Why do Super Clusters and Madden Julian Oscillation Exist over the Equatorial Region?

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Abstract

Over the tropics, two types of precipitation systems (PSs), super clusters (SCs) and Madden Julian Oscillation (MJO), are frequently observed, having similar meridionally symmetric structures about the equator but different eastward-propagating (EP) speeds. To investigate the reasons why these PSs exist, the dependence of the longitudinal variations of surface temperature (SST) is examined using a NICAM on an aqua-planet. In a longitudinally uniform-SST case, only SC-like fast-EP PSs appear. When the longitudinal variation of the SST increases, meanwhile, a stationary Walker circulation (WC) emerges and MJO-like slowly EP PSs occur on the western part of a high-SST area. It is expected in the real atmosphere that two different types of EP PSs can exist in parallel due to complex surface conditions: 1) SCs as free PSs and 2) MJOs as forced PSs. Here, free (forced) PSs mean convection, which is uncontrolled (controlled) by the longitudinal variation of the SST. It is also obtained that an asymmetric WC is produced, even though the SST variation symmetric about 180° longitude is forced. Owing to the WC, combined with the Hadley circulation, the MJO is generated and decayed locally, and westward-propagating PSs are dominantly observed in the subsidence areas of the WC.

1. Introduction

In the tropics, organized precipitation systems (PSs) are frequently observed, such as super clusters (SCs) and Madden Julian Oscillation (MJO) (Madden and Julian 1971). Wheeler and Kiladis (1999) showed that these PSs are meridionally symmetric about the equator, but have different eastward-propagating (EP) speeds as well as horizontal scales. The SCs, which are called “Kelvin” by Wheeler and Kiladis (1999), are large-scale disturbances of zonal wave-number 2−10 with speeds of about 15−25 m s⁻¹, while an MJO is a planetary-scale one of zonal wave-number 1−4 with speeds of less than 10 m s⁻¹. Hereafter, SCs and MJOs are simply classified using the critical EP speed (cc) of 10 m s⁻¹. That is, large- to planetary-scale PSs with EP speeds greater (smaller) than cc are grouped into SCs (MJOs). Our concern, then, is why two types of EP PSs, whose meridional structures are symmetric about the equator, appear or are needed.

Using general circulation models, in which subgrid-scale convection is parameterized, only SC-type fast-EP disturbances were obtained in the aqua-planet, where the zonal sea surface temperature (SST) is uniform (e.g., Hayashi and Sumi 1986; Lau and Held 1988). On the other hand, MJO-like slowly EP disturbances were simulated in the longitudinally variable-SST cases (e.g., Maloney et al. 2010).

Similar results were attained using a Non-hydrostatic ICosa-hedral Atmospheric Model (NICAM), where the microphysical process is included to explicitly represent clouds and precipitation. Multi-scale horizontal structures of SC-like fast-EP PSs with speeds of 17−20 m s⁻¹ and mesoscale westward-propagating (WP) cloud clusters were obtained in the longitudinally uniform-SST cases (Tomita et al. 2005; Nasuno et al. 2007, 2008). In these cases, the horizontal grid size (Δ) is 7 km or 3.5 km. On the other hand, using the realistic lower boundaries, such as non-uniform SST, land-sea contrast, and orography, Miura et al. (2009) simulated both SC-like and MJO-like EP PSs with speeds of 18 m s⁻¹ and 5−6 m s⁻¹, respectively. Therefore, it is suggested that the lower boundary conditions give essential impacts on their formations.

In this study, using the NICAM, only the dependence of the longitudinal variation of the SST is examined to pursue the reason why both SC and MJOs exist in parallel. Then, the cyclic occurrence of the MJO between the initiation and termination areas and the formation mechanism of WP PSs are discussed.

