equilibrium simulations. *Journal of Advances in Modeling Earth Systems*, *12*(9). Retrieved from https://doi.org/10.1029/2020ms002138 doi: 10.1029/2020ms002138

Wu, C.-M., & Arakawa, A. (2014, May). A unified representation of deep moist convection in numerical modeling of the atmosphere. part II. *Journal of the Atmospheric Sciences*, *71*(6), 2089–2103. Retrieved from https://doi.org/10.1175/jas-d-13-0382.1 doi: 10.1175/jas-d-13-0382.1

Yanase, T., Nishizawa, S., Miura, H., & Tomita, H. (2022, September). Characteristic form and distance in high-level hierarchical structure of self-aggregated clouds in radiative-convective equilibrium. *Geophysical Research Letters*, *49*(18). Retrieved from https://doi.org/10.1029/2022gl100000 doi: 10.1029/2022gl100000

Yuan, J., & Houze, R. A. (2010, November). Global variability of mesoscale convective system anvil structure from a-train satellite data. *Journal of Climate*, *23*(21), 5864–5888. Retrieved from https://doi.org/10.1175/2010jcli3671.1 doi: 10.1175/2010jcli3671.1

Zhang, C. (2013, December). Madden–julian oscillation: Bridging weather and climate. *Bulletin of the American Meteorological Society*, *94*(12), 1849–1870. Retrieved from https://doi.org/10.1175/bams-d-12-00026.1 doi: 10.1175/bams-d-12-00026.1

Zhang, C., & Ling, J. (2017, May). Barrier effect of the indo-pacific maritime continent on the MJO: Perspectives from tracking MJO precipitation. *Journal of Climate*, *30*(9), 3439–3459. Retrieved from https://doi.org/10.1175/jcli-d-16-0614.1 doi: 10.1175/jcli-d-16-0614.1

Figure 1.

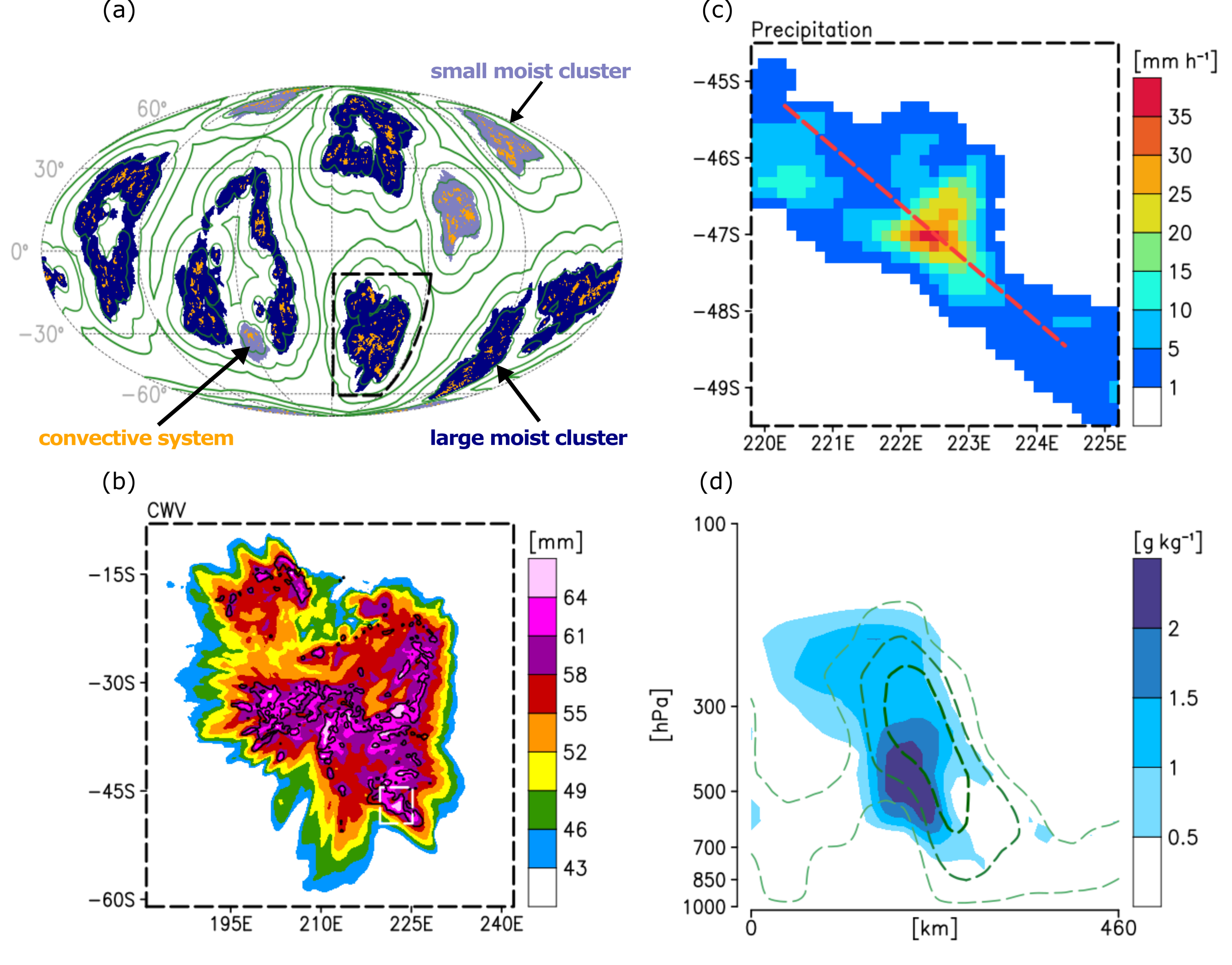
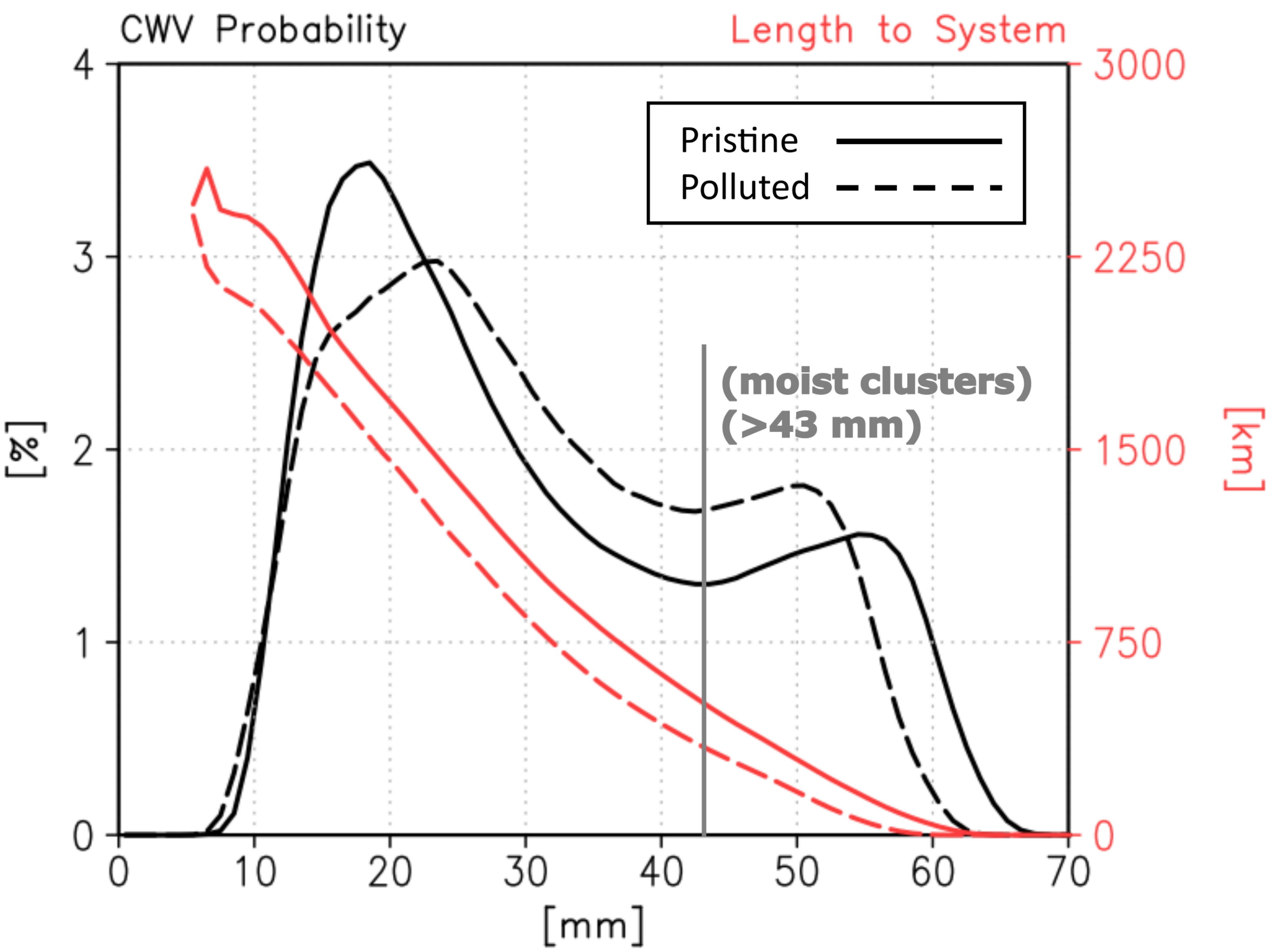
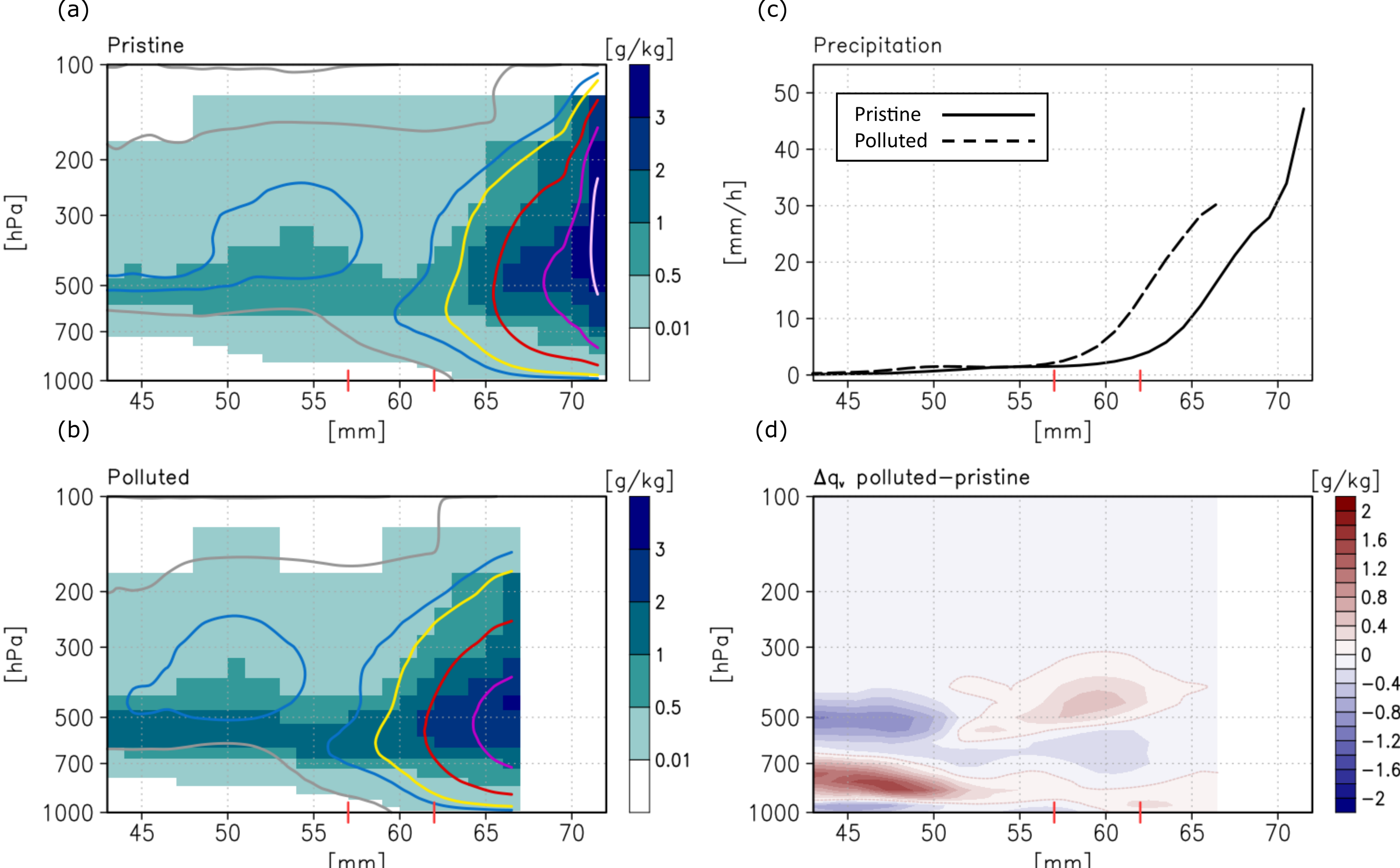

