The Cross-Equatorial Northerly Surge over the Maritime Continent and Its Relationship to Precipitation Patterns

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Abstract

This study describes the characteristics of the cross-equatorial northerly surge (CENS), a northerly flow that appears intermittently over the equatorial region between October and April, and its relationship to the precipitation patterns over the Maritime Continent. The CENS in this study was defined as the area-averaged northerly wind exceeding 5 m s\(^{-1}\) over 105°E–115°E, 5°S–EQ based on the QuikSCAT sea surface wind data. During the 10 winters from December 2000 to March 2009, 62 CENS events were extracted and classified into the following patterns: 11 events were associated with cold surges and termed the CS pattern; 20 events were associated with tropical intra-seasonal variations and termed the MJO pattern; 16 events were associated with both cold surges and tropical intra-seasonal variations and termed the CS–MJO pattern; and other 15 events were not associated with these patterns. In the CS pattern, the development and dissipation processes of the cold surge appeared, and the increased precipitation to the north of the island of Java was significant. In the MJO pattern, a wide area of northerly winds in the vicinity of the depression around 10°S continued for a longer period than in the CS pattern, and the increased precipitation west of Sumatra and south of Java was significant. The CS–MJO pattern showed features of the northerly wind fields of both the CS and MJO patterns and was associated with the greatest increase in precipitation of the three patterns in the Maritime Continent, in particular, in northwestern Java and both north and south of Java. The generation of CENS was an important environmental factor for inducing the wide positive precipitation anomaly compared to the climatological mean over the Maritime Continent.

1. Introduction

During the boreal winter, a low-level north-northeasterly flow, namely Asian winter monsoon is widely observed in East and Southeast Asia (Chan and Li 2004). It corresponds to the cold air outbreak in the lower layer associated with the development of the surface Siberia–Mongolia High (SMH), and is consistently observed from November to March over Eurasia. In the steady cold northerly flow, intermittent variations in temperature, pressure, and wind speed are often observed and called the cold (pressure) surge, an intra-seasonal variation in Asian winter monsoon. The
cold surge is associated with intensified northerly winds, decreased temperatures, and increased pressure over the South China Sea. Although there are various definitions of the cold surge according to the purposes of previous studies, an intensified northerly flow is simply defined as a cold surge even if it is not associated with any temperature variations (Wu and Chan 1995, 1997; Chang et al. 2006). This northerly flow area sometimes extends to the south over the South China Sea and up to the equatorial region. Recently, it is noticed that the cross-equatorial flow originating from mid-latitudes in the northern hemisphere is an important environmental factor related to heavy rainfall in Jakarta (Wu et al. 2007).

Wu et al. (2007) demonstrated that the strong northerly wind events occurred five times over the South China Sea in 2007, and in the strongest event, northerly wind blew across the equator and penetrated into the northern part of Java Island. This strong flow persisted for more than one week and coincided with the formation of the repeated torrential rains causing widespread floods. However, few studies have focused on enhancement processes of this northerly flow over the equatorial region. Thus, the specific mechanism of the convection enhancement and its association with this northerly flow over the equatorial Maritime Continent region are not well understood.

Most previous studies on the cold surge described its characteristics in terms of the wind, temperature and pressure over the northern part of the South China Sea. Several studies investigated the relationships between the cold surge over the northern part of the South China Sea and the variation in convection in the equatorial region. Compo et al. (1999) showed a strong correlation between the generation of the cold surge defined at 15°N, 115°E and convective activities in the southern part of Indonesia using 11 years of data from a European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis and Outgoing Longwave Radiation (OLR) data. Chang et al. (2003) argued that a strong cold surge was an important environmental factor for generation of the near-equatorial typhoon Vamei in 2001. Chang et al. (2005) investigated the long-term variations in convective activities over the Maritime Continent and the relationship to the cold surge. They revealed that a strong cold surge event enhances the convective activity over the Indochina Peninsula and the northern part of Sumatra. However, the characteristics of the northerly surge south of the equator have not been revealed.

In addition, one problem with previous studies is that there was no unified quantitative definition of the cold surge: its definition has varied depending on the purpose of the study. For instance, Wu and Chan (1995, 1997) defined the cold surge using surface meteorological data as a negative temperature anomaly (<2 K), a change in wind direction (>60°) and a northerly wind component greater than 8.1 m s⁻¹ in Hong Kong (22.4°N, 114.1°E). Meanwhile, Compo et al. (1999) defined the pressure surge using the ECMWF reanalysis data as a positive sea level pressure anomaly (>3 hPa) at 15°N, 115°E. Chang et al. (2005) defined the cold surge as a northerly wind component at 925 hPa that averaged more than 8 m s⁻¹ between 110–117.5°E, 15°N. These previous definitions do not take into account the intensity of the cold surge in the equatorial region (10°S–10°N). Hence, we redefined the northerly surge south of the equator to describe its relationship to the convective activities in the equatorial region.

