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The Impact of Long-lasting Northerly Surges of the East Asian Winter Monsoon on Tropical Cyclogenesis and its Seasonal March

Hiroshi G. TAKAHASHI

Research Institute for Global Change (RIGC),
Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan
Department of Geography, Tokyo Metropolitan University, Hachioji, Japan

Yoshiki FUKUTOMI

Research Institute for Global Change (RIGC),
Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan

and

Jun MATSUMOTO

Research Institute for Global Change (RIGC),
Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan
Department of Geography, Tokyo Metropolitan University, Hachioji, Japan

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Abstract

The impact of northerly surges of the East Asian winter monsoon on tropical cyclogenesis over the eastern Indian Ocean and maritime continent was examined for the 6-month period of October to March from 1979/1980 to 2006/2007 based on case studies and lag-composite analysis. We focused on long-lasting northerly surge events at 6- to 30-day (sub-monthly or intraseasonal) time scales over the South China Sea. In addition, we examined seasonal differences in the impact of northerly surges over the South China Sea on tropical atmospheric circulation.

The results show that northerly surges occur frequently in the period from October to March. Long-lasting northerly surges over the South China Sea intrude into tropical regions. Over the eastern Indian Ocean and maritime continent, the surges are associated with the appearance of tropical cyclones. However, the impact of these surges varies with the seasonal march. In October and November, tropical cyclones occur over the South China Sea during the northerly surge events, enhancing positive vorticity over the South China Sea. A cyclone pair symmetric with respect to the equator also appears over the eastern Indian Ocean in November and is responsible for the enhancement of the horizontal gradient of zonal wind by the northerly surge. In contrast, in December, January, and February, an asymmetric cyclone pair (the so-called Borneo vortex) develops around Borneo. The asymmetric cyclone pair around the maritime continent is associated with intensification of low-level wind along a channel between the islands of Borneo, Sumatra, and Java. In March, no clear tropical cyclone appears over the tropical regions in association with the northerly surge.

Corresponding author: Hiroshi G. Takahashi, Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan.
E-mail: hiroshi3@tmu.ac.jp

The seasonal difference in the impact of the long-lasting northerly surge of the East Asian monsoon on tropical cyclone development is associated with the background conditions of low-level atmospheric circulation over the eastern Indian Ocean and maritime continent. During November, cyclonic vorticity occurs in the lower troposphere over the eastern Indian Ocean, which is favorable for the development of the cyclone pairs. That is, the superposition of the northerly surges and mean fields produces a highly favorable condition for tropical cyclogenesis. In the other months, the horizontal structures of low-level zonal wind differ from those in November. During December, January, and February, a climatological northerly wind extends over the channel between Borneo and Sumatra, aiding in the deep intrusion of northerly surges into the equatorial region. Flow along this channel is also strongly affected by the land-sea distribution and orography.

1. Introduction

The periodic occurrence of northerly wind surges (known as "cold surges") on synoptic and intraseasonal time scales over East Asia is a common phenomenon of the East Asian winter monsoon. The Winter Monsoon Experiment (WMONEX) has investigated cold surges over East Asia and related atmospheric circulation over the tropics.

Cold surges bring rapid drops in temperature that affect local areas and residents and have thus been intensively investigated over the Japan Sea side of Japan as well as eastern coastal regions of the Eurasian continent such as South China and Hong Kong. A number of previous studies have described the spatial and temporal structures of the East Asian cold surges (e.g., Chang et al. 1983; Boyle 1986; Chang and Chen 1992; Chan and Li 2004).

Another impact of cold surges has also been partly revealed, namely modulation of tropical convective activity and associated atmospheric circulation. This study focuses on this impact. Several previous studies have investigated the interaction between the extra-tropics and tropics, particularly over the western and central equatorial Pacific (e.g., Kiladis et al. 1994; Meehl et al. 1996; Kiladis et al. 1997; Compo et al. 1999). Compo et al. (1999) reported the characteristics of the East Asian cold surges (which they termed "pressure surges") that intrude into the tropics. They found that on the sub-monthly (but not on the synoptic) time scale, "pressure surges" can intrude into the tropics and have potential impacts on tropical convective activity and related atmospheric circulation. Previous studies (e.g., Kiladis et al. 1994; Meehl et al. 1996; Kiladis et al. 1997) also showed that pressure surges on the sub-monthly time scale were associated with upper-level wave trains in the mid-latitudes.

Associated with the pressure surges, tropical cyclones sometimes occur over the tropics. Yu et al. (1998) showed that a Philippine Sea pressure surge excited a westerly wind burst event, which induced an El Nino event in 1997–1998. Love (1985) noted that cross-equatorial flows from the winter to summer hemispheres originated from the mid-latitudes of the winter hemisphere could generate tropical cyclones in the summer hemisphere. In addition, Chang et al. (2003) found that a tropical cyclone that formed over the maritime continent was probably associated with northerly wind surges over the South China Sea. They suggested that this so-called Borneo vortex was also associated with the northerly wind surges. Recently, Yokoi and Takayabu (2010) showed that a cold surge of the winter monsoon could lead to tropical cyclone development over the Bay of Bengal in April. Although these case studies investigated the linkage between the northerly surge of the East Asian monsoon and tropical cyclogenesis over the tropics, statistical studies have been limited.

Compared with studies of 30–60-day intraseasonal variation [i.e., the Madden Julian Oscillation (MJO)], relatively few studies have investigated intraseasonal variation at a sub-monthly time scale over the eastern Indian Ocean and maritime continent. Most previous studies dealing with the intraseasonal variations of the Asian winter monsoon and convective activity over the tropics during northern winter have focused on intraseasonal variation on the MJO time scale. Meanwhile, previous studies that investigated the interaction between the extra-tropics and tropics based on convective activity over the tropics have mainly discussed the combined effects of extra-tropical surges and tropical disturbances such as the MJO. This study focuses on the impact of northerly surges only. In addition, previous studies have investigated convective activity over the tropics associated with mid-latitude phenomena only during Northern Hemisphere winter. Hence, although northerly surges also occur during other seasons in the Asian monsoon region (Zhang et al. 1997a, 1997b), little is known about the impact of northerly surges of the East Asian winter monsoon on the tropical atmosphere over the eastern Indian Ocean and maritime continent during the late Northern Hemisphere fall to early spring seasons. In addition, northerly surges may have differing impacts on tropical circulation depending on the season, because background circulation over the tropics shows a seasonal march, particularly in the north-south migration of the intertropical convergence zone. However, the seasonal differences in the impact of northerly surges on tropical climate have not been discussed.

The primary purpose of this study is to understand the impact of the northerly surges of the East Asian winter monsoon at the sub-monthly time scale on tropical atmosphere over the Indian Ocean and maritime continent. As noted above, although previous studies that investigated the interaction between the extra-tropics and tropics based on convective activity over the tropics, this study investigates the impact of northerly surges only. In particular, we focus on the impact of the northerly surges on tropical cyclone development, as well as the seasonal modification associated with the seasonal changes in background atmospheric conditions.

The rest of this paper is arranged as follows. Section 2 documents the data used in this study. In Section 3, to clarify our target phenomenon, we describe two events in which the East Asian monsoon impacted the tropical region, namely recent meteorological disasters in South and Southeast Asia. As discussed, these events were likely associated with a linkage between northerly surges of the East Asian monsoon and tropical cyclones over the eastern Indian Ocean and maritime continent. Based on composite analysis of the northerly surge events, spatial structures in atmospheric circulation fields at the intraseasonal time scale over the eastern Indian Ocean and maritime continent are investigated in Section 4. Possible explanations for the impact of the northerly surges are discussed in Section 5, and conclusions are given in Section 6.

2. Data

This study used the Japanese 25-year Reanalysis (JRA-25; Onogi et al. 2007) and the Japanese Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS) datasets to examine the northerly surges themselves and the atmospheric circulation associated with them, including zonal and meridional winds (u, v). In addition, we calculated relative vorticity and stream function. The datasets are global in coverage, with 2.5° spatial resolution and 6-hourly temporal resolution. In this study, daily mean values of all atmospheric elements were calculated from the original data. To analyze convective activity over the tropics, an interpolated outgoing long-wave radiation (OLR) dataset provided by the National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory (ESRL) was also used. The dataset is also global in coverage, with 2.5° spatial resolution and daily temporal resolution. For composite analysis, data were compiled for the 28 Northern Hemisphere fall–winter–spring seasons of 1979/1980 to 2006/2007. JCDAS data for December 2006 and November 2007 were used for the case study in Section 3. To describe a heavy rainfall event in Malaysia, we used the Global Satellite Mapping of Precipitation (GSMaP) microwave radiometer (MWR) product (Kubota et al. 2007) produced from passive microwave radiometer data. The dataset is global between 60°S and 60°N in coverage, with 0.25° spatial resolution and 1-hourly temporal resolution. We used daily averaged values. Because Compo et al. (1999) noted that intraseasonal-scale "pressure surges" intrude into the tropics and can modulate tropical atmospheric circulation, we focus on the intraseasonal (or sub-monthly; 6 to 30 days) variations of atmospheric circulations. Six- to 30-day band-pass filtered atmospheric data were produced and were used for the composite analysis described in Section 4. A time filter was applied to the total daily-mean time series at each grid, following the method of Compo et al. (1999). All the data were temporally filtered into a sub-monthly (6–30-day) frequency band using a Lanczos digital filter (Duchon 1979) with 121 daily weights. The high number of weights could reduce the problem of Gibbs' phenomenon in the filtered data.

To address the difference in number of days per month, we used a unique definition of the months as follows: 2 October to 31 October, 1 November to 30 November, 1 December to 30 December, 31 December to 29 January, 30 January to 28 February, and 1 March to 30 March were defined as October, November, December, January, February, and March, respectively. Thus, all our months have 30 days. Because the difference between conventional months and our months is very small, we simply compare our results with those of previous studies using conventional month definitions.