(a)
small moist cluster
60°
30°
0°
−30°
−60°
convective system
large moist cluster
(c)
Precipitation
[mm h⁻¹]
−45S
−46S
−47S
−48S
−49S
220E 221E 222E 223E 224E 225E
35 30 25 20 15 10 5 1
(b)
CWV
[mm]
−15S
−30S
−45S
−60S
195E 210E 225E 240E
64 61 58 55 52 49 46 43
(d)
[g kg⁻¹]
100 300 500 700 850 1000
[hPa]
0 [km] 460
2 1.5 1 0.5

Figure 2.



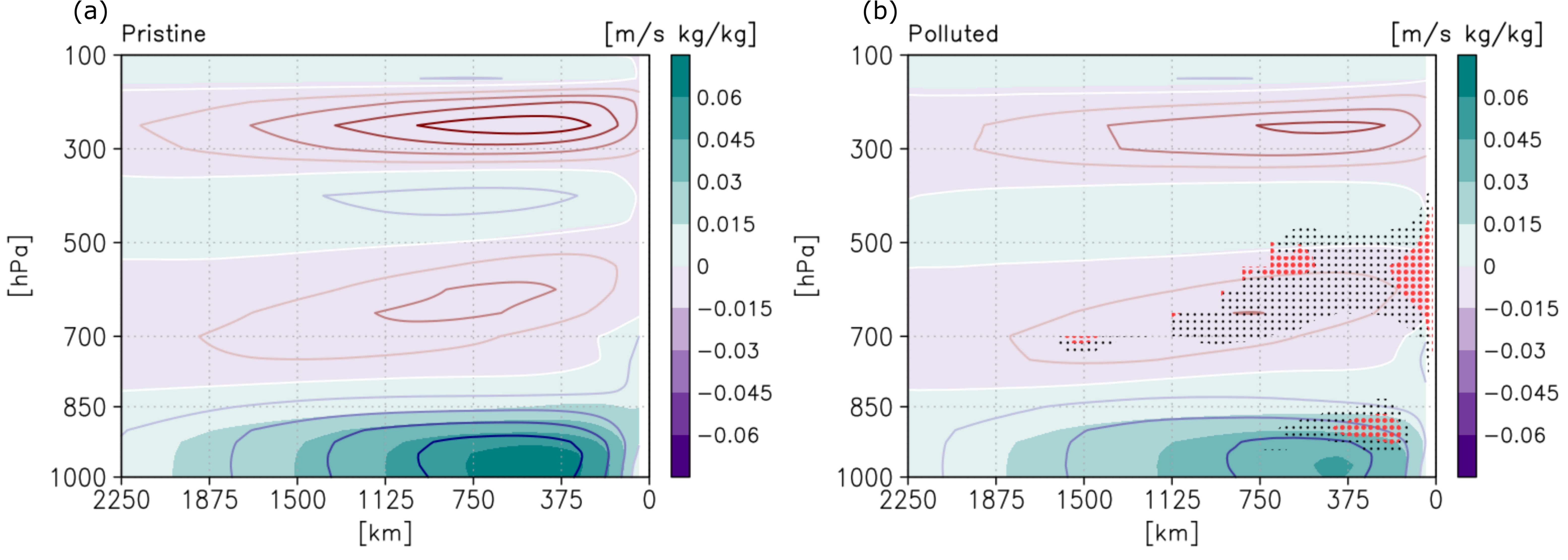
CWV Probability
Length to System
Pristine
Polluted
(moist clusters)
(>43 mm)
[%]
[km]
[mm]
0
1
2
3
4
0
750
1500
2250
3000
0
10
20
30
40
50
60
70

Figure 3.



(a)
Pristine
[g/kg]
(b)
Polluted
(c)
Precipitation
Pristine
Polluted
(d)
Δq_v polluted−pristine
[hPa]
[mm]
[mm/h]

Figure 4.


(a)
Pristine
[m/s kg/kg]
100
300
500
700
850
1000
[hPa]
2250
1875
1500
1125
750
375
0
[km]
0.06
0.045
0.03
0.015
0
−0.015
−0.03
−0.045
−0.06
(b)
Polluted
[m/s kg/kg]
100
300
500
700
850
1000
[hPa]
2250
1875
1500
1125
750
375
0
[km]
0.06
0.045
0.03
0.015
0
−0.015
−0.03
−0.045
−0.06

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

Chun-Yian Su[1,2], Chien-Ming Wu[2], Wei-Ting Chen[2], and John M. Peters[1]

[1]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA
[2]Department of Atmospheric Sciences, National Taiwan University, Taipei city, Taiwan

Key Points:

- Simulations of the global convection-permitting model provide a new perspective on aerosol indirect effects.
- Pollution facilitates the development of deep convection in a drier environment.
- The response of large-scale circulation to pollution limits the intensity of maximum precipitation.

Corresponding author: Chien-Ming Wu, `mog@as.ntu.edu.tw`

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.

