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Special Section: Using radiative-convective equilibrium to understand convective organization, clouds, and tropical climate

Key Points:
• Occurrence of self-aggregation is not deterministic near the marginal boundary between scattered and aggregated regimes
• Development of moisture contrast within the boundary layer is the key indicator for the occurrence of self-aggregation
• Convective organization and moisture inhomogeneity do not evolve synchronously

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

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Abstract An ensemble of 10 radiative-convective equilibrium (RCE) simulations near the sharp transition zone between scattered and aggregated states are examined in a square-domain cloud-resolving model. Surprisingly, the occurrence of self-aggregation is not deterministic near the boundary line of the two states, with six runs reaching aggregated states and four runs returning to scattered states. Spatial autocorrelation length analysis reveals that the development of moisture contrast in the boundary layer (BL) is the key indicator for self-aggregation. To reach aggregated RCE states, a part of the BL needs to be dry and extensive sufficiently to suppress convection triggered by collisions of intruding cold pools. Furthermore, the relation between moisture aggregation and convective organization is elucidated. In a shorter time-scale, convective organization is governed by cold pool dynamics. Meanwhile, large-scale moisture determines the region of active convection for time-scale longer than 2 days.

Plain Language Summary Radiative-convective equilibrium (RCE) describes a balance between the cooling of the atmosphere by radiation and the heating of that through latent heat release and surface heat fluxes. Under certain conditions, initially scattered convection and moisture can spontaneously organize into one or more spatially coherent clusters in RCE simulations. Understanding this spontaneous clumping phenomenon helps better understand the organizing processes of clouds in the tropics. Here, we investigate the behaviors of 10 RCE simulations using a model setting that marginally separates aggregated and scattered RCE states. Clear contrast between wet and dry regions is established in six simulations, but the other four return to a scattered situation. This result suggests that the marginal boundary between the aggregated and the scattered regimes might have a range of probability rather than a deterministic line.

1. Introduction

Radiative-convective equilibrium (RCE) is the statistical equilibrium state that atmosphere would reach in the absence of lateral energy transport. In the RCE, radiative cooling is balanced only by convective heating and surface heat fluxes. It has been widely used as simple idealization of tropical climate in numerical modeling (Manabe & Strickler, 1964; Tompkins & Craig, 1998). Recently, a unique feature known as convective self-aggregation has been observed in RCE simulations by cloud-resolving models (CRMs; Bretherton et al., 2005; Held et al., 1993; Tompkins, 2001a). Initially scattered convections organize into one or more spatially coherent clusters even under uniform boundary conditions and forcing. Understanding the physics of this spontaneous clumping behavior may advance our understanding of convective organization and tropical climate (see review of Wing et al., 2017).

While convective self-aggregation can occur across a wide variety of models using different dynamical cores and physical parameterizations (Wing et al., 2018, 2020), the underlining physics highly depend on model details. In prominent research by Muller and Held (2012, hereafter MH12), it is shown that self-aggregation in square-domain CRM has strong dependence on domain size and horizontal resolution. With horizontally homogeneous initial conditions, self-aggregation only occurs when domain size is larger (L ≥ 200 km) and horizontal resolution is coarser (dx ≥ 2 km). Yanase et al. (2020, hereafter Y20) further found a critical domain size in high-resolution regime. Their results show that self-aggregation occurs regardless of horizontal resolution if domain size is larger than 500 km.

This study is motivated by the RCE regime diagrams drawn in the horizontal resolution-domain size space (Figure 6a of MH12 and Figure 2b of Y20). We investigate an ensemble of RCE simulations using settings...
near the boundary of sharp transition between scattered and aggregated states (Line II in Figure 2b of Y20). We aim to understand how strict the boundary line is between the two regimes. Section 2 describes the CRM and experimental setup. Section 3 describes the behavior of 10 ensemble simulations and examines reasons for their diverse evolution. Section 4 presents a discussion about moisture aggregation and convective organization. Concluding remarks are offered in Section 5.