2. Explanation of cases and definitions of Hadley and Walker Circulations

Aqua-planet simulations of the NICAM are performed for a longitudinally uniform-SST case (Fig. 1a) and for longitudinally variable-SST cases with a wave-number 1 of amplitude ΔT (unit K; Fig. 1b). ΔT = 0 and ΔT = 2.25 cases are simulated for 60 days, and a ΔT = 4.5 case, for 180 days. The horizontal resolution Δ = 14 km is used. Initial conditions are given using the output of the Δ = 14 km climate simulation in the ΔT = 0 case at 60 days (Iga et al. 2010), when quasi-steady EP disturbances with a speed of about 15 m s⁻¹ are established.

The components of the Hadley circulation (HC) and the Walker circulation (WC) are defined as follows. When a variable (A) denotes zonal wind (u), vertical velocity (w), or diabatic heating due to the phase changes of water substance (Q), the HC component is defined as (Å), where 60- or 180-day time mean Å and longitudinal averaging (Å) are operated. Meanwhile, the WC component is defined as the difference between the time mean and the HC component, A − (Å). A standard deviation of the WC component is defined as σ = √(Å − (Å)²/m), where m is the grid number of the longitude. The maximum and minimum values

Fig. 1. Horizontal distributions of the SST (Iga et al. 2010). (Left) a longitudinally-uniform case and (right) a longitudinally-variable one of wave-number 1 with an amplitude ΔT = 4.5 (unit; K).
of \( w \) in the WC component are also calculated as a function of the height, and written as \( w_{\text{max}} \) and \( w_{\text{min}} \), respectively. The total of WC and HC components is simply represented by \( \tilde{A} \).

3. Results

3.1 Dependence of the emergence of SCs and MJOs on \( \Delta T \)

Time-mean distributions and longitude – time sections of precipitation are shown for \( \Delta T = 0, 2.25, \) and 4.5 cases (Figs. 2a, 2b, and 2c, respectively). For the \( \Delta T = 4.5 \) case, a longitudinal domain is separated into four regions, defined as A, B, C, and D (Fig. 2d). The distribution of the SST is symmetric about 180° (0° or 360°) longitude between B and C (A and D) regions.

For the \( \Delta T = 0 \) case (Fig. 2a), it is found from the time-mean distribution that precipitation varies slightly in the longitudinal direction, but from the longitudinal – time section that only SC-like fast-EP PSs with a speed of about 15 m s\(^{-1} \) are attained. This speed is similar to those for the \( \Delta = 3.5 \) km or \( \Delta = 7 \) km cases, as already pointed out by Tomita et al. (2005) and Miura et al. (2007). It is also noticed that the WP PSs have the speeds of about \(-9 \) m s\(^{-1} \). For the \( \Delta T = 2.25 \) case (Fig. 2b), in addition to fast-EP PSs in the low-SST area, slowly EP PSs appear in the high-SST area, but insignificantly. For the \( \Delta T = 4.5 \) case (Fig. 2c), SC-like fast-EP PSs are suppressed, and, instead, nearly-steady disturbances become intense and slowly EP PSs appear together, especially in the C region. The former PSs are forced by the longitudinal variation of the SST and this component corresponds to the WC. The latter slowly EP PSs repeatedly emerge with an occurrence cycle of about 15–30 days (see Figs. 3c and 4c, too). The distinct WP PSs are seen in the A and D regions. It is interesting that the WP PSs move with the speeds of about \(-9 \) m s\(^{-1} \), similarly to those in Figs. 2a and 2b. It is noticed that the magnitude of precipitation is intense and concentrated over the C region. However, average precipitation becomes weak as \( \Delta T \) increases, when Fig. 2 is compared.

Similar features obtained in Fig. 2 are found in the OLR-field (outgoing long-wave radiation at the top of the atmosphere) (Fig. 3) and \( w \)-field (not shown), since precipitation, cloud activity, and upward motions are closely related. The low OLR areas correspond to convective ones with high cloud tops. The WP PSs are not well seen in the A and D regions (Fig. 3c) and, thus, it is anticipated that they have middle-to-shallow cloud tops. Similar EP features can be seen in the \( u \)-field (Fig. 4). It is noticed that the westerly winds in the C region increase as \( \Delta T \) increases.