This study defines the cross-equatorial northerly surge (CENS) by focusing on the characteristics of the northerly flow over the southern part of the South China Sea and the equatorial Maritime Continent. The objective of this study is to identify the characteristics of the CENS and its relationship to the precipitation patterns over the Maritime Continent.

2. Data description

The present study used the daily sea surface wind data averaged over 3 days from the Quick Scatterometer (QuikSCAT) sea surface winds (Freilich and Dunbar 1999; Chelton and Freilich 2005) to estimate the low-level wind field. We also used the 6 hourly air temperatures and the geopotential heights at 925 hPa from the Japan Meteorological Agency (JMA) operational Climate Data Assimilation System (JCDAS) data (Onogi et al. 2007). To estimate the precipitation over the Maritime Continent, 3 hourly precipitation data from the Tropical Rainfall Measuring Mission (TRMM) 3B42 rainfall product (Huffman et al. 2007) were used. Furthermore, the daily mean data from the National Oceanic and Atmospheric Administration (NOAA) Interpolated OLR (Liebmann and Smith 1996) were used to identify the convective activity of the tropical intra-seasonal variation. The spatial resolutions of the data were 0.25° × 0.25° for QuikSCAT
and TRMM3B42, 1.25° × 1.25° for JCDAS and 2.5° × 2.5° for OLR. We analyzed 10 winters: November, December, January, February, March and April from 1999 to 2009.

3. Climatology of the wind, geopotential height and temperature in boreal winter

We first described the climatological characteristics of Asian winter monsoon flow over the southern part of the South China Sea and the Maritime Continent. Figure 1 shows the 10-year mean of the sea surface wind field in January derived from the QuikSCAT data from 2000 to 2009. The north-easterly wind prevails in the South China Sea and it changes to northerly in the equator region and northwesterly in the region further south. We focused on the appearance and intensification of this north-northwesterly flow, especially over the equatorial Maritime Continent.

In order to show the basic seasonal march of the winter monsoon northerly flow and temperature/height fields over the South China Sea and the...

Fig. 1. The 10-year means of sea surface wind over the South China Sea and the Maritime Continent for January 2000 to 2009. The rectangular boxes indicated by solid and dashed line are the area for the cross-equatorial northerly surge and the intra-seasonal variation indices. The horizontal line is the location for the cold surge index.
Maritime Continent, climatologically averaged latitudinal time progresses are shown in Figs. 2, 3. Figure 2 shows a time–latitude cross-section of the 10-winter average of the meridional sea surface wind and the wind vectors from November to April over the South China Sea, which was examined between 105°E and 115°E. The northerly wind area in the South China Sea extended south of the equator from late November to March. It is found that the climatological maximum northerly wind in the equatorial region was observed in early to mid-February, and the southernmost region of the northerly area reached 12°S in mid-February. Figure 3 is the same as Fig. 2, except that it shows the temperatures and geopotential heights at 925 hPa. The high pressure and low temperature area near the surface level extended southward from November to January. Especially from January to March, these areas abruptly and intermittently penetrated the south. These climatological characteristics suggested that the changes in the surface pressure and temperature that accompanied the cold surge might affect the atmospheric fields south of the equator.

Next, we determined the specific characteristics by examining data of the winter of 2008–2009. Figure 4 shows a time–latitude cross-section of the meridional sea surface wind from November 2008 to April 2009, and Fig. 5 shows the temperatures and geopotential heights at 925 hPa for that period. The 10-year mean of the southward extension of the northerly wind area corresponded to the high pressure and low temperature area. During 2008–
2009, however, these southward extensions did not generally correspond. For example, as indicated by white and black starts in Figs. 4 and 5, southward extensions of the northerly wind were found around 21 December, 13 January and 7 February, and it penetrated the south significantly around 7 February, whereas the high pressure and low temperature around 13 January were remarkable. Moderate northerly winds south of the equator observed around 1 March were accompanied by a low, rather than a high, pressure and a high temperature. In other words, the intensification of the northerly winds over the Maritime Continent was not necessarily accompanied by an extension of the high pressure and low temperature field, and various backgrounds likely exist for each case. In addition, the “cold” surge does not always cross the equator because the low temperature area did not extend south of the equator in December 2008 and in March 2009. Therefore, to investigate the association between the northerly flow and rainfall activity over the Maritime Continent, the background of the cold surge needs to be considered. In Section 4, we consider how the northerly flow across the equator occurred and the background patterns that were present during the four months from December to March.

