Intraseasonal Variability in Diurnal Rainfall over New Guinea and the Surrounding Oceans during Austral Summer

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(Manuscript received 21 November 2006, in final form 9 November 2007)

ABSTRACT

High-resolution Tropical Rainfall Measuring Mission (TRMM) rainfall data for six wet seasons (December–March) were used to investigate the time and space structure of the diurnal cycle of rainfall over and around New Guinea, a major island of the Maritime Continent. The diurnal cycle shows a systematic modulation associated with intraseasonal variability in the large-scale circulation pattern, with regimes associated with low-level easterlies or westerlies over the island. Lower-tropospheric easterly (westerly) wind components correspond to periods of inactive (active) convection over the islands that are associated with the passage of intraseasonal atmospheric disturbances such as the Madden–Julian oscillation (MJO). A striking feature is the diurnal rainfall that develops over the central mountain ranges in the evening and propagates toward the southwest (northeast) of the island with an inferred phase speed of about 2–3 m s^{-1} under low-level easterly (westerly) flow. In the case of the easterly regime, diurnal rainfall is strongly concentrated over the southwestern part of the island, inhibited from spreading offshore southwest of New Guinea. Under the westerly regime, in contrast, the rainfall area spread far and wide along the low-level westerlies from the island toward the Pacific Ocean. Significant offshore rainfall propagation extending from the island appears during the night over the north-northeastern coast and moves with a phase speed of about 7–8 m s^{-1}, reaching the open ocean the following day. Possible processes for controlling the variability in diurnal rainfall through the interaction between large-scale circulation and previously denoted complex local circulation over the island are discussed.

1. Introduction

A diurnal cycle of convection and precipitation is prominent over the Maritime Continent. The strong diurnal signal is characterized by a distinct land–sea contrast between evening and morning that is related to surface heating (Murakami 1983; Nitta and Sekine 1994; Yang and Slingo 2001). The cloud–rainfall cycle is not homogenous over all islands, however, because of complex local circulations related to the peculiar orography of the islands (Ohsawa et al. 2001). New Guinea, a major island in the Maritime Continent, has a mountain range that extends northwest to southeast across the island (Fig. 1). Peak elevations exceed 3000 m, and orographic forcing influences the patterns of diurnal rainfall over the island (Zhou and Wang 2006). Typically, convective rainfall systems develop over both the central mountains and coastal areas early in the afternoon. These systems subsequently migrate to remaining inland areas (Liberti et al. 2001; Nesbitt and Zipser 2003; Hirose and Nakamura 2005; Zhou and Wang 2006). Liberti et al. (2001) also described offshore propagation of cloud systems that move northward toward the open ocean. This propagation was evident up to 600 km off the coast of the island. Propagation of diurnal rainfall appears over other islands as well, and is a unique feature of the Maritime Continent (Yang and Slingo 2001). The detailed characteristics of such diurnal propagation have been described for major is-

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DOI: 10.1175/2007JCLI1784.1

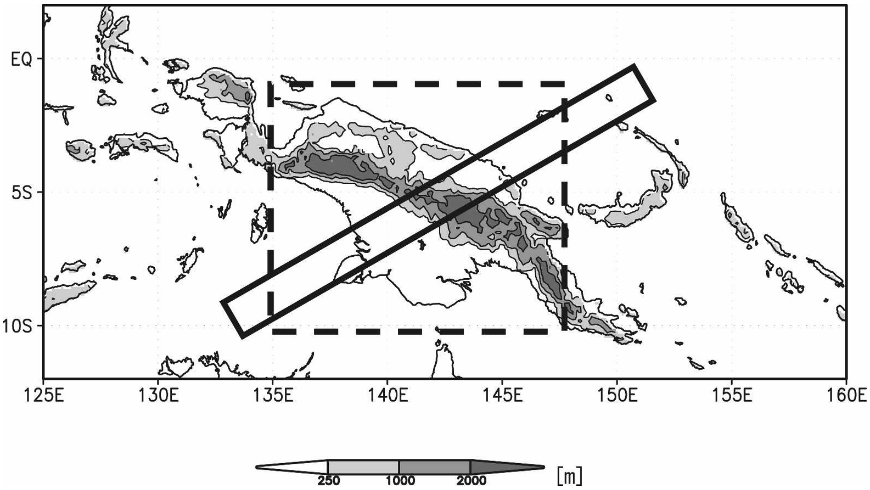


FIG. 1. Orography over New Guinea. The dashed rectangular box shows the area within which the area mean zonal wind time series were calculated. The cross-island rectangle denotes the calculation domain for the time–distance cross diagrams in Fig. 10.

lands such as Sumatra and Borneo (Mori et al. 2004; Sakurai et al. 2005; Ichikawa and Yasunari 2006).

General features of the diurnal variation over the islands are modified as the large-scale circulation changes under the influence of scale interactions. The circulation patterns near the Maritime Continent are subject to intraseasonal variability related to the passage of the intraseasonal-scale disturbances associated with the Madden–Julian Oscillation (MJO; Madden and Julian 1971, 1972) and seasonal changes in circulation. Recently, Ichikawa and Yasunari (2006) showed that the rainfall over Borneo that propagates to the leeward side of the island is associated with the large-scale low-level easterly or westerly tropospheric winds that vary at intraseasonal time scales associated with the MJO. Modulation in the diurnal propagation signal also occurs over Sumatra; eastward propagation of convection accompanies only low-level westerlies related to the passage of large-scale disturbances, whereas westward propagation of convection occurs year-round (Sakurai et al. 2005). The timing and duration of convection also vary in association with the passage of intraseasonal disturbance. Previous studies using satellite cloud imagery have shown that the amplitude of the diurnal cycle is strongest during the convectively inactive phase of the MJO, and that it decreases during the active phase (Sui and Lau 1992; Chen and Takahashi 1995). Further investigation, including a regional-scale study, is needed to reveal details of the dynamics of convection and rainfall over the entire Maritime Continent.

This study examines intraseasonal variations in diurnal rainfall over New Guinea and the adjacent oceans. The focus here is on the austral summer season (December–March) when large-scale convection is enhanced by the southward migration of the intertropical convergence zone (ITCZ). Section 2 outlines the data used in this study and the methods used to composite the data. Section 3 uses composite analysis results to describe the time–space structure of rainfall activity during the different circulation regimes related to intraseasonal oscillation. Section 4 includes a summary and discussion.

2. Data and methods

The present study uses Tropical Rainfall Measuring Mission (TRMM) 3B42 (version 6) rainfall product (Huffman et al. 2007) for six full wet seasons (December–March) from 1998 to 2004. Data were obtained from the TRMM Science Data and Information System (TSDIS), distributed by the National Aeronautics and Space Administration (NASA) Goddard Distributed Active Archive Center (DAAC). The 3B42 product contains estimated rain rates (mm h^{-1}) derived from a combination of infrared radiation (IR), passive microwave, and radar data from TRMM and IR data from geostationary satellites. The data are 3 hourly and cover the domain between 50°S and 50°N, with a horizontal resolution of 0.25° × 0.25°. In addition, the National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) Atmospheric Model Intercomparison Project II (AMIP-II) reanalysis dataset (Kanamitsu et al. 2002) was used to describe the large-scale circulation field. The reanalysis dataset contains daily averages with a horizontal resolution of 2.5° × 2.5°.