3. Case study of Asian monsoon northerly surges

To clarify the target phenomenon of this study, we give two examples of associations between East Asian monsoon northerly surges and tropical cyclones over the eastern Indian Ocean and maritime continent. The first case is Cyclone "Sidr," which struck Bangladesh and India in November 2007. Cyclone Sidr developed over the Bay of Bengal and moved northward. The other case is a heavy

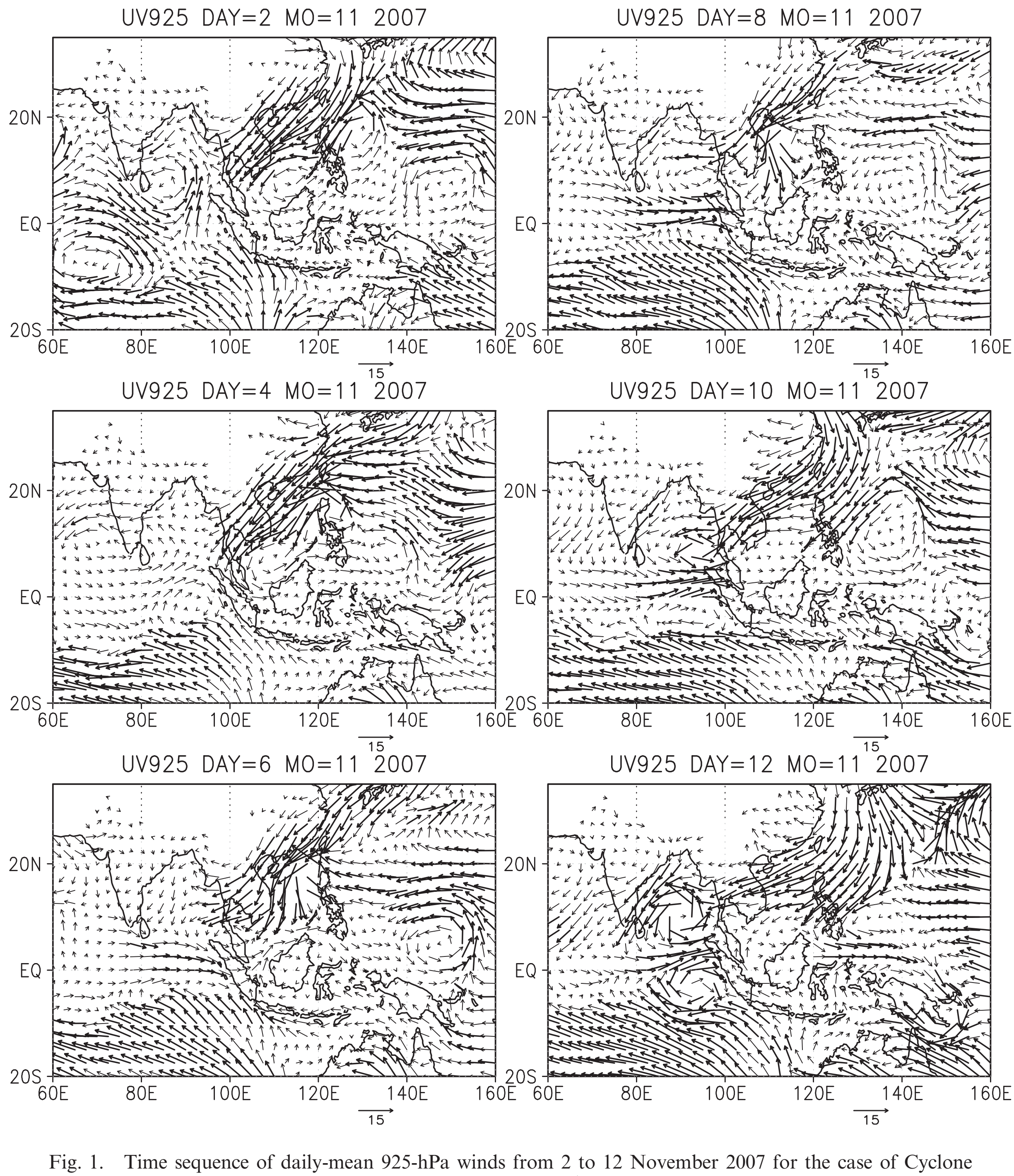

Fig. 1. Time sequence of daily-mean 925-hPa winds from 2 to 12 November 2007 for the case of Cyclone Sidr. Thick arrows indicate wind speed greater than 7 m s^{-1}.

rainfall event that occurred over the Malay Peninsula in December 2006. From December 2006 to February 2007, several heavy precipitation events occurred in the Malay Peninsula (Malaysian Meteorological Service 2007; personal communication). Although the case study event did not have the highest recorded rainfall amount during this winter, it was considered representative of several heavy precipitation events in Malaysia at the end of 2006.

3.1 Cyclone Sidr

To illustrate the temporal development of Cyclone Sidr, the lower tropospheric (925 hPa) circulation fields are shown in Fig. 1. The Asian northeasterly winds reached the Indochina Peninsula on 2 November and continued until 6 November 2007. Simultaneously, a cyclone pair developed over the eastern Indian Ocean from 4 to 12 November 2007, likely associated with the northerly wind surge that originated from the mid-latitudes. The northern cyclonic vortex of the pair developed into Cyclone Sidr by 12 November 2007. Cyclone Sidr moved northward, seriously impacting communities in Bangladesh and India. On 6 November, a cyclonic circulation occurred around the northern tip of Sumatra that was associated with intensification of horizontal wind shear over the region due to intrusion of the mid-latitude northeasterly surge into the tropics. Around the Indochina Peninsula, the northerly winds turned clockwise from northerly to easterly winds. The development of a tropical cyclone over the South China Sea was also associated with the northerly surge. Moreover, the tropical cyclone over the South China Sea probably intensified or maintained easterly winds over the Indochina Peninsula to Bay of Bengal regions around 8 November 2007. Thus, the northerly surge was associated with the development of the tropical cyclone at the early stage. Note that the northerly surge over the South China Sea lasted for more than one week, from 2 to 10 November. The period of the northerly surge was much longer than the time scale of the mid-latitude baroclinic waves. In this study, we focus on these long-lasting northerly surges.

To examine temporal variations of the northerly surge, the time-latitude cross-section in meridional winds at 925 hPa along the South China Sea (105°E–115°E; shading) and East China Sea (120°E–130°E; contour) is shown in Fig. 2. During the development phase of the tropical cyclone from

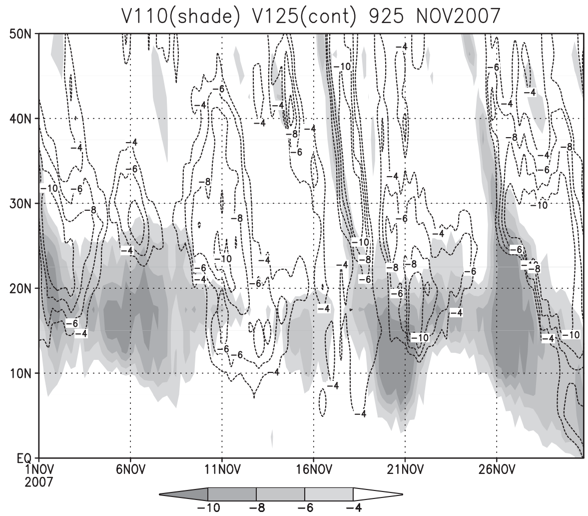

Fig. 2. Time-latitude cross-section of daily-mean 925-hPa meridional wind averaged over 105°E–115°E (shade) and 120°E–130°E (contour) for November 2007. Unit is m s^{-1}.

4 to 10 November 2007, the northerly component persisted over the South China Sea. The northerly episode was longer over the South China Sea (low latitudes) than over the East China Sea (mid-latitudes). The long-lasting northerly surge in early November 2007 produced long-lasting northeasterly winds over the South China Sea and was associated with development of the cyclone pair over the eastern Indian Ocean.

3.2 A heavy precipitation event in Malaysia

As the second case, we describe a heavy precipitation event over the Malay Peninsula in December 2006, which was associated with the Asian winter monsoon northerly surge. The northerly surge was found from 21 to 29 December 2006 over the South China Sea (Fig. 3). Concurrent with the northerly surge, the cyclonic circulation over Borneo (the "Borneo vortex") gradually developed from 23 to 31 December 2006. Heavy precipitation was observed over the southern tip of the Malay Peninsula on 25, 27, and 31 December and was associated with the northerly surge and the Borneo vortex. A cyclonic circulation also developed over the southern part of the island of Java and was likely associated with a westerly wind burst over the Java Sea, located between Borneo and Java. The result suggests that the northerly surge over the South