2. Model and Experiment Design

The CRM used in this study is a regional atmospheric model constructed with Scalable Computing for Advanced Library and Environment (SCALE-RM Version 5.3.6; Nishizawa et al., 2015; Sato et al., 2015). The governing equations are based on three-dimensional fully compressible non-hydrostatic equations. Six-class single-moment bulk microphysical scheme (Tomita, 2008) is used. Surface fluxes are represented through bulk method (Beljaars & Holtslag, 1991; Wilson, 2001). Subgrid-scale turbulent processes are parameterized by the Smagorinsky-Lilly scheme (Brown et al., 1994; Scotti et al., 1993), while vertical mixing in the boundary layer is parameterized by the Mellor-Yamada Nakanishi-Niino scheme (MYNN; Mellor & Yamada, 1982; Nakanishi & Niino, 2004). Radiative fluxes are calculated through a k-distribution-based broadband radiation transfer model (MSTRN-X; Sekiguchi & Nakajima, 2008).

The experiment setup closely follows the configuration recommended by the RCE Model Intercomparison Project (RCEMIP; Wing et al., 2018). Key settings are summarized here. The Coriolis parameter is set to zero, and insolation is fixed at 409.6 W m$^{-2}$ with a zenith angle of 42.05° (no diurnal cycle). Sea surface temperature is uniform and fixed at 300 K. Initial profiles of temperature and moisture are specified using analytical functions designed to approximate typical tropical sounding. Zonal and meridional winds are set to zero. To break symmetry, random thermal noise with maximum amplitudes of 0.1 K is added in the lowest five model levels. A stretched vertical grid with 74 vertical levels and model top of 33 km is used. A pair of five ensemble simulations is performed in two supercomputers. One is the Oakforest-PACS (OFP) operated by the University of Tokyo, and the other is the Fugaku operated by the RIKEN Center for Computational Science (R-CCS). All simulations employ a square domain of 384 km and horizontal mesh-size of 2 km. In the horizontal resolution-domain size space, this configuration lies at the boundary between scattered and aggregated states (Line II in Figure 2b of Y20). Each run is integrated for 50 days. Simulation in the Oakforest-PACS is denoted as “OFP_x” Simulation in the Fugaku is denoted as “Fugaku_x” (x ranges from 1 to 5).

3. Results

In this section, the behaviors of 10 ensemble simulations are investigated. Before moving on to the result, an issue of initial condition is discussed. The distribution of initial perturbation in potential temperature is shown in Figure S1 in Supporting Information S1. Several statistics are summarized in Table S1 in Supporting Information S1. In general, no distinct difference is found, and the disparity in initial condition shows no clear connection to final state. Therefore, we consider the diverse behavior of self-aggregation is not strongly affected by the disparity in the initial random perturbations (see Section 3.1 for more discussion).

3.1. Evolution to Distinct RCE States

First, we provide a general overview of the 10 ensemble simulations by examining precipitable water (PW). Here, the spatial standard deviation of PW ($\sigma_{PW}$) is used to measure the degree of self-aggregation (Figure 1a; Wing et al., 2017). During the first 10 days, the spatial variation in PW increases continuously in all runs. Yet, after Day 10, the evolution disperses and develops into different RCE states. At Day 50, a strong single dry patch is established in six runs, whereas moisture distribution returns to scattered state in the other four (Figure 1b; Movie S1). Note that the simulations have not reached statistical equilibrium after 50-day integration. Six ensemble runs (four aggregated cases and two scattered cases) are then integrated for additional 50 days. All cases reach equilibrium after Day 80. In the equilibrium state, a strong single dry patch is kept in the aggregated cases, while moisture distribution remains disorganized in the scattered cases (Figure S2 in Supporting Information S1; Movie S2).
A notable result is that four out of the six aggregated runs are from the Fugaku. We suspected that simulations carried out in the Fugaku might have a higher probability of reaching aggregated state than those in the OFP. Thus, we further examine the dependence on initial random perturbations by repeating the three scattered OFP runs (OFP_3, 4, 5) in the Fugaku. The results are shown in Figure S3 in Supporting Information S1. Only the restart run of the OFP_4 reached a scattered state again, while the other two became aggregated. This result suggests that we might have observed chaotic situation where tiny differences perhaps coming from compilers and architectures of the supercomputers can lead to distinct RCE states.