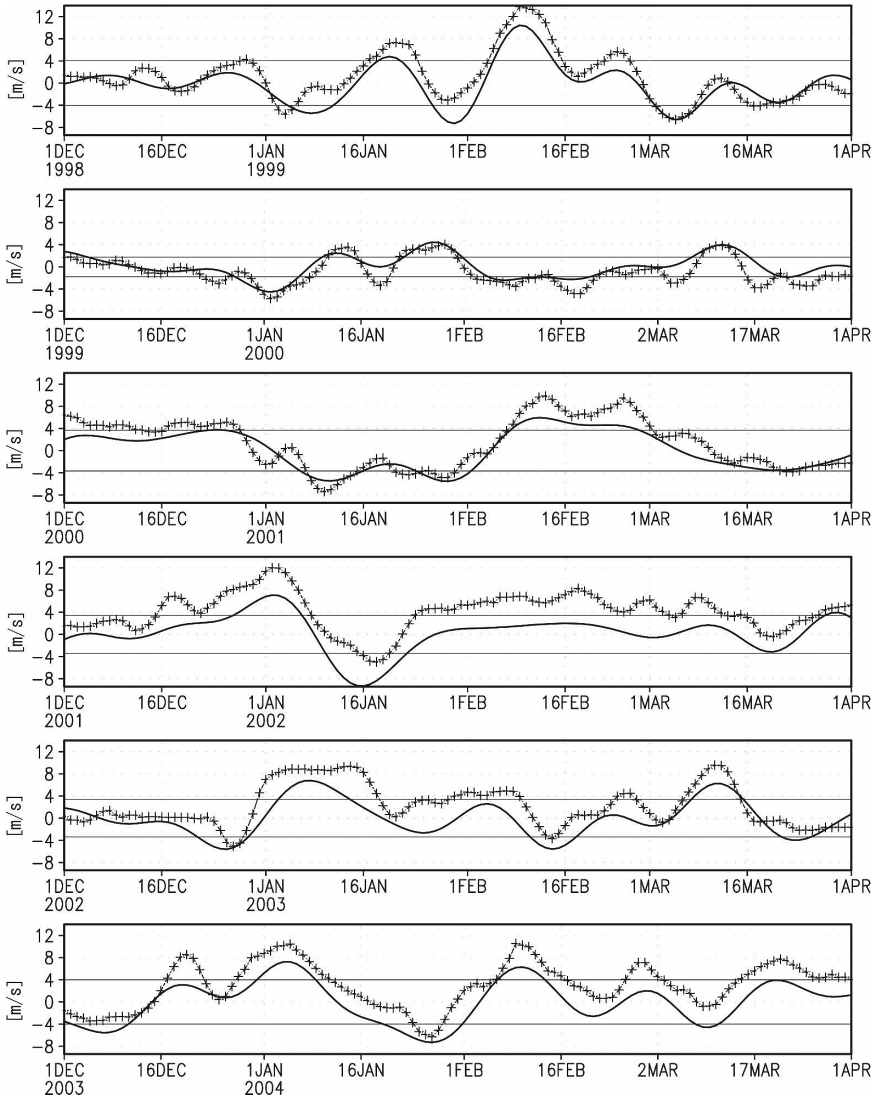


FIG. 2. Zonal wind at 700 hPa for an area over New Guinea (rectangular box in Fig. 1) smoothed by a 5-day running mean (crossed line) and by a 15–90-day bandpass filter (solid line). The ±1 standard deviations of 15–90-day filtered data in each winter are also shown.

Outgoing longwave radiation (OLR) datasets (Liebmann and Smith 1996) archived at the National Oceanic and Atmospheric Administration (NOAA)/Climate Prediction Center (CPC) were also used. The OLR datasets are constructed from NOAA's polar-orbiting satellite data crossing over the equator in the afternoon and have been interpolated spatially and temporally to a daily 2.5° × 2.5° grid.

This study discusses the intraseasonal modulation of diurnal rainfall over and around New Guinea. Changes in convection and rainfall under different circulation regimes are revealed by composite analyses of high-resolution TRMM rainfall data and large-scale circulation field data centered on New Guinea. Figure 2 shows a time series of zonal wind at 700 hPa averaged over New Guinea (10.0°–2.5°S, 135.0°–147.5°E; the rectangular box in Fig. 1) and smoothed by a 5-day running mean. The wind data were further smoothed by using a 15–90-day bandpass filter as shown in Fig. 2 (solid line). The intraseasonal variability within 15–90 days was extracted using the Lanczos filter (Duchon 1979), with the response function exhibiting half amplitude at periods of 15 and 90 days. Oscillations in the low-level zonal wind associated with variations in the large-scale circulation field are a prominent feature over and around New Guinea. Intermittent fluctuations in the low-level flow are associated with convective variability influenced by the passage of intraseasonal time-scale distur-

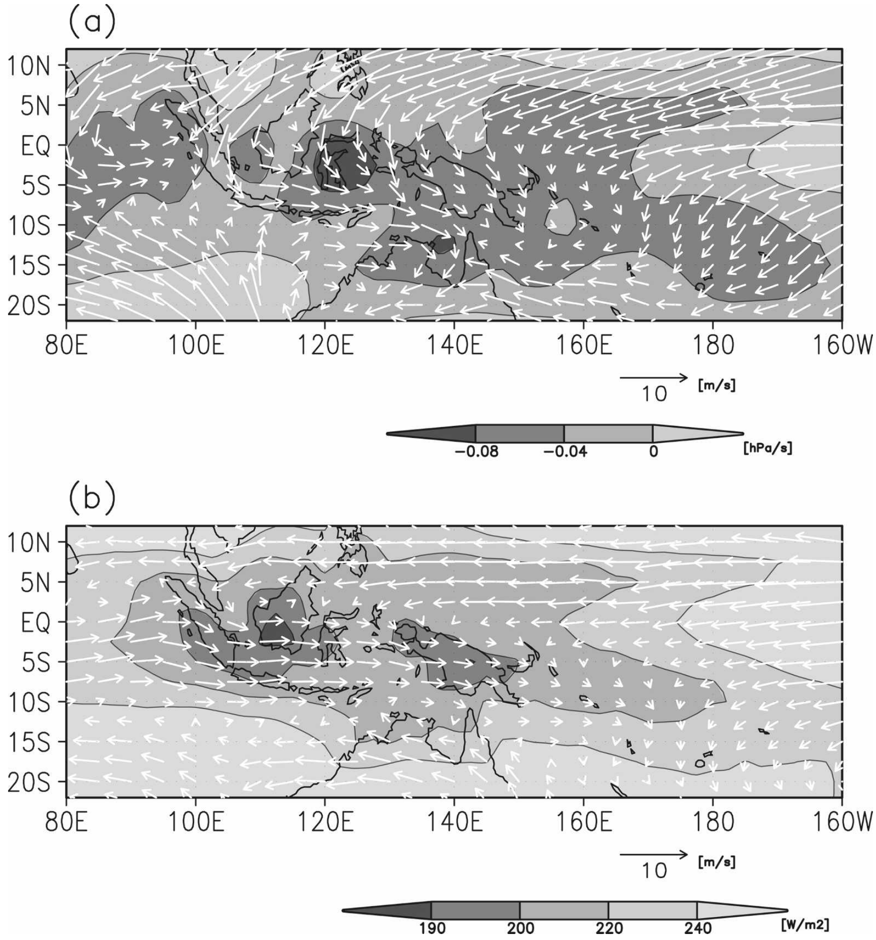


FIG. 3. Austral summer (December–March, 1998/99–2003/04) mean fields of (a) wind at 925 hPa (vector) and pressure-coordinated vertical velocity at 500 hPa (shaded), and (b) wind at 700 hPa (vector) and OLR (shaded).

bances such as the MJO. As the MJO propagates eastward from the equatorial Indian Ocean toward the Pacific Ocean, low-level winds change from easterly to westerly over the Maritime Continent as the MJO enhances or suppresses convection. That is, low-level equatorial westerly (easterly) winds prevail during periods of active (inactive) convection over the Maritime Continent because of the MJO (Chang et al. 2005), although the strongest westerlies tend to lag slightly behind the time of strongest convection (Wheeler and McBride 2005). This study defines the easterly and westerly phases in the lower level as indicators that exhibit an intraseasonal pattern. Previous studies (Ichikawa and Yasunari 2006) have also associated the easterly and westerly phases related to the MJO with variability in diurnal rainfall. Because the elevation of the steep orography over the island is 2000–2500 m on average (apart from some local maxima), zonal winds at 700 hPa near 3000 m were used to classify the wind regime. To extract the intraseasonal variation, wind data were then partitioned into easterly and westerly regimes in the intraseasonal (15–90 day) filtered time series anomalies if relative maxima exceeded one standard deviation of the seasonal mean in each summer. Within the 7 seasons lasting 121 days each, 104 (124) days were classified as easterly (westerly) phase. TRMM 3B42 rainfall data and circulation field data were composited in grid boxes for each classified wind regime.

3. Results

a. Differences in large-scale atmospheric conditions

To describe the clear large-scale circulation field changes under the different wind regimes, we first show the mean feature of the atmospheric condition during the austral summer season in Fig. 3. Figure 3a shows wind at 925 hPa and pressure-coordinated vertical velocity at 500 hPa. During the austral summer season, widespread upward motion occurs from the equatorial Indian Ocean toward the Pacific. At lower levels (925 hPa), the prevailing easterly over the Northern Hemisphere turns counterclockwise across the equator over the Maritime Continent. The westerly thus dominates along the equatorial southern latitude over the islands. The counterclockwise turning of the airflow is associated with the blocking and deflection by the land terrain of the Malay Peninsula–Sumatra (Chang et al. 2005). In addition, the conservation of potential vorticity acts to maintain the cross-equator flow (Lim and Chang 1981). The significant westerly over the Maritime Continent becomes weak east of New Guinea, meeting with the prevailing easterly that is dominant all over the Pacific. Then, low-level convergence and related midlevel upward motion, which are associated with the so-called South Pacific convergence zone (SPCZ), appear over the south-central Pacific. The low-level convergence over the south central Pacific is associated with a surface pressure trough that appears as a persistent feature in the austral summer climatology (Sadler et al. 1987), migrating from the northwest Pacific between spring and summer as part of a large-scale clockwise phase rotation of surface low pressure across the Indian Ocean and western Pacific (Matsumoto and Murakami 2000). Then, meridional and zonal convergence of winds equatorward of the Siberian and North Pacific highs occurs for the low-level trough (Matsumoto and Murakami 2002), thereby activating convection around the SPCZ. Aside from a pronounced SPCZ south of the Maritime Continent, the prevailing westerly over the equatorial southern latitude forms a cyclonic circulation around the northern part of the Australian Continent and is associated with the Australian monsoon trough.