Plain Language Summary

How does air pollution affect thunderstorm intensity over the tropical ocean? Past studies have proposed different opinions but generally neglect the interplay between the development of thunderstorms and the long-range movement of air that redistributes the Earth's thermal energy and moisture. Here, we address this question by investigating 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 show that tropical thunderstorms with given moisture are more vigorous under the polluted scenario. However, pollution makes the thunderstorms keep less moisture in their surroundings, limiting the maximum intensity of thunderstorms and weakening the large-scale air motion that supplies moisture to thunderstorms. Our results suggest that the interplay between the development of thunderstorms and the long-range movement of air is crucial in determining the effects of pollution in the tropical atmosphere.

1 Introduction

Deep convective clouds (DCCs) play a critical role in the global climate system via their role in the Earth's energy budget (Arakawa, 2004; Hartmann et al., 2001). They can aggregate into organized convective systems that span hundreds to a thousand kilometers (Houze, 2004) and contribute significantly to tropical rainfall (Chen et al., 2021; Houze et al., 2015; Nesbitt et al., 2006; Tao & Chern, 2017; Yuan & Houze, 2010). Observations suggest that updrafts of tropical DCCs can be invigorated by enhanced aerosol concentrations that arise from human activities and natural sources (Andreae et al., 2004; Koren et al., 2008; Niu & Li, 2012; Pan et al., 2021; Storer et al., 2014). By acting as cloud condensate nuclei (CCN) or ice nuclei (IN), aerosols change cloud properties by influencing cloud microphysics and dynamics, meanwhile influencing cloud-radiation feedbacks (i.e., aerosol indirect effects (AIEs); see reviews of Fan et al. (2016) and Tao et al. (2012)). A deeper understanding of AIEs on tropical DCCs and organized convective systems could improve the prediction of extreme precipitation events in global weather and climate models. However, the underlying mechanisms of how the updrafts are invigorated remain elusive and are often debated (Fan et al., 2018; Fan & Khain, 2021; W. W. Grabowski & Morrison, 2020, 2021; Igel & van den Heever, 2021). A particular challenge of understanding AIEs using observations is that the observed aerosol concentrations in the environments of DCCs often covary with other meteorological factors, such as convective available potential energy and vertical wind shear (W. W. Grabowski, 2018; Nishant & Sherwood, 2017; Varble, 2018), and the influences of meteorological and aerosol variability are difficult to disentangle from one another. Further, there is evidence from simulations that AIEs on DCCs vary as a function of meteorological conditions such as shear 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 surrounding environment, Abbott and Cronin (2021) carried out simulations using a small domain (128x128 km^2) three-dimension cloud-resolving model (3-D CRM) with parameterized large-scale dynamics under the weak temperature gradient (WTG) approximation (Sobel et al., 2001). Abbott and Cronin (2021) suggested that enhanced CCN concentrations produce clouds that mix more condensed water into the surrounding air. This enhances the environment favorably for subsequent convection by moistening the free troposphere and reducing the deleterious effects of entrainment. The humidity-entrainment mechanism they proposed is distinct from past work, which linked stronger updrafts with latent heat released by cloud condensation (Fan et al., 2018) or freezing (Rosenfeld et al., 2008) independently from possible changes in the environment. Anber et al. (2019) also used a small domain (192x192 km^2) 3-D CRM with parameterized large-scale dynamics to carry out simulations with different number concentrations of CCN but found a contrasting result. In their simulations, convection and mean precipitation get weaker when the CCN concentration increases. They suggested that the changes are associated with the modulation of coupling between convective processes and large-scale motions that overall reduces surface enthalpy fluxes.

Using a large domain (10000 km) two-dimension CRM configured in radiative-convective equilibrium (RCE; Manabe & Strickler, 1964), van den Heever et al. (2011) found a weak response of the large-scale organization of convection and the domain-averaged precipitation to enhanced CCN concentrations. They suggested that AIEs on the three tropical cloud modes are opposite in sign, offsetting each other, thus producing a weak domain-wide response. In contrast, a more recent study by Beydoun and Hoose (2019) that used a large channel-shaped domain (2000x120 km^2) 3-D CRM found a comparatively large decrease in domain-averaged precipitation in their RCE simulations with enhanced CCN concentrations. They suggested that enhanced CCN concentrations lead to the weakened large-scale organization of convection, increased midlevel and upper-level clouds, decreased radiative cooling, and decreased domain-averaged precipitation.

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

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.

2 Model Description and Experiment Design

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

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

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

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

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 intercomparison project (Wing et al., 2018, 2020), in which convection self-organizing into multiple moist clusters (Fig. 1a). Fig. 1b shows the spatial distribution of column water vapor (CWV) of a moist cluster, indicating high heterogeneity that is coupled to spatial convection structures. Precipitation stronger than 30 mm h^{-1} (Fig. 1c) is found in a convective system with intense resolved updrafts (>1 m s^{-1}) (Fig. 1d). Fig. 1 with more detail will be introduced in the following section.

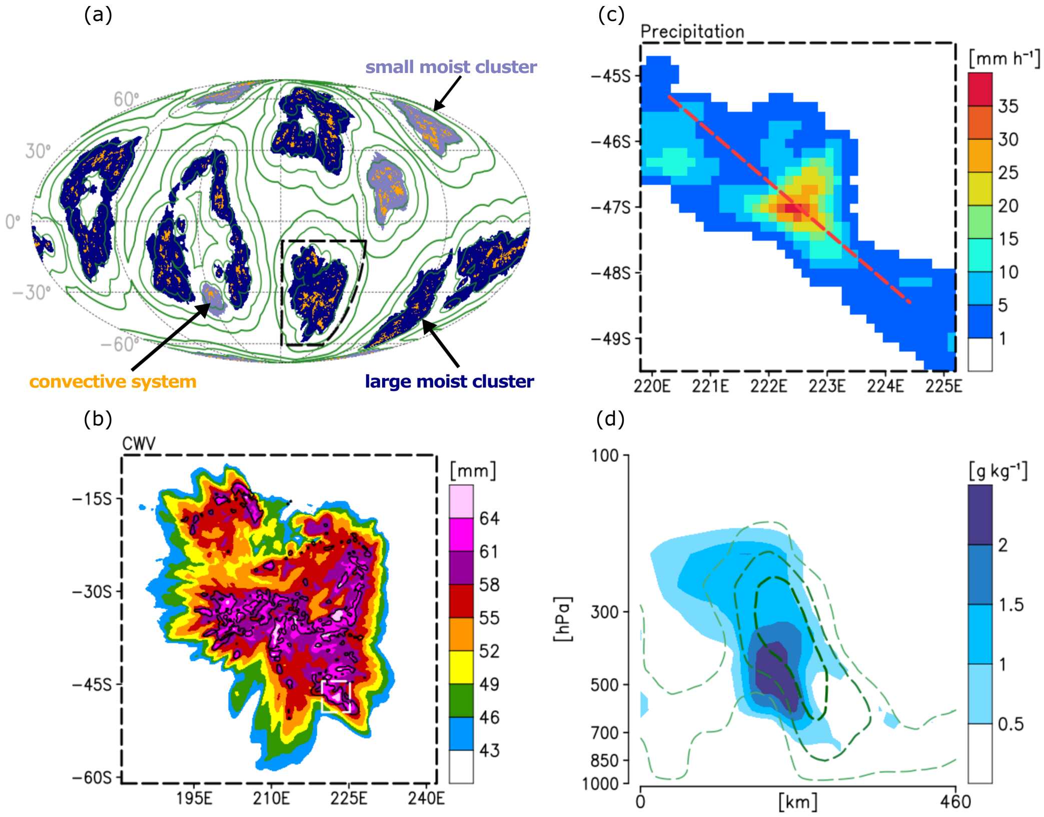


Figure 1. A snapshot of moist clusters smaller (light blue shaded) and larger (navy shaded) than 1000 km of horizontal scale, convective systems (orange shaded), and distance to the nearest convective system (green contours of 375, 1125, 1875 km) of the pristine run on day 106.5 (a). Column water vapor (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.

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 CWV value that corresponds to the smallest value along the curve in Fig. 2 between the local maxima at dry and moist CWV values as the threshold to define moist clusters (i.e., 43 mm in both runs). The difference in area coverage percentage of moist clusters in the global domain between the two runs is less than 3 %. The moist clusters in the polluted run are notably drier than that in the pristine run. Further, the number of moist clusters in the polluted run is 23 % more than that in the pristine run. Sixty-five percent of moist clusters are smaller than 1000 km of horizontal scale in the polluted run, and there are 45 % of them in the pristine run.