4. Cross-equatorial northerly surge

In the present study, we defined a “cross-equatorial northerly surge” (CENS) event, as a more direct background of convective activity over
the equator and the Maritime Continent in boreal winter. The CENS index was defined as an area-averaged meridional wind over 105°E–115°E, 5°S–EQ indicated by the rectangle box with solid line in Fig. 1 based on the QuikSCAT sea surface wind data. While the CENS index exceeded 5 m s⁻¹ continuously, it was considered to be one CENS event. Based on the background circulation field, we classified the occurrence pattern of the CENS event.

During the 10 winters from December to March of 1999 to 2009, there were 62 CENS events with various backgrounds. The major predominant backgrounds of the CENS events were the cold surge originating from the mid-latitudes which has a few days to a week time span (Wu and Chan 1995; Chang et al. 2005) and a tropical intra-seasonal variation which has 30–60 days time scale corresponded to the Madden–Julian Oscillation (MJO; Madden and Julian 1971, 1972, 1994). Therefore, we compared the characteristics of the CENS events that were dominated by the cold surge and by the tropical intra-seasonal variation. The cold surge was defined, according to Chang et al. (2005), as an event in which the average sea surface meridional wind between 110°E and 117.5°E and along 15°N exceeded 8 m s⁻¹. The area for the index is indicated by the solid line in Fig. 1. The tropical intra-seasonal variation was defined as convectively active over the Maritime Continent when the 30-day running mean OLR over 100°E–120°E, EQ–15°N indicated by the rectangle box with dashed line in Fig. 1 was less than 210 W m⁻².

Fig. 4. As in Fig. 2 but for 2008–2009. Starts represent cases of southward extension of the northerly wind indicated in the text.
The threshold value was defined by the averaged OLR of 240 W m$^{-2}$ in the Maritime Continent area in the northern winter with consideration of averaged standard deviation of 30 W m$^{-2}$, as an approximately consistent value with the previous studies (Murakami 1980; Lau and Chan 1985). As a result, of the 62 CENS events, 11, 20 and 16 were found to be accompanied by the cold surge, tropical intra-seasonal variation and both the cold surge and tropical intra-seasonal variation, respectively (Table 1). In addition, 15 CENS events were not accompanied by the cold surge or the tropical intra-seasonal variation.

Based on these classifications, we applied a composite analysis to the cold surge pattern (CS pattern: 11 cases), the tropical intra-seasonal variation pattern (MJO pattern: 20 cases) and the pattern that was dominated by both (CS–MJO pattern: 16 cases). In order to investigate the relationship between the intensification of the CENS and time evolution of the background circulation field, we applied lag composite analysis. We excluded cases

Table 1. Numbers of the events with and without CS, MJO and CS–MJO background among the 62 CENS events.

<table>
<thead>
<tr>
<th></th>
<th>MJO</th>
<th>no MJO</th>
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<tr>
<td>CS</td>
<td>16</td>
<td>11</td>
<td>27</td>
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<tr>
<td>no CS</td>
<td>20</td>
<td>15</td>
<td>35</td>
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<td>total</td>
<td>36</td>
<td>26</td>
<td>62</td>
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in which the CENS event occurred within 3 days of a former CENS event. The day at which the CENS index reached its maximum value was defined as day 0; 3 days before the maximum was reached was defined as day $-3$; and 3 days afterward was defined as day $+3$.

Figure 6 shows the composite sea surface wind on day 0 for the (a) CS, (b) MJO and (c) CS–MJO patterns. Gray shading and contour lines in the upper (lower) figure show the northerly (westerly) components of the sea surface wind. The solid (dashed) line indicates the positive (negative) wind component with 3 m s$^{-1}$ interval. Thick solid line indicates 0 m s$^{-1}$ in meridional wind speed.