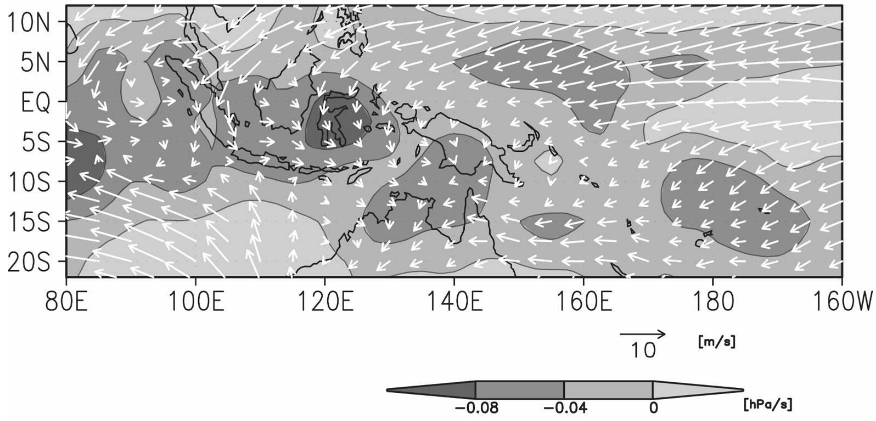
The wind at 700 hPa and the OLR field during austral summer are shown in Fig. 3b. In relation to the large-scale monsoonal westerly at 925 hPa, the equatorial westerly dominates at 700-hPa height from the Indian Ocean toward New Guinea in the Southern Hemisphere where it becomes enclosed by the prevailing easterly over the other regions. Much of the convective activity occurs over the whole of the Maritime Continent, extending from the Indian Ocean toward the Pacific. The deepest convection is concentrated around the major islands, centered over the Sumatra–Borneo–Sulawesi region and over New Guinea. To the east of New Guinea, the active convective region extends to the southern-central Pacific.

The general features of the atmospheric condition during austral summer are greatly changed between the low-level wind regimes. In the case of the easterly regime (Fig. 4a), large-scale upward motion appears over the western part of the Maritime Continent. As can be observed in the climatological features (Fig. 3a), easterly winds north of the equator change to westerlies over the Indian Ocean to the western part of the islands across the equator. However, the westerlies weaken west of New Guinea, and converge with easterlies over the Pacific Ocean. The midlevel upward motion occurs from northern Australia to New Guinea. This upward motion is independent of the surrounding region because widespread upward motion over the western part of the Maritime Continent weakens west of New Guinea (~130°–135°E). Over the northern side of New Guinea, the stronger ascent motion is significantly suppressed compared to the climatological large-scale upward motion over that region in Fig. 3a.

In the westerly regime (Fig. 4b), the climatological features of the circulation field pattern are enhanced. Apparently, the large-scale upward motion spread broadly from around Sulawesi Island to a widespread area over the equatorial southern Pacific associated with the strengthening of the SPCZ. Cross-equatorial westerlies extend from the islands toward the Pacific to enhance the SPCZ. The most pronounced upward motion (<0.08 hPa s^{-1}) appears off the southeast coast of New Guinea (~10°S, 150°–170°E) in the prevailing westerlies extending from the island. The strong westerly at equatorial southern latitudes is also linked to the enhanced cyclonic circulation over the north of Australia, which suggests the intensification of the Australian monsoon trough. Strong upward motion is thus present over the northern tip of Australia in association with the enhanced cyclonic circulation over northwestern Australia.

Figure 5 shows the composite low-level wind (700 hPa) and OLR for each wind regime. At 700 hPa, strong intraseasonal variability was identified, and the wind direction changes dramatically from easterly to westerly over and around New Guinea between the two regimes. In addition to the wind pattern changes, the large-scale convection that is associated with the variability of the induced large-scale upward motion also changes considerably between the regimes. In the easterly regime, convective activity is centered over the western Maritime Continent around Sumatra and Borneo. The convection over the eastern Maritime Continent extends around western New Guinea. Westerlies spread from the Indian Ocean toward the western Maritime Continent near the equator. In contrast, east of 130°E easterly winds prevail over New Guinea and the western Pacific but gradually weaken in southern latitudes west of New Guinea (~120°–130°E).

Under the westerly regime (Fig. 5b), the westerlies at (a)Easterly



(b)Westerly

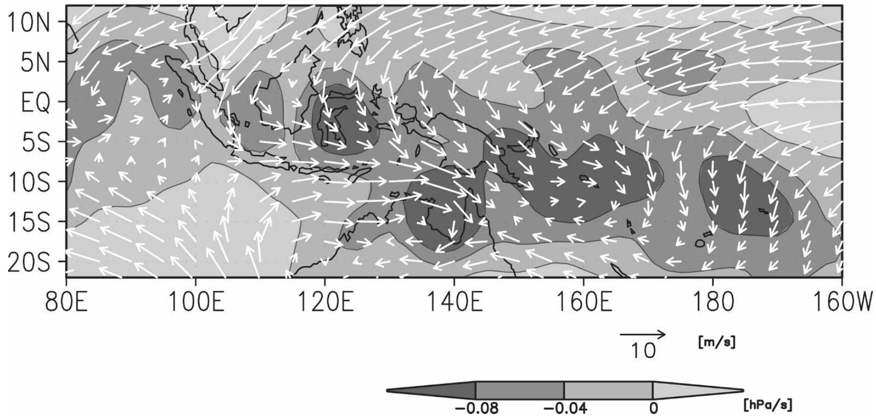


FIG. 4. Wind field at 925 hPa (vector), and pressure-coordinated vertical velocity at 500 hPa (shaded) for the (a) easterly and (b) westerly wind regimes.

equatorial southern latitudes further extend to the central Pacific. Enhanced convection approaches the western Pacific and then spreads around New Guinea to the surrounding open sea. In particular, the deeper convection stretches from the north-northeast coast of the island toward the Pacific along the strong westerly belt in association with the enhancement in SPCZ. A prominent cyclonic circulation dominates a large area north of New Guinea compared to the summer mean. South of New Guinea, clockwise turning of the air is evident over northern Australia, and thus strong westerlies prevail over New Guinea in association with pronounced cyclonic circulations in both hemispheres. It is apparent from Figs. 4 and 5 that the changes from easterly to westerly regimes over New Guinea are characterized by the strengthening of the SPCZ and Australian monsoon trough that appears as a major feature in a passage of MJO during austral summer (Wheeler and McBride 2005).

Thermodynamic conditions in the atmosphere also change between the two wind regimes. Figure 6 shows composites of midtropospheric relative humidity (averaging from 700 to 400 hPa) and atmospheric instability (defined as the difference in equivalent potential temperature between 850 and 500 hPa). Over New Guinea, the atmosphere is more humid and more stable during the westerly regime than during the easterly regime. In the westerly regime, wetter atmospheric conditions spread from the western part of the Maritime Continent to the central Pacific and to the north of Australia. Thermodynamic instability is enhanced over the northeastern part of the island under the westerly regime. During the easterly regime, more humid air is present over the northwestern tip to the southwestern part of New Guinea, where relatively active convection is present, extending from the western part of the Maritime Continent. The atmosphere is unstable over the island in the easterly regime. Thermodynamic conditions in our composite would be enhanced by the results of McBride and Frank (1999), who analyzed Aus-