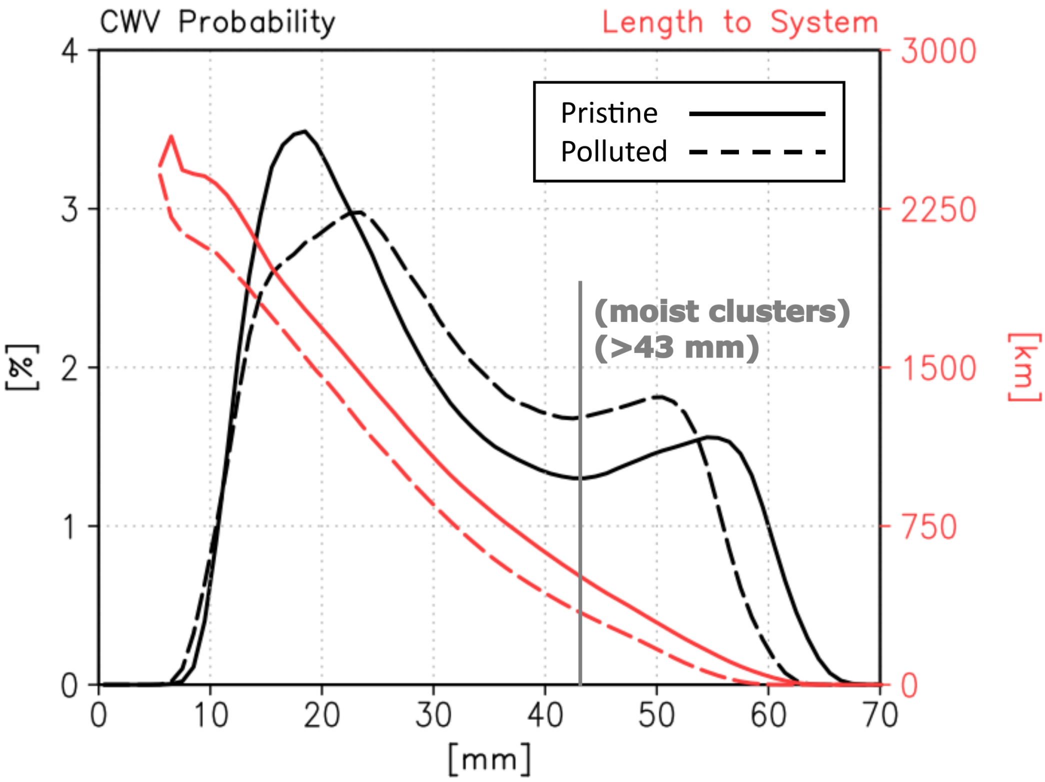


Figure 2. Probability distribution of column water vapor (black) and distance to the nearest convective system conditional sampled by column water vapor (red) from days 90 to 120. The gray line labels 43 mm of column water vapor, which is set as the criteria for defining a moist cluster.

We evaluate AIEs by first identifying the updraft regions of convective systems as laterally connected columns of vertical velocity >0.1 m s^{-1} in any level between 700 to 400 hPa (Fig. 1a-b). A critical characteristic of tropical deep moist convection is the rapid intensification of precipitation once CWV has exceeded a critical value, which characterizes the effect of water vapor on the buoyancy of clouds through entrainment (Bretherton et al., 2004; Neelin et al., 2009; Peters & Neelin, 2006). Hence, we investigate the influence of pollution on this precipitation-CWV dependency. Analyses among all updraft regions with a given CWV indicate that both of our simulations mimic the precipitation-CWV dependency seen in nature, with a rapid increase in mixed-phase cloud condensate, updraft intensity (Fig. 3a-b), and precipitation (Fig. 3c) occurring in both simulations above a certain threshold in CWV. However, a distinct difference of the polluted run from the pristine one is that the threshold CWV which heralds the increase in convective 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 resemble the convection structures of deep convection at the developing and mature stage, and the profiles to the left resemble deep convection at the dissipating stage, in which mixed-phase cloud condensates concentrate at mid-level free atmosphere beneath which weak downdrafts due to water loading take place. In the dissipating stage, moisture in the polluted run is more heavily distributed over the mid-to-low free atmosphere (Fig. 3d). The water vapor mixing ratio there is 1.5 g kg^{-1} more than that in the pristine run. The difference may be caused by the stronger evaporation of raindrops as we found there is more mass but nearly the same number of falling raindrops beneath clouds in the polluted run leading to two times stronger surface precipitation (figure not shown). These raindrops could be from the melting of graupel and hail since the warm-rain process is suppressed due to pollution.

Past studies have shown that humidity in the lower free atmosphere is critical to the onset of tropical deep convection (Derbyshire et al., 2004; Holloway & Neelin, 2009, 2010; Schiro et al., 2016; Tompkins, 2001). The enhanced moisture in the lower free atmosphere increases the buoyancy of entraining plumes, leading to an increased chance of deep convection. The signal of the exceeding moisture in the mid-to-low free atmosphere in the polluted run extends to the CWV regimes of developing and mature convection (Fig. 3d), in which the increase in moisture in the mid-to-high atmosphere reflects the prevalence of convection (Fig. 3a-b). The modulated moisture distribution, originating from the response of dissipating stage of convection to changes in cloud microphysics, enhances conditional instability, potentially contributing to the development of subsequent convection. Further investigations on the mechanism will be carried out in the future.

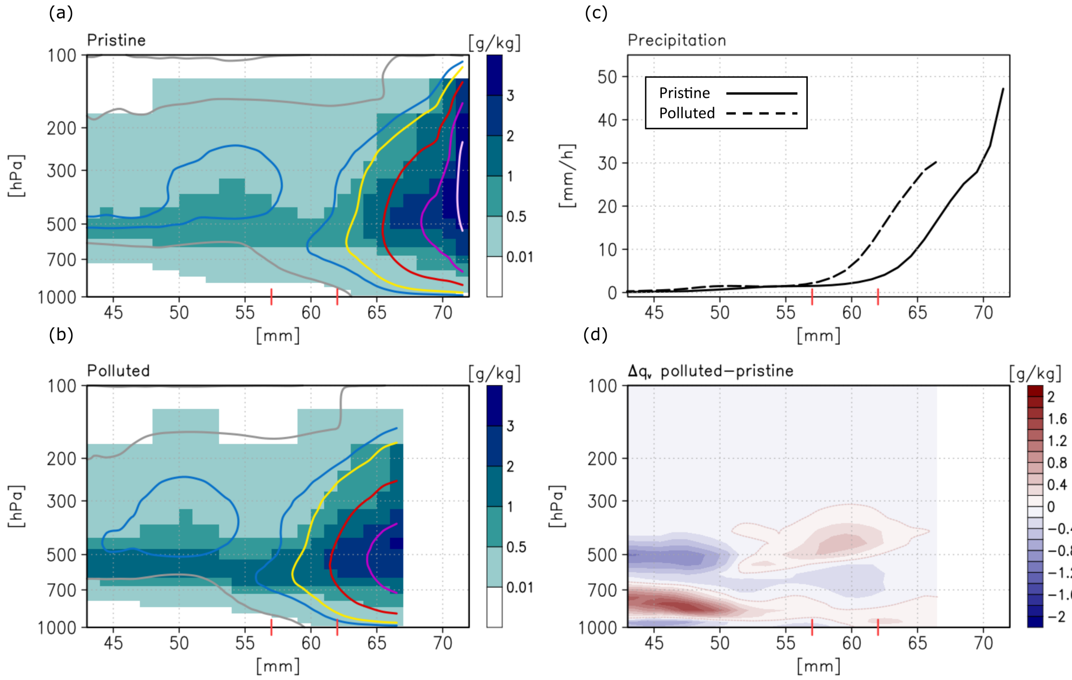


Figure 3. Mass mixing ratio of cloud water and cloud ice (shaded) and vertical velocity (contours at 0, 0.1, 0.2, 0.5, 1, 2 m s^{-1}) within the updraft regions of convective systems conditional sampled by column water vapor of the pristine (a) and the polluted (b) run from days 90 to 120. Precipitation 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 pristine run is absent in the polluted run (Fig. 3). The polluted run has notably drier moist clusters (Fig. 2), leading to the weaker maximum intensity of updraft and precipitation (30 vs. 47 mm h^{-1}). As the moisture distribution is maintained by large-scale circulation, we investigate the influence of pollution on large-scale circulation by sorting the distance to the nearest convective system and projecting horizontal winds in the direction pointing to the nearest system (green contours in Fig. 1a). Large-scale circulation has often been visualized with a streamfunction in moisture space when analyzing self-aggergated runs to RCE (Arnold & Putman, 2018; Bretherton et al., 2005; Holloway & Woolnough, 2016; C. Muller & Bony, 2015; C. J. Muller & Held, 2012). The streamfunction analyzed in past studies is designed to investigate the energy transport between dry areas and moist clusters but it does not represent circulation in physical space. It is natural to analyze large-scale circulation in physical space when using a global convection-permitting model with an appropriate choice of the source of momentum and energy transport. The result shows that both runs exhibit typical structures of tropical circulation, including low-level inflow, mid-level outflow, and deep convection outflow (Johnson et al., 1999), but every component of the circulation is weaker in the polluted run (Fig. 4).

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 from the edges of moist clusters to the nearest convective system in the pristine run is 1.5 times longer than that in the polluted run. Meanwhile, inhibiting the warm-rain process by pollution could increase the mid-level static stability as a result of a latent heating dipole associated with the freezing water and melting ice above and below the freezing level. Previous studies suggested that an increase in mid-level static stability promotes detrainment (Johnson et al., 1999; Patrizio & Randall, 2019; Posselt et al., 2008, 2012). Overall, cloud condensates in the polluted run are more likely to be exported from moist clusters to dry areas rather than stay in moist clusters and then re-evaporate. The export of clouds impedes the moisture-convection feedback in which moistening environment by convection plays a key role in favoring subsequent development of convection (W. Grabowski & Moncrieff, 2004; Holloway & Neelin, 2009). The above inference is supported by Fig. 4b, which shows that the exceeding cloud condensates in the polluted run coincide with the mid-level outflow of the large-scale circulation.

