Eastward-Propagating Property of Large-Scale Precipitation Systems Simulated in the Coarse-Resolution NICAM and an Explanation of its Appearance

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Abstract

Using the Non-hydrostatic ICosahedral Atmospheric Model (NICAM) on an aqua-planet with a uniform longitudinal sea surface temperature, precipitation systems (PSs) with coarse horizontal resolutions are studied. An eastward-propagating (EP) property of the PSs is seen even though the horizontal resolution becomes coarser to 112 km, as long as the vertical stratification is kept conditionally unstable. The appearance or disappearance of the EP property is explained in comparison with mesoscale (100 km) and large-scale (1,000 km) PSs, a non-precipitation system (NPS), and a system simulated by a dry model with positive-only wave CISK heating (DP). By assuming that the height and the updraft intensity of convection are common in these systems, the turnover times of representative convections are estimated. Compared with the time scale of the equatorial beta (T_β), where its effect essentially works and the distinct EP property appears, the turnover times of the large-scale PS and DP are longer than T_β , producing the EP property, whereas those of the NPS and mesoscale PSs are shorter, inducing no EP property. These results are consistent with observations and model outputs (Nakazawa 1988; Nasuno et al. 2007, 2008).

1. Introduction

Organized precipitation systems (PSs) consist of various kinds of convective and stratiform clouds, and diabatic heating due to precipitation plays essential roles in their formation and maintenance. These systems are popular in the tropics and occur as large-scale super clusters (SCs) and planetary-scale Madden Julian Oscillation (MJO; Madden and Julian 1971). Such PSs have a unique eastward-propagating (EP) property (e.g., Wheeler and Kiladis 1999) and an internal multi-scale structure (MSS) (e.g., Nakazawa 1988). Here, the EP property in this study means that it is more remarkable compared with the westward-propagating (WP) one when the equatorial beta effect is included. The MSS is defined as meso- to large-scale organized structures in which new convective cells are successively generated around older ones. The vertical slanted structures of convective cells are also observed and seem tightly connected with the MSS. The PSs usually have contrasting horizontal structures of vertical motions, where upward motions are concentrated in the wide areas of downward ones.

The Non-hydrostatic ICosahedral Atmospheric Model (NICAM) is a useful tool for studying the EP property and MSS because it has full physical processes such as dynamics, radiation, turbulence, and microphysics to represent realistic tropical motions. As the horizontal resolution increases (i.e., the grid size Δ becomes smaller), detailed features of temporal convective motions, EP property, and MSS are realistically reproduced. Indeed, the aqua-planet simulations of the NICAM (Tomita et al. 2005;

Nasuno et al. 2007, 2008) succeeded in simulating these features in SCs in the cases of $\Delta = 3.5$ km or 7 km. These outputs give us abundant information and hints to achieve a fundamental understanding of these features. However, abundant information does not always lead to a clear understanding. For example, the formation mechanism of the EP property, which is our present target, is still controversial, even though the NICAM simulation reproduced the realistic EP property. Observed and simulated large-scale PSs have the EP property, while mesoscale PSs have WP property (e.g., Nakazawa 1988; Nasuno et al. 2007, 2008). Here, large-scale PSs are simply defined as those having horizontal scales of 1,000 km, and mesoscale ones as those with horizontal scales of 100 km. To explain the appearance or disappearance of the EP property, it is needed to seek essential mechanisms from all possibilities.

In this study, PSs simulated with coarse horizontal resolutions are investigated and compared with a non-precipitation system (NPS) and a system simulated by a dry model with positive-only wave CISK heating (DP), in which diabatic heating is included only when the vertical velocity around the cloud base is positive (e.g., Lau and Peng 1987). One explanation of the EP property why large-scale PSs and DP strikingly differ from the mesoscale PSs and NPS is made on the basis of the turnover times of convections.

