Investigating Tropical Cloud Organization and Its Interaction with Large-Scale Circulation Using Global Storm-Resolving Model

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1. Introduction

The ubiquitous clouds developing in the tropics not only influence local weather but also play an important role in regulating the Earth's climate. With the advance of wide-range satellite observation, it is well-known that tropical clouds tend to organize into large clusters maintaining many individual cloud cells. These organized cloud systems span a broad range of spatial and temporal scales and contribute significantly to tropical rainfall, weather disasters, hydrological cycle, and energy balance. Therefore, understanding the physics of tropical cloud organization and its interaction with large-scale circulation is essential to understanding the tropical weather and global climate.

The interaction between tropical clouds and large-scale circulation is a long-lasting question in atmospheric science due to its complicated multiscale nature. It involves processes and phenomenon ranging from kilometer-scale, hundred-kilometer mesoscale, up to planetary-scale of thousands of kilometers. The surging advance of supercomputing provides a great opportunity to explore the multiscale interactions between clouds and large-scale circulation. For example, global simulations at kilometer-scale explicitly simulating how small and intermediate scales of motions couple to large-scale circulation systems (Tomita et al., 2005; Miura et al., 2007; Satoh et al., 2008; Skamarock et al., 2012, 2014; Zängl et al., 2014; Stevens et al., 2019). In this research, idealized aquaplanet experiments by a global storm-resolving model, named "Model for Prediction Across Scales-Atmosphere (MPAS-A)", were performed to investigate the cloud organization mechanisms and their relationship with large-scale circulation.

2. Model and Experimental Designs

MPAS-A is a global, nonhydrostatic atmosphere model that was designed to seamlessly resolve weather and climate phenomena of different spatiotemporal scales (Skamarock et al., 2012, 2014). The defining feature of MPAS-A is the use of unstructured Voronoi (hexagonal) tessellations for horizontal meshes, which allows for either a global mesh with quasi-uniform cells or for a variable mesh with smaller cells (i.e., higher horizontal resolution) in regions of interest transitioning to larger cells elsewhere on the globe. This unique feature makes MPAS-A suitable both for real-time numerical weather prediction and for fundamental studies of weather-to-climate phenomena (Rios-Berrios et al. 2020, 2022).

An idealized aquaplanet framework was utilized as a simplified representation of the Earth without considering the complexed influences of land, topography, sea-ice, and seasons (Neale and Hoskins, 2001; Blackburn and Hoskins, 2013). The entire globe was configured as a water-covered surface with a time-invariant sea-surface temperature (SST). The latitudinally-varying SST profile of the control aquaplanet experiment was given as follows (Neale and Hoskins, 2001):

$$\text{CTRL: } SST(\emptyset) = \begin{cases} 27 \times \left[1 - \frac{1}{2}\left(sin^4\left(\frac{3}{2}\emptyset\right) + sin^2\left(\frac{3}{2}\emptyset\right)\right)\right]\ ^oC, & |\emptyset| \le \frac{\pi}{3} \\ 0\ ^oC, & \text{otherwise} \end{cases} \qquad \text{Equation (1)}$$

To remove seasonal variation driven by the Sun, a perpetual equinox insolation, symmetric about the equator, was specified by fixing the declination angle at 0° and fixing the solar constant at 1,365 W m^{-2}. A global quasi-uniform mesh configuration with 60-km horizontal-resolution was utilized in current research to reduce computation cost. A set of sensitivity experiments using different surface boundary conditions (i.e., globally-uniform or latitudinally-varying SST), external forcing (i.e., globally-uniform or latitudinally-varying solar insolation), and the Earth rotation rate (without or with the Earth rotation rate), was further performed to disentangle the convective aggregation processes in the full aquaplanet simulation in MPAS-A. Each simulation was integrated to its quasi-equilibrium state, and the last 20-days were analyzed.

