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On the roles of the northeast cold surge, the Borneo vortex, the Madden-Julian Oscillation, and the Indian Ocean Dipole during the extreme 2006/2007 flood in southern Peninsular Malaysia

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[1] The mid-December 2006 to late January 2007 flood in southern Peninsular Malaysia was the worst flood in a century and was caused by three extreme precipitation episodes. These extreme precipitation events were mainly associated with strong northeasterly winds over the South China Sea. In all cases, the northeasterlies penetrated anomalously far south and followed almost a straight trajectory. The elevated terrain over Sumatra and southern Peninsular Malaysia caused low-level convergence. The strong easterly winds near Java associated with the Rossby wave-type response to Madden-Julian Oscillation (MJO) inhibited the counter-clockwise turning of the northeasterlies and the formation of the Borneo vortex, which, in turn, enhanced the low-level convergence over the region. The abrupt termination of the Indian Ocean Dipole (IOD) in December 2006 played a secondary role as warmer equatorial Indian Ocean helped in the MJO formation. **Citation:** Tangang, F. T., L. Juneng, E. Salimun, P. N. Vinayachandran, Y. K. Seng, C. J. C. Reason, S. K. Behera, and T. Yasunari (2008), On the roles of the northeast cold surge, the Borneo vortex, the Madden-Julian Oscillation, and the Indian Ocean Dipole during the extreme 2006/2007 flood in southern Peninsular Malaysia, *Geophys. Res. Lett.*, *35*, L14S07, doi:10.1029/2008GL033429.

1. Introduction

[2] The flood that occurred in southern Peninsular Malaysia during mid-December 2006 to late January 2007 (hereafter referred as the 2006/2007 flood) was the worst occurrence in a century. Exacerbated by the conditions on the ground (e.g., poor drainage) in most areas, the duration of the flood extended over a month. The number of people evacuated exceeded 200,000 with 16 reported deaths. The initial estimate of economic losses due to the flood was reported to be around USD 500 million. Although floods in Peninsular Malaysia during the northeast monsoon season are relatively common, the 2006/2007 flood was considered unusual. This is because the usual flood locations during this season are in northeastern Peninsular Malaysia whereas the 2006/2007 flood was concentrated in the south [e.g., *Juneng et al.*, 2007]. In fact, almost the entire southern part of Peninsular Malaysia was inundated during the peak period. The 2006/2007 flood also occurred during the peak period of the 2006/2007 El Niño event. Climatologically, Peninsular Malaysia experiences normal or slightly above normal rainfall during the peak of an El Niño event [*Juneng and Tangang*, 2005]. For several months from mid-September to mid-December 2006, the Maritime Continent region experienced anomalously low precipitation associated with the 2006/2007 El Niño and the 2006 Indian Ocean Dipole (IOD) event [*Vinayachandran et al.*, 2007].

[3] The 2006/2007 flood was caused by three episodes of heavy precipitation events (Figure 1a). The duration of each episode was only several days but the accumulated rainfall recorded during each episode at most rain-gauge stations in the area was several times higher than climatological monthly means. For example, the Malaysian Drainage and Irrigation Department Air Panas station (2.47°N, 103.05°E) recorded about 782 mm of rainfall during a four-day period from 18–21 December 2006 which is about four times the December average. The occurrence of the three heavy precipitation episodes was associated with three dominant factors namely, the strong northeast cold surge; the absence of the Borneo vortex; and the influence of eastward propagating Madden-Julian Oscillation (MJO) disturbances. These extreme precipitation episodes were basically part of the deep cumulus and heavy precipitation system in the Maritime Continent during the boreal winter. The interaction between these systems i.e. the synoptic-scale Borneo vortex, the northeast cold surge and the MJO, largely determines the variability of the organized convection, particularly over the western part of the region [*Chang et al.*, 2005]. Interestingly, the flood also occurred following the termination of the 2006 Indian Ocean Dipole event. The abrupt termination of the IOD event in December 2006 could also have provided a favorable condition for the extreme weather event to occur. This study is intended to investigate the roles of these circulation systems in contributing to the occurrence of the heavy rainfall episodes that led to the 2006/2007 flood.

