Structure of Tropical Convective Systems in Aqua-Planet Experiments: Radiative-Convective Equilibrium Versus the Earth-Like Experiment

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Abstract

A previous study shows that tropical convective systems share a similar structure regardless of horizontal scale: lower-level horizontal convergence precedes maximum precipitation and this convergence rises and tilts over time. We conduct a series of aqua-planet experiments (APEs) using the Non-hydrostatic Icosahedral Atmospheric Model (NICAM) to investigate whether this structure is maintained under different conditions with an Earth-like APE (CTL-exp) and a radiative convective equilibrium (RCE-exp) where sea surface temperature is uniform and no planetary rotation is applied. The experiments are conducted with the 56 km mesh size with explicit convective calculation without a cumulus parameterization scheme. CTL-exp shows a well-known multi-scale convective structure where a smaller convective system propagates westward along the equator whereas a larger convective system propagates eastward. In RCE-exp, the simulation also has a multi-scale structure but the larger-scale convective system no longer propagates in a preferred direction. The convective systems in CTL-exp have a similar tilting structure to tropical convective systems regardless of horizontal scale, while the larger scale convective system in RCE-exp show a smaller tilting structure. We speculate that the difference in CTL-exp and RCE-exp structures comes from the propagation speed of the convective systems.

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1. Introduction

Convective systems in the tropics have a common structure regardless of their spatial scale (Mapes et al. 2006). According to observational data from the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE), the relation between precipitation and horizontal convergence at the horizontal scales of 50, 500, and 2000 km shows that lower-level convergence intensifies prior to peak precipitation, and the altitude of the strong convergence increases with time. The temporal variation of the convergence is faster as horizontal scale decreases. Mapes et al. (2006) indicate that various tropical convective systems of different scales, from meso-scale convective systems (MCSs) to Madden-Julian oscillations (MJOs), have a similar structure, and proposed that they occur via a ‘stretched building block’ conceptual model.

Under a radiative-convective equilibrium (RCE) condition over a uniform sea surface temperature (SST), we expect randomly generated MCS or their aggregation (Breherton et al. 2005). Convective systems under RCE are now widely investigated because their aggregation is thought to be related to the observed large-scale organization of convective systems such as MJO. However, it is not completely clear whether the convective systems under RCE have the same structure as observed tropical convective systems. In this study, we perform a series of aqua-planet experiments (APEs) with explicitly resolving convective motions in order to understand the relationship between convective aggregation and the time-vertical structure.

We conduct four types of APE to understand convective structures in different horizontal scales by changing the rotation of Earth and the SST distribution. In particular, we consider two extreme cases in which an Earth-like APE which has the observed zonal symmetric SST distribution with the Earth rotation and an APE under RCE which has no rotation and a uniform SST. We also consider two intermediate cases in which the APE has rotation and a uniform SST, and has no rotation and the observed zonal symmetric SST distribution. The structure of convective systems are analyzed by regression coefficients between precipitation and horizontal convergence in the lag-height cross section by following the method described by Mapes et al. (2006).

2. Experimental design

We perform APEs using the Non-hydrostatic Icosahedral Atmospheric Model (NICAM; Tomita and Satoh 2004; Satoh et al. 2008, 2014). An advantage of NICAM is that it can be used to perform sub-kilometer simulations (Miyamoto et al. 2013, 2015; Kajikawa et al. 2016), which may be necessary to calculate meso-scale circulations at a global scale. However, for the purpose of our comparison between idealized APEs under the Earth-like and RCE conditions, we take a less expensive approach with a coarse resolution model. Following Yoshizaki et al. (2012), we use grid division level 7 of the horizontal resolution, which has a horizontal mesh size of 56 km.

According to Yoshizaki et al. (2012), the 56-km mesh experiment without a convective parameterization scheme shows a multi-scale structure of convective systems along the equator with westward propagating convective signals with propagation speed of about 15 m s⁻¹. We performed four types of simulations by changing Earth’s rotation, Ω, and the SST distribution. The control experiment (CTL-exp) is under the Earth-like condition with the rotation speed of the Earth Ω = Ω_E and a zonal symmetric SST distribution similar to that observed on Earth (Qobs; Neale and Hoskins 2001). The radiative-convective equilibrium experiment (RCE-exp) sets the rotation speed to zero (Ω = 0) and uses a uniform SST of 20°C. The other two experiments repeated the conditions of CTL-exp but used Ω = 0 or a uniform SST of 20°C. Numerical integrations are performed for 40 days after sufficiently long spin-up simulations with a coarser resolution model (grid division level 5 or 224 km mesh size), and the final 30 days are analyzed.

