NOTES AND CORRESPONDENCE

Statistical Relation between Maximum Vertical Velocity and Surface Precipitation of Tropical Convective Clouds in a Global Nonhydrostatic Aquaplanet Experiment

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Abstract

This study investigated the properties of heavy precipitation and its associated vertical motion in an aquaplanet experiment with a 3.5-km mesh global cloud-system resolving model (GCRM). The statistics of precipitation and vertical velocity were examined in terms of the precipitation top height (PTH) and the maximum in-cloud vertical velocity in each column ($w_{max}$) for the grid points with the top 1% and 1–10% of the surface precipitation rate ($pr_{sfc}$) in the $10^\circ N$–$10^\circ S$ domain. To support the findings, realistic simulation cases were also analyzed.

In the columns with the top 1% (1–10%) of $pr_{sfc}$, peak frequencies of $w_{max}$ height were found at $z = 4$–6 (1–4) km with the PTH several kilometers above that. Thermodynamic conditions were more humid and warmer in these columns than in the columns with average precipitation. These results were common to all simulation cases. Composite time evolution of convection with heavy surface precipitation was also examined for the aquaplanet experiment. The results suggest that the vigorous upward motion in the middle (lower) troposphere for columns with the top 1% (1–10%) of $pr_{sfc}$ enabled efficient moisture transport from the boundary layer to the middle troposphere.

1. Introduction

The importance of tropical deep convection to global atmospheric circulation has been widely accepted since Riehl and Malkus (1958) first proposed the “hot tower hypothesis.” Recently, however, controversy over the hot tower theory has reemerged based on studies of long-term satellite observations (e.g., Liu et al. 2007) as well as cloud-resolving simulations (e.g., Fierro et al. 2009), which have indicated that occurrences of deep convective cores over tropical oceans were fewer than those originally assumed. The present study aims to gain insight into the properties of deep convection in a vast tropical domain using simulation data by a global cloud-system resolving model (GCRM).

A companion paper (Nasuno and Satoh 2011, hereafter referred to as NS11) describes the characteristics of tropical in-cloud vertical motion in a 3.5-km aquaplanet experiment using a GCRM (the Nonhydrostatic Icosahedral Atmospheric Model, NICAM). NS11 compares vertical profiles of simulated precipitation and latent heating with those observed by the Tropical Rain-
fall Measurement Mission (TRMM), and shows that the model reproduces the general morphology of precipitation and total latent heating profiles fairly well, although deficiencies of cloud representation are also noted (Masunaga et al. 2008; Satoh et al. 2010). NS11 focuses on the time evolution of convective updrafts and the relationship between thermodynamic conditions and vertical motions in the context of the multi-scale organization of convection. They argue that differences between active and suppressed regions of convection in the 3.5-km mesh aquaplanet experiment primarily reflect the large-scale structure of convective disturbances that were spontaneously generated in the model. Noticeably, strong vertical motion in the middle troposphere selectively occurs with heavy precipitation in NS11’s analysis, although the frequency of such events is low. This finding is consistent with the results of recent studies reporting the rare occurrence of undiluted ascent in the tropics (Zipser 2003; Liu et al. 2007; Fierro et al. 2009).

The primary objective of this paper is to further investigate properties of the vertical motion and thermodynamic conditions, focusing on heavy precipitating events. For this purpose, the statistics of maximum vertical motion \( \langle w, \text{max} \rangle \) in the columns with the top 1% and 1–10% of intense surface precipitation \( \langle pr, \text{sfc} \rangle \) are analyzed in a similar manner to that described in NS11.

To examine the robustness of the results, two realistic simulations using NICAM are also analyzed.

2. Simulation data and method of analysis

The aquaplanet experiments and realistic simulations were performed using NICAM (Satoh et al. 2008a). The experimental design of the aquaplanet case (hereafter referred to as case A) has been described by Tomita et al. (2005). A zonally invariant sea surface temperature (SST) was assumed (Neale and Hoskins 2001), and ten days integration was performed with a horizontal mesh size of 3.5 km and 54 vertically stretched layers \( (z = 35 \text{ m to 40 km}) \). Full-level snapshot data at the fifth day of integration and outputs at six levels \( (z = 35 \text{ m, 1 km, 2 km, 5 km, 10 km, and 14 km}) \) at 10-min intervals for the following 3 h are analyzed in this study. Two other simulations (Miura et al. 2007a; Satoh et al. 2010) used a realistic land-ocean distribution with 40 vertically stretched layers \( (z = 80 \text{ m to 38 km}) \). One is the global 3.5-km-mesh simulation, the design of which was described by Miura et al. (2007a). This case was initialized using the National Centers for Environmental Prediction (NCEP) final analysis data at 00UTC 25 December 2006 and integrated for 7 days (hereafter referred to as case R). The model dynamics and physics were approximately the same as those in the aquaplanet experiment, with the exception of revisions in the advection and turbulent schemes (Miura et al. 2007b). Data from seven snapshots at 1-day intervals are used in this study. The experimental design of the second simulation with a realistic land-ocean distribution was described by Satoh et al. (2010), where a horizontally stretched grid system (Tomita 2008a) was used (hereafter referred to as the case RS). This simulation was initialized at 00UTC 1 January 2007 using grid point values (GPV) from the Japan Meteorological Agency (JMA). Data from 24 snapshots at 1-h intervals in the domain of horizontal mesh sizes \( < 5 \text{ km} \) (approximately within a 10-degree radius of a point located on the equator at 110°E) are analyzed here. A cloud microphysical scheme, including five prognostic variables for condensates (NSW6, Tomita 2008b), was used in the case RS, whereas a simple scheme including two prognostic variables for water condensates (Grabowski 1998, hereafter referred to as G98) had been used in the case A and R.