2. Model description

To study the PSs and NPS, NICAM (e.g., Satoh et al. 2008) is used on an aqua-planet, where the sea surface temperature (SST) is fixed to be uniform in the longitudinal direction. The diurnal variation of the solar radiation is included. Here, $\Delta = 14$ km, 56 km, and 112 km are used. No scheme of cumulus parameterizations is included. Although the resolution is coarse to resolve convective cells, convective motions are always induced because the vertical stratification is kept conditionally unstable due to the fixed SST and radiative cooling in the atmosphere. At least, we can get large-scale PSs even though Δ is large to 112 km. The initial conditions are given using the outputs of the NICAM climate simulation with $\Delta = 14$ km (Iga et al. 2010), where quasi-steady EP disturbances with a speed of about 15 m s^{-1} are established.

To simulate the NPS, as one method, the production term from cloud to rain (the autoconversion term) is excluded from the cloud microphysical processes of NICAM (Tomita 2008). Since this is the main production term for precipitation, the features of NPS are obtained, although other generation processes of precipitation such as the melting one from ice/snow particles still exist. In addition, as a second method, the terminal velocities of precipitation particles are excluded to make all hydrometeors move together with air parcels. Similar results are obtained in both methods, so that the first results are presented as the NPS.

3. Characteristic features of the PSs and NPS simulated by the NICAM

In this section, the results of PS cases are shown at the beginning and, then, those of NPS case are presented. Longitude-time sections of the vertical velocity (w) along the equator are shown

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Fig. 1. Longitude-time sections of w (10^{-2} m s^{-1}) averaged between 3°S and 3°N at the height of 2.6 km for (a) $\Delta = 14 \text{ km}$ PS, (b) $\Delta = 56 \text{ km}$ PS, (c) $\Delta = 112 \text{ km}$ PS, and (d) $\Delta = 56 \text{ km}$ NPS cases. Blue and black horizontal bars inside denote the longitudinal intervals in Figs. 3 and 4, respectively.

in Fig. 1 for (a) $\Delta = 14 \text{ km}$ PS, (b) $\Delta = 56 \text{ km}$ PS, (c) $\Delta = 112 \text{ km}$ PS, and (d) $\Delta = 56 \text{ km}$ NPS cases. For the $\Delta = 14 \text{ km}$ PS case (Fig. 1a), large-scale EP PSs with a speed of about 15 m s^{-1} are attained, while mesoscale PSs propagate in the opposite direction, as described in Nasuno et al. (2007, 2008). The westward tilting of cells is seen and the MSS is obtained. For the $\Delta = 56 \text{ km}$ PS case (Fig. 1b), the EP speed is similar to that in Fig. 1a, although the fine structures become diminished due to the coarse resolution. The westward tilting of cells appears much weaker than that in Fig. 3a and the MSS disappears mostly. For the $\Delta = 112 \text{ km}$ PS case (Fig. 1c), the weak EP property is still seen, but the WP one is noticed. Although the EP speeds change slightly, the EP features can be seen more clearly in other variables; outgoing long-wave radiation at the top of the atmosphere (OLR) and a zonal wind (u) (Fig. 2). It is interesting that large-scale PSs, which may be resolvable for the $\Delta = 112 \text{ km}$ case, have the EP property.

Longitude-height sections of wind vectors (u , w) and diabatic heating (dh) are shown in Fig. 3. Cooled layers at a height of about 4 km correspond to the melting layer. Several intense upward motions are seen, and intense heating occurs just above the melting layer. The MSS and vertical slanted structure are found for $\Delta = 14 \text{ km}$ PS case (Fig. 3a) but become weak or disappear for the $\Delta = 56 \text{ km}$ PS and $\Delta = 112 \text{ km}$ PS cases (Figs. 3b and 3c, respectively). It is suggested that the representation of MSS is deeply dependent on the horizontal resolution of the model, whereas the EP property is not.

Horizontal distributions of wind vectors [u , meridional velocity (v)], pressure, and dh at the height of 7.95 km are shown in

Fig. 2. Same as Fig. 1c, except for (a) OLR (K) and (b) u (m s^{-1}) at the height of 2.6 km.