Figure 1. (a) Temporal evolution of standard deviation of precipitable water (PW; $\sigma_{PW}$; mm) for the 10 radiative-convective equilibrium simulations. One-day running means of hourly time series are shown in all figures. Simulations with (without) clear moisture contrast in final state are shown in solid (dashed). (b) Corresponding snapshots of precipitable water (shading; mm) and precipitation (pink contour; 10 mm day$^{-1}$) at Day 50.
3.2. Length Scale of Moisture: Boundary Layer Versus Free Troposphere

Previous research pointed out that even though PW evolves dominantly by moisture variation in the free troposphere (FT), boundary layer (BL) processes are essential for self-aggregation (D. Yang, 2018a, 2018b, 2019, 2021; Yao et al., 2021). To investigate whether there are differences between aggregated and scattered cases in the moisture evolutions of FT and BL, we examine the spatial autocorrelation length of moisture ($l_m$; details of calculations in Text S1 in Supporting Information S1). In FT, while the length scale ($l_{m,FT}$) increases gradually during the first 10 days for all simulations, it shows diverse evolution after Day 10 (Figure 2a). Generally, the evolution of $l_{m,FT}$ is consistent with that of $\sigma_{PW}$. However, things are different in BL (Figure 2b). During the first 10 days, $l_{m,BL}$ is small in all runs and does not grow along with the increasing $l_{m,FT}$. After Day 15, $l_{m,BL}$ begins to grow in the six aggregated cases but remains small in the four scattered cases. The most interesting case is the OFP_5, in which $l_{m,FT}$ grows after Day 10 but converges to scattered cases at about Day 40. Meanwhile, $l_{m,BL}$ of OFP_5 does not grow during the whole integration, except for a tiny perturbation at about Day 25. This result indicates that the development of moisture contrast in BL is the key for the transition from scattered state to aggregated state. Note that $l_{m,FT}$ and $l_{m,BL}$ have comparable values (~80 km) in the aggregated cases at Day 50.

To understand the distinct evolution of moisture between aggregated and scattered cases, horizontal distributions of moisture in BL and FT at Day 15 are shown in Figure 2c (OFP_1; aggregated case) and Figure 2d (OFP_3; scattered case). In both cases, spatial patterns of moisture in BL are dominated by cold pools, with dry air near downdraft centers and humid air near gust fronts (Movie S3). Nonetheless, differences are observed in dry patches (cyan contour in Figures 2c and 2d). In the aggregated case, dry patches first developing in FT extend downward into BL, with coherent dry pattern in vertical direction. On the contrary, in the scattered case, BL moisture is less correlated with FT moisture. To support our argument that dry patches are established first in FT and extend downward to finally influence large-scale moisture distribution in BL, temporal evolution of $l_m$ at each height is shown (Figure S4 in Supporting Information S1). In all simulations, $l_m$ increases first in middle troposphere (4–8 km) around Day 5, while the peak of $l_m$ gradually shifts downward to lower troposphere (2–4 km) from Day 5 to Day 20. Meanwhile, $l_m$ in BL remains small despite the expansion of dry patches in FT. The speed of downward extension of dry patches from FT to BL appears important in determining whether the system will reach an aggregated state.

3.3. Cold Pool Dynamics and Dry Patch Expansion

As shown in Section 3.2, the development of moisture contrast in BL is the key indicator for the occurrence of self-aggregation, and cold pools play an important role in reorganizing BL moisture. Then, we examine how cold pools interact with convection and how these interactions affect the buildup of self-aggregation (Jeevanjee & Romps, 2013; Muller & Bony, 2015; Tompkins, 2001b; D. Yang, 2018a).