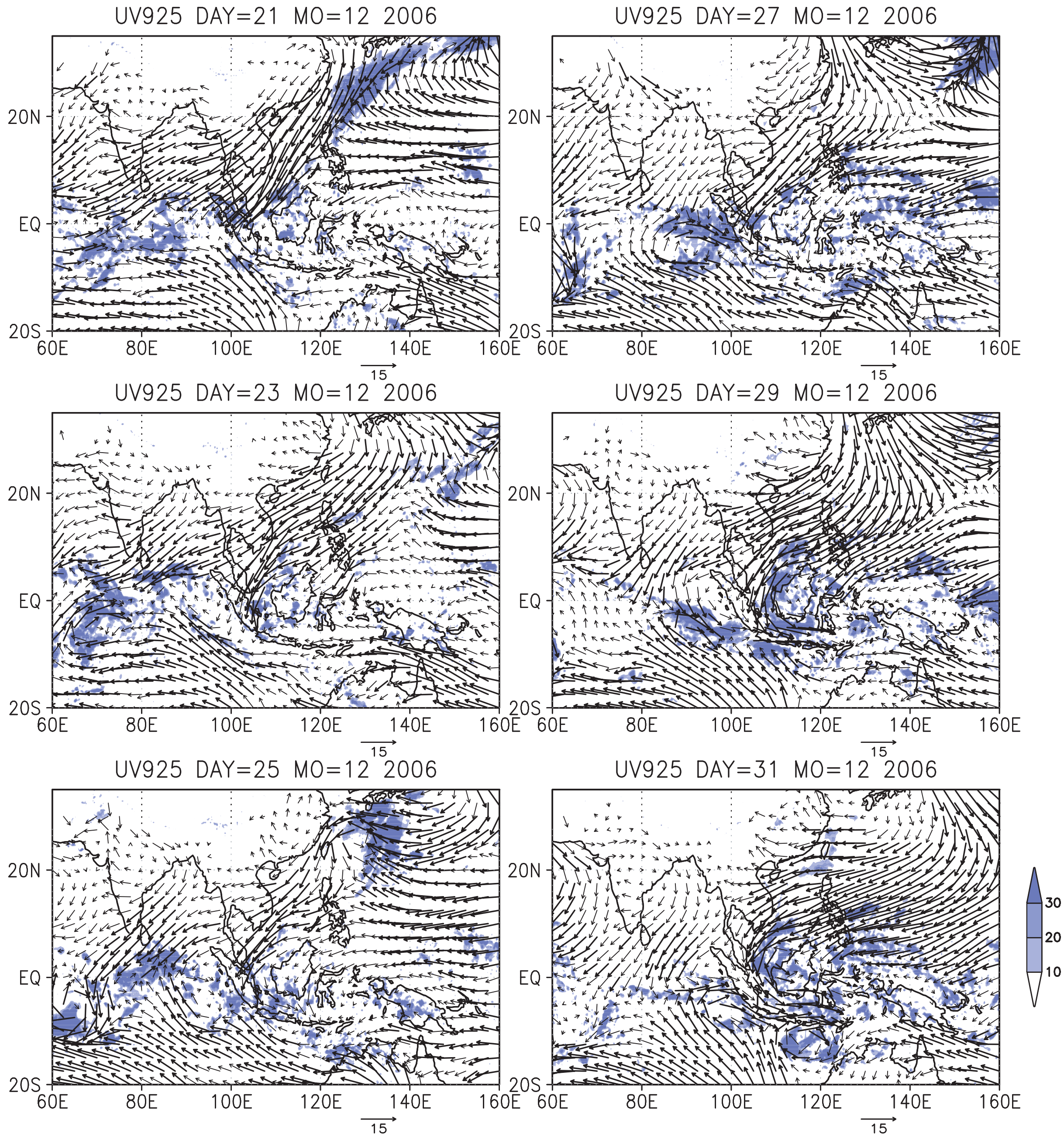

Fig. 3. Time sequence of daily-mean 925-hPa winds from 21 to 31 December 2006 for the case of a heavy precipitation event in the Malay Peninsula. Thick arrows indicate wind speed greater than 7 m s^{-1}. In addition, daily rainfall amount is plotted, to describe the heavy precipitation evnet. Unit of rainfall amount is mm day^{-1}.

China Sea was associated with the formation of the cyclone pair over the maritime continent. The cyclonic circulation of the pair developed first in the Northern Hemisphere and subsequently in the Southern Hemisphere. Interestingly, counterclockwise circulation over Borneo extended across the equator, even though the Coriolis force changes sign across the equator. This observation suggests that the development of the asymmetric cyclone pair over the maritime continent was strongly affected by the land-sea distribution and orography. In general, development of cyclonic circulations over the tropics associated with equatorward surges from the extra-tropics can be explained by advection of absolute vorticity from the extra-tropics, which is converted into relative vorticity because of the conservation of absolute vorticity.

In this case, the low-level northerly winds continued for a long time (Fig. 4). During the development phase (from 23 to 29 December 2006) of the cyclonic circulation over Borneo, the northerly wind in the lower troposphere was dominant.

A common feature of these two cases of northerly surge of the East Asian winter monsoon is that the northerly surges lasted longer than the mid-latitude baroclinic waves. Moreover, the long-lasting northerly surges were associated with the development of cyclone pairs over the eastern Indian Ocean and maritime continent, at least in these two cases. We additionally examined several other cases of long-lasting northerly surges over the South China Sea that were associated with the development of cyclonic circulation over the eastern Indian Ocean and maritime continent (not shown). Here, we focus on these northerly surges and their impact on tropical cyclogenesis over the eastern Indian Ocean and maritime continent. To understand the linkage between the northerly surges and tropical cyclone development over the eastern Indian Ocean

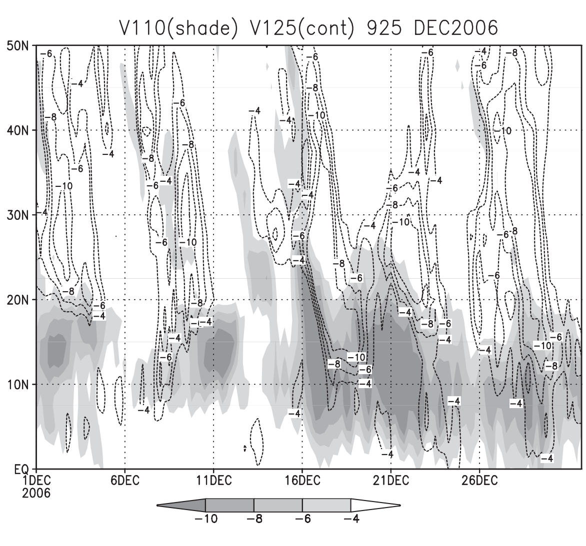

Fig. 4. Same as Fig. 2 but for December 2006.

and maritime continent, we present the results of composite analysis in the next section.

4. Climatology of long-lasting northerly surges

As described in the previous section, the long-lasting northerly surges were associated with the development of cyclone pairs over the eastern Indian Ocean and maritime continent. However, we could not reject the possibility of an accidental coincidence in the seeming linkage between the surges and tropical cyclones. To confirm the link between the northerly surges and tropical cyclone development, this section presents a lag-composite analysis. We examined many cases of northerly surges over the Asian monsoon region (not shown) and found that some cases were associated with the development of tropical cyclones, whereas some others were not. Thus, statistical evaluation of the linkage was necessary.

4.1 Climatological northerly surge activity

To determine a reference area for composite analysis, the climatological northerly surge activity from October to March over the study regions was compiled in Fig. 5. This figure shows the spatial distribution of total variances in the 925-hPa meridional wind and climatological wind field at 925 hPa. Large variance was found over the South China Sea, as also reported in previous studies. Because our goal was to understand the impacts of northerly surges on tropical cyclone development, we particularly sought northerly surges that intruded deeply into the tropics. In terms of the climatological northerly surge activity and our study purpose, we found that low-level meridional wind over the South China Sea was a proper reference index. Examination of the spatial distribution of total variance in 925-hPa meridional wind in each month revealed large variance over the South China Sea in all months (not shown). This finding implies that northerly surges are active over the 6 months from October to March in this region.

Compo et al. (1999) showed that sub-monthly-scale surges can extend into the tropics. Given that finding and our focus on long-lasting surges, the 6- to 30-day filtered meridional winds were suitable as an index for the lag-composite analysis. Then, we calculated the zonal average of filtered meridional wind at 925 hPa over the South China Sea between 105°E and 115°E along 10°N. Using the zonally averaged meridional wind, long-lasting northeasterly surge events could be defined as follows:

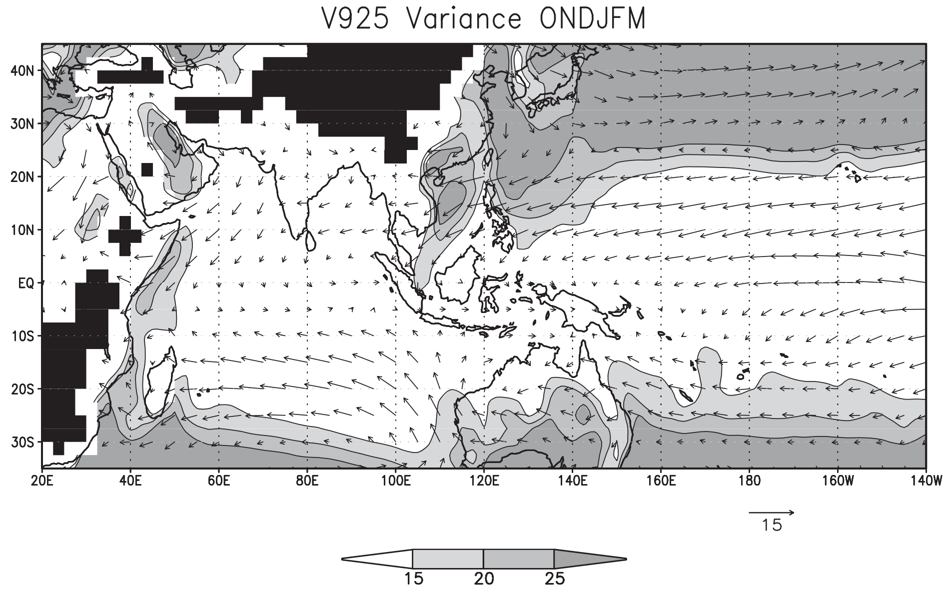

Fig. 5. Gray shading indicates climatological total variance in the 925-hPa meridional wind over the 6 months from October to March. Unit is $m^2\ s^{-2}$. Arrows indicate the climatological mean 925-hPa winds averaged from October to March. Unit is $m\ s^{-1}$.