8 m s$^{-1}$ and the northerly wind extended up to 7$^\circ$S north of Java. The zonal wind seen on the bottom of Fig. 6a shows that a westerly wind dominated east of 105$^\circ$E south of the equator. This westerly and southerly wind at around 110$^\circ$E corresponded to the Australian monsoon flow in the southern hemisphere, which seems to turn around Australia. A strong westerly wind was also found north of 25$^\circ$N and was accompanied by a strong cold surge from the Asian Continent. In the MJO pattern (Fig. 6b), the northerly component was weaker than in the CS pattern. However, a northerly wind speed above 6 m s$^{-1}$ was found up to 5$^\circ$S, and the northerly wind extensively dominated beyond 10$^\circ$S. At the bottom of Fig. 6b, a westerly wind can be
seen which dominated the region south of the equator from west of 95°E to east of 140°E. Compared to the CS pattern, the zonal wind west of 110°E changed from easterly to westerly, which corresponds to the presence of a convectively active tropical intra-seasonal variation (Madden and Julian 1972, 1994; Sui and Lau 1992). The CS–MJO pattern (Fig. 6c) showed features of both the CS and MJO patterns. A strong northerly wind in the East China Sea and the South China Sea was found, which was similar to the CS pattern, and a northerly wind prevailed beyond 10°S, which was similar to the MJO pattern. A westerly wind dominated south of the equator, similar to the MJO pattern. In other words, the CS–MJO pattern exhibited features of the CS pattern north of the equator and features of the MJO pattern south of the equator.

In order to compare the intensity and duration of the CENS events in each pattern in detail, time–height cross-section of the composite meridional wind and time series of the composite CENS index from day −5 to day 5 are shown in Fig. 7. Upper figures in Fig. 7 indicate that the strongest peak of the northerly wind was appeared in the CS pattern. The northerly wind in the CS–MJO pattern was also strong compared to that in the MJO pattern. From the bottom figures in Fig. 7, it is indicated that the strongest peak of the CENS index on day 0 was appeared in the CS pattern while the smallest index on day −5 was appeared in the CS pattern too. The mean duration of the CENS index which exceeded 5 m s$^{-1}$ was about 6, 4 and 5 days in the CS, MJO and CS–MJO patterns, respectively. The duration of the CENS index of the CS pattern was the most long-lasting, whereas the duration of a little weaker northerly surge below 5 m s$^{-1}$ was the most short-lived of the three. In other words, the CENS index in the CS pattern increased rapidly from day −5 to day 0, while the index in the MJO and CS–MJO patterns did not increase rapidly but relatively intensified on day −5 already.
Figure 8 shows the composite temperatures (upper) and geopotential heights (lower) at 925 hPa on day 0 for the (a) CS, (b) MJO and (c) CS–MJO patterns. In the CS pattern (Fig. 8a), the low temperature area over eastern China and the East China Sea extended in a tongue shape to eastern Vietnam and the South China Sea at low levels. Corresponding to the low temperature area, a high geopotential area dominated over eastern China, the East China Sea, the Indochina Peninsula and the northern South China Sea. These distributions are characteristic of the occurrence of a cold surge that is accompanied by the southward and eastward extension of the SMH. In the MJO pattern (Fig. 8b), the low temperature area retreated to the north. The high temperature area present in the Indochina Peninsula provides an outstanding zonal contrast with the temperature. The high geopotential height over the continent was reduced in this area. In addition, the lower geopotential height due to active convection of the tropical intraseasonal variation was significant in the southern hemisphere compared with the CS pattern. The CS–MJO pattern in Fig. 8c has the temperature and geopotential height features of both the CS and MJO patterns. Similarly to the CS pattern, a tongue-shaped area of the low temperature/high geopotential height was distributed over a significant portion of the Indochina Peninsula and the South China Sea. The area below 10°C extended further south than in the CS pattern. Similarly to the MJO pattern, a low geopotential height was observed in the southern hemisphere. In the CS–MJO pattern, the meridional contrast of tempera-
tures and geopotential heights tended to be larger than in the other two patterns.

Next, we investigated the anomaly from the climatological 10-winter mean on day $-3$, day 0 and day +3 for an individual pattern. Figures 9, 10 and 11 illustrate the composite sea surface wind anomalies in the CS, MJO and CS–MJO patterns, respectively, on (a) day $-3$, (b) day 0 and (c) day +3. Figures 12, 13 and 14 show the composite air temperature and geopotential height anomalies at 925 hPa for the CS, MJO and CS–MJO patterns, respectively, on (a) day $-3$, (b) day 0 and (c) day +3.