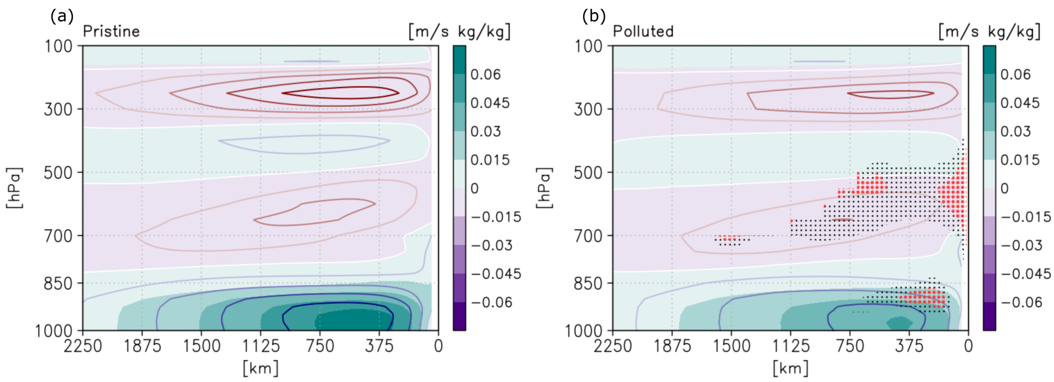


Figure 4. Water vapor flux (shaded) and horizontal winds (contours from -4 to 4 m s^{-1} with an interval of 1 m s^{-1} using a color scale from maroon to white to navy) projected to the direction of pointing to the nearest convective system in the pristine (a) and the polluted (b) run from days 90 to 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

4 Summary and Discussion

This study investigates the response of tropical convection-circulation interaction to enhanced CCN concentrations using non-rotating RCE simulations of a global convection-permitting model run at 15 km horizontal resolution. Deep convection in the model is represented in a way that the explicit simulation of convection seeds cloud-aerosol interaction and is responsible for strong precipitation events. The simulations allow for the large-scale organization of convection realistically inducing circulation without artificial constraints of scale separation assumption, domain size, or domain shape. The novel finding in this study is that pollution facilitates the development of deep convection in a drier environment, while the response of large-scale circulation limits the intensity of maximum precipitation. 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.

Connecting our result to the existing driving and maintaining mechanisms of CSA 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:

1. 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).
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 that the large-scale organization of convection (i.e., CSA) in non-rotating RCE simulations and MJO-like (i.e., Madden-Julian Oscillation; Madden & Julian, 1971) disturbance in rotating RCE simulations share the same driving mechanism (i.e., cloud-radiation feedbacks) in which AIEs can be critical. One of the characteristics of MJO propagation is that MJOs suffer from a barrier effect when it propagates over the Maritime Continent (MC) (Kim et al., 2014; Zhang & Ling, 2017). The development of convective systems over the water in the MC region plays a crucial role in carrying the MJO signal through the MC (Ling et al., 2019). Around the globe, MC is a major source of different types of aerosol (Reid et al., 2012; Salinas et al., 2013; Shpund et al., 2019). The modulation of the size of moist clusters and the geographical distribution of convective systems by enhanced CCN concentrations potentially provides a new perspective on the existing MJO theories (Jiang et al., 2020; Zhang, 2013). A possible approach for the investigation is to evaluate sub-seasonal hindcasts of an active MJO event with different aerosol emission scenarios.

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.

Acknowledgments

Chien-Ming Wu and Chun-Yian Su's efforts were supported by National Science and Technology Council (NSTC) in Taiwan grant 111-2111-M-002-012-NSTC. Wei-Ting Chen was supported by Ministry of Science and Technology (MOST) in Taiwan grant 109-2628-M-002-003-MY3. J. Peters was supported by National Science Foundation (NSF) grants AGS-1928666, AGS-1841674, and the Department of Energy Atmospheric System Research (DOE ASR) grant DE-SC0000246356. We thank Dr. Jen-Her Chen in Central Weather Bureau for his support of this work.

References

Abbott, T. H., & Cronin, T. W. (2021, January). Aerosol invigoration of atmospheric convection through increases in humidity. *Science*, *371*(6524), 83–85. Retrieved from `https://doi.org/10.1126/science.abc5181` doi: 10.1126/science.abc5181

Anber, U. M., Wang, S., Gentine, P., & Jensen, M. P. (2019, September). Probing the response of tropical deep convection to aerosol perturbations using idealized cloud-resolving simulations with parameterized large-scale dynamics. *Journal of the Atmospheric Sciences*, *76*(9), 2885–2897. Retrieved from https://doi.org/10.1175/jas-d-18-0351.1 doi: 10.1175/jas-d-18-0351.1

Andreae, M. O. (2009, January). Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions. *Atmospheric Chemistry and Physics*, *9*(2), 543–556. Retrieved from https://doi.org/10.5194/acp-9-543-2009 doi: 10.5194/acp-9-543-2009

Andreae, M. O., Rosenfeld, D., Artaxo, P., Costa, A. A., Frank, G. P., Longo, K. M., & Silva-Dias, M. A. F. (2004, February). Smoking rain clouds over the amazon. *Science*, *303*(5662), 1337–1342. Retrieved from https://doi.org/10.1126/science.1092779 doi: 10.1126/science.1092779

Arakawa, A. (2004, July). The cumulus parameterization problem: Past, present, and future. *Journal of Climate*, *17*(13), 2493–2525. Retrieved from https://doi.org/10.1175/1520-0442(2004)017<2493:ratcpp>2.0.co;2 doi: 10.1175/1520-0442(2004)017⟨2493:ratcpp⟩2.0.co;2

Arakawa, A., & Wu, C.-M. (2013, July). A unified representation of deep moist convection in numerical modeling of the atmosphere. part i. *Journal of the Atmospheric Sciences*, *70*(7), 1977–1992. Retrieved from https://doi.org/10.1175/jas-d-12-0330.1 doi: 10.1175/jas-d-12-0330.1

Arnold, N. P., & Putman, W. M. (2018, April). Nonrotating convective self-aggregation in a limited area AGCM. *Journal of Advances in Modeling Earth Systems*, *10*(4), 1029–1046. Retrieved from https://doi.org/10.1002/2017ms001218 doi: 10.1002/2017ms001218

Arnold, N. P., & Randall, D. A. (2015, October). Global-scale convective aggregation: Implications for the madden-julian oscillation. *Journal of Advances in Modeling Earth Systems*, *7*(4), 1499–1518. Retrieved from https://doi.org/10.1002/2015ms000498 doi: 10.1002/2015ms000498

Beydoun, H., & Hoose, C. (2019, April). Aerosol-cloud-precipitation interactions in the context of convective self-aggregation. *Journal of Advances in Modeling Earth Systems*, *11*(4), 1066–1087. Retrieved from https://doi.org/10.1029/2018ms001523 doi: 10.1029/2018ms001523

Bretherton, C. S., Blossey, P. N., & Khairoutdinov, M. (2005, December). An energy-balance analysis of deep convective self-aggregation above uniform SST. *Journal of the Atmospheric Sciences*, *62*(12), 4273–4292. Retrieved from https://doi.org/10.1175/jas3614.1 doi: 10.1175/jas3614.1

Bretherton, C. S., Peters, M. E., & Back, L. E. (2004, April). Relationships between water vapor path and precipitation over the tropical oceans. *Journal of Climate*, *17*(7), 1517–1528. Retrieved from https://doi.org/10.1175/1520-0442(2004)017<1517:rbwvpa>2.0.co;2 doi: 10.1175/1520-0442(2004)017⟨1517:rbwvpa⟩2.0.co;2

Chang, Y.-H., Chen, W.-T., Wu, C.-M., Moseley, C., & Wu, C.-C. (2021, November). Tracking the influence of cloud condensation nuclei on summer diurnal precipitating systems over complex topography in taiwan. *Atmospheric Chemistry and Physics*, *21*(22), 16709–16725. Retrieved from https://doi.org/10.5194/acp-21-16709-2021 doi: 10.5194/acp-21-16709-2021

Chen, P.-J., Chen, W.-T., Wu, C.-M., & Yo, T.-S. (2021, May). Convective cloud regimes from a classification of object-based CloudSat observations over asian-australian monsoon areas. *Geophysical Research Letters*, *48*(10). Retrieved from https://doi.org/10.1029/2021gl092733 doi: 10.1029/2021gl092733

Coppin, D., & Bony, S. (2015, December). Physical mechanisms controlling the initiation of convective self-aggregation in a general circulation model. *Journal of Advances in Modeling Earth Systems*, *7*(4), 2060–2078. Retrieved from https://doi.org/10.1002/2015ms000571 doi: 10.1002/2015ms000571