2. Data

[4] Tropical Rainfall Measuring Mission (TRMM) data [*Huffman et al.*, 2007] were used to assess precipitation

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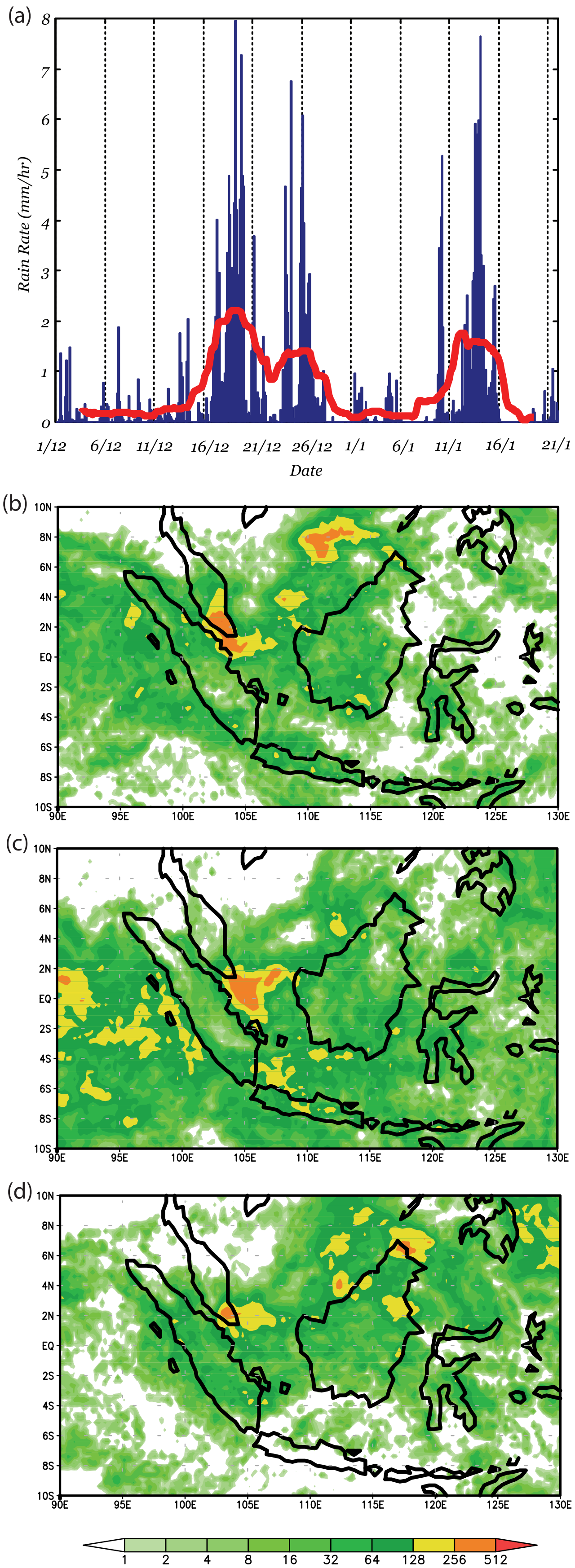

rate during the episodes. The seasonal and monthly precipitation data are from the Climate Anomaly Monitoring System – OLR Precipitation Index (CAMS-OPI) data set [*Janowiak and Xie*, 1999]. The low-level winds were obtained from the National Center Environmental Prediction (NCEP) reanalysis [*Kalnay et al.*, 1996] and the sea surface temperature (SST) data are from TRMM Microwave Imager (TMI) (http://www.ssmi.com). The outgoing long-wave radiation (OLR) data are obtained from the National Oceanic Atmospheric Agency (NOAA) Interpolated OLR [*Liebmann and Smith*, 1996].

3. Results and Discussion

3.1. The Role of Northeast Cold Surges

[5] The three extreme precipitation episodes that led to the 2006/2007 flood occurred during 17–20 December 2006, 24–28 December 2006 and 11–14 January 2007, respectively (Figure 1a). The spatial distributions of accumulated rainfall indicate that in all episodes, southern Peninsular Malaysia consistently received higher rainfall (Figures 1b–1d). These extreme precipitation episodes occurred during a period of stronger northeasterly winds over the southern South China Sea. Figures 2a–2c shows the 925hPa wind vectors during the beginning of each episode i.e. 00Z December 17, 2006, 00Z December 26, 2006 and 00Z January 11, 2007. During these periods, anomalously strong northeasterly winds over the central South China Sea penetrated further south to southern Peninsular Malaysia and the Sumatra region in a straight trajectory. However, it was only during the first episode that the strongest equatorward spread of the cold surge from eastern Asia was evident. This cold surge strengthens the northeasterly winds near the surface and the regional topography acts to restrict the flow as it is channeled towards the equator [*Chang et al.*, 2005]. Although the surge from the north is relatively cooler and drier, it becomes moister as it travels over the warmer parts of the southern South China Sea [*Johnson and Houze*, 1987]. It plays an important role in the episodes of enhanced deep convection over the equatorial South China Sea [e.g., *Cheang*, 1977].