3. Results and Discussion

The full aquaplanet simulation (i.e., the control experiment) at 60-km horizontal-resolution by MPAS-A realistically simulated the large-scale circulation and the cloud structures as observed in the Earth (Rios-Berrios et al., 2020). Figure 1 showed the zonal-mean latitude-height structure of large-scale circulation and clouds (left) and the horizonal distribution of clouds (right). In the tropics, an upward-motion branch developed and extended deeply up to 15 km, with deep convection growing upon the warm ocean surface. Convective bands formed at the equatorial convergence line forced by the imposed SST contrast, with regional organization patterns at mesoscales to synoptic scales. In the sub-tropics, a downward-motion branch developed and suppressed convective activities near 20°. In the mid-latitude, a second circulation cell with weaker strength and lower vertical extension compared to the first circulation cell in the tropics developed, and clouds grew upon the cold ocean surface and organized in elongated frontal structures.

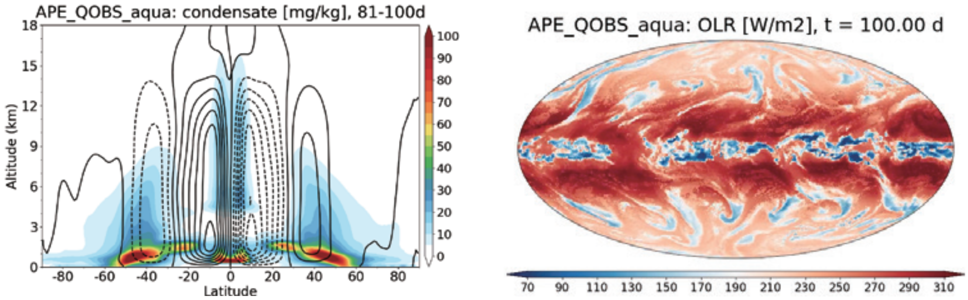

Figure 1. Large-scale circulation and cloud structure in the full aquaplanet

Left figure shows the zonal-mean latitude-height structure of cloud water contents (shading; mg kg^{-1}) and stream functions (contour; solid lines for clockwise circulation and dashed lines for counter-clockwise circulation) averaged over the last 20-days. Right figure shows the horizonal snapshot of outgoing longwave radiation (OLR; W m^{-2}) at Day 100.

To disentangle the convective aggregation processes in the full aquaplanet simulation in MPAS-A, a set of sensitivity experiments using different surface boundary conditions (i.e., globally-uniform or latitudinally-varying SST), external forcing (i.e., globally-uniform or latitudinally-varying solar insolation), and the Earth rotation rate (without or with the Earth rotation rate), was further performed. Figure 2 showed the horizonal distributions of clouds at the quasi-equilibrium state of each experiment. The results of the sensitivity experiments suggested that the organization structure and distribution of clouds in the full aquaplanet were governed by the internal self-aggregation processes, forced aggregation processes, and large-scale dynamics associated with the Earth rotation.

In the uniform-SST experiment, individual clouds spontaneously aggregated into hundred-kilometer mesoscale cloud clusters in the moist regions and were advected by mean flows over the globe. Clouds were organized through the internal interaction between convection, moisture, radiation, and atmospheric circulation, consistent with the mechanisms in high-resolution regional storm-resolving models under radiative-convective equilibrium, which describes the statistical equilibrium state that the atmosphere would reach in the absence of lateral energy transport (Wing et al., 2017). On the other hand, in the latitudinally-varying-SST experiment, convective bands formed at the equatorial convergence line forced by the imposed SST contrast, with quasi-stationary aggregation patterns gradually developing in the equatorial convective bands (Müller and Hohenegger, et al. 2019). The quasi-stationary aggregation patterns weakened as mean flows developed. In its quasi-equilibrium state, convective aggregation oscillated between bands and zonally aggregated patterns.

The comparison between the simulations with and without the Earth rotation showed that the global distribution and organization structure of clouds in the full aquaplanet simulation were largely modulated by the large-scale dynamics associated with the Earth rotation through its interplay with large-scale circulation. In the tropics, clouds clustered in bands and zonally aggregated patterns through the internal self-aggregation and forced aggregation processes, with tropical cyclones developing from the equatorial convective bands through rotation dynamics. In the mid-latitude, elongated frontal systems developed through mid-latitude wave dynamics and interacted with background mean flows.