Cronin, T. W., & Wing, A. A. (2017, December). Clouds, circulation, and climate sensitivity in a radiative-convective equilibrium channel model. *Journal of Ad-*

vances in Modeling Earth Systems, *9*(8), 2883–2905. Retrieved from https://doi.org/10.1002/2017ms001111 doi: 10.1002/2017ms001111

Derbyshire, S., Beau, I., Bechtold, P., Grandpeix, J.-Y., Piriou, J.-M., Redelsperger, J.-L., & Soares, P. (2004, October). Sensitivity of moist convection to environmental humidity. *Quarterly Journal of the Royal Meteorological Society*, *130*(604), 3055–3079. Retrieved from https://doi.org/10.1256/qj.03.130 doi: 10.1256/qj.03.130

Dunion, J. P. (2011, February). Rewriting the climatology of the tropical north atlantic and caribbean sea atmosphere. *Journal of Climate*, *24*(3), 893–908. Retrieved from https://doi.org/10.1175/2010jcli3496.1 doi: 10.1175/2010jcli3496.1

Emanuel, K., Wing, A. A., & Vincent, E. M. (2014, February). Radiative-convective instability. *Journal of Advances in Modeling Earth Systems*, *6*(1), 75–90. Retrieved from https://doi.org/10.1002/2013ms000270 doi: 10.1002/2013ms000270

Fan, J., & Khain, A. (2021, January). Comments on "do ultrafine cloud condensation nuclei invigorate deep convection?". *Journal of the Atmospheric Sciences*, *78*(1), 329–339. Retrieved from https://doi.org/10.1175/jas-d-20-0218.1 doi: 10.1175/jas-d-20-0218.1

Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A. T., … de Souza, R. A. F. (2018, January). Substantial convection and precipitation enhancements by ultrafineaerosol particles. *Science*, *359*(6374), 411–418. Retrieved from https://doi.org/10.1126/science.aan8461 doi: 10.1126/science.aan8461

Fan, J., Wang, Y., Rosenfeld, D., & Liu, X. (2016, October). Review of aerosol–cloud interactions: Mechanisms, significance, and challenges. *Journal of the Atmospheric Sciences*, *73*(11), 4221–4252. Retrieved from https://doi.org/10.1175/jas-d-16-0037.1 doi: 10.1175/jas-d-16-0037.1

Fan, J., Yuan, T., Comstock, J. M., Ghan, S., Khain, A., Leung, L. R., … Ovchinnikov, M. (2009, November). Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. *Journal of Geophysical Research*, *114*(D22). Retrieved from https://doi.org/10.1029/2009jd012352 doi: 10.1029/2009jd012352

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., … Zhang, H. (2021). The earth's energy budget, climate feedbacks, and climate sensitivity [Book Section]. In V. Masson-Delmotte et al. (Eds.), *Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change* (p. 923–1054). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi: 10.1017/9781009157896.009

Grabowski, W., & Moncrieff, M. (2004, October). Moisture–convection feedback in the tropics. *Quarterly Journal of the Royal Meteorological Society*, *130*(604), 3081–3104. Retrieved from https://doi.org/10.1256/qj.03.135 doi: 10.1256/qj.03.135

Grabowski, W. W. (2018, October). Can the impact of aerosols on deep convection be isolated from meteorological effects in atmospheric observations? *Journal of the Atmospheric Sciences*, *75*(10), 3347–3363. Retrieved from https://doi.org/10.1175/jas-d-18-0105.1 doi: 10.1175/jas-d-18-0105.1

Grabowski, W. W., & Morrison, H. (2020, July). Do ultrafine cloud condensation nuclei invigorate deep convection? *Journal of the Atmospheric Sciences*, *77*(7), 2567–2583. Retrieved from https://doi.org/10.1175/jas-d-20-0012.1 doi: 10.1175/jas-d-20-0012.1

Grabowski, W. W., & Morrison, H. (2021, January). Reply to "comments on 'do ultrafine cloud condensation nuclei invigorate deep convection?'". *Journal of the Atmospheric Sciences*, *78*(1), 341–350. Retrieved from https://doi.org/10

.1175/jas-d-20-0315.1 doi: 10.1175/jas-d-20-0315.1

Hamada, A., Murayama, Y., & Takayabu, Y. N. (2014, October). Regional characteristics of extreme rainfall extracted from TRMM PR measurements. *Journal of Climate*, *27*(21), 8151–8169. Retrieved from https://doi.org/10.1175/jcli-d-14-00107.1 doi: 10.1175/jcli-d-14-00107.1

Hartmann, D. L., Moy, L. A., & Fu, Q. (2001, December). Tropical convection and the energy balance at the top of the atmosphere. *Journal of Climate*, *14*(24), 4495–4511. Retrieved from https://doi.org/10.1175/1520-0442(2001)014<4495:tcateb>2.0.co;2 doi: 10.1175/1520-0442(2001)014⟨4495:tcateb⟩2.0.co;2

Holloway, C. E., & Neelin, J. D. (2009, June). Moisture vertical structure, column water vapor, and tropical deep convection. *Journal of the Atmospheric Sciences*, *66*(6), 1665–1683. Retrieved from https://doi.org/10.1175/2008jas2806.1 doi: 10.1175/2008jas2806.1

Holloway, C. E., & Neelin, J. D. (2010, April). Temporal relations of column water vapor and tropical precipitation. *Journal of the Atmospheric Sciences*, *67*(4), 1091–1105. Retrieved from https://doi.org/10.1175/2009jas3284.1 doi: 10.1175/2009jas3284.1

Holloway, C. E., & Woolnough, S. J. (2016, February). The sensitivity of convective aggregation to diabatic processes in idealized radiative-convective equilibrium simulations. *Journal of Advances in Modeling Earth Systems*, *8*(1), 166–195. Retrieved from https://doi.org/10.1002/2015ms000511 doi: 10.1002/2015ms000511

Houze, R. A. (2004, December). Mesoscale convective systems. *Reviews of Geophysics*, *42*(4). Retrieved from https://doi.org/10.1029/2004rg000150 doi: 10.1029/2004rg000150

Houze, R. A., Rasmussen, K. L., Zuluaga, M. D., & Brodzik, S. R. (2015, September). The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the tropical rainfall measuring mission satellite. *Reviews of Geophysics*, *53*(3), 994–1021. Retrieved from https://doi.org/10.1002/2015rg000488 doi: 10.1002/2015rg000488

Igel, A. L., & van den Heever, S. C. (2021, August). Invigoration or enervation of convective clouds by aerosols? *Geophysical Research Letters*, *48*(16). Retrieved from https://doi.org/10.1029/2021gl093804 doi: 10.1029/2021gl093804

Jeevanjee, N., & Romps, D. M. (2013, March). Convective self-aggregation, cold pools, and domain size. *Geophysical Research Letters*, *40*(5), 994–998. Retrieved from https://doi.org/10.1002/grl.50204 doi: 10.1002/grl.50204

Jiang, X., Adames, Á. F., Kim, D., Maloney, E. D., Lin, H., Kim, H., … Klingaman, N. P. (2020, August). Fifty years of research on the madden-julian oscillation: Recent progress, challenges, and perspectives. *Journal of Geophysical Research: Atmospheres*, *125*(17). Retrieved from https://doi.org/10.1029/2019jd030911 doi: 10.1029/2019jd030911

Johnson, R. H., Rickenbach, T. M., Rutledge, S. A., Ciesielski, P. E., & Schubert, W. H. (1999, August). Trimodal characteristics of tropical convection. *Journal of Climate*, *12*(8), 2397–2418. Retrieved from https://doi.org/10.1175/1520-0442(1999)012<2397:tcotc>2.0.co;2 doi: 10.1175/1520-0442(1999)012⟨2397:tcotc⟩2.0.co;2

Khain, A. P., BenMoshe, N., & Pokrovsky, A. (2008, June). Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification. *Journal of the Atmospheric Sciences*, *65*(6), 1721–1748. Retrieved from https://doi.org/10.1175/2007jas2515.1 doi: 10.1175/2007jas2515.1

Khairoutdinov, M. F., & Emanuel, K. (2018, December). Intraseasonal variability in a cloud-permitting near-global equatorial aquaplanet model. *Journal of the Atmospheric Sciences*, *75*(12), 4337–4355. Retrieved from https://doi.org/10.1175/jas-d-18-0152.1 doi: 10.1175/jas-d-18-0152.1

Kim, D., Kug, J.-S., & Sobel, A. H. (2014, January). Propagating versus non-propagating madden–julian oscillation events. *Journal of Climate*, *27*(1), 111–125. Retrieved from https://doi.org/10.1175/jcli-d-13-00084.1 doi: 10.1175/jcli-d-13-00084.1

Koren, I., Feingold, G., & Remer, L. A. (2010, September). The invigoration of deep convective clouds over the atlantic: aerosol effect, meteorology or retrieval artifact? *Atmospheric Chemistry and Physics*, *10*(18), 8855–8872. Retrieved from https://doi.org/10.5194/acp-10-8855-2010 doi: 10.5194/acp-10-8855-2010

Koren, I., Martins, J. V., Remer, L. A., & Afargan, H. (2008, August). Smoke invigoration versus inhibition of clouds over the amazon. *Science*, *321*(5891), 946–949. Retrieved from https://doi.org/10.1126/science.1159185 doi: 10.1126/science.1159185