[6] During the second and third episodes, the cold surge outflow was weak. However, in all three episodes, there were strong easterly winds from the western Pacific. These easterly flows were also restricted and channeled towards the equator and hence contributed to the strengthening of the northeasterly winds over the southern South China Sea. In these cases, the northeasterly winds penetrated further south, directly into southern Peninsular Malaysia and Sumatra in a straight trajectory. The low-level winds interacted with the terrain over the region and this resulted in a low-level convergence and widespread deep convection

Figure 1. (a) Area-averaged (1°N–2.5°N, 102.5°E–105°E) precipitation rate (mm/hr) for a period of 1 December 2006 – 21 January 2007. The thick red line indicates the five-day running means, (b–d) Accumulated rainfall for first, second and third extreme precipitation episodes, respectively. Unit is in mm.

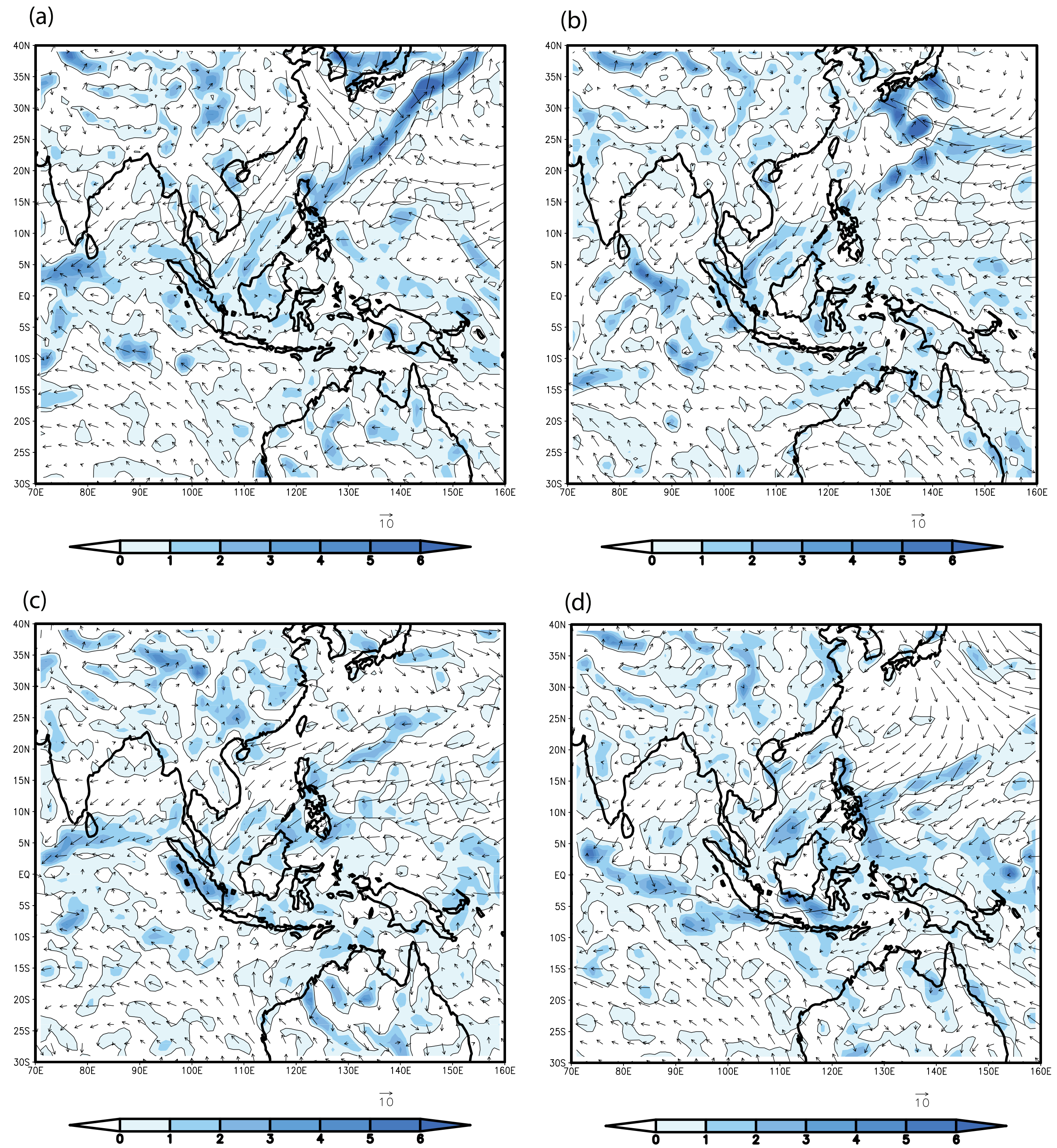

Figure 2. The 925 hPa winds (ms^{-1}) and divergence (shaded, $10^{-5}s^{-1}$) during the beginning of each extreme episode (a) 00Z 17 December 2006, (b) 00Z 26 December 2006 and (c) 00Z 11 January 2007. (d) The 925 hPa winds and divergence during 00Z 30 December 2006 when there was no heavy precipitation over southern Peninsular Malaysia.

over Sumatra and southern Peninsular Malaysia, eventually leading to heavy precipitation over the region.

3.2. The Role of the Borneo Vortex

[7] The northeasterly cold surge often interacts with the synoptic scale disturbance known as the Borneo vortex which could result in the strengthening of the system. The 9–11 December 2004 extreme precipitation that caused severe flood over the northeastern coast of the Peninsular was associated with such an interaction [*Juneng et al.*, 2007]. The formation of the rare typhoon Vamei was also associated with this interaction [*Chang et al.*, 2003]. However, during the 2006/07 flooding, the Borneo vortex was noticeably absent. There appears to be a relationship between the trajectory of the winds, the tendency for counter-clockwise turning and the formation of a Borneo vortex. The distribution of enhanced deep convection was related to this relationship. The absence of the Borneo vortex and the lack of counter-clockwise turning of the northeasterly winds inhibited low-level moisture from being