For the \( \Delta T = 0 \) case (Figs. 2a, 3a and 4a), the vertical stratification is kept conditionally unstable due to the fixed SST in the longitudinal direction and radiative cooling in the atmosphere, and the HC is produced owing to the forcing of the latitudinal variation of the SST. Under this environment, only SC-like fast EP PSs are induced and, then, the HC plays an essential role for their formation and maintenance (solid curves in Fig. 5a). Roughly speaking, nearly-steady features about rough outlines of PSs, in which the inner convection develops and decays repetitively, are realized when they are observed moving with their propagating speeds. In other words, they can be called free PSs. Here, “free” PSs mean convective activity, which is free from the longitudinal variation of the SST.

For the \( \Delta T = 4.5 \) case (Figs. 2c, 3c and 4c), on the other hand, at least, two convective modes are obtained; stationary WC and slowly EP PSs. The latter ones are considered to be forced PSs, and the WC in collaboration with the HC plays an important role for their formation and maintenance. “Forced” PSs, which mean convective activity forced by the longitudinal variation of the SST, are remarkable, especially in the C region. The slowly EP forced PSs correspond to the MJOs from our classification of the propagation of \( w \) in the WC component are also calculated as a function of the height, and written as \( w_{\text{max}} \) and \( w_{\text{min}} \), respectively. The total of WC and HC components is simply represented by \( \tilde{A} \).

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gation speed, although the horizontal scale and occurrence period of the simulated MJOs do not necessarily agree with observed ones. Since the surface conditions in the real atmosphere usually vary in the longitudinal direction, it is anticipated that both types of EP PSs can exist in parallel.

3.2 Features of HC and WC viewed from u-, w-, and Q-fields and relations to PSs

From the Section 3.1, it is concluded that the HC is necessary for the formation of SCs, while the WC is essential for the formation of the MJO. Then, it is interesting to examine the components of the HC and WC separately.

Figure 5 presents the vertical profiles of the HC, and \( \sigma_u, \sigma_T, \sigma_w, w_{\text{max}} \), and \( w_{\text{min}} \) of the WC for the (a) \( \Delta T = 0 \), (b) 2.25, and (c) 4.5 cases. The \( w \) and \( Q \) of the HC decrease as \( \Delta T \) increases, while the \( u \) increases. Generally, upward motions are predominant in the whole troposphere, and heating is found similarly to the upward motions, except in the lower layer. The WC is detected even for the \( \Delta T = 0 \) case, but their amplitudes \((w_{\text{max}} \text{ and } w_{\text{min}})\) and deviations \((\sigma_u \text{ and } \sigma_T)\) are very small compared with those of the HC. For the \( \Delta T = 2.25 \) case, the amplitudes and deviations of \( w \) and \( Q \) are also small in most layers. For the \( \Delta T = 4.5 \) case, on the other hand, the \( \sigma_u \) and \( \sigma_T \) become large and have similar intensity to those of the HC component, especially in the upper layer. The magnitude of \( w_{\text{max}} \) becomes large as \( \Delta T \) increases, while the magnitude of \( w_{\text{min}} \) does not change so much. The enhancement of \( \sigma_u \) and \( \sigma_T \) and large magnitudes of \( w_{\text{max}} \) for the \( \Delta T = 4.5 \) case indicate the appearance of the stationary WC.

Figure 6 shows a longitude-height section of the WC component for the \( \Delta T = 4.5 \) case. Generally, upward motions and heating are remarkable in the B and C regions, whereas the opposite features are seen in the A and D regions. Cooling due to the melting of snow falls in the A, B, C, and D regions for the \( \Delta T = 4.5 \) case. Wind vectors and a color bar denote \((u, 400w)\) and \( Q \), respectively. A red line between 90°−270° longitude denotes the high-SST area.