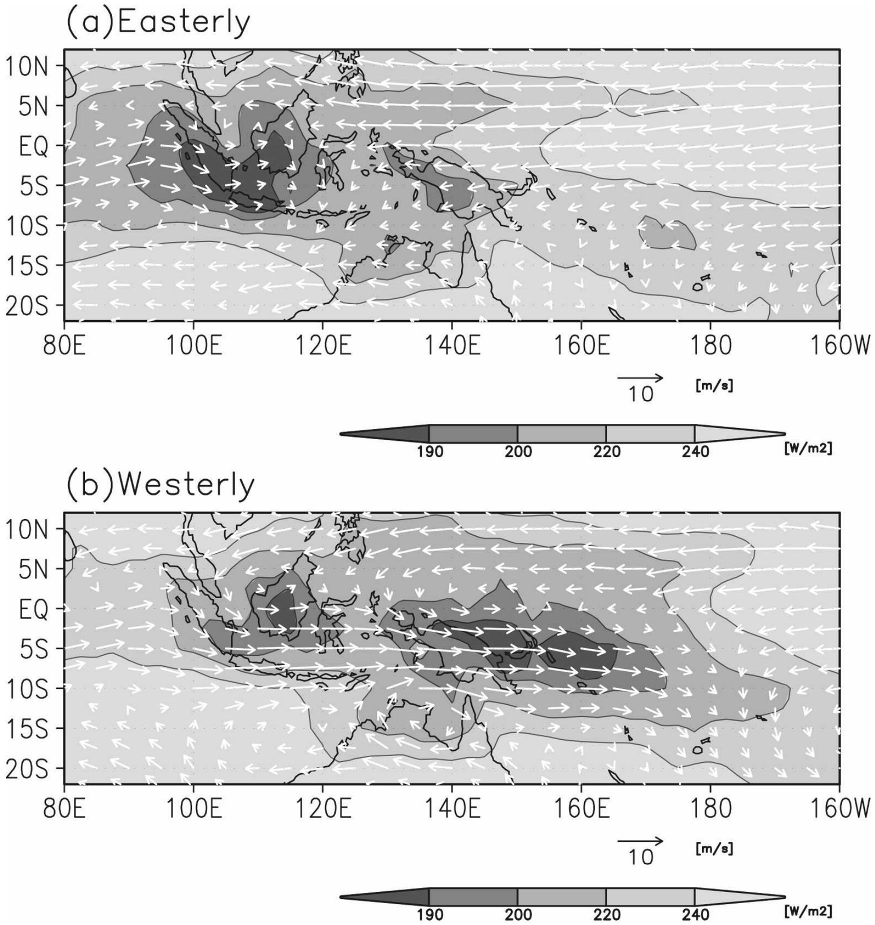


FIG. 5. Wind field at 700 hPa (vector) and OLR (shaded) for the (a) easterly and (b) westerly wind regimes.

tralian Monsoon Experiment (AMEX) data. In their study, the variations in convective activity in the Australian monsoon trough were clearly related to variations in lower and midlevel troposphere moisture. In addition, the atmospheric stratification of density and moisture through dynamical processes occurred in association with the large-scale flow rather than with the in situ response to local convection. McBride and Frank further demonstrated that the static stability was less stable during convectively inactive phases than during active phases (in relation to the large-scale circulation). This finding is consistent with our comparison of the easterly trade flow and the wetter monsoonal westerly.

b. Variability in diurnal rainfall

Figure 7 shows the composite mean rainfall distribution and 850-hPa wind for each regime over and around New Guinea, where large differences in the circulation field appear between the two phases (see Figs. 4 and 5). The detailed characteristics of the daily rainfall distribution change greatly between the two wind regimes. Rainfall is strongly influenced by the complex terrain on the island as well as by large-scale wind fields. In the easterly regime, rainfall is concentrated over the south-southwestern side of the island, where low-level winds weaken and converge. Rainfall is not observed over the windward (northeastern) side of the island. Rainfall is also suppressed over the offshore area west of New Guinea. Rainfall is localized over land areas in northern Australia. Figure 4a shows that upward motion extends from southern New Guinea to Australia, but rainfall does not occur between the two land areas.

In contrast, during the westerly regime (Fig. 7b), rainfall associated with large-scale enhanced convection is widespread over the island and offshore. The distribution of rainfall spreads out, especially over the northeastern–eastern side of New Guinea and extending eastward to the equatorial southern Pacific toward the SPCZ under the low-level westerlies. Enhanced offshore rainfall off the northeast coast near New Britain

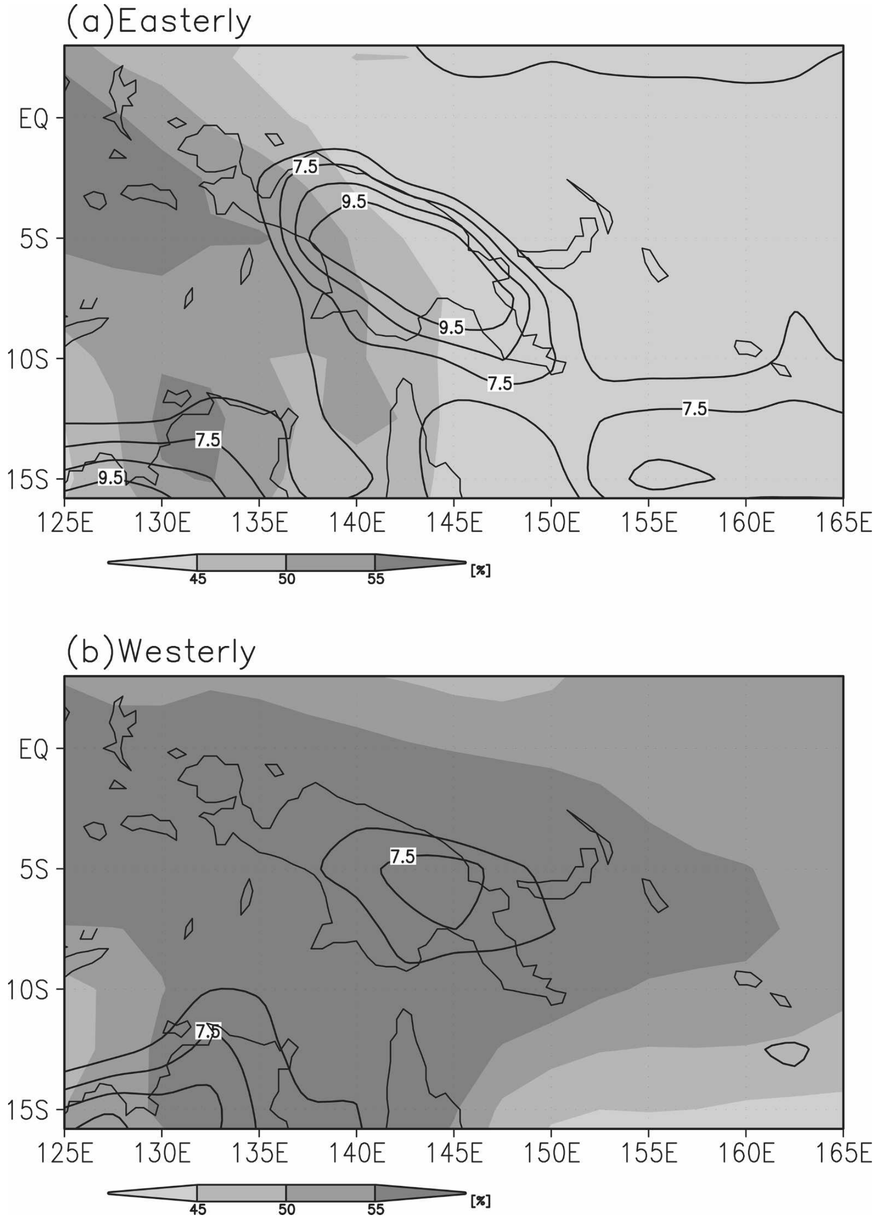


FIG. 6. Relative humidity at 700–400 hPa (shaded) and thermodynamic instability in the atmosphere defined as the difference in the equivalent potential temperature (θ_e) between 850 and 500 hPa [contour; θ_e(850 hPa) $-$ θ_e(500 hPa)] for the (a) easterly and (b) westerly wind regimes. The contour interval of the atmospheric stability is 1×250^{-1} K hPa^{-1} from 6.5 to 9.5×250^{-1} K hPa^{-1}.

Island (east of New Guinea) is prominent. In contrast, rainfall is suppressed locally on the leeward side (south) of New Britain Island. Significant rainfall can also be seen over the offshore area to the south of New Guinea, spreading from northern Australia in association with a cyclonic circulation, where Fig. 4b suggests strong upward motion. However, rainfall in this region is separate from the widespread rainfall area over the SPCZ.

Diurnal rainfall activity also has different patterns under the two wind regimes. Figures 8 and 9 show diurnal variations in rainfall during easterly and westerly periods, respectively. In easterly regimes, the prominent diurnal cycle is over New Guinea and northern Australia. Comparison of the diurnal variation between the two land areas reveals the unique characteristic of the diurnal cycle over New Guinea. Rainfall over Australia associated with solar heating starts at 1500 LT, becomes prominent at 1800 LT, and ceases at 0000 LT.