Precipitation top height (PTH) and maximum vertical velocity in precipitating air columns \( \langle w, \text{max} \rangle \) are defined by the same criteria as used in NS11. The PTH is defined as the highest level of precipitating grids in the air columns, where precipitating grid points are identified by a precipitation rate \( > 0.3 \text{ mm h}^{-1} \). The precipitation rate is calculated from the vertical fluxes of precipitating condensates (i.e., rainwater and snow in the G98 scheme and rainwater, snow, and graupel in the NSW6 scheme). These are computed separately for each category of precipitating condensates and then summed. Here, the air-relative fluxes (mass of condensates \( \times \) terminal velocities) are considered to facilitate interpretation of the results (NS11). The formulation of terminal velocities is similar to that of G98 (Eq. 17 and Fig. 2) and NSW6 (Eq. 28 of Tomita 2008b)\(^1\), assuming the Marshall-Palmer distribution for drop sizes of precipitating condensates. The terminal velocities of snow and rainwater by the G98 (NSW6) scheme in the simulations range from 0.6–1.4 \((1.2–2.4)\) and 3–7 \((2–4)\) m s\(^{-1}\), respectively, while those for graupel (NSW6) range from 3–8 m s\(^{-1}\). Surface precipitation rate \( \langle pr, \text{sfc} \rangle \) is diagnosed from vertical flux of precipitating condensates at the lowest level. Magnitude and height of \( \langle w, \text{max} \rangle \) are vertically surveyed for cloudy grid points in each air column (NS11 Subsection 3.2). Statistics for the 10°N–10°S domain (on oceanic grid points for the realistic land-ocean distribution cases) are ex-

\(^1\) A density factor (square root of the ratio of air density at the ground level to that at each level) was multiplied for rainwater in NSW6.
Fig. 1. Probability of maximum in-cloud vertical velocity for each precipitating column ($w_{\text{max}}$) in the 10°N–10°S domain (open circle) and for columns containing the top 1% (closed circle) and 1–10% (cross) of surface precipitation rates ($pr_{\text{sfc}}$) in the case A. The abscissa (ordinate) is logarithmic in (a) ([b]). Log-normal distributions are also plotted (dashed lines) in (a). (c) Cumulative frequency of $pr_{\text{sfc}}$. The bin widths for $w_{\text{max}}$ in (a) and (b) and for $pr_{\text{sfc}}$ in (c) are 0.1 in logarithmic scale, 0.5 m s$^{-1}$, and 3 mm h$^{-1}$, respectively.
Fig. 2. Average profiles of (a) vertical velocity, (b) relative humidity for water saturation, (c) temperature difference, (d) zonal velocity for the precipitating columns with the top 1% of $pr_sfc$ (thick solid lines), top 1–10% of $pr_sfc$ (thick broken lines), and all the precipitating columns (thin lines) in the 10°N–10°S domain. In (c), differences from the averages over all the precipitating columns are drawn. The case A (black lines), R (red lines), and RS (blue lines) are presented. Averages in the 10°N–10°S domain are plotted in the case A and R. Oceanic regions are used for the case R and RS.

amine for all the simulation cases (cf. NS11; Takayabu 2002; Satoh et al. 2008b).