To study the vertical structure of convective systems of different horizontal scales, we prepared horizontally averaged mesh data with horizontal scales of 5°, 15° and 90° in addition to a grid-scale data over the equatorial belt between 2.5°N and 2.5°S. To obtain ample data, samples are prepared for the zonally segmental areas starting four orientations: 0°, 90°E, 180° and 90°W. At each level of resolution, we analyze vertical structures of regression coefficients between precipitation and horizontal convergence in
the lag-height cross-section. This method precisely follows that of Mapes et al. (2006).

3. Results

Figure 1 shows full disk views of the outgoing longwave radiation and precipitation for the four experiments (Supplement S1 shows the animations). In CTL-exp, the equatorial convective areas and the mid-latitude storm tracks are represented as in the real world. The results show that, in the equatorial area, convective systems are organized in the zonal direction and exhibit aggregative characteristics. This result is similar to those obtained at much higher resolution by Tomita et al. (2005; 3.5, 7 and 14 km mesh size), and is consistent with those obtained using a coarse-resolution model without a convective parameterization scheme by Yoshizaki et al. (2012; 14, 28, and 56 km mesh size) and Takasuka et al. (2015; 224 km mesh size). The experiment with no rotation but with the Qobs SST distribution (Fig. 1b) shows a sharp precipitation band meandering near the equator. Upper-level clouds are associated with the equatorial precipitation band and advect poleward from the equatorial band. Almost no clouds exist at mid- and high-latitude, indicating that the Hadley circulations extend to the poles in each hemisphere in case of no rotation (Satoh 1994; Satoh et al. 1995). The experiment with the uniform SST of 20°C with rotation (Fig. 1c) shows a tropical cyclone world in which almost all clouds are aggregated as cyclones (Khairoutdinov and Emanuel 2013; Reed and Chavas 2015). The equatorial areas are predominantly cloud-free in the full disk views (Fig. 1c), but clouds may appear near the equator in Hovmöller diagrams of precipitation (Fig. 2c). RCE-exp (Fig. 1d) shows a state of self-aggregation in which convective clouds are organized in large scale at distances of about 10,000 km. Similar results have been obtained in a much coarser-resolution global RCE simulation (Popke et al. 2013).

Figure 2 shows the Hovmöller diagrams of precipitation averaged between 2.5°N and 2.5°S for the four experiments. These diagrams show evolutions of convective systems along the equatorial belt. CTL-exp (Fig. 2a) shows a well-known multi-scale structure composed of westward propagating convective systems with a period of a few days and large-scale eastward propagating systems, an example of which is shown by the signal propagating through 0° at 150 h. The propagation speeds are estimated as 10.3 m s⁻¹ (120° per 360 h) and 12.3 m s⁻¹ (180° per 450 h) for the westward and eastward systems, respectively. This multi-scale structure is similar to that obtained by Yoshizaki et al. (2012), in which these signals are referred to as the westward and eastward organized propagating precipitation systems, respectively. They are also similar to the hierarchical structure obtained using a model with much finer resolution by Tomita et al. (2005).

The Hovmöller diagram for the experiment with the observed SST without rotation (Fig. 2b) shows an equatorial cross-section of the migration of the intertropical convergence zone (ITCZ). Propagating convective systems are observed within the convective region, but they have various propagation speeds along the equator probably due to meandering of ITCZ. The experiment with rotation and the uniform SST (Fig. 2c) shows a westward propagation similar to that in CTL-exp, but with less frequency. The larger-scale signal with eastward propagation is also evident; an example starts at about 150° W at 0 h. In Fig. 2d, RCE-exp also shows a multi-scale structure of convective systems at about 10° and 90° horizontal scales; the latter has wave number 4 patterns or a scale of about 10,000 km. Note that since RCE-exp is under a spherically uniform condition, the wave number defined by Fig. 2d is an example of that along a great circle of the sphere.

Hereafter, we focus on CTL-exp and RCE-exp to analyze the vertical structure of the multi-scale convective systems. The relationship between precipitation and horizontal convergence at different horizontal scales for CTL-exp and RCE-exp are shown by Figs. 3 and 4, respectively. These figures show contours of regression coefficients between precipitation and horizontal convergence in the unit of mm hr⁻¹ with the horizontal axis of lag time in hours and the vertical axis of height in km. The vertical structures are analyzed for four different horizontal scales in Figs. 3 and 4; (a) is for a grid scale (56 km) and (b), (c) and (d) are for the horizontal average of 5°, 15° and 90°, respectively. The autocorrelation of precipitation as a function of the lag time (shown in the lower panels for each experiment) shows that a typical time scale of precipitation is a few hours for the grid scale (Fig. 3a), while it becomes about 12 hours for the larger scales in (Fig. 3c).