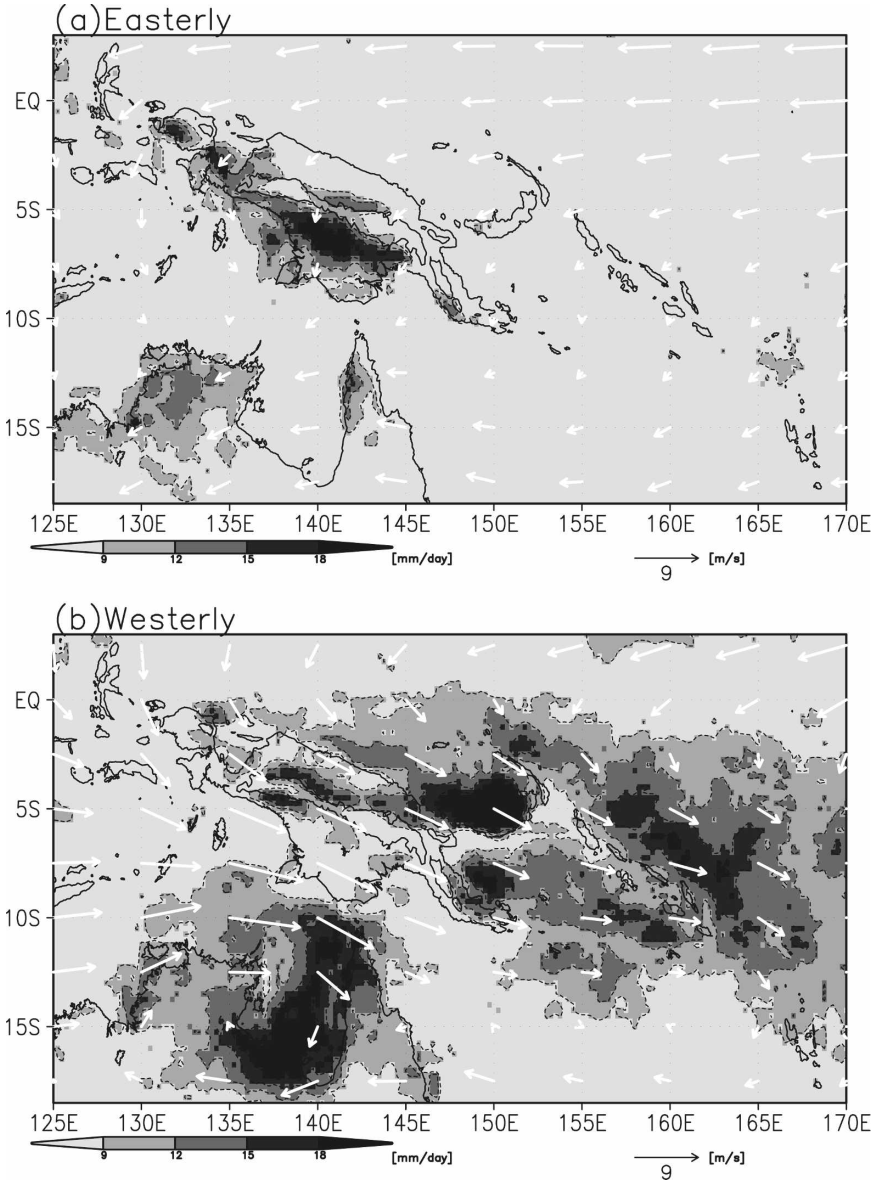


FIG. 7. Composite rainfall distribution and wind at 850 hPa for the (a) easterly and (b) westerly wind regimes. The orography is shown by the 1500-m contour.

In contrast, the diurnal rainfall over New Guinea continues until midnight because of the complex local circulations induced by the orography of the island. Rainfall over the island is suppressed between 0900 and 1200 LT, but then gradually develops over the central mountain range and southern coast by 1500 LT. Rainfall is prominent along the central mountain range at 1800 LT. Rainfall activity is further enhanced at 2100 LT along the south side of the mountain range. From 0000 to 0300 LT, rainfall spreads to the southwestern side of the island and subsequently continues until early morning (0600 LT) over the southern plains. After 0600 LT, significant rainfall gradually propagates off the southwest coast.

During the westerly regime (Fig. 9), diurnal rainfall is widespread. A distinct contrast in rainfall is observed between the land and the surrounding ocean, which is most apparent between the late evening (1800–2100 LT; land) and early morning (0600–0900 LT; ocean). Rainfall over the open sea surrounding the small islands continues throughout the day with a weaker diurnal variation. As with the easterly regime, diurnal rainfall over the island has a particular evolution: it persists until midnight (0300 LT), whereas rainfall re-

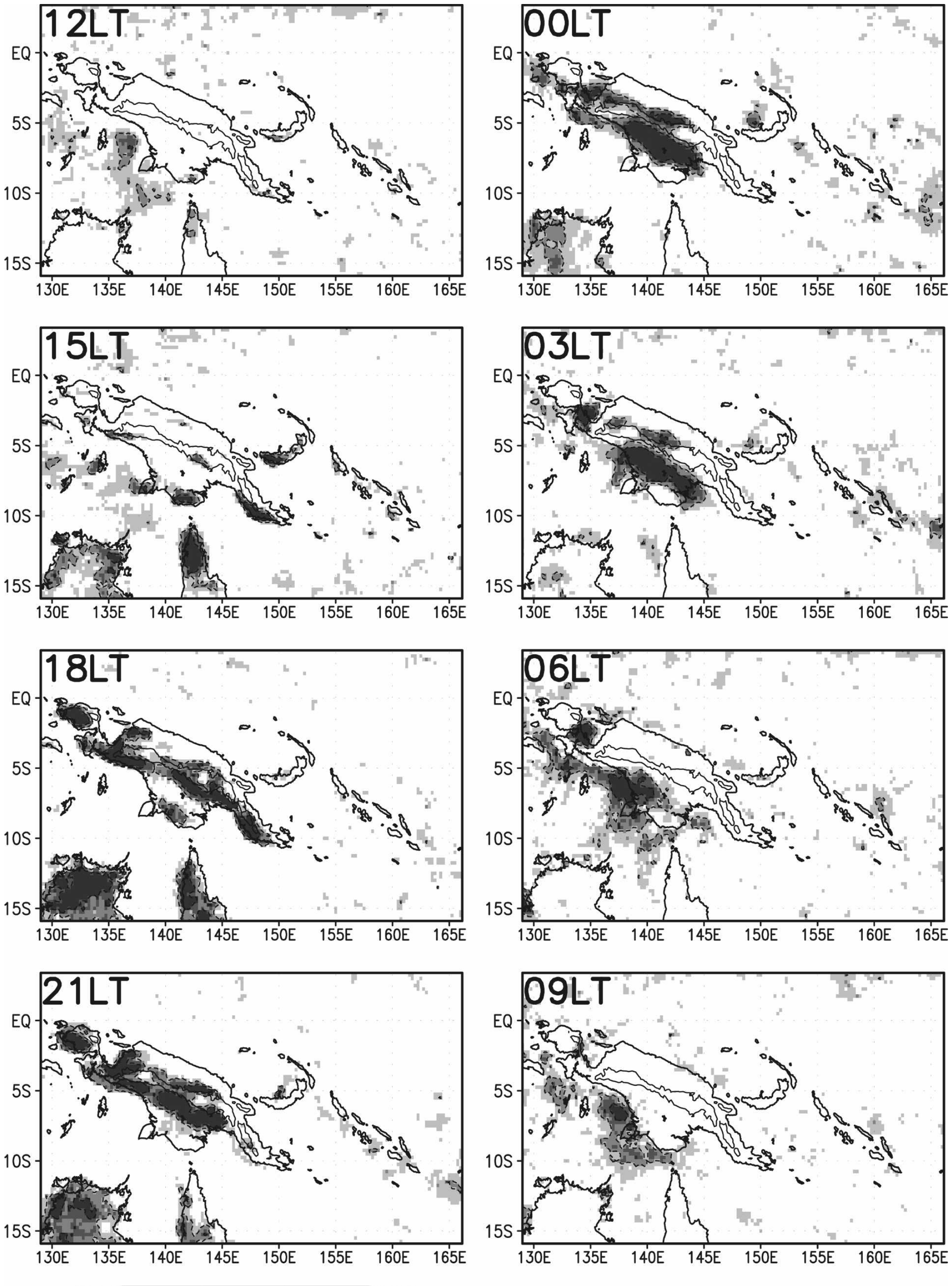


FIG. 8. Time series of rainfall distribution over New Guinea in the easterly regime. Contours of 0.6 and 1.0 mm h^{-1}. The orography is shown by the 1500-m contour.

lated to the daytime convection over Australia stops at 0000 LT. Over New Guinea, rainfall is suppressed between 0600 and 1200 LT and gradually increases by 1500 LT. Rainfall occurs over both sides of the mountain range on the island at 1800 LT. At 2100 LT, rainfall along the central mountain range intensifies. From 0000 to 0300 LT, rainfall spreads to both sides of the island, but the rain is more significant over northern New