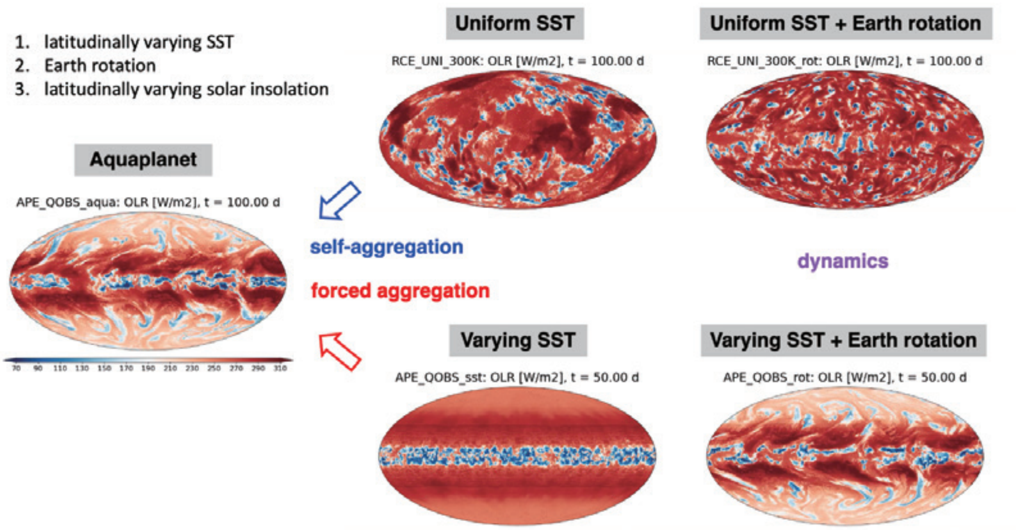

Figure 2. Horizontal distribution of clouds in the aquaplanet-type experiments using different combinations of surface boundary conditions and the Earth rotation rate

The horizonal snapshots of OLR (W m^{-2}) at the quasi-equilibrium state of each experiment are shown. Left figure is for the full aquaplanet experiment that uses latitudinally-varying SST, latitudinally-varying solar insolation, and the Earth rotation. The four sensitivity experiments using different combinations of surface boundary conditions (globally-uniform or latitudinally-varying SST) and Earth rotation (without or with the Earth rotation rate) are shown in the middle and right panels. All four sensitivity experiments have globally-uniform solar insolation.

Overall, our experiments showed a close relationship between cloud aggregation processes and the structure of large-scale circulation. While the forced aggregation mechanisms rising from the latitudinally-varying-SST drove the large-scale circulation in the meridional direction, self-aggregation processes rising from the internal interaction between convection, moisture, and radiation, influenced the large-scale circulation in the zonal direction.

4. Conclusions

Organized cloud systems contribute significantly to rainfall, global hydrological cycle, and energy balance. Understanding the physics of cloud organization and its interaction with large-scale circulation is essential to understanding regional weather and global climate. The surging advance of supercomputing provides a great opportunity to explore the multiscale interactions between clouds and large-scale circulation. This study used a global storm-resolving model, named "Model for Prediction Across Scales-Atmosphere (MPAS-A)", to investigate cloud organization mechanisms and their relationship with large-scale circulation. An idealized aquaplanet framework was utilized as a simplified representation of the Earth to reduce complexities and computation cost. A series of experiments using different surface boundary conditions, external forcing, and the Earth rotation rate, was performed to disentangle the convective aggregation processes in the full aquaplanet.

The simulation results using MPAS-A showed that the convective organization of tropical clouds interacted closely with large-scale circulation and strongly modulated its structure. The forced aggregation mechanisms rising from the latitudinally-varying-SST drove the large-scale circulation in the meridional direction, while the self-aggregation processes rising from the internal interaction between convection, moisture, and radiation, influenced the large-scale circulation in the zonal direction. Overall, the use of the global storm-resolving model helped understand the convective organization processes in the Earth and their two-way interaction with large-scale atmospheric circulation.

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