Lebo, Z. (2018, February). A numerical investigation of the potential effects of aerosol-induced warming and updraft width and slope on updraft intensity in deep convective clouds. *Journal of the Atmospheric Sciences*, *75*(2), 535–554. Retrieved from https://doi.org/10.1175/jas-d-16-0368.1 doi: 10.1175/jas-d-16-0368.1

Lebo, Z. J., & Morrison, H. (2014, March). Dynamical effects of aerosol perturbations on simulated idealized squall lines. *Monthly Weather Review*, *142*(3), 991–1009. Retrieved from https://doi.org/10.1175/mwr-d-13-00156.1 doi: 10.1175/mwr-d-13-00156.1

Ling, J., Zhang, C., Joyce, R., ping Xie, P., & Chen, G. (2019, March). Possible role of the diurnal cycle in land convection in the barrier effect on the MJO by the maritime continent. *Geophysical Research Letters*, *46*(5), 3001–3011. Retrieved from https://doi.org/10.1029/2019gl081962 doi: 10.1029/2019gl081962

Madden, R. A., & Julian, P. R. (1971, July). Detection of a 40–50 day oscillation in the zonal wind in the tropical pacific. *Journal of the Atmospheric Sciences*, *28*(5), 702–708. Retrieved from https://doi.org/10.1175/1520-0469(1971)028<0702:doadoi>2.0.co;2 doi: 10.1175/1520-0469(1971)028⟨0702:doadoi⟩2.0.co;2

Manabe, S., & Strickler, R. F. (1964, July). Thermal equilibrium of the atmosphere with a convective adjustment. *Journal of the Atmospheric Sciences*, *21*(4), 361–385. Retrieved from https://doi.org/10.1175/1520-0469(1964)021<0361:teotaw>2.0.co;2 doi: 10.1175/1520-0469(1964)021⟨0361:teotaw⟩2.0.co;2

Matsugishi, S., & Satoh, M. (2022, May). Sensitivity of the horizontal scale of convective self-aggregation to sea surface temperature in radiative convective equilibrium experiments using a global nonhydrostatic model. *Journal of Advances in Modeling Earth Systems*, *14*(5). Retrieved from https://doi.org/10.1029/2021ms002636 doi: 10.1029/2021ms002636

Morrison, H., & Milbrandt, J. A. (2015, January). Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. part i: Scheme description and idealized tests. *Journal of the Atmospheric Sciences*, *72*(1), 287–311. Retrieved from https://doi.org/10.1175/jas-d-14-0065.1 doi: 10.1175/jas-d-14-0065.1

Muller, C., & Bony, S. (2015, July). What favors convective aggregation and why? *Geophysical Research Letters*, *42*(13), 5626–5634. Retrieved from https://doi.org/10.1002/2015gl064260 doi: 10.1002/2015gl064260

Muller, C., Yang, D., Craig, G., Cronin, T., Fildier, B., Haerter, J. O., ... Sherwood, S. C. (2022, January). Spontaneous aggregation of convective storms. *Annual Review of Fluid Mechanics*, *54*(1), 133–157. Retrieved from https://doi.org/10.1146/annurev-fluid-022421-011319 doi: 10.1146/annurev-fluid-022421-011319

Muller, C. J., & Held, I. M. (2012, August). Detailed investigation of the self-aggregation of convection in cloud-resolving simulations. *Journal of the Atmospheric Sciences*, *69*(8), 2551–2565. Retrieved from https://doi.org/10.1175/jas-d-11-0257.1 doi: 10.1175/jas-d-11-0257.1

Neelin, J. D., Peters, O., & Hales, K. (2009, August). The transition to strong convection. *Journal of the Atmospheric Sciences*, *66*(8), 2367–2384. Retrieved from https://doi.org/10.1175/2009jas2962.1 doi: 10.1175/2009jas2962.1

Nesbitt, S. W., Cifelli, R., & Rutledge, S. A. (2006, October). Storm morphology and rainfall characteristics of TRMM precipitation features. *Monthly Weather Review*, *134*(10), 2702–2721. Retrieved from https://doi.org/10.1175/mwr3200.1 doi: 10.1175/mwr3200.1

Nishant, N., & Sherwood, S. C. (2017, June). A cloud-resolving model study of aerosol-cloud correlation in a pristine maritime environment. *Geophysical Research Letters*, *44*(11), 5774–5781. Retrieved from https://doi.org/10.1002/2017gl073267 doi: 10.1002/2017gl073267

Niu, F., & Li, Z. (2012, September). Systematic variations of cloud top temperature and precipitation rate with aerosols over the global tropics. *Atmospheric Chemistry and Physics*, *12*(18), 8491–8498. Retrieved from https://doi.org/10.5194/acp-12-8491-2012 doi: 10.5194/acp-12-8491-2012

Pan, Z., Rosenfeld, D., Zhu, Y., Mao, F., Gong, W., Zang, L., & Lu, X. (2021, May). Observational quantification of aerosol invigoration for deep convective cloud lifecycle properties based on geostationary satellite. *Journal of Geophysical Research: Atmospheres*, *126*(9). Retrieved from https://doi.org/10.1029/2020jd034275 doi: 10.1029/2020jd034275

Patrizio, C. R., & Randall, D. A. (2019, July). Sensitivity of convective self-aggregation to domain size. *Journal of Advances in Modeling Earth Systems*, *11*(7), 1995–2019. Retrieved from https://doi.org/10.1029/2019ms001672 doi: 10.1029/2019ms001672

Pendergrass, A. G., Reed, K. A., & Medeiros, B. (2016, November). The link between extreme precipitation and convective organization in a warming climate: Global radiative-convective equilibrium simulations. *Geophysical Research Letters*, *43*(21). Retrieved from https://doi.org/10.1002/2016gl071285 doi: 10.1002/2016gl071285

Peters, O., & Neelin, J. D. (2006, May). Critical phenomena in atmospheric precipitation. *Nature Physics*, *2*(6), 393–396. Retrieved from https://doi.org/10.1038/nphys314 doi: 10.1038/nphys314

Popke, D., Stevens, B., & Voigt, A. (2013, January). Climate and climate change in a radiative-convective equilibrium version of ECHAM6. *Journal of Advances in Modeling Earth Systems*, *5*(1), 1–14. Retrieved from https://doi.org/10.1029/2012ms000191 doi: 10.1029/2012ms000191

Posselt, D. J., van den Heever, S., Stephens, G., & Igel, M. R. (2012, January). Changes in the interaction between tropical convection, radiation, and the large-scale circulation in a warming environment. *Journal of Climate*, *25*(2), 557–571. Retrieved from https://doi.org/10.1175/2011jcli4167.1 doi: 10.1175/2011jcli4167.1

Posselt, D. J., van den Heever, S. C., & Stephens, G. L. (2008, April). Trimodal cloudiness and tropical stable layers in simulations of radiative convective equilibrium. *Geophysical Research Letters*, *35*(8). Retrieved from https://doi.org/10.1029/2007gl033029 doi: 10.1029/2007gl033029

Reid, J. S., Xian, P., Hyer, E. J., Flatau, M. K., Ramirez, E. M., Turk, F. J., ... Maloney, E. D. (2012, February). Multi-scale meteorological conceptual analysis of observed active fire hotspot activity and smoke optical depth in the maritime continent. *Atmospheric Chemistry and Physics*, *12*(4), 2117–2147. Retrieved from https://doi.org/10.5194/acp-12-2117-2012 doi: 10.5194/acp-12-2117-2012

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., … Andreae, M. O. (2008, September). Flood or drought: How do aerosols affect precipitation? *Science*, *321*(5894), 1309–1313. Retrieved from `https://doi.org/10.1126/science.1160606` doi: 10.1126/science.1160606

Salinas, S. V., Chew, B. N., Miettinen, J., Campbell, J. R., Welton, E. J., Reid, J. S., … Liew, S. C. (2013, March). Physical and optical characteristics of the october 2010 haze event over singapore: A photometric and lidar analysis. *Atmospheric Research*, *122*, 555–570. Retrieved from `https://doi.org/10.1016/j.atmosres.2012.05.021` doi: 10.1016/j.atmosres.2012.05.021

Schiro, K. A., Neelin, J. D., Adams, D. K., & Lintner, B. R. (2016, September). Deep convection and column water vapor over tropical land versus tropical ocean: A comparison between the amazon and the tropical western pacific. *Journal of the Atmospheric Sciences*, *73*(10), 4043–4063. Retrieved from `https://doi.org/10.1175/jas-d-16-0119.1` doi: 10.1175/jas-d-16-0119.1

Seigel, R. B., van den Heever, S. C., & Saleeby, S. M. (2013, April). Mineral dust indirect effects and cloud radiative feedbacks of a simulated idealized nocturnal squall line. *Atmospheric Chemistry and Physics*, *13*(8), 4467–4485. Retrieved from `https://doi.org/10.5194/acp-13-4467-2013` doi: 10.5194/acp-13-4467-2013

Shpund, J., Khain, A., & Rosenfeld, D. (2019, August). Effects of sea spray on microphysics and intensity of deep convective clouds under strong winds. *Journal of Geophysical Research: Atmospheres*, *124*(16), 9484–9509. Retrieved from `https://doi.org/10.1029/2018jd029893` doi: 10.1029/2018jd029893