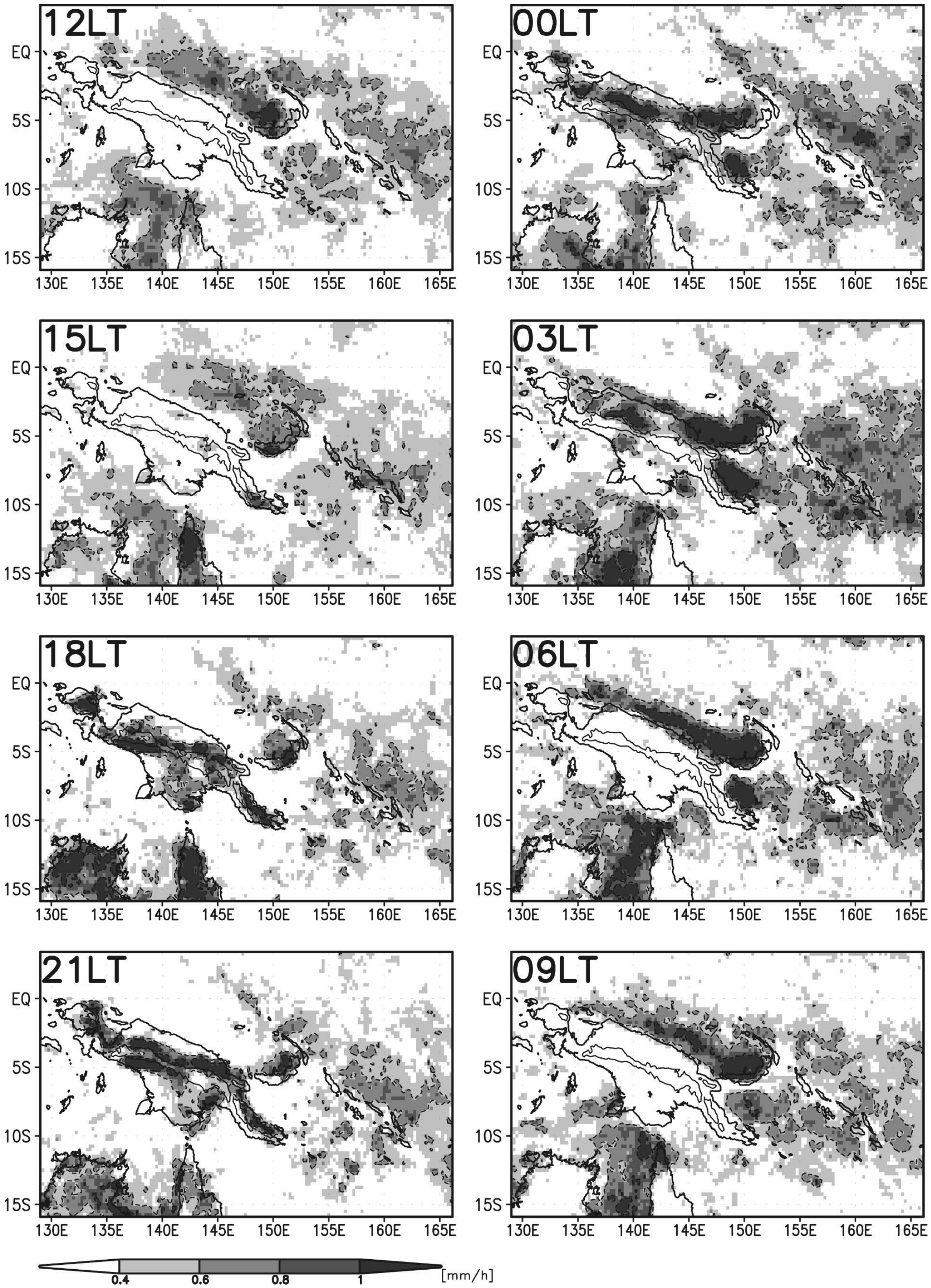


FIG. 9. As in Fig. 8, but for the westerly regime.

Guinea. At 0300 LT, rainfall increases over the basin in northern New Guinea (see topographic detail in Fig. 1).

After 0300 LT, offshore activity is enhanced around New Guinea in the westerly regime (Fig. 9). Pronounced rainfall systems are prominent along the north-northeastern coast and the southeastern tip of New Guinea. Rainfall in those two regions gradually propagates away from the island, and spreads out east-

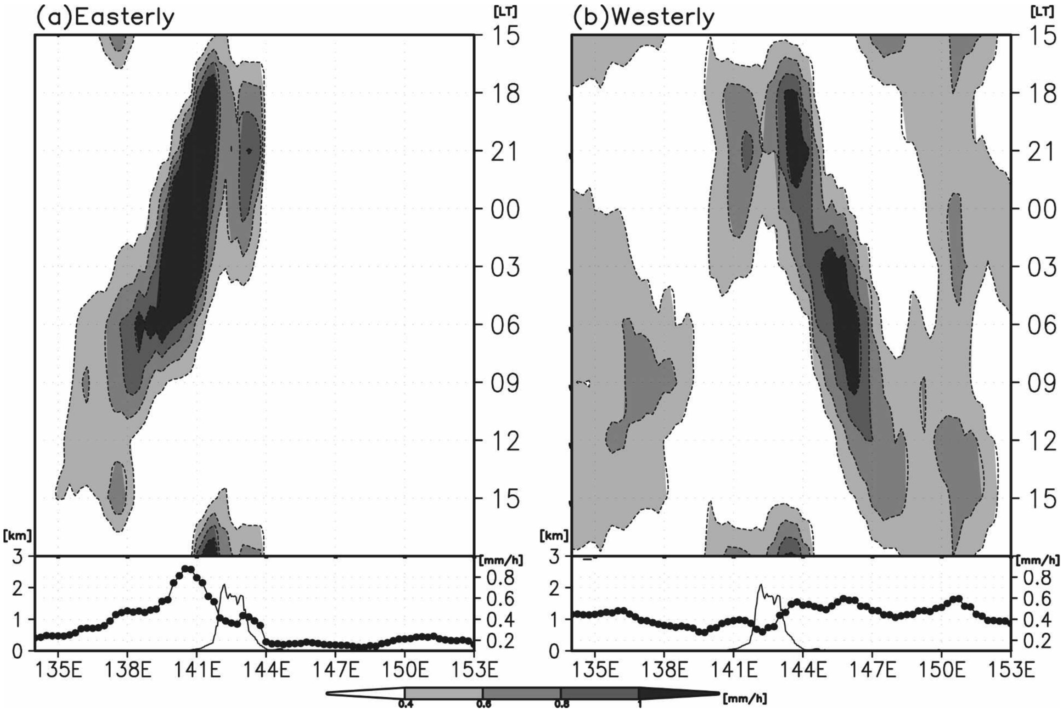


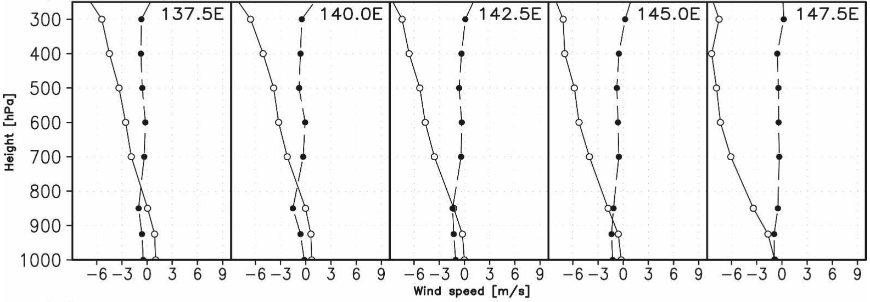
FIG. 10. Time–distance cross sections of the (a) easterly and (b) westerly regime rainfall along the cross-island rectangle in Fig. 1 averaged in the domain perpendicular to the central mountain range. Land terrain (solid line) and daily accumulated rainfall (circled line) are described at the bottom of each diagram.

ward and offshore during morning to daytime hours, propagating toward the area of widespread rain over the central equatorial Pacific. Along the north coast, offshore rainfall usually begins by 0000 LT between New Guinea and New Britain, and slowly intensifies until 0300 LT. At 0600 LT, an organized rainfall system develops along the northern coast and then propagates northeastward between 0900 and 1500 LT. The offshore-propagating rainfall that started at the northern coast gradually weakens by between 1800 and 2100 LT, and merges with offshore activity around the small islands (east of 150°E) between 0000 and 0300 LT. The linear rainfall area over the western Pacific (equator, ~145°–150°E) tends to linger until 0300 LT the following day. This nocturnal convection may be related to the northward-propagating mesoscale systems observed by Liberti et al. (2001) during the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE).

The diurnal cycle over the open sea away from the island is strongly linked to the propagating offshore rainfall under the westerly regime, as shown in Fig. 9. Rainfall over the Pacific is most pronounced from 0000 to 0300 LT, when offshore rainfall develops along the coast. It is interesting to note that at 0000 LT within the domain east of 155°E rainfall is observed only over the ocean, and not over the small islands. The rainfall weakens during the day until evening. West of the small islands, daytime rainfall weakens as the rain systems that propagated from the southeastern tip of the island (from 1800 to 2100 LT) diminish. In contrast, east of the small islands, relatively weak rainfall at 1500 LT becomes gradually stronger after 1800 LT. Subsequently, rainfall increases again sometime between 0000 and 0300 LT. The rainfall north-northeast of New Guinea is linked to the SPCZ, whereas the rainfall over southwestern New Guinea is related to activity north of Australia. Activity off the Australian coast spreads to the south of New Guinea by 0300–0900 LT, and gradually dissipates in the early afternoon.