Fig. 4. Remarkable anti-cyclonic circulation and high pressure around 14°N in the upper troposphere are noticed for $\Delta = 14 \text{ km}$ PS (not shown) and $\Delta = 56 \text{ km}$ PS cases (Fig. 4a). This vortex motion is similar to the Rossby response patterns for localized heating, which is located around the equator (e.g., Gill 1980). The similar features are also observed for the positive-only wave CISK case (e.g., Lau and Peng 1987). The vortex motion is also seen,

Fig. 3. Longitude-height sections of wind vectors [u (m s^{-1}), w (10^{-2} m s^{-1})] and dh (color; 10^{-4} K s^{-1}) for (a) $\Delta = 14 \text{ km}$ PS, (b) $\Delta = 56 \text{ km}$ PS, (c) $\Delta = 112 \text{ km}$ PS, and (d) $\Delta = 56 \text{ km}$ NPS cases along the equator.

Fig. 4. Horizontal distributions of wind vectors [u (m s^{-1}), v (m s^{-1})], pressure (contour; hPa), and diabatic heating (color; 10^{-4} K s^{-1}) at the height of 7.95 km for (a) $\Delta = 56$ km PS, (b) $\Delta = 112$ km PS, and (c) $\Delta = 56$ km NPS cases.

although unclear for the $\Delta = 112$ km PS case (Fig. 4b), compared with that of the $\Delta = 56$ km PS case.

Next, the results of the NPS case are shown. On the contrary, the NPS differs from PSs in many aspects. For the $\Delta = 56$ km NPS case (Fig. 1d), simulated disturbances propagate westward with a speed of about -10 m s^{-1} , close to that of the environmental winds. No MSS (Fig. 3d) or no response pattern (Fig. 4c) is attained. If a fine-mesh model is applied to the NPS, it is anticipated that reproduced convection becomes finer as Δ becomes smaller, because the NPS indicates many features of small-scale convection. Then, Benard cell-like convection with an aspect ratio of $O(1)$ would be obtained when Δ is small enough to describe each convective cell as seen in Nakajima and Matsuno (1988) (or a redrawn figure by Yoshizaki and Kato 2012), where the two-dimensional model with a simple warm rain was used on the non-rotating plane. Similar results are expected even though the rotating plane is applied or the cloud physics becomes complicated.

Fig. 5. Schematic convection in regions I, II, III, and IV. A time scale is calculated along the blue lines, where absolute averaged intensities of upward motion, downward motion, and horizontal wind are assumed to be W , $W/2n$, and W , respectively, and the vertical and horizontal distances are $H/2$ and $(n + 1/2)H$, respectively. A half domain is indicated.

4. Estimates of turnover times of NPS, PS, and DP

In the previous section, EP large-scale PSs were attained for the $\Delta = 112$ km case. Then, it is needed to explain the appearance of the EP property in the large-scale PSs. Here, the large-scale PSs are compared with the NPS, mesoscale PSs, and DP. For the DP, a single small area of intense upward motion and widely broad ones of downward motions are generally obtained (e.g., Lau and Peng 1977; Yoshizaki 1991). Since the environmental atmosphere is stably stratified and adiabatic heating occurs in the areas of downward motions, weak downward motions are realized as preferred patterns. Then, it is anticipated that infinitely wide areas of downward motions would be attained, when the model domain is sufficiently broad in the horizontal directions.

Representative motions for NPS, PSs, and DP are simply called “convections”. The circulation of convection, which represents a closed stream line, is estimated. No Earth rotation is counted, since convections are assumed to be aligned in the eastward direction over the equator. Consider a two-dimensional (x, z)