First, we examine the horizontal distribution of convective available potential energy (CAPE) and precipitation in the aggregated (OFP_1; Figure 3a) and scattered case (OFP_3; Figure 3b). In both cases, distribution of CAPE is dominated by moisture variation in BL, with highest CAPE at humid outflow boundaries and lower CAPE near downdraft centers. New convections tend to form at humid outflow boundaries, especially when multiple cold pools collide together (Fuglestvedt & Haerter, 2020; Meyer & Haerter, 2020; Torri & Kuang, 2019; Zuidema et al., 2017). Differences between aggregated and scattered cases are observed in their dry patches (cyan contour in Figures 3a and 3b). In the aggregated case, lower value of CAPE is prevalent and covers an area as comparable as dry patches in FT. In contrast, CAPE remains high in the scattered case since BL is still humid uniformly. The small extent of non-precipitating area in or near dry patches (green contour in Figure 3b) indicates that convection is still active. Convection transports humid air in BL upward and destroys the dry anomalies in FT (Movie S4).

The result above suggests that the dryness in the FT is not sufficient to suppress convection. A dry BL is needed to work against the active triggering of convection by cold pools. The cross-section of moisture anomalies along the dry patch center (red-letter D in Figures 3a and 3b) supports this argument. In both aggregated (Figure 3c) and scattered cases (Figure 3d), dry anomalies are commonly found in the whole column, with larger magnitudes in the lower troposphere (1–4 km). The difference between aggregated and scattered cases is evident in the BL. While extensive dry anomalies are well maintained in the aggregated
Figure 2. Temporal evolutions of autocorrelation length of moisture ($l_m$) in (a) free troposphere and (b) boundary layer. (c–d) Snapshots of specific humidity at 0.11 km (shading; g kg$^{-1}$), 1–10-km integrated specific humidity (cyan contour; 18 mm), and precipitation (pink contour; 10 mm day$^{-1}$) at Day 15.
case, dry anomalies are less organized and much weaker in the scattered case. We can detect this contrast clearly if we apply the 5-day running means to filter high-frequency fine structures (green contour in Figures 3c and 3d).

Next, we examine the growth and decay of the dry patches analyzed above. Distinct evolutions are shown in the vertical profiles of moist static energy (MSE; Figure 3e). Around Day 10, MSE profile is similar between the two dry patches. From Day 10 to Day 15, continuous drying is evident in the whole column for both cases. This drying is slightly stronger in the growing dry patch, especially in BL and lower troposphere. From Day 15 to Day 20, the two dry patches experience different evolutions. In the aggregated case, it shows continuous drying in the whole troposphere, with especially large tendencies in BL. In contrast, drying
tendency is completely stalled in the scattered case. Around Day 25, a strong dryness is established in lower
troposphere in the aggregated case, while the atmosphere becomes humid again in the scatted case.

Finally, we synthesize our results with past studies. Several studies have reported that the competition between
two opposite effects on the moisture variance in BL is crucial to the occurrence of self-aggregation (Coppin &
Bony, 2015; Muller & Bony, 2015; Y20). While evaporation-driven cold pools act to homogenize BL properties
between moist and dry regions, longwave radiative cooling near the BL top maintains strong subsidence that
transports dry air from FT into BL. This concept is consistent with our results and can explain the diverse
evolutions between aggregated and scattered cases. During the developing stage of dry patch (Day 10–15),
radiative cooling in middle troposphere (4–7 km) strengthens and works to extend dry patch (Figure
3f). The subsidence driven by radiative cooling maintains the dryness in BL and acts against outflows of cold pools.
After Day 15, however, BL in the scattered case is neither dry nor extensive enough to protect itself from con-
vective triggering by cold pools. Dry patch weakens and disappears completely around Day 25. In summary,
our results show that the build-up of self-aggregation is strongly associated with evolution of BL moisture.