3. Results

Figure 1 shows the probability density function (PDF) of $w_{max}$ in the case A. To investigate vertical motion associated with heavy precipitation, $w_{max}$ is classified by the $pr_sfc$. The precipitation rate for the top 1% (10%) cumulative probability is 46 (7) mm h$^{-1}$ (Fig. 1c). In the case R and RS, these rates are 50 (6.5) and 43 (5.8) mm h$^{-1}$, respectively (not shown). The PDF of $w_{max}$ has approximately log-normal distributions for all categories, consistent with oceanic observations of convective updrafts (LeMone and Zipser 1980). The mean and standard deviations of $w_{max}$ for the columns with the top 1% and 1–10% of $pr_sfc$ and all the precipitating columns are (0.63, 0.23), (0.06, 0.28), and (–0.53, 0.44) in logarithm (Fig. 1a), leading to peak frequencies of $w_{max}$ at approximately 3, 1, and 0.3 m s$^{-1}$, respectively. The slopes of probability for the columns with the top 1% of $pr_sfc$ and for all the precipitating columns are nearly parallel in the upper ranges of $w_{max}$ (Fig. 1b), which indicate that these vigorous updrafts are exclusively associated with the top few percentages of intense precipitation events.

Figure 2a presents average profiles of vertical velocity in the columns with the top 1% and 1–10% of $pr_sfc$, and all the precipitating columns for the three
Simulation cases. Peak magnitudes of upward motion in the columns with the top 1% of \( pr_{sfc} \) are 5–7 times larger than those for the top 1–10%. The heights of the peak velocity are in the middle troposphere (\( z = 4–6 \) km) for the top 1%, and higher than those for the top 1–10% (\( z = 2–3 \) km). Thermodynamic conditions in the columns with heavy precipitation are more humid below \( z = 12 \) km and warmer in \( z = 2–14 \) km than those averaged over all the precipitating columns (Figs. 2b, c), indicating stronger latent heat release in the deep troposphere in these columns. Figure 2d shows the average profiles of zonal wind, which was dominant in the equatorial regions in the three experiments. In the case A, the vertical shear of zonal wind in the columns with heavy precipitation is weaker than that averaged over all the precipitation columns (Fig. 2d). Significant easterly shear in the case RS is associated with a Madden-Julian Oscillation event (Satoh et al. 2010). Generally, the cases A and R are very similar in comparison with the case RS.

Figure 3 shows two-dimensional histograms of the height of occurrence of \( w_{max} \) and PTH. Histograms for the precipitating columns with \( w_{max} > 1 \) m s\(^{-1} \) are also presented, as well as those categorized by the \( pr_{sfc} \). The fractions of these columns to all precipitating columns are 9.4, 11.1, and 8.0% for the case A, R, and RS, respectively. The frequency distributions for all the precipitating columns are nearly on a diagonal line, indicating precipitation production by upward motion around the PTH (Figs. 3a–c). In the frequency distributions for precipitating columns with \( w_{max} > 1 \) m s\(^{-1} \) and the columns with heavy surface precipitation, \( w_{max} \) height is generally lower than the PTH (Figs. 3d–l), indicating the occurrence of \( w_{max} \) in organized convection with precipitating condensates already formed above (e.g., Fig. 12 of NS11). The height ranges of peak occurrence differ between the columns with the top 1% and 1–10% of \( pr_{sfc} \) in all the simulation cases. For the top 1% (1–10%), maximum occurrences of \( w_{max} \) height are found at \( z = 4–6 \) (1–4) km with the PTH a few kilometers above that (Figs. 3g–l). The probability distributions for the columns with \( w_{max} > 1 \) m s\(^{-1} \) (Figs. 3d–f) include double peaks. The peaks in the lower troposphere nearly coincide with those of the top 1–10% of \( pr_{sfc} \) columns (Figs. 3j–l). Such correspondence is not found in the upper troposphere, suggesting that updrafts (\( w_{max} > 1 \) m s\(^{-1} \)) in the upper troposphere are not necessarily associated with heavy surface precipitation.

Temporal variation of the vertical motion and thermodynamic conditions in the columns with heavy precipitation is investigated using the six-level 10-min interval outputs of the case A. Maximum \( pr_{sfc} \) during the 3-h period are calculated in each column, and columns with maximum \( pr_{sfc} > 46 \) mm h\(^{-1} \) (7 mm h\(^{-1} \) < \( pr_{sfc} < 46 \) mm h\(^{-1} \)) are defined here as the “top 1% (1–10%) \( pr_{sfc} \) columns.” Composite analyses for the \( pr_{sfc} \) categories are presented in Fig. 4, where the base time is equivalent to the time of maximum \( pr_{sfc} \) for each column.