In the CS pattern (Figs. 9, 12), the cold surge developed from day $-3$ to day 0 and decayed from day 0 to day +3, which was associated with the extension of the low temperature/high pressure area over the Asian Continent. From day $-3$ to day 0 (Figs. 9a, b), the northerly wind anomalies intensified throughout the South China Sea and northeast of the Philippines. The intensified northerly wind propagated southward from the northern South China Sea, and the northerly wind anomaly reached Java Island. The zonal component shows that the westerly anomaly increased in the East China Sea and the Philippine Sea, which corresponded to an intensification of the cold surge from the Asian Continent. On day +3 (Fig. 9c),

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Fig. 9. Composite sea surface wind anomalies in the CS pattern from the 10-winter mean for DJFM on (a) day $-3$, (b) day 0 and (c) day +3. Gray shading in the upper (lower) figure shows the northerly (westerly) components of the sea surface wind anomaly. The shaded areas and vectors indicate that the anomaly exceeded the 90% significance level. The solid (dashed) line indicates positive (negative) northerly and westerly wind anomaly with 2 m s$^{-1}$ interval. The thick solid line indicates 0 m s$^{-1}$ in wind speed anomaly.
the southerly wind anomaly found on the seacoast of China indicated that the cold surge had decayed. The decay of the cold surge was also indicated by the change in the westerly anomaly in the Philippine Sea to an easterly anomaly. Furthermore, the low temperature/high geopotential areas extended southward to the Indochina Peninsula and the South China Sea from day −3 to day 0, and afterward these areas extended east to the East China Sea and the northern Philippine Sea. These phenomena represent the characteristics of the background of the cold surge: the low temperature/high pressure areas extend or separate from the SMH to the south and move east. Therefore, we conclude that the CENS is caused by a cold surge accompanied by an extension of the low temperature/high pressure area.

In the MJO pattern (Figs. 10, 13), the depression corresponding to the active convection of the tropical intra-seasonal variation around 10°S was distributed widely to the south of the equator. The northerly wind anomaly was present south of the equator, whereas weak northerly or southerly wind anomalies were found north of the equator. From day −3 to day 0 (Figs. 10a, b), the northerly wind anomaly intensified in the southern part of South China Sea, Java Sea and south of Java in the eastern Indian Ocean. The widespread strong westerly anomaly around 10°S and the significant low pressure anomaly around 10°S (Figs. 13a, b) were associated with the active convective area of the tropical intra-seasonal variation. In mainland China and its seacoast, a high temperature/low pressure anomaly indicates that the cold surge is inactive. On day +3 (Figs. 10c, 13c), the northerly wind anomaly south of the equator and the westerly

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**Fig. 10.** As in Fig. 9 but for the MJO pattern.
anomaly around 10°S still dominated and corresponded to the continuous depression south of 10°S. Compared to the CS pattern, the northerly wind tended to be distributed widely and long-lasting. Thus, we conclude that the CENS in the MJO pattern is caused by the intensified northerly wind south of the equator accompanied by the depression centered around 10°S, which is associated with the tropical intra-seasonal variation.

The CS–MJO pattern showed features of both the CS and the MJO patterns, as shown in Figs. 6 and 8. From day −3 to day 0 (Figs. 11a, b), the northerly wind anomalies intensified in the East China Sea and the South China Sea and were present to the south of Sumatra and Java. Around 10°S, a strong westerly wind anomaly was also observed. On day +3, the northerly and westerly wind anomalies in the eastern Indian Ocean continuously dominated, while the northerly wind anomalies weakened in the South China Sea. From Fig. 14, it can be seen that the low pressure anomaly south of 10°S was dominant from day −3 to day +3, whereas the significant low temperature/high pressure anomalies over mainland China, Indochina Peninsula and northern part of the South China Sea intensified, reached their maxima on day 0 and then weakened on day +3. In other words, the northerly wind flows widely and continuously compared with the CS pattern, and the CENS becomes stronger than in the MJO pattern because the cold surge variations over several days coincided with the long-lasting background of the tropical intra-seasonal variation.

Finally, we describe the CENS events without either the cold surge or the tropical intra-seasonal variation. In the 15 such events detected over 10

![Fig. 11. As in Fig. 9 but for the CS–MJO pattern.](image-url)
years, six coincided with a cyclonic disturbance over the sea to the west of Australia (not shown). Events that coincided with this disturbance were found frequently in the MJO and CS-MJO patterns as well. These disturbances mostly propagated westward and some were analyzed as an equatorial Rossby wave of the meridional mode number 1 with the propagating speed of 5–10 m s\(^{-1}\) accompanied by the MJO. Therefore, it is possible that the strong wind and depression caused by the westward-propagating disturbance affect the development of the CENS. While six other events did not satisfy either the CS or the MJO index, these seem to resemble those which belong to either CS or MJO patterns (not shown).