- First, we chose days of "relatively stronger northerly surge." When the filtered meridional wind over 105–115°E at 10°N latitude (South China Sea) on a given day fell below -0.6σ (stronger northerly wind), where σ is the standard deviation from the mean, that day was defined as a day of relatively stronger northerly surge.
- Second, we selected "long-lasting northerly surge events." A 7-day period having more than 4 days of relatively stronger northerly surge was considered a long-lasting northerly surge event.
- Third, within the 7-day period of a long-lasting northerly surge event, the first day was labeled Day 0 for the lag-composite analysis.

After many trials and errors, the criterion of 0.6σ was determined, and the two events described in the previous section were both categorized as long-lasting northerly surge events. An example time series of filtered meridional wind over 6 months is shown in Fig. 6(a) for the winter of 1979/1980. To examine seasonal differences in the occurrence frequency of long-lasting northerly surges over the South China Sea, the number of such surge events over 28 years is shown in Fig. 6(b). Long-lasting northerly surges occurred most frequently in February. Long-lasting northerly surge events were also found in late fall to early spring. This finding is consistent with the seasonal march of the frequency of northerly surges reported by Zhang et al. (1997a, 1997b), although they used different definitions of surges.

4.2 Impact of long-lasting northerly surges on tropical atmospheric circulation and its seasonal changes

To understand the impact of long-lasting northerly surges of the East Asian winter monsoon on tropical atmospheric circulation over the Indian Ocean and maritime continent, lag-composite maps of low-level (925 hPa) winds and relative vorticity were produced.

In October (Fig. 7), low-level summer monsoon westerlies are shown over the Bay of Bengal. The low-level summer monsoon westerly and winter monsoon northeasterly winds converge over the Indochina Peninsula. Wind convergence over Indochina can be associated with late summer rainfall over the Indochina Peninsula (Takahashi and Yasunari 2006). Another interesting feature is the appearance of a tropical cyclone around the Philippines, associated with intensification of cyclonic circulation (positive vorticity) due to cross-equatorial flow from the Southern Hemisphere and northerly surge from the Northern Hemisphere extra-tropics. Climatologically, vigorous tropical cyclone activity occurs around the Philippines in October.

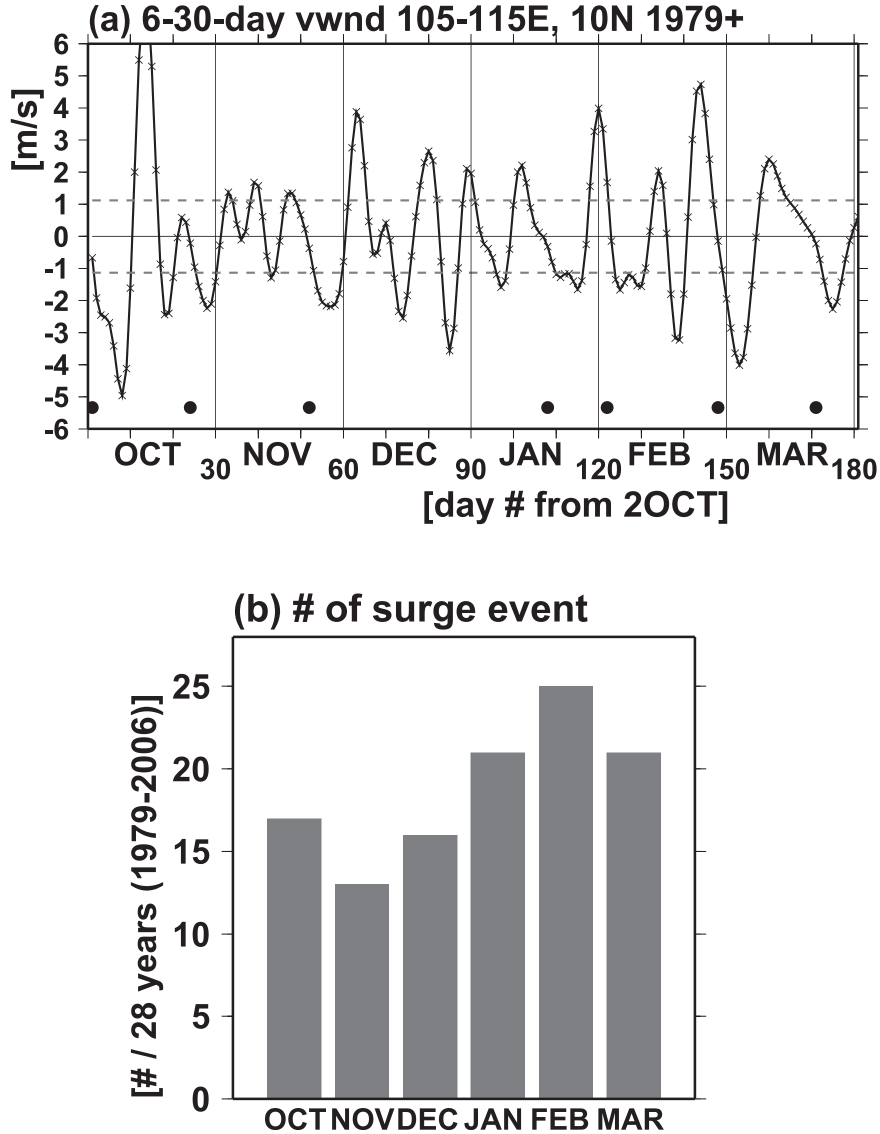

Fig. 6. Time series of the filtered 925-hPa meridional wind over the reference region (a). The closed circles denote the Lag 0 day in the composite analysis. The number of long-lasting northerly surge events in each month over 28 years, as determined by our definition (b).

In November (Fig. 8), on Day 0, a pair of cyclonic circulations is shown over the eastern Indian Ocean, although the cyclonic circulation in the Southern Hemisphere is somewhat weak. Northeasterly winds of the Asian winter monsoon are stronger over the South China Sea compared with those in October. Easterly winds over the Bay of Bengal, the Indochina Peninsula, and the South China Sea and westerly winds along the equator, which are part of the cyclonic circulation pair over the eastern Indian Ocean, produce strong horizontal wind shear. On Day 4, a pair of cyclonic circulations with strong relative vorticity is organized over the Indian Ocean (around 80°E). The formation processes of the cyclone pair over the eastern Indian Ocean are similar to those of Cyclone Sidr. The cyclonic circulations in both hemispheres move westward. In addition, positive vorticity is formed around the Philippines, similar to the development of cyclonic circulation in October.

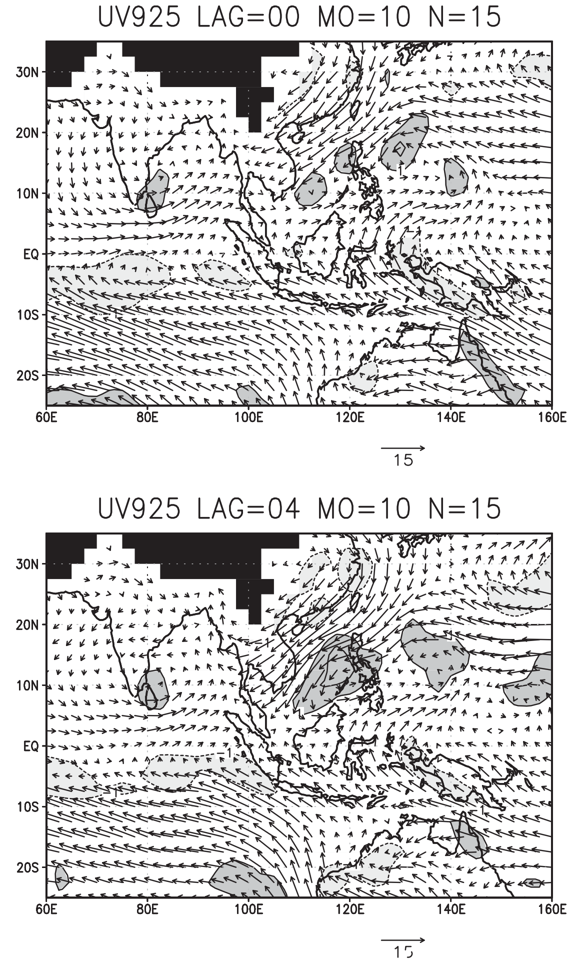

Fig. 7. Lag-composite of total fields of 925-hPa horizontal wind based on the long-lasting northerly surges in October. The sample number used in the composite is shown in the upper right of each panel. The lag-composites on Day 0 (upper panel) and Day 4 (lower panel) are plotted. Shading and contours indicate the relative vorticity at 925 hPa. Dark (Light) gray indicates positive (negative) vorticity. Dark (Light) shading denotes more (less) than 1×10^{-5} (-1×10^{-5}) s^{-1}.

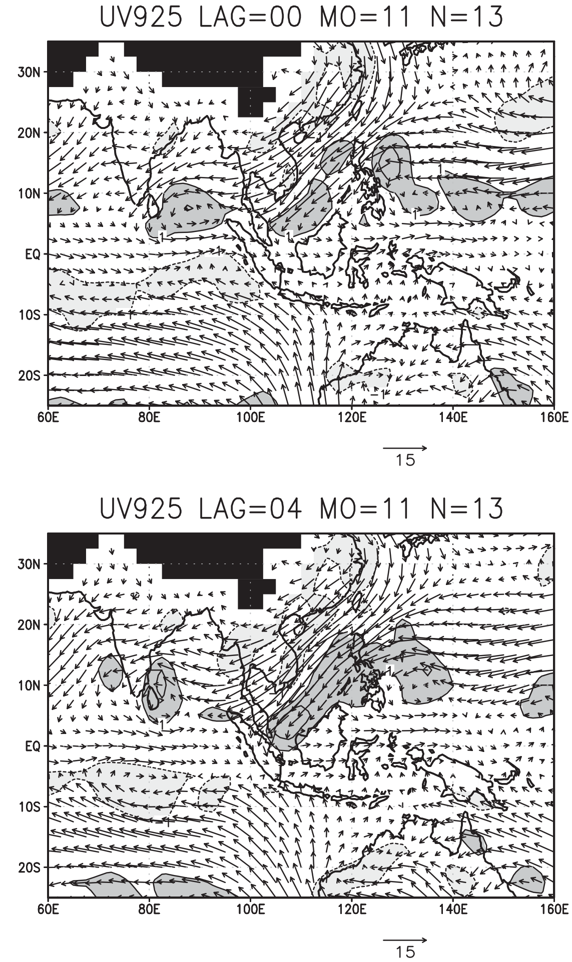

Fig. 8. Same as Fig. 7 but for November.