Singh, M. S., & O'Gorman, P. A. (2013, August). Influence of entrainment on the thermal stratification in simulations of radiative-convective equilibrium. *Geophysical Research Letters*, *40*(16), 4398–4403. Retrieved from `https://doi.org/10.1002/grl.50796` doi: 10.1002/grl.50796

Singh, M. S., & O'Gorman, P. A. (2015, June). Increases in moist-convective updraught velocities with warming in radiative-convective equilibrium. *Quarterly Journal of the Royal Meteorological Society*, *141*(692), 2828–2838. Retrieved from `https://doi.org/10.1002/qj.2567` doi: 10.1002/qj.2567

Sobel, A. H., Nilsson, J., & Polvani, L. M. (2001, December). The weak temperature gradient approximation and balanced tropical moisture waves. *Journal of the Atmospheric Sciences*, *58*(23), 3650–3665. Retrieved from `https://doi.org/10.1175/1520-0469(2001)058<3650:twtgaa>2.0.co;2` doi: 10.1175/1520-0469(2001)058⟨3650:twtgaa⟩2.0.co;2

Stevens, B., Satoh, M., Auger, L., Biercamp, J., Bretherton, C. S., Chen, X., … Zhou, L. (2019, September). DYAMOND: the DYnamics of the atmospheric general circulation modeled on non-hydrostatic domains. *Progress in Earth and Planetary Science*, *6*(1). Retrieved from `https://doi.org/10.1186/s40645-019-0304-z` doi: 10.1186/s40645-019-0304-z

Storer, R. L., van den Heever, S. C., & L'Ecuyer, T. S. (2014, April). Observations of aerosol-induced convective invigoration in the tropical east atlantic. *Journal of Geophysical Research: Atmospheres*, *119*(7), 3963–3975. Retrieved from `https://doi.org/10.1002/2013jd020272` doi: 10.1002/2013jd020272

Su, C.-Y., Chen, W.-T., Chen, J.-P., Chang, W.-Y., & Jou, B. J.-D. (2020). The impacts of cloud condensation nuclei on the extreme precipitation of a monsoon coastal mesoscale convection system. *Terrestrial, Atmospheric and Oceanic Sciences*, *31*(2), 131–139. Retrieved from `https://doi.org/10.3319/tao.2019.11.29.01` doi: 10.3319/tao.2019.11.29.01

SU, C.-Y., CHEN, W.-T., WU, C.-M., & MA, H.-Y. (2022). Object-based evaluation of tropical precipitation systems in DYAMOND simulations over the maritime continent. *Journal of the Meteorological Society of Japan. Ser. II*, *100*(4), 647–659. Retrieved from `https://doi.org/10.2151/jmsj.2022-033` doi: 10.2151/jmsj.2022-033

Su, C.-Y., Wu, C.-M., Chen, W.-T., & Chen, J.-H. (2021a, July). The effects of the unified parameterization in the CWBGFS: the diurnal cycle of precipitation over land in the maritime continent. *Climate Dynamics*, *58*(1-2), 223–233. Retrieved from `https://doi.org/10.1007/s00382-021-05899-2` doi: 10.1007/s00382-021-05899-2

Su, C.-Y., Wu, C.-M., Chen, W.-T., & Chen, J.-H. (2021b, October). Implementation of the unified representation of deep moist convection in the CWBGFS. *Monthly Weather Review*, *149*(10), 3525–3539. Retrieved from `https://doi.org/10.1175/mwr-d-21-0067.1` doi: 10.1175/mwr-d-21-0067.1

Tao, W.-K., Chen, J.-P., Li, Z., Wang, C., & Zhang, C. (2012, April). Impact of aerosols on convective clouds and precipitation. *Reviews of Geophysics*, *50*(2). Retrieved from `https://doi.org/10.1029/2011rg000369` doi: 10.1029/2011rg000369

Tao, W.-K., & Chern, J.-D. (2017, April). The impact of simulated mesoscale convective systems on global precipitation: A multiscale modeling study. *Journal of Advances in Modeling Earth Systems*, *9*(2), 790–809. Retrieved from `https://doi.org/10.1002/2016ms000836` doi: 10.1002/2016ms000836

Tao, W.-K., Li, X., Khain, A., Matsui, T., Lang, S., & Simpson, J. (2007, December). Role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations. *Journal of Geophysical Research*, *112*(D24). Retrieved from `https://doi.org/10.1029/2007jd008728` doi: 10.1029/2007jd008728

Tompkins, A. M. (2001, March). Organization of tropical convection in low vertical wind shears: The role of water vapor. *Journal of the Atmospheric Sciences*, *58*(6), 529–545. Retrieved from `https://doi.org/10.1175/1520-0469(2001)058<0529:ootcil>2.0.co;2` doi: 10.1175/1520-0469(2001)058⟨0529:ootcil⟩2.0.co;2

Tsai, W.-M., & Wu, C.-M. (2017, September). The environment of aggregated deep convection. *Journal of Advances in Modeling Earth Systems*, *9*(5), 2061–2078. Retrieved from `https://doi.org/10.1002/2017ms000967` doi: 10.1002/2017ms000967

van den Heever, S. C., & Cotton, W. R. (2007, June). Urban aerosol impacts on downwind convective storms. *Journal of Applied Meteorology and Climatology*, *46*(6), 828–850. Retrieved from `https://doi.org/10.1175/jam2492.1` doi: 10.1175/jam2492.1

van den Heever, S. C., Stephens, G. L., & Wood, N. B. (2011, April). Aerosol indirect effects on tropical convection characteristics under conditions of radiative–convective equilibrium. *Journal of the Atmospheric Sciences*, *68*(4), 699–718. Retrieved from `https://doi.org/10.1175/2010jas3603.1` doi: 10.1175/2010jas3603.1

Varble, A. (2018, April). Erroneous attribution of deep convective invigoration to aerosol concentration. *Journal of the Atmospheric Sciences*, *75*(4), 1351–1368. Retrieved from `https://doi.org/10.1175/jas-d-17-0217.1` doi: 10.1175/jas-d-17-0217.1

Wing, A. A., Emanuel, K., Holloway, C. E., & Muller, C. (2017, February). Convective self-aggregation in numerical simulations: A review. *Surveys in Geophysics*, *38*(6), 1173–1197. Retrieved from `https://doi.org/10.1007/s10712-017-9408-4` doi: 10.1007/s10712-017-9408-4

Wing, A. A., & Emanuel, K. A. (2014, February). Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations. *Journal of Advances in Modeling Earth Systems*, *6*(1), 59–74. Retrieved from `https://doi.org/10.1002/2013ms000269` doi: 10.1002/2013ms000269

Wing, A. A., Reed, K. A., Satoh, M., Stevens, B., Bony, S., & Ohno, T. (2018, March). Radiative–convective equilibrium model intercomparison project. *Geoscientific Model Development*, *11*(2), 793–813. Retrieved from `https://`

doi.org/10.5194/gmd-11-793-2018 doi: 10.5194/gmd-11-793-2018

Wing, A. A., Stauffer, C. L., Becker, T., Reed, K. A., Ahn, M.-S., Arnold, N. P., … Zhao, M. (2020, September). Clouds and convective self-aggregation in a multimodel ensemble of radiative-convective equilibrium simulations. *Journal of Advances in Modeling Earth Systems*, *12*(9). Retrieved from https://doi.org/10.1029/2020ms002138 doi: 10.1029/2020ms002138

Wu, C.-M., & Arakawa, A. (2014, May). A unified representation of deep moist convection in numerical modeling of the atmosphere. part II. *Journal of the Atmospheric Sciences*, *71*(6), 2089–2103. Retrieved from https://doi.org/10.1175/jas-d-13-0382.1 doi: 10.1175/jas-d-13-0382.1

Yanase, T., Nishizawa, S., Miura, H., & Tomita, H. (2022, September). Characteristic form and distance in high-level hierarchical structure of self-aggregated clouds in radiative-convective equilibrium. *Geophysical Research Letters*, *49*(18). Retrieved from https://doi.org/10.1029/2022gl100000 doi: 10.1029/2022gl100000

Yuan, J., & Houze, R. A. (2010, November). Global variability of mesoscale convective system anvil structure from a-train satellite data. *Journal of Climate*, *23*(21), 5864–5888. Retrieved from https://doi.org/10.1175/2010jcli3671.1 doi: 10.1175/2010jcli3671.1

Zhang, C. (2013, December). Madden–julian oscillation: Bridging weather and climate. *Bulletin of the American Meteorological Society*, *94*(12), 1849–1870. Retrieved from https://doi.org/10.1175/bams-d-12-00026.1 doi: 10.1175/bams-d-12-00026.1

Zhang, C., & Ling, J. (2017, May). Barrier effect of the indo-pacific maritime continent on the MJO: Perspectives from tracking MJO precipitation. *Journal of Climate*, *30*(9), 3439–3459. Retrieved from https://doi.org/10.1175/jcli-d-16-0614.1 doi: 10.1175/jcli-d-16-0614.1