5. The cross-equatorial northerly surge and precipitation

The present study focuses on the relationship between the CENS and precipitation over the Maritime Continent, especially in the Java Sea and Java Island.

Figure 15 shows the precipitation over the South China Sea and the Maritime Continent using (a) the 10-winter mean for DJFM from 1999 to 2009, (b) the composite analysis of the 62 CENS events and (c) the composite anomaly of the 62 CENS events from the 10-year winter mean (b-a). As shown in Fig. 15a, the climatological winter mean precipitation was mostly high over the land area,
including Java Island, south and western Sumatra, western Kalimantan, central Sulawesi, the eastern Philippines, and the eastern Malay Peninsula. The precipitation was about 0.5 mm hr$^{-1}$ over the land and about 0.3 mm hr$^{-1}$ over the ocean. In the southern and western Java Sea and the eastern Indian Ocean south of Sumatra Island, the precipitation was about 0.5 mm hr$^{-1}$ and similar to that over the land. For CENS (Fig. 15b), on the other hand, the precipitation over the sea was greater than that over the land. The precipitation was about 0.4–1.0 mm hr$^{-1}$ over the central and southern portions of the Java Sea and about 0.5 mm hr$^{-1}$ over the eastern Indian Ocean south of Sumatra and Java, and the precipitation increased over the Timor Sea to the northwest of Australia and the Philippine Sea. Over the land area, the precipitation reached 0.4–1.0 mm hr$^{-1}$ over the western and northern coast of Java and 0.4–0.8 mm hr$^{-1}$ over the eastern Philippines and the northwestern coast of Australia, but decreased to 0.2 mm hr$^{-1}$ in Sumatra and Kalimantan. The difference between the CENS events and the climatological mean (Fig. 15c) indicated that the precipitation increased widely over the sea south of 5$^\circ$S and east of Kalimantan, including the central and southern Java Sea, the eastern Indian Ocean and the central and east of the Philippines. In particular, a positive anomaly of 0.6 mm hr$^{-1}$ was found to the north of western Java.

Figure 16 shows composite precipitations on day 0 (upper) and the differences from the 10-winter mean for DJFM (lower) in the (a) CS, (b) MJO and (c) CS–MJO patterns. In the lower figure, the solid contour represents an anomaly of 0 mm hr$^{-1}$, and only anomalies over 90% significance are repre-
presented by color shading. The upper figures show that greater amounts of precipitation were present over the sea in all three patterns. In the CS pattern (Fig. 16a), precipitation above 1.0 mm hr\(^{-1}\) was observed to the north of Java, south of Sulawesi, in the eastern Philippines and west of Kalimantan, whereas little precipitation below 0.4 mm hr\(^{-1}\) was found to the west of Sumatra and south of Java. From the bottom of Fig. 16a, the positive anomaly north of Java and negative anomaly southwest of Sumatra and south of Java were significant. In the MJO pattern (Fig. 16b), on the other hand, little precipitation was observed in the northern Java Sea, and precipitation at about 0.6–1.0 mm hr\(^{-1}\) was observed over the eastern Indian Ocean to the west of Sumatra and the south of Java. A negative anomaly in the Java Sea and a positive anomaly southwest of Kalimantan and northwest of Australia were found. In the central Philippines and northwest of Australia, heavy precipitation over 1.0 mm hr\(^{-1}\) and positive anomalies above 0.6 mm hr\(^{-1}\) were observed too. In the CS–MJO pattern, a large amount of precipitation above 0.8 mm hr\(^{-1}\) was observed both north and south of Java, eastern Philippines, northwest of Kalimantan and northwest of Australia. Striking positive anomalies above 0.6 mm hr\(^{-1}\) were found over these areas, including Java Island. The CS–MJO pattern has features of both the CS and MJO patterns; moreover, the CS–MJO pattern shows much more precipitation with a striking positive anomaly compared with the other two patterns.