4. Discussion: Indices for Moisture Aggregation and Convective Organization

As pointed out by Wing (2019), it is still challenging to measure the strength of self-aggregation objectively
since it involves multiple processes across a wide range of temporal and spatial scales. A single index is hard
to capture all aspects of self-aggregation. Opposite results might be obtained when different metrics are uti-
zed (Cronin & Wing, 2017; Wing & Cronin, 2016). Here, we employ three types of indices to quantify the
simulations, following the RCEMIP (Wing et al., 2020; details of calculations in Text S2 in Supporting Informa-
tion S1). While spatial variance of column relative humidity (CRH; \( \sigma_{CRH}^2 \); Wing & Cronin, 2016) reflects
the broadening of moisture distribution, the organization index \( I_{org} \) (Tompkins & Semie, 2017) measures
the degree of clustering of convective cells. Subsidence fraction \( f_{sub} \) (Coppin & Bony, 2015) captures the
development of large-scale overturning circulation. Notable differences are found in their evolutions. While
\( \sigma_{CRH}^2 \) (Figure 4a) shows diverse evolutions between aggregated and scattered cases, \( I_{org} \) (Figure 4b) and \( f_{sub} \)
(Figure 4c) show little diversity. \( I_{org} \) is always larger than 0.5, indicating convective cells are clustered rather
than randomly distributed. This can be seen in the horizontal distribution of precipitation (Figure 1). We
consider $I_{org}$ does not evolve synchronously with large-scale moisture because the triggering and organization of clouds in SCALE-RM are governed by small-scale cold pools. Meanwhile, for all simulations, $f_{sub}$ remains near 0.5, suggesting that large-scale overturning circulation with a concentrated upward branch has not developed in the aggregated cases after 50-day integration. For the six 100-day-extended runs, as dry patch continuously expands in the aggregated cases, notable differences between aggregated and scattered cases appears in $I_{org}$ and $f_{sub}$ (Figure S5 in Supporting Information S1). In equilibrium, the development of moisture contrast in aggregated cases slightly raises $I_{org}$ and $f_{sub}$ to higher values than those of scattered cases.

Two additional experiments are included in Figure 4 to clarify the meanings of aggregation indices. “xMYNN” denotes the simulation turning off the MYNN scheme, and “L128” denotes the simulation using smaller domain size of 128 km. As shown in Section 3, the expansion of dry regions in our simulations is slower and weaker than that in previous studies. The system reaches an RCE state with a single dry patch rather than the typical pattern of a concentrated moist patch surrounded by dry airs. Here, the xMYNN run is a reference to the typical case of self-aggregation (Movie S5), whereas the L128 run represents unaggregated state (Movie S6). By comparing these two experiments with the 10 ensemble simulations, interesting results are found. For all simulations, $I_{org}$ (Figure 4b) shows clear increasing trends regardless of the diverse evolution in moisture field (Figure 4a). The development of strong moisture contrast in xMYNN only raises $I_{org}$ to a higher level than those of weakly aggregated and scattered cases. This means that moisture aggregation is not a sufficient reason for the increasing tendency of $I_{org}$. This might be due to the feature that the organization of convective systems is probably governed by cold pools in SCALE-RM. As for $f_{sub}$ (Figure 4c), while it starts to increase after Day 15 and reaches about 0.7 at Day 50 in xMYNN, $f_{sub}$ remains near 0.5 in the other experiments. This result indicates that after 50-day integration, clear overturning circulation with a concentrated upward branch is established only in xMYNN but not in the others. $f_{sub}$ in the six 100-day-extended runs shows an interesting comparison. After longer integration, $f_{sub}$ in the aggregated cases raise to a value slightly higher than 0.5 (Figure S5c in Supporting Information S1). This result suggests that, considering with moisture variation ($\sigma_{CRH}$), it takes longer time for large-scale overturning circulation to establish. The marginal behavior of ensemble simulations near the transition boundary clearly manifests the different time-scale between moisture and large-scale overturning circulation.