Figure 10 shows a time–distance cross section for a domain perpendicular to the central mountain range of New Guinea (as shown in Fig. 1) to highlight differences in rainfall propagation under the different wind regimes. The direction of rainfall propagation changes systematically, from the southwest during the easterly regime to the northeast during the westerly regime. Under both regimes, rainfall develops in the afternoon over the central mountain range and subsequently propagates to northeast/southwest lowland areas with a phase speed of 2–3 m s^{-1}. In the easterly regime, the rainfall spreads offshore during the morning but is lo-

(a)Easterly



(b)Westerly

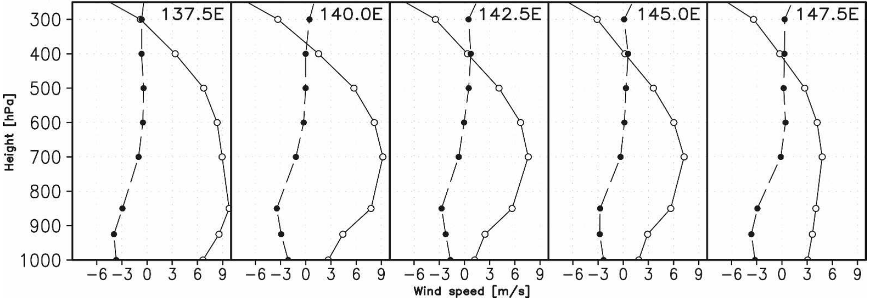


FIG. 11. Vertical profile of wind velocities (open circle = zonal wind; closed circle = meridional wind) along the cross-island rectangular section in Fig. 1 under the (a) easterly and (b) westerly regimes.

calized near the coast and gradually dissipates. In the westerly regime, significant rainfall propagates in the offshore area northeast of the island. The rainfall propagates faster over water than over land, with an inferred phase speed of about 7–8 m s^{-1}. Offshore propagation continues until the following day and is linked to the afternoon peak in rainfall over the open Pacific. Moderate rainfall also occurs over the southwestern part of New Guinea during the westerly regime. Over southwestern New Guinea, rainfall propagation from the central mountain range weakens at night, but then offshore rainfall spreads from north of Australia to New Guinea. Rainfall that is propagated southwestward (northeastward) in the easterly (westerly) regime causes an increase in daily rainfall over that side of the island. In particular, in the easterly regime, rainfall over the southern plain increases dramatically.

Figure 11 shows the vertical profiles of zonal and meridional wind velocities along the cross-island rectangle in Fig. 1. Wind direction and velocity are both important factors in rainfall propagation. These profiles can thus be used to discern the relationship between phase speeds and surrounding atmospheric winds. In both regimes, zonal wind profiles show greater variability than meridional wind profiles. In the easterly regime, the wind direction varies significantly below 850 hPa from the northeast to southwest across the island (see Figs. 4a and 7a). Over the island (at 142.5°E), the moderate northeasterly winds occur below 850 hPa. The wind speed is ~2 m s^{-1} at 850 hPa. On the other hand, the wind south of the island (at 137.5° and 140°E) is weak northerly at 850 hPa and changes to northwesterly below 925 hPa. Above 700 hPa, the winds at each region are easterly and velocity increases to ~10 m s^{-1} at 250 hPa, with a weak northerly component. Comparing the rainfall variability with the wind profile, the rainfall propagation phase speed from the central mountain range to the southwestern plain area is about 2–3 m s^{-1}, close to the northeasterly wind speed at 850 hPa (at 142.5°E). The southwestward propagation becomes weakened south of the island, where the wind field changes to northwesterly in the lower level.

In contrast, under the westerly regime (Fig. 11b), northwesterly winds prevail below 850 hPa over and around the island (see Figs. 4b and 7b). At the northern side of the island (at 142.5° and 145°E), where rainfall propagates prominently northeastward, winds are westerly at low to midlevels (700–500 hPa) with a maximum (~8 m s^{-1}) at 700 hPa. The westerly wind speed weakens away from the island (147.5°E). Wind direction becomes easterly in the upper troposphere over New Guinea. The direction of the downslope rainfall propagation over the island is inconsistent with the large-scale wind field at all heights in the troposphere, and thus is not a result of advection by the prevailing background wind. Offshore propagation is also prominent over the northern coast in the westerly regime. The rainfall propagates east-northeastward, as shown in Fig. 9. The inferred propagation phase speed is rather close to the westerly wind speed at 700 hPa (145°E). Thus, advection may partly cause the eastward propagation of offshore rainfall that subsequently merges with the SPCZ.

4. Summary and discussion

High-resolution TRMM rainfall data were used to investigate intraseasonal variations in diurnal rainfall over New Guinea and adjacent oceans during the austral summer season (December–March). Systematic intraseasonal variability, associated with the easterly and westerly phases in low-level flow, determines the spatial and temporal characteristics of the diurnal rainfall. The easterly (westerly) regime is accompanied by suppressed (enhanced) large-scale convection and dry (humid) conditions around New Guinea during the passage of intraseasonal disturbances such as the MJO. This variability appears most prominently in the large-scale features of the atmosphere as it changes to an active SPCZ from easterly phase to westerly phase. Also, the strong cyclonic circulation associated with the Australian monsoon trough is enhanced at the south of the island and is related to the strong monsoonal westerly in the westerly regime.

Diurnal rainfall characteristics vary between the easterly and westerly phases of the low-level flow associated with the large-scale circulation field changes. Figure 12 presents schematics of the diurnal cycle of convection/rainfall activity over New Guinea, based on our study results. In addition, the hypothesized diurnal cycle of winds over the island—extrapolated from the study by Zhou and Wang (2006), who consider the effect of land–sea breezes and orographic forcing on the diurnal evolution of precipitation by the regional model simulations—is also described in Fig. 12. The dynamic evolution of the diurnal rainfall differs between the easterly and westerly regimes. A striking feature of the diurnal variability in the regimes is that rainfall activity is propagated southwest (northeast) in the easterly (westerly) regime, and is mainly concentrated over the southwestern part of the island (widespread from the island to offshore over the Pacific). Under both regimes, rainfall over the island is strongly suppressed from the morning to early afternoon (0900–1200 LT). It develops over, and spreads from, the central mountain range in the evening.

A local circulation forced by high orography is important for convective development and propagation (as demonstrated by Zhou and Wang 2006). In their simulation, convection occurred over a mountaintop in response to a forced ascent resulting from upslope winds. Near inland coastal regions, the ascent was also associated with the afternoon sea-breeze front. Data from numerical simulations have further revealed that ascent and convection are enhanced over the mountains because the sea breeze penetrates inland by late afternoon and early evening (1800–2000 LT). Subsequently, rainfall propagates toward the lowlands as downslope winds develop. Similar mechanisms are responsible for diurnal rainfall variations over the island under the two regimes, and intraseasonal changes in the large-scale circulation field may partly modulate the local circulation. In addition, the downslope propagation could be attributable to a converging sea breeze that penetrates into and remains over New Guinea in late evening (2100 LT). Once the convection develops, cold downdrafts from the cloud system itself may force convergence ahead of the previous convective system, causing a self-sustaining process that maintains convection, as noted by previous authors (Tucker and Crook 1999; Satomura 2000).

Rainfall propagation in the easterly regime occurs only west of New Guinea. At the bottom of the mountain slope during the night, 850-hPa northeasterlies further enhance the southwestward propagation of rainfall onto the southwestern plain. The inferred phase speed is about 2–3 $\mathrm{m\ s^{-1}}$, close to the wind speeds at 850 hPa ($\sim 2\ \mathrm{m\ s^{-1}}$). Under the easterly regime, thermodynamic conditions may favor the development of deeper storms because of greater atmospheric instability. Thus, deeper storms occur over southwestern New Guinea as the rainfall propagates to the southwestward. When convection is propagated to the southern plain (0000–0300 LT), significant rainfall can be sustained by the convergence of downslope winds and the low-level large-scale circulation. Because of the prevailing westerly component offshore of southwestern New Guinea, the rainfall area does not propagate directly to the southern coast but instead tends to propagate westward toward the southwest coast. The interaction between the orographical wind and the prevailing wind would also contribute to inducing deep convection over southwestern New Guinea. Rainfall gradually moves offshore between midnight and early morning (0600 LT), and persists until late morning (0900–1200 LT). Again, large-scale prevailing winds toward the island could force convective development by forcing convergence between the prevailing low-level winds and land breezes from New Guinea. However, rainfall offshore is localized to near the coast.