circulation of convection with a height H and an updraft W , which is given at $x = H/2$ and $z = 0$ (Fig. 5). It is assumed that H and W are common in all systems. Horizontal velocity u_i and vertical velocity w_i in region i ($i = \text{I, II, III, and IV}$) are simply given as $[u_1 = 2W(x - H/2)/H, w_1 = 2W(H/2 - z)/H]$, $[u_2 = -W(x + nH)/nH, w_2 = W(z - H/2)/nH]$, $[u_3 = W(x + nH)/nH, w_3 = -W(z + H/2)/nH]$, and $[u_4 = 2W(H/2 - x)/H, w_4 = 2W(z + H/2)/H]$, respectively, where n (a positive constant) is an areal ratio of downward motion to upward one. Here, the continuity equation $\partial u_i / \partial x + \partial w_i / \partial z = 0$ is satisfied only in the inner region. The representative circulation is calculated with the assumptions of the vertical scale of upward motions, $H/2$, and the horizontal one of downward motions, nH . Then, a time scale of convection A , T_A , is defined as follows.

$$T_A = H/2W + nH/W + (2n + 1)H/W = (6n + 3)H/2W. \quad (1)$$

Figure 6 shows schematic circulations of convections for NPS, PS, and DP. The horizontal scale L corresponds to $(n + 1)$

Fig. 6. Schematic circulations in a two-dimensional model for (a) NPS, (b) PS, and (c) DP. The dotted areas are ones of upward motions. $S_{w>0}$ and $S_{w<0}$ mean the areas of upward and downward motions, respectively.

Table 1. Estimates of the turnover times of NPS, mesoscale PS, large-scale PS and DP. $W = 10 \text{ m s}^{-1}$ and $H = 16 \text{ km}$ are used.

	NPS	Meso-scale PS	Large-scale PS	DP
L (km)	16	100	1000	∞
n	0.5	3.1	31	∞
Turnover Time (h)	1.3	4.8	42	∞

$1/2)H$. Here, H and W are assumed to be 16 km and 10 m s^{-1} , respectively. For the NPS, upward and downward motions have similar horizontal sizes to the height. Then, $n = 1/2$ is selected and T_{NPS} is estimated to be roughly 1.3 h . For the DP, $n = \infty$ is chosen, since the convection of the DP has an infinite area of downward motions. For the PS cases, the estimations of n are similarly made by giving lengths of meso- and large-scales. However, the convection of the PS is generally transient and a strict definition of the closed circulation is difficult to make. For the mesoscale PSs, using the $nH = 50 \text{ km}$, the time scale $T_{\text{meso PS}}$ is estimated as 4.8 h . Similarly, for the large-scale PSs, the time scale $T_{\text{large PS}}$ is obtained as 42 h , using $nH = 500 \text{ km}$. The horizontal scales, n , and turnover times for NPS, mesoscale PS, large-scale PS, and DP are summarized in Table 1.

Independently of turnover times of convections, other time scales, which control the motions from the governing physical system, are needed. Yoshizaki (1991) stressed that the effect of the equatorial beta is essential for the appearance of the EP property. Then, a time scale T_β , which is defined as $(\pi/2\beta NH)^{1/2}$, is adopted. Here, one vertical mode is assumed and vertical scaling H/π is used. Applying a static stability $N = 10^{-2} \text{ s}^{-1}$, a beta parameter $\beta = 2.3 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$, a height 16 km , and an equatorial radius of deformation $(NH/2\beta\pi)^{1/2} = 1,050 \text{ km}$, T_β is estimated as roughly 5.7 h .

Then, a following relationship is attained:

$$T_{\text{NPS}} < T_{\text{meso PS}} < T_\beta < T_{\text{large PS}} < T_{\text{DP}}. \quad (2)$$

From this relationship, only large-scale PS and DP have larger time scales than T_β , and have a possibility of the EP property, whereas the NPS and mesoscale PS do not. Indeed, Nakazawa (1988) observed the EP large-scale and the WP mesoscale PSs, and Nasuno et al. (2007, 2008) also simulated similar features.

Until now, we discussed the time scales of NPS, PS, and DP. The same argument is available by using the horizontal scales.