The lag-composite results for the northerly surges in December, January, and February are very similar. Thus, here we show the result for February only. The atmospheric circulation in February (Fig. 9) differs largely from that in November. Over the Indian Ocean, the maritime continent, a channel between Borneo and Sumatra, and the western equatorial Pacific, cross-equatorial flows prevail in December, January, and February, associated with the southward movement of convective activity over the Indian Ocean and western Pacific (Matsumoto and Murakami 2002). Pairs of cyclonic circulations are found over Borneo/offshore of northwestern Australia and northwest of New Guinea/northeastern Australia on Day 0. By Day 4, the cyclonic circulation with positive vorticity over Borneo is enhanced and is probably the Borneo vortex. This enhancement of positive vorticity is associated with the northerly surge. In the Southern Hemisphere, cyclonic circulation develops offshore of northwestern Australia. Another pair of cyclonic circulations west of New Guinea weakens or remains unchanged, implying that the paired cyclonic circulation is not associated with the long-lasting northerly surges over the South China Sea.

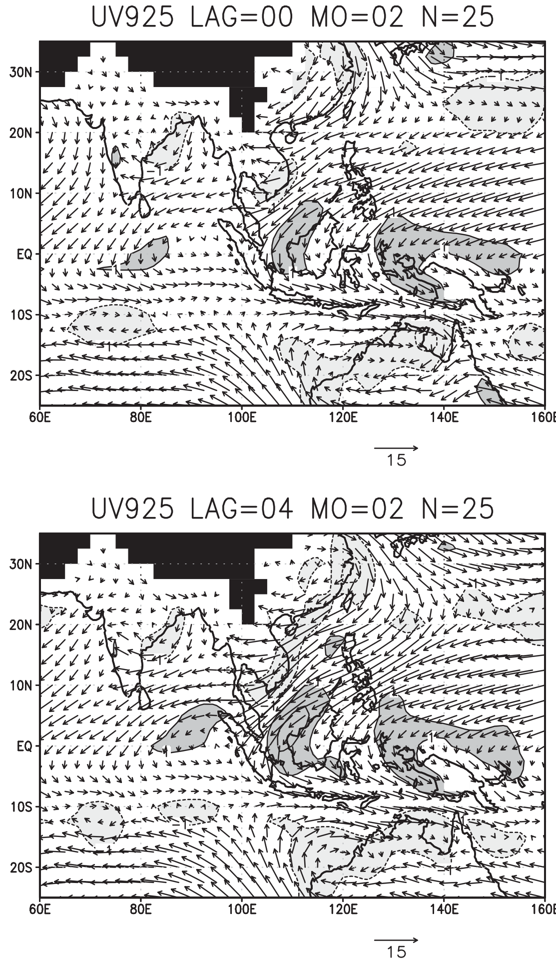

Fig. 9. Same as Fig. 7 but for February.

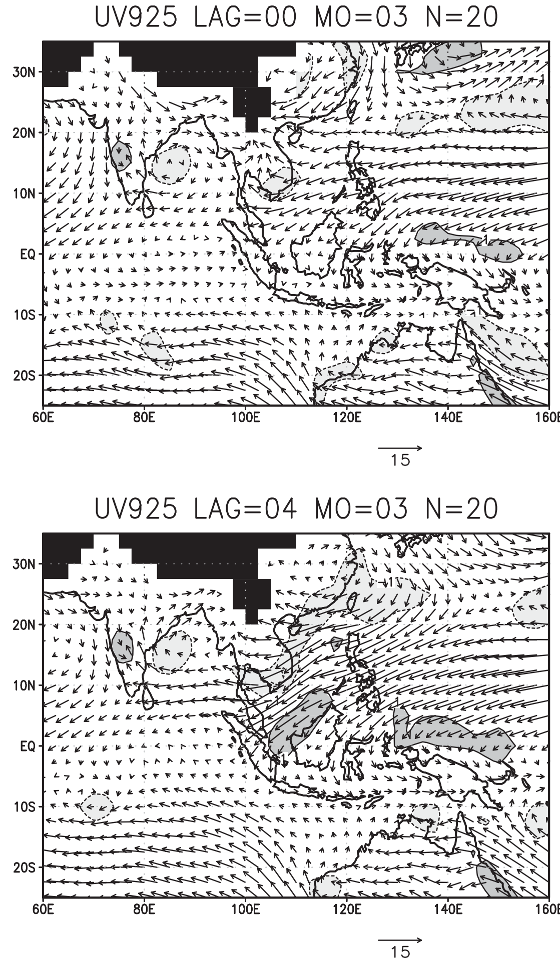

Fig. 10. Same as Fig. 7 but for March.

Asian winter monsoon northeasterlies weaken or disappear over East Asia and Southeast Asia from February to March (Fig. 10). No clear tropical cyclone is found in March. Over the western Bay of Bengal, anticyclonic circulation exists on Day 0. On Day 4, anticyclonic circulation develops over the Bay of Bengal and merged with a large-scale anticyclonic flow of the Asian winter monsoon. Over the Bay of Bengal, southerly winds are enhanced in association with the mid-latitude northerly surges.

In this manner, tropical atmospheric circulations are largely modulated by the northerly surges of the East Asian winter monsoon. As impacts of the northerly surges, tropical cyclones occur around the Philippines, the eastern Indian Ocean, or maritime continent, except in March. Note that the surge impacts on tropical cyclone development depend on the season. To understand the process of tropical cyclone development over the eastern Indian Ocean and maritime continent, the next subsection provides a lag-composite analysis of the filtered horizontal winds.

4.3 Development of tropical cyclones associated with long-lasting northerly surges

To understand the development of tropical cyclones over the eastern Indian Ocean and maritime continent regions, we conducted lag-composite analysis of the 6- to 30-day band-pass filtered horizontal winds and stream functions at 925 hPa and examined OLR anomalies.

In October (Fig. 11), an anomalous cyclonic circulation over the South China Sea is observed on Day 3, which gradually develops after the beginning of the long-lasting northerly surge event. Be-

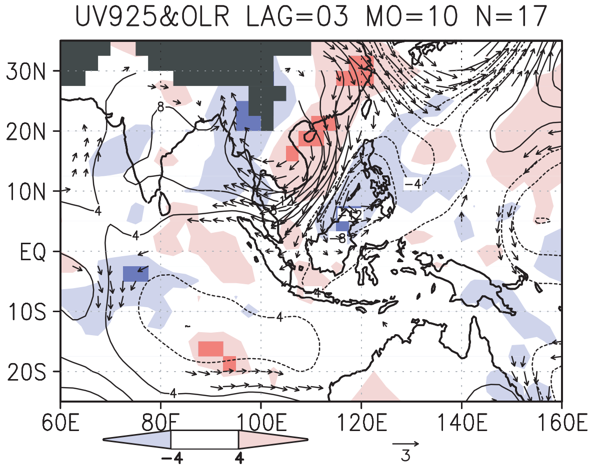

Fig. 11. Lag-composite analysis for the 6- to 30-day band-pass filtered 925-hPa horizontal wind, stream function, and OLR anomalies in October for Day 3. The sample number used in the composite is shown in the upper right of each panel. Wind-anomaly vectors with a local significance level of 90% are plotted. The contours denote stream function, and the stream function anomaly was multiplied by 10^{-6}. Blue (Red) color indicates enhanced (suppressed) convective activity. Dark-colored grids of the OLR anomaly have a local significance level of 90%. Light-colored grids of the OLR anomaly are not statistically significant, but the anomaly is less than 4 W m^{-2} or more than 4 W m^{-2}.

cause no clear anomalous cyclonic circulation is found over the Philippine Sea before the northerly surge event (not shown), the development of cyclonic circulation over the South China Sea is associated with the northerly surge. Significant negative OLR anomaly is also found over the South China Sea on Day 3, suggesting the development of a tropical cyclone with convective activity.

In November (Fig. 12), westerly wind anomalies as part of a cyclone pair are seen along the equator in the eastern Indian Ocean around Day 0. Significant negative OLR anomaly is found on Day −1, Day 0, and Day 1 over the eastern Indian Ocean. When the northerly surge reaches the Indochina Peninsula on Day 1, easterly wind anomalies are enhanced over the Indochina Peninsula to the head of the Bay of Bengal. The enhancement of easterly winds along a latitudinal band between 5 and 20°N of the Indochina Peninsula and Bay of Bengal is favorable for tropical cyclone development over the eastern Indian Ocean due to the increased horizontal shear of low-level zonal wind. Interestingly, an anomalous cyclonic circulation also occurs on the Southern Hemisphere side of the eastern Indian Ocean on Day 1. The cyclone pair over the eastern Indian Ocean is statistically significant, which implies that the cyclone pair frequently occurs during the long-lasting northerly wind surge period in November. On Day 3, the cyclone pair over the Indian Ocean (around 80°E) develops and moves westward with convective activity. On Day 5, the pair over the Indian Ocean reaches the Indian subcontinent. In addition, anomalous cyclonic circulation appears over the Philippines on Day 5. The cyclonic circulation over the Philippines is also associated with the long-lasting northerly surge.