![Fig. 1. Full disk views of the outgoing longwave radiation (gray scale bar: W m⁻²) and precipitation (coloured bar: mm hr⁻¹) for the four experiments: (a) with rotation and the Qobs SST distribution (CTL-exp), (b) with no rotation and the Qobs SST distribution, (c) with rotation and the uniform SST, and (d) with no rotation and the uniform SST (RCE-exp).](image-url)
and (Fig. 3d).

For CTL-exp, the vertical structures show that the horizontal convergence precedes precipitation in the lower layer for all the scales (Fig. 3a, 3b, 3c, and 3d), similar to the observational results shown in Mapes et al. (2006; their Fig. 3). The vertical scale of the larger regression coefficients becomes deeper toward the 0-lag time (center of the lag-axis). The slopes of the contours of regression coefficients become steeper as horizontal scale decreases, a characteristic similar to that shown by Mapes et al. (2006). As horizontal scale decreases, the time scale of the horizontal convergence evolution becomes shorter for the scales less than 15° (Fig. 3a, 3b, and 3c).

For RCE-exp, on the other hand, while the 5° scale has a regression slope similar to that found in CTL-exp, the regressions for the 15° and 90° scales do not show a clear slope. This suggests that the organized convective systems of the larger scales are different to those in CTL-exp. In the experiment with no rotation and the Qobs SST distribution, a clear slope is only seen for the grid scale (Supplement S2). In the experiment with rotation and the uniform SST, we found a regression slope with the horizontal con-
Convergence preceding precipitation in these larger scales, suggesting that this experiment simulates organized convective systems as in the real atmosphere (Supplement S3).

The slopes of the contours of regression coefficients are summarized in Table 1. This is obtained by subjectively fitting a slope to the maximum of the contours in each figure, as indicated by red segments. For CTL-exp, the slope becomes steeper as the horizontal scale decreases (Fig. 3). The slopes for the convective systems at the grid scale are almost the same between CTL-exp and RCE-exp, suggesting that these systems are common to these two experiments. The experiment with rotation and the uniform SST also shows a steeper slope at the grid scale (Supplement S3).

For the larger scales, RCE-exp shows smaller slopes and weaker signals (Fig. 4), whereas CTL-exp shows a clear dependence, suggesting different dynamical mechanisms of the large scale convective systems between CTL-exp and RCE-exp.

4. Summary

We conducted a series of aqua-planet experiments using a coarse resolution NICAM without using a convective parameterization scheme. Conditions for the four experiments were: (a) the Earth-like configuration with rotation and the zonal symmetric Qobs SST distribution (CTL-exp); (b) without rotation but with the Qobs SST distribution; (c) with rotation but with a uniform SST of 20°C; and (d) without rotation but with a uniform SST of 20°C (RCE-exp). The vertical structures of convective systems are analyzed in terms of regression coefficients between precipitation and horizontal convergence for different horizontal scales: a grid scale (56 km), 5°, 15° and 90° (10,000 km). Both CTL-exp and RCE-exp show a multiscale structure of convective systems from the grid scale to the largest scale. For CTL-exp, all the convective systems with these horizontal scales have a slope of the contours of regression coefficients; that is, the lower-level horizontal convergence precedes the precipitation peak and the vertical depth of the horizontal convergence increases with time. For RCE-exp, on the other hand, larger scale convective systems such as 15° and 90° do not have such a steeper slope. Since the largest convective system of RCE-exp is almost stationary and not propagating, we speculate that the differences in the regression slope are partly associated with propagation speed of convective systems. Our results suggest that the largest convective systems of RCE-exp have a different dynamical mechanism from that observed in the equatorial areas of CTL-exp or the real atmosphere.

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Supplement

S1. Animation of the outgoing longwave radiation and precipitation for the four experiments: (a) with rotation and the Qobs SST distribution (CTL-exp), (b) without rotation and with the Qobs SST distribution, (c) with rotation and the uniform SST; and (d) with no rotation and the uniform SST (RCE-exp).

S2. Lag-height structure of regressions between precipitation and horizontal convergence at four spatial scales for the experiment with no rotation and the Qobs SST distribution: (a) grid
scale (56 km), (b) 5°, (c) 15°, and (d) 90°. Autocorrelation of precipitation is shown at the bottom of each plot.

S3. Lag-height structure of regressions between precipitation and horizontal convergence at four spatial scales for the experiment with rotation and the uniform SST: (a) grid scale (56 km), (b) 5°, (c) 15°, and (d) 90°. Autocorrelation of precipitation is shown at the bottom of each plot.

References


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*SOLA*: https://www.jstage.jst.go.jp/browse/sola