To relate types of PSs with \( u-, w-, \) and \( Q\)-fields, the longitudinal domain is separated into four regions (Fig. 2d). Figure 7 shows the vertical profiles of \( u, w, \) and \( Q \) for the \( \Delta T = 4.5 \) case, which are averaged longitudinally with an interval of 90 degrees. The obtained fields are considered to be sums of the environmental fields (HC and WC) for PS occurrences and the nonlinear terms related to activities of PSs. Although they are non-separable, it is assumed that the fields represented in Fig. 7 indicate the general features of the environmental fields for PS occurrences. Then, the \( w \)- and \( Q\)-fields in the B and C regions, especially C region, are intense in the whole troposphere and favorable for the occurrence of deep convection. In these regions, roughly speaking, deep EP PSs are prevalent, although WP PSs are also observed. In the A and D regions, on the other hand, different vertical profiles of \( w \) are noticed. Upward motions change downward ones with height in the D region, while two weak peaks of upward motions are noticed in the A region. The WP PSs with middle-to-shallow cloud tops take place under these environments.

The large differences of the zonal winds are noticed in four regions.
It is anticipated that these fields, especially \( w \)- and \( Q \)-fields, might give considerable impacts for the formation and maintenance of these PSs. About the \( Q \)-field, it is known that top-heavy heating likely induces the propagating property of PSs (e.g., Yoshizaki 1991). Including the propagation property, the detailed investigations are left for future works.

4. Discussion

4.1 Cyclic occurrence of the MJO between fixed initiation and termination areas

It is well known from observations of the MJO that initiation and termination areas are limited around the Indian and western Pacific Oceans, respectively, and cyclic occurrence takes place between these areas (e.g., Matthews 2008). The slowly EP PSs in Figs. 2c, 3c and 4c develop and decay successively only in the C region. Then, the WC may control the successive occurrence of the MJO-like disturbances around the fixed areas. However, the exact correspondence of the specific areas is difficult using only variable-SST cases, and other unexamined factors, such as land-sea contrast and orography, should be considered. Further quantitative studies are required to obtain robust conclusions about the formation of the MJO, including the intensity and sizes of the WC and HC.

4.2 Formation mechanism of WP PSs

Although the EP property of large- to planetary-scale PSs in the equatorial areas was primary concerns in this study, elucidation of the formation of WP PSs is also important and necessary. The WP PSs exist only when EP is more frequent with smaller horizontal scales, especially in A and D regions (Fig. 2c). Similarities and differences of EP and WP PSs should be explained: for example, the weaker activity of the WP PSs for the \( \Delta \tau = 0 \) case. At least, two formation mechanisms of WP PSs have been proposed. The first is splitting large-scale PSs, and the WP PSs are WP components (e.g., Yoshizaki 1991). In that study, since the initial impulses of the PSs (= heating) are directed upward, no horizontal propagation bias is anticipated and both EP and WP PSs might be similarly excited. After the splitting, however, EP and WP PSs have different destines due to the effect of the equatorial beta, and only EP PSs are likely to survive (Yoshizaki 1991). The second is types of \( n = 1 \) equatorial Rossby waves, where \( n \) means the number of latitudinal nodes (e.g., Yasunaga et al. 2010). These waves have shallow equivalent depths compared with dry equatorial ones and are classified into convectively coupled equatorial waves. However, the second is required to explain the reason why these waves are selectively excited. Further investigations for these propagating PSs are needed to get a deeper understanding.

5. Summary

Our primary concern was why two large- to planetary-scale PSs (SC and MJO) with different EP speeds can exist, although they have similar meridionally symmetric structures about the equator. The dependence on the longitudinal variations of the SST was examined using the NICAM. For the longitudinally uniform-SST case, only SC-like PSs appear as fast EP free PSs. For the longitudinally variable-SST cases, on the other hand, at least, two convective modes occur; stationary WC and slowly EP PSs. The slowly EP PSs correspond to the MJO from our definition and are called slowly EP forced PSs. In the real atmosphere, two types of EP PSs can appear in parallel due to the complex surface conditions. The asymmetric WC is also obtained, even though the SST variation is symmetric about 180° longitude is forced.

The cyclic occurrence of the MJO between fixed initiation and termination areas and the formation mechanism of WP PSs were discussed. Owing to the WC, combined with the HC, the MJO is generated and decayed locally, and WP PSs are dominantly seen in the subsidence areas of the WC. The combination of WC and HC produces various types of PSs as observed.

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References


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