In the top 1% (1–10%) \( pr_{sfc} \) columns, updraft cores are found at \( z = 5 \) (2) km at the time of maximum \( pr_{sfc} \) (Figs. 4a, b). Clouds (total condensates \( \leq 0.2 \times 10^{-3} \) kg kg\(^{-1} \)) are generated in the lower troposphere 2 (1) h prior to the peak \( pr_{sfc} \), grow into the upper troposphere producing heavy precipitation (Fig. 4c), and remain suspended for more than 3 h. In both columns, transport of moisture from the boundary layer to the middle troposphere is obvious (Figs. 4c, d). The moistening and diabatic warming reach higher levels in the top 1% \( pr_{sfc} \) columns than in the top 1–10% \( pr_{sfc} \) columns. The top 1% \( pr_{sfc} \) columns are in a relatively moist environment with upward motion throughout the troposphere even after termination of precipitation (downward motion is formed in a thin layer near the surface). In the top 1–10% \( pr_{sfc} \) columns, moistening in the lower troposphere also remains after the weakening of \( pr_{sfc} \) in subsiding motions.

4. Summary and discussion

In this study, the statistical properties of vertical motion and thermodynamic conditions in columns with heavy precipitation are investigated using a global 3.5-km mesh aquaplanet experiment dataset (case A). Maximum vertical motion (\( w_{max} \)) in the top 1% and 1–10% of intense surface precipitation (\( pr_{sfc} \)) is examined in a manner similar to that described in NS11. The same analyses for realistic simulations using the global (Miura et al. 2007a; case R) and regionally stretched (Satoh et al. 2010; case RS) NICAM are also presented to support the findings. In the global (regionally stretched) simulations, the cloud microphysical scheme of G98 (NSW6) is used.

Two-dimensional histograms of \( w_{max} \) height and precipitation top height (PTH) show peak occurrences of \( w_{max} \) at \( z = 4–6 \) (1–4) km for the top 1% (1–10%) of \( pr_{sfc} \) with the PTH a few kilometers above that. Thermodynamic conditions are more humid and warmer in the columns with heavy precipitation than in the columns with average precipitation. These properties are common to all three simulation cases and consistent with the results of NS11, where intense \( w_{max} \) in the middle troposphere selectively occurred in an active part of large-scale, well-organized convective systems.
Fig. 3. Two-dimensional histograms of PTH and height of $w_{max}$ for (a)–(c) all the precipitating columns in the 10°N–10°S domain, precipitating columns with (d)–(f) $w_{max} > 1$ m s$^{-1}$, (g)–(i) top 1% of $\text{pr}_{sfc}$, and (j)–(l) top 1–10% of $\text{pr}_{sfc}$. The case A (a, d, g, j), R (b, e, h, k), and RS (c, f, i, l) are presented. The bin widths for PTH and $w_{max}$ height are 1 km. The probabilities are vertically interpolated following the method of NS11. Contour lines are drawn for 0.1% km$^{-2}$ and 0.2% km$^{-2}$ and at 0.5% km$^{-2}$ intervals. The light (dark) shading depicts 1–2% km$^{-2}$ (> 2% km$^{-2}$). Broken lines indicate $w_{max}$ height equals PTH.
The composite time evolutions of convection in the columns with the top 1% and 1–10% of pr_{sfc} are investigated for the aquaplanet experiment. The results show the occurrence of vigorous upward motion in the lower to middle troposphere in these columns, which enables efficient transport of moisture from the boundary layer to the middle troposphere. This finding is consistent with the results of NS11, where the category with w_{max} height in the middle troposphere produced the heaviest precipitation via a tight linkage between vertical motion and moist processes. The deep convection associated with very heavy precipitation events (top 1%) occurred within a warm, moist environment throughout the troposphere for the duration of the event lifecycles. Moistening effects in the lower troposphere by convection including low-level updrafts (e.g., top 1–10% pr_{sfc} columns) are also suggested.

Besides the similarity among the three simulation cases in the major points described above, differences are also noted in the mean profiles of temperature, mois-
ture, and vertical motion. The results suggest significant impact of different cloud microphysical schemes. For example, temperature minimum in the middle troposphere (\(z = 4–6\) km) associated with the melting process is formed in the case RS using the NSW6 scheme; this process was not considered in the G98 scheme. In the case RS, frequencies of \(w_{\text{max}}\) height at \(z = 8–12\) km with PTH in the upper troposphere are more pronounced than those in the case A and R. A large amount of graupel, as well as snow, was produced in the case RS (Satoh et al. 2010), and the peak frequency in the upper troposphere are attributable to cloud microphysical processes associated with them.

It is also possible that differences between the case RS and other two cases were partly due to the limited domain of analysis in the former. For example, vertical wind shear was more pronounced over the regional domain for the case RS than that over the \(10^\circ\text{N}–10^\circ\text{S}\) domain for the case R, which may have induced difference in mesoscale convective organization. The dependence on horizontal resolution is also a critical issue with respect to the statistics of vertical motion presented here (Weisman et al. 1997; Khaireudinov et al. 2009). This preliminary study will be followed by further investigations using global simulation with the NSW6 scheme and sufficiently fine mesh sizes.

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References


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