The precipitation over the land area in Java is seems to be suppressed compared with the surrounding positive anomalous regions in all three patterns. We propose that large-scale phenomena
do not significantly affect the precipitation over the land because the diurnal-scale local circulation dominates over the land, as shown in many previous studies (Mori et al. 2004; Sakurai et al. 2005; Wu et al. 2008; Wu et al. 2009). However, the precipitation over the land has different features in each background. In the MJO pattern, the precipitation over the land was especially small, and a negative anomaly was found in western Java. In the CS–MJO pattern, on the other hand, a large amount of precipitation was present in western Java, and a striking positive anomaly was found in northwestern Java. The positive anomaly in northwestern Java was also found in the CS pattern. We conclude that the increase in precipitation in the CS and CS–MJO patterns contributes strongly to the precipitation in the boreal winter over northwestern Java.

6. Discussion

The present study shows the relationship between the generation of the CENS and the precipitation pattern over the Maritime Continent. Here we discuss the factors that influence the increased precipitation in the CS, MJO, and CS–MJO patterns.

In the CS pattern where the CENS was appeared in association with a cold surge, the convective activities over the Java Sea and the northern part of Java Island were enhanced. This was also shown in the results of Chang et al. (2005), who described the relationship between the cold surge and convective activities over the South China Sea. They investigated the precipitation patterns under various conditions that were related to the formation of the Borneo vortex over the sea to the west of Borneo and the intensity of the cold surge. Although they did not specifically mention the precipitation in the equatorial region, positive precipitation anomalies appeared over the Java Sea and Java Island during the cold surge events when the Borneo vortex did not form (Figs. 7c, 9a, and 9b of Chang et al. 2005), which is similar to the CS pattern in the present study. When the Borneo vortex formed, southwesterly winds were enhanced over the southern part of the South China Sea and the Java Sea (Chang et al. 2005), it means that the CENS tended to weaken. In addition, because the easterly winds over the equator were greatly strengthened and the meridional component of the wind decreased (Chang et al. 2005), the CENS tended to weaken during very strong cold surge events. Thus, the CS pattern in the present study is consistent with the situation when the Borneo vortex did not occur and the intensity of the cold surge was weak or moderate in Chang et al. (2005). As a factor related to the increased precipitation around the Java Sea
and the northern part of Java Island, a case study of the heavy rainfall events in Jakarta on 31 January and 1 February 2007 by Wu et al. (2007) suggested that a vertical wind shear between a strong cross-equatorial northerly flow at low levels and southeasterly flow at upper levels is greatly enhanced and contributes to the organization of orographic convective systems over Java. Future studies should investigate in detail these dynamic factors related to the increased precipitation in the CS pattern.

In the MJO pattern where the CENS was appeared during a convectively active phase of the tropical intra-seasonal variation, convective activities over the sea west of Sumatra and south of Java were enhanced. The regions of increased precipitation are consistent with Hidayat and Kizu (2010), who showed that the increase in precipitation due to the MJO over ocean is more significant than that over land. Sui and Lau (1992), Chen and Houze (1997), Sui et al. (1997), and Tian et al. (2006) demonstrated that the long-term average precipitation is increased by diurnal modulation of precipitation during the passage of the MJO; their results are consistent with the features of the MJO pattern in the present study, though the diurnal modulation of precipitation was not noted in this study. In general, diurnal variations in precipitation due to thermally induced local circulation and orographic effects dominate over the Maritime Continent (Murakami 1983; Williams and Houze 1987; Nitta and Sekine 1994; Yang and Slingo 2001).

Fig. 16. Composite precipitations on day 0 (upper) and the anomalies from the 11-winter mean for DJFM (lower) in the (a) CS, (b) MJO and (c) CS–MJO patterns. The solid contour in the lower figure represents an anomaly of 0 mm hr$^{-1}$. Positive anomalies are indicated by light gray shading and only anomalies above the 90% significance level are represented by color shading.
Over the region west of Sumatra, the diurnally generated precipitation systems over Sumatra propagate westward (Mori et al. 2004; Sakurai et al. 2005; Wu et al. 2008; Wu et al. 2009). Ichikawa and Yasunari (2006, 2007, 2008) showed that the characteristics of the propagation of the diurnal precipitation vary with the phases of environmental winds, which are associated with the intra-seasonal variation. Therefore, in order to clarify the factor of the significant increase in precipitation west of Sumatra in the MJO pattern, further study on the relationship between the CENS and the modulation of the diurnal variation in precipitation is expected.

In the CS–MJO pattern where the CENS appeared during a phase in which a convectively active phase of the intra-seasonal variation and a cold surge coincide, the increase in precipitation over the Maritime Continent was much larger than that in the other two patterns. The CS–MJO pattern had characteristics of both the CS and the MJO patterns. That is, the increase in precipitation was widely induced over the Maritime Continent. The following factors are supposed and should be clarified in the future study: 1) the enhanced vertical wind shear over the Java Sea and the northern part of Java Island and 2) the modulation of the diurnal precipitation by the intra-seasonal variation associated with MJO over the regions west of Sumatra and south of Java.