In February (Fig. 13), northerly surge over the South China Sea and easterly anomalies over the Indochina Peninsula are found. In association with the northerly surge, a pair of anomalous cyclonic circulations appears over Borneo and south of Java on Day 3. In addition, strong westerly wind anomalies (westerly wind bursts) between the paired cyclonic circulations are shown over the Java Sea; the cyclonic circulation of the Southern Hemisphere part of the pair is associated with the appearance of the westerly wind burst along the Java Sea. Although westerly wind bursts generally occur along the equator, westerly winds are also enhanced along the Java Sea. This result indicates that the development of cyclonic circulation around Borneo is affected by the differential frictional force between land and sea, as well as by orographic barriers. Note that the counterclockwise circulation over Borneo extends across both hemispheres, even though the Coriolis force changes sign across the equator. The development of the anomalous cyclonic circulation over Borneo is similar to that in December and January. By Day 5, cyclonic circulation develops over Borneo. The cyclonic circulation of the Southern Hemisphere part of the pair moves westward.

Associated with the northerly surge, anomalous cyclonic circulation occurs around Borneo in December (not shown) and in January (not shown), similar to the composite result for February. However, the anomalous cyclonic circulation around Borneo in January is weaker than those in December and in February. In addition, significant anomalous convective activity is found around Borneo or over the Java Sea only in December.

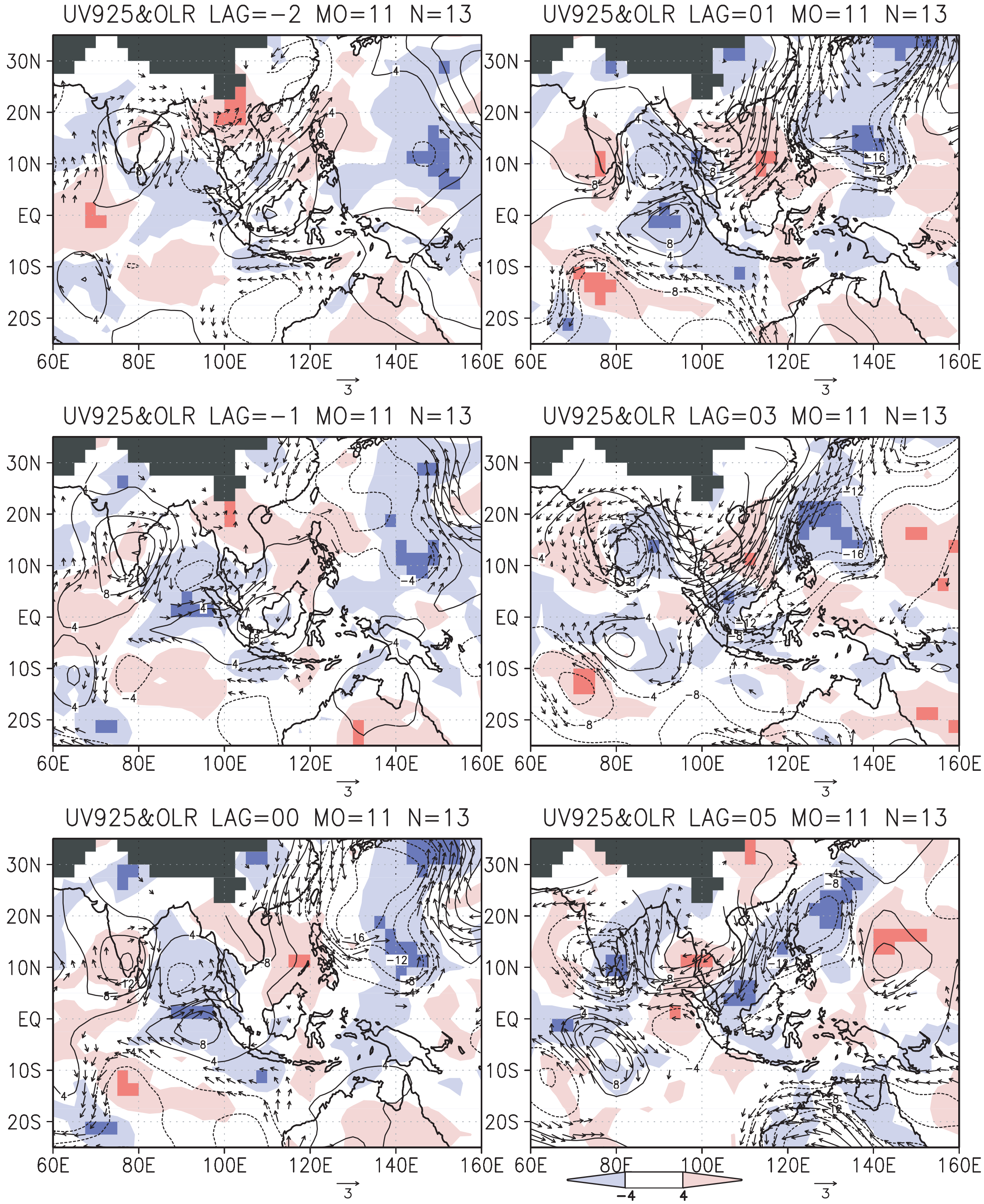

Fig. 12. Lag-composite analysis for the 6- to 30-day band-pass filtered 925-hPa horizontal wind, stream function, and OLR anomalies in November for Day −2, Day −1, Day 0, Day 1, Day 3, and Day 5. The plotted values are the same as in Fig. 11.

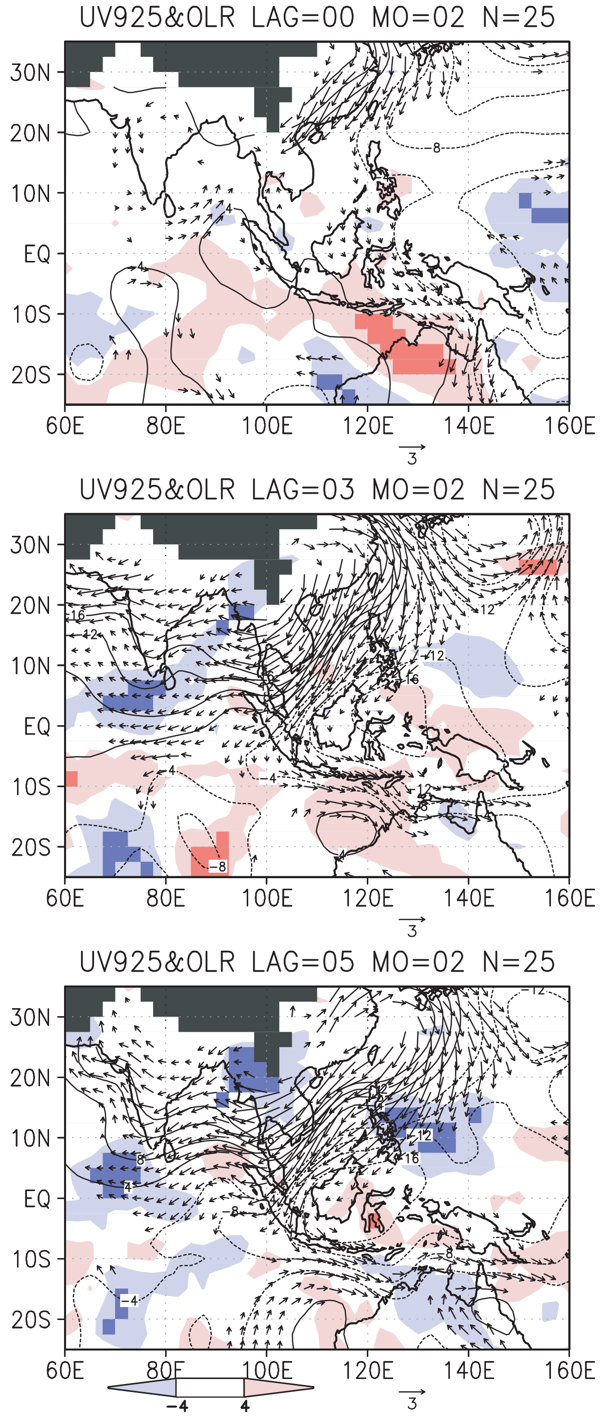

Fig. 13. Lag-composite analysis for the 6- to 30-day band-pass filtered 925-hPa horizontal wind, stream function, and OLR anomalies in February for Day 0, Day 3, and Day 5. The plotted values are the same as in Fig. 11.

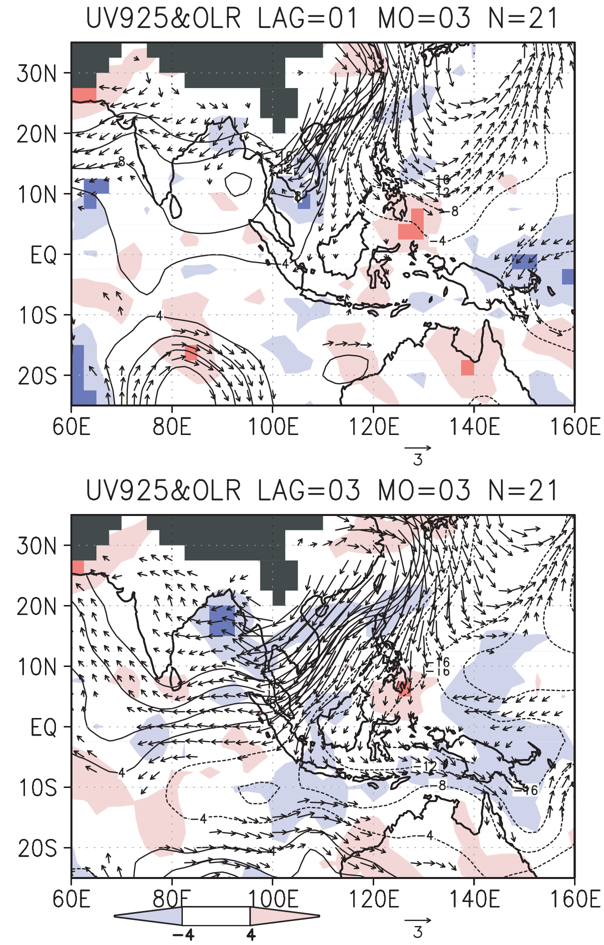

Fig. 14. Lag-composite analysis for the 6- to 30-day band-pass filtered 925-hPa horizontal wind, stream function, and OLR anomalies in March for Day 1 and Day 3. The plotted values are the same as in Fig. 11.