To further investigate how moisture distribution reflects on convective activities, cumulative precipitation is examined. A span of 2 days is chosen here (B. Yang & Tan, 2020). The fraction of convection-free regions ($R_{free}$) defined as the area with cumulative precipitation less than 0.01 mm is used as a metric to evaluate the role of large-scale moisture on the distribution of convection in a longer time-scale (Figure 4d). This convection-based index well reflects the diverse final states in moisture field, with a clear separation between aggregated and scattered cases. A 2-day accumulated $I_{org}$ ($I_{org, accum}$) is also calculated to obtain the longer time-scale component of convective aggregation in $I_{org}$ (details of calculations in Text S2 and Figure S6 in Supporting Information S1). Just like $R_{free}$, $I_{org, accum}$ is able to capture the difference between aggregated and scattered cases in moisture field (Figure S7 in Supporting Information S1). $I_{org, accum}$ also remains around 0.55 in the scattered cases, suggesting near-random distribution of convection. The results illustrate that care should be taken when interpreting the relation between moisture aggregation and convective organization, especially on the temporal and spatial scale of interest. Here, moisture aggregation means broadening of moisture contrast, while convective organization indicates clustering of convective systems. The degree of convective clustering might not evolve synchronously with moisture contrast, as convection clusters on a wide range of scales through various processes. Different convective-based indices capture different aspects of convective organization. For example, in our model, small-scale cold pool dynamics govern the convective clustering in a shorter time-scale. $I_{org}$ mainly reflects this process. Meanwhile, large-scale moisture contrast contributes to convective organization on a longer time-scale. $R_{free}$ or $I_{org, accum}$ is a good metric to measure this behavior.

5. Conclusion

An ensemble of 10 RCE simulations in a square-domain CRM with settings near the boundary line of a sharp transition between the scattered and aggregated states (Line II in Figure 2b of Y20). Surprisingly, the occurrence of self-aggregation in SCALE-RM was not deterministic in that marginal zone. Diverse evolution
was found in moisture field. While a clear single dry patch was established in six runs, the moisture contrast weakened and returned to scattered state in the others. This diverse behavior was not explained by the disparity in initial random perturbations. The development of moisture contrast in BL was the key indicator for the occurrence of self-aggregation. The evolution of the contrast was explained by the competition between evaporation-driven cold pools and radiative cooling near the BL top. To reach aggregated RCE state, dry patches in BL needs to become extensive sufficiently to prevent penetrations of cold pools.

The relation between moisture aggregation and convective organization was elucidated. Regardless of the distinct difference in moisture distribution, the degree of convective clustering measured by \( I_{\text{agg}} \) evolved similarly in all simulations. In a shorter time-scale, small-scale cold pool dynamics governed convective activities, with convective clouds clustering around humid outflow boundaries of gust fronts. In a longer time-scale, large-scale moisture determined the area of active convection, with enhanced activities confined to regions of high column humidity. \( R_{\text{free}} \) or \( I_{\text{agg,accum}} \) was a good metric to capture the latter behavior, and it well reflected the diverse final state of moisture in our simulations. These results suggested that a proper metric that can capture the specific temporal and spatial scale of interest should be chosen carefully when we try to explain the relation between moisture aggregation and convective organization.

Finally, several future perspectives are discussed. In this study, the diverse evolution of self-aggregation around the marginal transition zone of aggregated and scattered regimes was investigated for the first time by SCALE-RM. This non-deterministic feature should occur only near the marginal boundaries within a narrow band. Model setups far away from the boundaries would be deterministic. It would be worthwhile to explore whether this marginal behavior also exists in other models. The width of marginal zones is also a topic worthy of further research. In addition, it would be interesting to examine the other two regime boundaries (Line I and III in Figure 2b of Y20). Testing mechanism-denial experiments at the marginal boundaries might provide insights on the essential ingredients of self-aggregation.

Data Availability Statement

The SCALE-RM is freely available at the official website (https://scale.riken.jp/download/), and model configuration files, scripts, and post-processing data can be accessed in the Open Science Framework (https://osf.io/musrp/).

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