Yoshizaki and Kato (2012) studied the formation mechanism of an MSS observed in PSs. In addition to its formation mechanism, they stressed that the characteristic features of PSs, such as a conditionally unstable stratification, a contrasting horizontal structure of vertical motion, an inhomogeneous physics in a horizontal direction, and non-conservation of total water content, are interrelated and concluded that the drop of hydrometeors produces such unique PS features. Similarly, the EP property of large-scale PS over the equatorial regions, coupling with the equatorial beta, may appear as a manifestation of PS features. Therefore, further theoretical and numerical studies of the PSs are needed from this viewpoint.

5. Summary

The EP property of large-scale PSs simulated in the coarse-resolution NICAM was studied. It remains even though the horizontal resolutions of models become coarser to 112 km . Here, four systems were considered; (1) NPS, (2) mesoscale PSs, (3) large-scale PSs, and (4) DS with positive-only wave CISK heating. The appearance of the EP property in the large-scale PSs and DP, and the disappearance in the mesoscale PSs and NPS were explained as follows. By considering the circulations of representative convections and assuming common height and updraft intensity in these systems, the turnover times were estimated. In addition to the turnover times of convections, the independent time scale

related to the equatorial beta (T_β), which highlights the EP property, was introduced for comparison. Then, the large-scale PSs and DP have longer and infinite turnover times, respectively, than T_β , indicating the appearance of the EP property, whereas the NPS and mesoscale PSs have shorter turnover times than T_β , resulting in no EP property. These results are consistent with observations and model outputs (Nakazawa 1988; Nasuno et al. 2007, 2008).

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References

- Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447–462.
- Iga, S., M. Yoshizaki, M. Satoh, T. Nasuno, H. Tomita, and K. Yasunaga, 2010: Global aquaplanet experiments using the NICAM new codes. *Proc. Spring Meeting*, Japan Meteor. Soc., **97**, 76 (in Japanese).
- Kiladis, G. N., M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy, 2009: Convectively coupled equatorial waves. *Rev. Geophys.*, **47**, RG2003, 1–42.
- Lau, K.-M., and L. Peng, 1987: Origin of low-frequency (intraseasonal) oscillations in the tropical atmosphere. Part I: Basic theory. *J. Atmos. Sci.*, **44**, 950–972.
- Madden, R., and P. Julian, 1971: Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702–708.
- Nakajima, K., and T. Matsuno, 1988: Numerical experiments concerning the origin of cloud clusters in the tropical atmosphere. *J. Meteor. Soc. Japan*, **66**, 309–329.
- Nakazawa, T., 1988: Tropical super clusters within intraseasonal variations over the western Pacific. *J. Meteor. Soc. Japan*, **66**, 823–839.
- Nasuno, T., H. Tomita, S. Iga, H. Miura, and M. Satoh, 2007: Multiscale organization of convection simulated with explicit cloud processes on an aquaplanet. *J. Atmos. Sci.*, **64**, 1902–1921.
- Nasuno, T., H. Tomita, S. Iga, H. Miura, and M. Satoh, 2008: Convectively coupled equatorial waves simulated on an aquaplanet in a global nonhydrostatic experiment. *J. Atmos. Sci.*, **65**, 1246–1265.
- Satoh, M., T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S. Iga, 2008: Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations. *J. Comp. Phys.*, **227**, 3486–3514.
- Tomita, H., 2008: New microphysics with five and six categories with diagnostic generation of cloud ice. *J. Meteor. Soc. Japan*, **86A**, 121–142.
- Tomita, H., H. Miura, S. Iga, T. Nasuno, and M. Satoh, 2005: A global cloud-resolving simulation: Preliminary results from an aqua planet experiment. *Geophys. Res. Lett.*, **32**, L08805, doi:10.1029/2005GL022459.
- Wheeler, M., and G. N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain. *J. Atmos. Sci.*, **56**, 374–399.
- Yoshizaki, M., 1991: Selective amplification of the eastward-propagating mode in a positive-only wave-CISK model on an equatorial beta plane. *J. Meteor. Soc. Japan*, **69**, 353–373.
- Yoshizaki, M., and T. Kato, 2012: The formation mechanism of multi-scale structures appearing in convective precipitation systems. *J. Meteor. Soc. Japan*, (submitted).