The linkage between the northerly surge and tropical cyclone development over the eastern Indian Ocean and maritime continent is unclear in March (Fig. 14). Tropical cyclones associated with the East Asian northerly surges do not tend to develop in March over the eastern Indian Ocean and maritime continent. In addition, southeasterly anomalies are found over the Bay of Bengal. March is sometimes referred to as the pre-summer monsoon season over and around the Indochina Peninsula. The precipitation in March around the head of Bay of Bengal is associated with the northward transport of water vapor from the Bay of Bengal, which is consistent with negative OLR anomalies over that region.

In this manner, the impacts of northerly surges from the mid-latitudes on the development of tropical cyclones over the eastern Indian Ocean and maritime continent depend on the season. Furthermore, symmetric cyclone pairs tend to occur over the eastern Indian Ocean in November rather than in other months. In December, January, and February, asymmetric cyclone pairs frequently occur over Borneo.

5. Discussion

The previous section demonstrated the association between the long-lasting northerly surges of the East Asian winter monsoon and the development of tropical cyclones over the eastern Indian Ocean and maritime continent. This section discusses the possible dynamics behind the impacts of the long-lasting northerly surges on tropical cyclogenesis.

5.1 Difference in background circulations

The findings above raise a number of questions. Why did the symmetric cyclone pair over the eastern Indian Ocean linked to the northerly surges of the East Asian winter monsoon develop only in November? Why did Borneo vortexes associated with the northerly surges not occur in October and November but frequently appear in December, January, and February? To answer these questions, climatological zonal and meridional winds at 925 hPa are shown in Figs. 15, 16, respectively.

In November, a strong westerly core is located just along the equator over the eastern Indian Ocean, sandwiched between easterly wind cores in both hemispheres (Fig. 15). The horizontal structure of the low-level zonal wind in November is symmetric with respect to the equator. Hence, the superposition of the northerly surges and the background condition in November provides a very favorable condition for the dynamical development

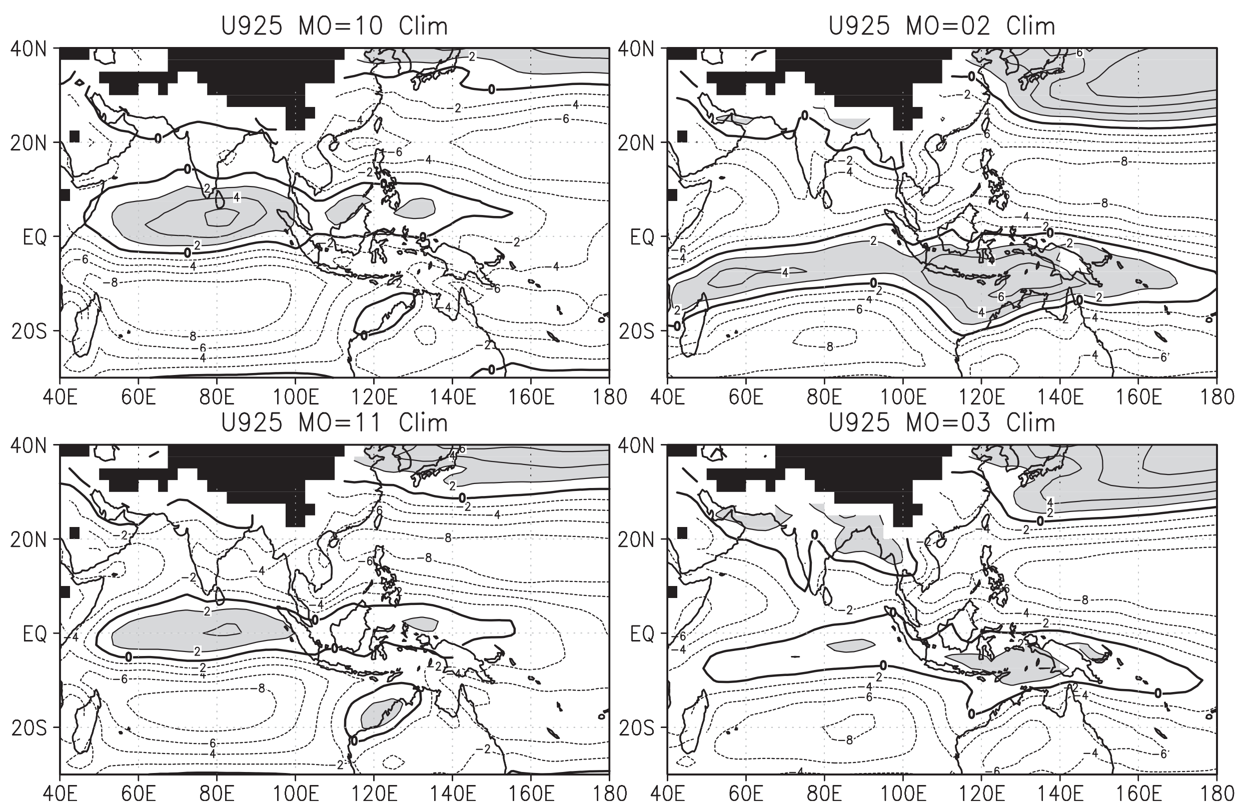

Fig. 15. Climatological zonal wind at 925 hPa in October (upper left), November (lower left), February (upper right), and March (upper right). The unit is m s^{-1}. Shading indicates westerly wind stronger than 2 m s^{-1}.

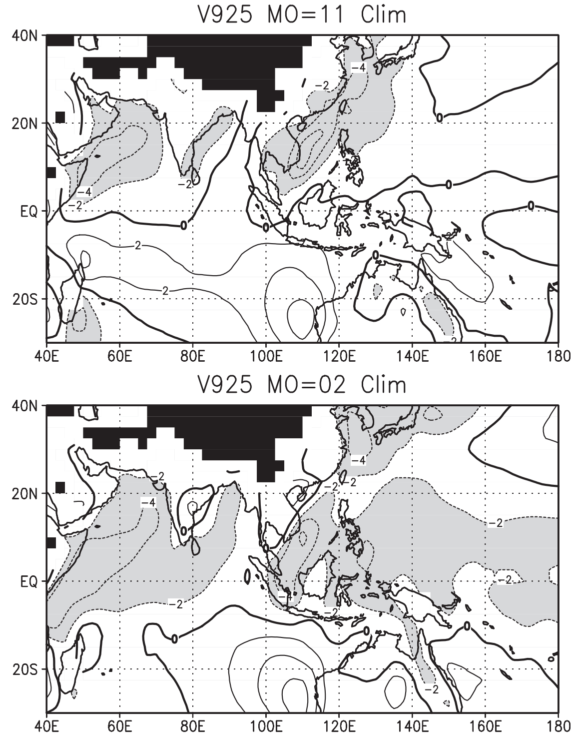

Fig. 16. Climatological meridional wind at 925 hPa in November (upper) and February (lower). The unit is m s^{-1}. Shading indicates northerly wind stronger than 2 m s^{-1}.

of symmetric cyclone pairs over the region. Interestingly, the zonal wind structures in the other months, even in October and March, are not symmetric, a condition that is unfavorable for development of cyclone pairs.

Unfortunately, little information is available on sub-monthly tropical disturbance over the eastern Indian Ocean in Northern Hemisphere fall. Shinoda and Han (2005) described similar cyclone pairs on a sub-monthly time scale over the whole fall season (September to November). The structure of the cyclone pairs in their study is similar to our lag-composite result. Their and our findings indicate that cyclone pairs sometimes develop over the eastern Indian Ocean. However, we showed the development of cyclonic pairs associated with the northerly surges of the East Asian winter monsoon, whereas cyclone pairs that developed over the eastern Indian Ocean in Shinoda and Han's study (2005) were probably associated with surges from the Southern Hemisphere or a tropical cyclone in the Southern Hemisphere at an initial stage of the cyclone pair. Hence, the development process in their study was likely different from that in our study.

In December, January, and February, Borneo vortexes frequently develop around Borneo. The climatological low-level northerly wind is dominant over the South China Sea (Fig. 16), which helps the northerly surges extend into the channel between Borneo and Sumatra, namely over the Java Sea. As discussed in Section 3, the Borneo vortex develops frequently over the region, probably reflecting the land-sea distribution, orographic effects, and background atmospheric circulations. Because a cross-equatorial southerly wind from the Southern Hemisphere prevails over Borneo in October and November, the northerly surges cannot enter the area over the Java Sea. Lag-composite analysis showed that tropical cyclones develop over the South China Sea in October and November, which can be explained by the existence of southerly wind over Borneo. Therefore, the background atmospheric circulation is associated with tropical cyclone activity over the South China Sea in October and November. In March, the northerly surges also do not enter the channel between Borneo and Sumatra (Fig. 10), which is associated with less frequent occurrence of the Borneo vortex.