7. Conclusions

This study describes the characteristics of the cross-equatorial northerly surge (CENS) during the 10 years from December 1999 to March 2009 and the relationship between CENS and the precipitation patterns over the Maritime Continent. The CENS was defined here as an area-averaged meridional wind that exceeds 5 m s\(^{-1}\) over 105°E–115°E, 5°S–EQ based on the QuikSCAT sea surface wind data. During 10 years, 62 CENS events were extracted and classified into the following patterns: 11 events were associated with the cold surge and termed the CS pattern; 20 events were associated with the tropical intra-seasonal variation and termed the MJO pattern; 16 events were associated with the both the cold surge and the MJO and termed the CS–MJO pattern; and other 15 events were not associated with these patterns.

In the CS pattern, the northerly winds were enhanced over the equator as a result of the southward propagation of the northerly wind field with the cold surge that originated from the cold SMH. Before and after the peak of the CENS, the development and dissipation processes of the cold surge were significant. Before the peak of the CENS, a tongue-shaped cold and high pressure area was distributed over the eastern part of Vietnam and the South China Sea, and the northerly winds were widely enhanced over the East China Sea, the South China Sea, and the Philippine Sea. At the peak of the CENS, an area of strong northerly winds extended to the south and up to Java. After the peak of the CENS, the cold and high pressure area extended further east over the East China Sea and the Philippine Sea, and the northerly winds weakened.

In the MJO pattern, the northerly winds over the equator were enhanced as a result of the formation of a depression around 10°S, which was associated with the tropical intra-seasonal variation. The CENS lasted for a longer period in the MJO pattern than in the CS pattern. Before the peak of the CENS, the northerly winds over the South China Sea, the East China Sea, and the northern part of the Philippine Sea were weak, and a warm and low-pressure area was distributed over mainland China. In contrast, significant northerly wind anomalies were seen in the vicinity of the depression around 10°S. At the peak of the CENS, the depression around 10°S was enhanced, and the northerly winds in the southern hemisphere intensified significantly. After the peak of the CENS, the northerly winds were continuously associated with the depression.

The CS–MJO pattern has the features of the northerly wind field of the CS pattern in the northern hemisphere and those of the MJO pattern in the southern hemisphere. The northerly wind component over the equator in the CS–MJO pattern was the greatest of the three patterns, and the northerly wind area extended beyond 10°S. The lower temperature/higher pressure was distributed in the region north of 10°N, while the higher temperature/lower pressure was distributed in the regions south of 10°S: the meridional contrast between the pressure and temperature was very significant. Before the peak of the CENS, a tongue-shaped cold and high-pressure area extended over the Indochina Peninsula and the South China Sea, similar to the CS pattern. After the peak of the CENS, the northerly winds and the depression continued over a wide area of the Maritime Continent, although the cold and high-pressure area decayed slightly.
The CENS is an important environmental factor for the formation of precipitation over the Maritime Continent. The positive anomalies of precipitation compared to the climatological mean were significant, especially over the oceans south of 5°S (the Java Sea and the eastern part of the Indian Ocean) and east of Kalimantan. Based on the differences between the three patterns, the following characteristics were identified. In the CS pattern, the precipitation was heavy over the northern part of Java, east of the Philippines and west of Kalimantan but light over the oceans west of Sumatra and south of Java. In the MJO pattern, the precipitation was heavy over the central part of the Indian Ocean, the Java Sea and the central Philippines but light over the Java Island. In the CS–MJO pattern, the precipitation was heavy over Java Island, the eastern part of the Indian Ocean, the Java Sea, east of the Philippines and west of Kalimantan. In other words, it is revealed that the major environment causing the increase of precipitation in each area was different over the Maritime Continent; the precipitation in the Java Sea was controlled by the CS pattern, whereas that in southwest of Sumatra, south of Java and northwest of Australia was controlled by the MJO pattern. Moreover, the cold surge coincided with the tropical intra-seasonal variation (CS–MJO pattern) contributed significantly to the increase of the precipitation in those areas. The convective activities associated with these patterns are thought to contribute to precipitation during the boreal winter season; future studies should investigate its specific contributions to and dynamic mechanisms for increased precipitation.

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