It is interesting to note that, in the easterly regime, the diurnal rainfall is concentrated over the islands,

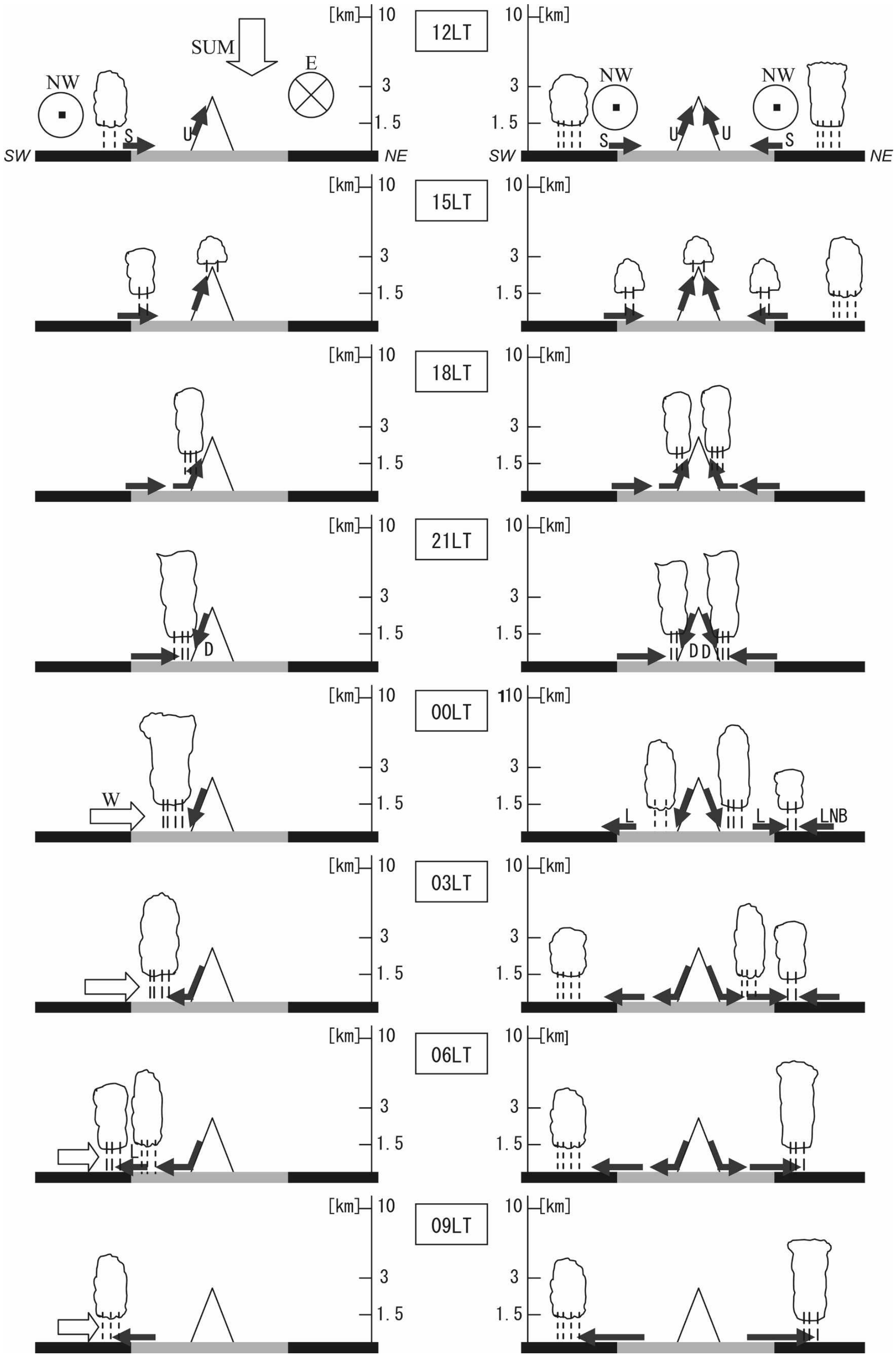


FIG. 12. Schematics of diurnal rainfall/convective activity over New Guinea along the cross-island rectangle in Fig. 1 for the (left) easterly and (right) westerly regimes. The hypothesized local circulation, extrapolated from Zhou and Wang (2006), is superposed as is denoted by the thin arrow (D: downslope wind; U: upslope wind; L: land breeze; LNB: land-breeze flow from New Britain; S: sea breeze). The circumscribed cross (dot) denotes the large-scale easterly (northwesterly) flow component described as east (northwest) into (out of) the section. The thick arrow in the easterly regime indicates the large-scale suppressed upward motion (SUM) and westerly wind component (W).

particularly on the southwestern side. During the easterly regime, relatively moistened air spreads over the southwestern part of the island extending from the western part of the Maritime Continent. In addition, the large-scale low-level convergence and related upward motion occur over the southern part of the island and north of Australia but are suppressed over the north of the island. The convection and rainfall are thus favored over the southwestern part of the island. On the other hand, during the easterly regime, the atmospheric environment is basically drier because the center of the large-scale MJO system is located over the western part of the Maritime Continent and the wetter monsoonal westerly weakens. In that situation, rainfall activity occurs only over the island because of the strong diurnal cycle activating the strong convection. However, rainfall tends to be suppressed over the surrounding oceans during the convectively inactive phase in the MJO (as noted in Chen and Takahashi 1995). Thus, enhanced rainfall is concentrated over the southwestern part of the island. The strong inhibition in diurnal rainfall over the windward side (northern side) of the island might be partly related to the dynamical blocking of easterly flow from the Pacific by the higher land terrain, which leads to low-level divergence and suppressed upward motion. However, details of such modification by the orography for wind patterns are beyond the scope of this study. Future studies could include numerical modeling to clarify the large-scale impact of the peculiar orography of New Guinea on circulation fields.

Under the westerly regime, rainfall propagates on both the eastern and western slopes of the central mountain range through coupling of the large-scale circulation and widespread upward motion. Nevertheless, northeastward propagation of rainfall is prominent over the island, and the rainfall continues until 0300 LT. Offshore rainfall occurs on both sides of the island from nighttime to noon, but the development processes in the two areas differ dramatically. Significant rainfall propagation extending from the island appears offshore northeast of New Guinea in a region of large-scale enhanced upward motion in association with the low-level westerlies. On the other hand, nocturnal rainfall offshore the southwest of New Guinea spreads north from northern Australia in association with a low-level cyclonic circulation and localized updraft there. This rainfall over the southwestern offshore area is further favored by a convergent land breeze from New Guinea. On the other hand, the pronounced offshore propagation off the northeast coast of New Guinea starts over the sea between New Guinea and New Britain at night, presumably due to the convergence of low-level northwesterlies and the land breeze from the two islands sometime between 0000 and 0300 LT. The rain system extends northwestward along the coast because of penetration of the moist air by the prevailing northwesterlies and because of land breeze convergence between midnight and morning (0300–0600 LT). Then, organized convection develops along the northern coast and propagates east-northeastward at about 7–8 m s^{-1}. The phase speed is close to the 700-hPa westerly wind speed ($\sim$8 m s^{-1}), which suggests that advection by low-level winds is partly responsible for the propagation of the rainfall system. However, propagation is northeastward as well as eastward. A land breeze that blows northeastward perpendicular to the north coast continues in the early morning and promotes the offshore propagation. In addition, the occurrence of a gravity wave resulting from the strong diurnal signal over land might be a key factor in offshore propagation as was suggested by previous studies (Yang and Slingo 2001; Mapes et al. 2003). Zhou and Wang (2006) actually showed that offshore propagation of rain is triggered by the combined effect of a land breeze and the gravity waves forced previously by deep convection over the mountain ridges of New Guinea, and they demonstrated that this mechanism also strongly influences offshore propagation. Furthermore, the low-level northerly component around the equator over the Pacific facilitates the development of longer-lived convection over northern New Guinea as the north wind converges with the land breeze (Liberti et al. 2001). These mechanisms support ongoing rainfall until the following day (1200–1500 LT), and the rain can spread far into the Pacific under the strong low-level westerlies and large-scale upward motion that are induced by enhanced convergence related to the SPCZ.

As discussed above, the development and propagation of diurnal rainfall occurs as large-scale circulations interact with local circulations induced by orography. Several mechanisms may control the behavior of the diurnal cycle. Further detailed investigation is warranted to reveal the processes that organize convection. Such studies should include an analysis of results from numerical simulations, perhaps using high-resolution cloud-resolving models.

Acknowledgments. The authors thank Prof. K. Nakamura, Prof. H. Masunaga, and Dr. H. Fujinami for their valuable comments and suggestions. Thanks are also due to Dr. Munehisa K. Yamamoto for archiving the 3B42 data. This study was partly supported by the 21st Century COE Program "Dynamics of the Sun–Earth–Life Interactive System (SELIS)" of Nagoya University, Japan.

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