5.2 Dynamical structure of the symmetric cyclone pair

This subsection investigates the dynamical structure of the symmetric cyclone pair over the eastern Indian Ocean in November. The pair of cyclonic circulations in November in our lag-composite analysis is clearly symmetric horizontally (Fig. 12). In addition, the cyclone pair moves westward. According to recent understanding of convectively coupled equatorial waves, based on the classical wave theory of Matsuno (1966), the structure of the cyclone pair can be understand as $n = 1$ equatorial Rossby waves (e.g., Numaguti 1995; Kiladis et al. 1995; Kiladis et al. 2009). The vertical structure of the zonal winds is shown in Fig. 17. Previous studies indicated that the vertical structure of zonal wind between a cyclone pair is barotropic up to about 300 hPa (e.g., Kiladis et al. 1995); our result shows a similar vertical structure (Fig. 17). This correspondence implies that the cyclone pair might be explained as westward-propagating $n = 1$ equatorial Rossby waves. The horizontal size of the cyclonic circulation in the Northern Hemisphere is

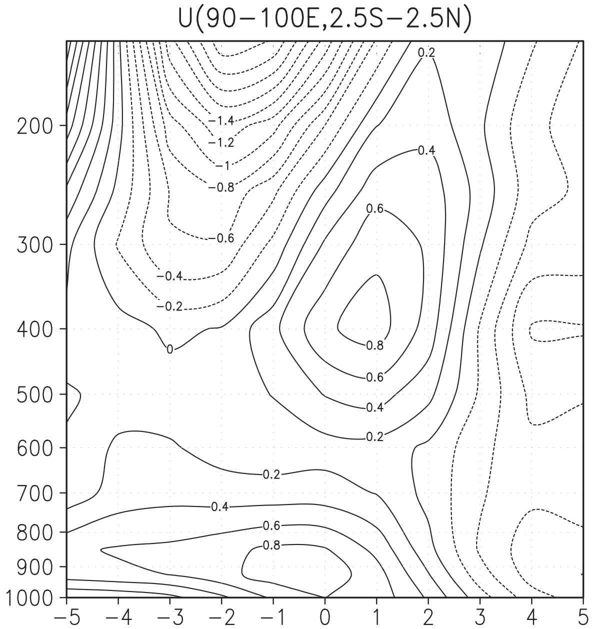

Fig. 17. Time-height cross section of filtered zonal wind over the eastern Indian Ocean (90–100°E, 2.5°S–2.5°N) in November. The unit is m s^{-1}.

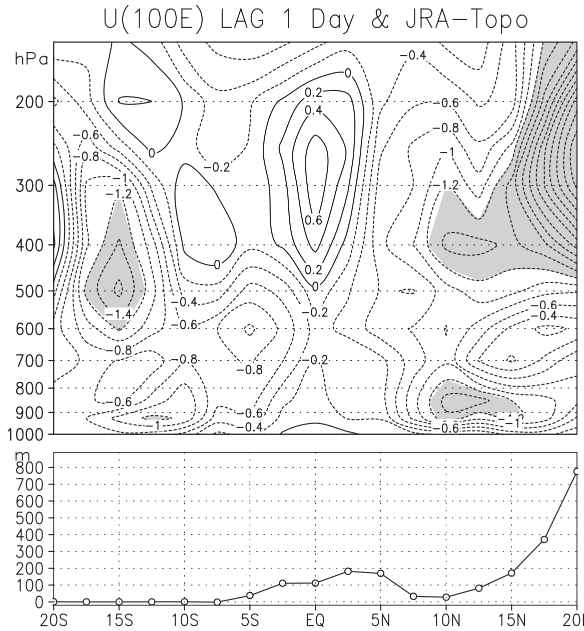

Fig. 18. Latitude-pressure cross-section of the lag-composite of filtered zonal wind at 100°E on lag Day 1 in November (upper panel). The unit is m s^{-1}. Shading denotes an easterly wind anomaly stronger than 1.2 m s^{-1}. The lower panel shows orography from the JRA-25 reanalysis product, averaged over 97.5–102.5°E as a function of latitude. The unit is m.

also consistent with previous reports (Kiladis et al. 2009). Figure 12 shows the cyclone pair with convective activity over the eastern Indian Ocean from Day −1. Thus, convectively coupled equatorial Rossby waves should be found from Day −1. The vertical structure changes somewhat before and after Day −2, which can be associated with the timing of the development of $n = 1$ equatorial Rossby waves.

5.3 *Orographic effect on tropical cyclogenesis*

This subsection discusses the possible effect of orography on tropical cyclone development. In this study, the horizontal length of the northern cyclone in the pair over the eastern Indian Ocean in November is approximately 1800 km (Fig. 12). Interestingly, that horizontal length is the same as the width of the Bay of Bengal at 10°N. In addition, the horizontal scale of the Bay of Bengal corresponds to the half wavelength of $n = 1$ equatorial Rossby waves over the western equatorial Pacific (e.g., Kiladis et al. 1995; Kiladis et al. 2009). During the development phase of the cyclone pair on Day −1, the cyclone is anchored just over water of the Bay of Bengal, which suggests that orography in the Asian monsoon region may be a factor in the frequent development of cyclone pairs over the eastern Indian Ocean.

Figure 18 shows the latitude-pressure cross section of zonal wind at 100°E on Day 1 in November, when easterly wind over the Bay of Bengal and Indochina Peninsula intensified in association with northerly surge. Easterly wind intensification over the Bay of Bengal contributes to increasing cyclonic vorticity over the eastern Indian Ocean. The lower panel shows the mean orography in JRA-25 reanalysis data at 2.5° scale. The strongest lower easterly core is located around 10°N. In other words, the easterly wind associated with the wind core is concentrated in a narrow low-altitude channel over the Malay Peninsula and Indochina Peninsula, probably associated with orographic barrier effects of the Sumatra and Indochina landmasses, although the real orography is higher and more complicated.

5.4 How can the long-lasting surges generate tropical cyclones?

A key question is how can long-lasting northerly surges of the East Asian winter monsoon effectively trigger tropical cyclones over the eastern Indian Ocean and maritime continent? In general, equatorward flow advects high absolute vorticity, which results in increased relative vorticity in the tropics. Thus, long-lasting northerly surges can inject vorticity into the tropics. In addition, the generation of tropical cyclones involves interaction between atmospheric circulation and convective activity. The long-lasting surges maintain the horizontal shear of low-level winds, providing a favorable condition for the development of tropical cyclones over a long period. Therefore, tropical cyclones probably tend to develop during long-lasting surges.

On the other hand, the interaction between atmospheric circulation and convection is complicated, making it difficult to clarify cause-effect relationships. For example, once convections occur, circulation may automatically develop as a thermodynamic response to convective heating. In contrast, after cyclonic circulation without convection is formed, large-scale convective activity can occur due to moisture convergence in the planetary boundary layer. Both mechanisms possibly work in tropical regions. These topics cannot be investigated using reanalysis data for two main reasons. First, reanalysis datasets are generally produced using large-scale global climate models with cumulus convection parameterization; however, the development of convective activity is closely associated with mesoscale convections or convective systems. Second, the temporal resolutions of reanalysis products (or the observation intervals of input data) are generally much longer than the development time scale of mesoscale convections. Thus, numerical modeling is required to understand the development of cyclone pairs over the eastern Indian Ocean and maritime continent, using a convective system-resolving model.

6. Conclusion

This study investigated the impact of northerly surges of the Asian winter monsoon on tropical cyclogenesis over the eastern Indian Ocean and maritime continent during 28 winters (from October to March) in 1979/1980–2006/2007. Using JRA-25 reanalysis and OLR datasets, we focused on long-lasting surges over the South China Sea at 6- to 30-day (intraseasonal) time scales that intrude over the eastern Indian Ocean and maritime continent.

We analyzed two extreme events and found that the twin cyclones over the eastern Indian Ocean in November and over the maritime continent in December were associated with northerly surges over the South China Sea that originated from the mid-latitudes. A symmetric cyclone pair over the eastern Indian Ocean developed into Cyclone Sidr in November 2007. In the heavy rainfall event in the Malay Peninsula at the end of 2006, another asymmetric cyclone pair was observed around Borneo and south of Java. The common feature of these two events is the long-lasting northerly surge observed over the South China Sea. In addition, the surge events lasted more than 1 week, which is longer than the duration of mid-latitude baroclinic waves. To understand how long-lasting northerly surges over the South China Sea impact the appearance of cyclone pairs, lag-composites of low-tropospheric winds and OLR were constructed, based on the long-lasting northerly surges over the South China Sea. The results show that the northerly surges of the East Asian winter monsoon have a significant impact on tropical cyclone development over the eastern Indian Ocean and maritime continent and that their impact varies seasonally.

In our results, during October and November, a tropical cyclone develops around the Philippines, which is responsible for the intensification of horizontal wind shear due to the northerly surge. A symmetric cyclone pair is generated over the eastern Indian Ocean in November, which is also due to the increased cyclonic vorticity around the northern cyclone. The cyclone pair moves westward with time and can be viewed as $n = 1$ equatorial Rossby waves. During Northern Hemisphere winter (December, January, February), an asymmetric cyclone pair occurs over the maritime continent. In the development of the asymmetric cyclone pair, the northern cyclone first appears around Borneo, followed by westerly wind burst along the Java Sea. In addition, a southern cyclone develops off Java and is associated with the westerly wind burst. The asymmetric cyclone pair and westerly wind burst are both strongly affected by the land-sea distribution and orography.

The seasonally different impacts of the long-lasting northerly surges are associated with the background conditions of atmospheric circulation. In November, the horizontal structure of low-level zonal winds over the eastern Indian Ocean produces favorable conditions for the development of the cyclone pairs. The horizontal structure of the low-level zonal winds in the other months of northern winter is not symmetric around the equator. During Northern Hemisphere winter (December, January, and February), climatological northerly flow extends along a channel between Borneo and Sumatra, which aids in the deep intrusion of northerly surge to near the equator. In addition, orographic effects strongly affect flow along the channel. Therefore, the seasonally different impacts of the northerly surges on tropical atmosphere are associated with the background circulation. Subjects for further study include the detailed formation mechanisms of the symmetric cyclone pair over the eastern Indian Ocean at the early stage of tropical cyclogenesis in November and of the Borneo vortex in the northern winter, as well as the orographic effects associated with tropical cyclone development over the Bay of Bengal.

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