transported over the west coast of Borneo and reduced deep convection in this area. On the other hand, strong counter-clockwise turning of the northeasterly winds and the presence of the Borneo vortex helps to enhance the convection over western and southern parts of Borneo. A comparison with other periods of equally strong northeasterly winds over the South China Sea (e.g., 00Z 30 December 2006, Figure 2d) indicated that the counter-clockwise turning of the wind was more pronounced in these periods and a Borneo vortex forms with its center located just off western tip of Borneo. The lack of heavy rainfall over southern Peninsular Malaysia and Sumatra during 30 December 2006 is an indication of the low-level moisture transport being intercepted by the Borneo vortex circulation and also transported by the strong cross-equatorial flow. This is indicated by the strong low-level moisture flux convergence over western and southern parts of Borneo during this period (not shown). The pronounced counter-clockwise turning of the northeasterly wind and the formation of Borneo vortex during this period were associated with enhanced westerly winds over and north of Java (Figure 2d). During the first episode (Figure 2a), strong easterly winds over and south of Java prevailed and this inhibited the counter-clockwise turning of the northeasterly wind and indirectly inhibited the formation of Borneo vortex. The existence of the strong easterly winds over and south of Java, as we show below, was MJO related.

3.3. The Role of the Madden-Julian Oscillation

[8] Despite the similarity of the low-level convergence over southern Peninsular Malaysia in the three episodes, there were notable differences in the large-scale circulation patterns especially over the eastern-central Indian Ocean. These differences were attributed to the eastward propagation of the MJO disturbances over the region during these periods. On the intra-seasonal timescale, the large-scale circulations over the Indian Ocean and Maritime Continent were very much influenced by the MJO event which was present during the episodes. Depending on the phase of the MJO, the anomalous large-scale circulations associated with the Rossby wave-type responses may act to strengthen or weaken a cold surge event. Generally, the frequency of cold surges and vortex days is reduced during periods when MJO is present.

[9] *Chang et al.* [2005] have indicated that the primary impact of MJO is to inhibit weak cold surges and to impact on the Borneo vortex. The chance of a cold surge occurring during MJO phases 1 and 2 (refer to *Chang et al.* [2005] for a definition of these phases) is about one half that of phase 3 and 4 and that of non-MJO cases. This tendency is due to the existence of anomalous southerly winds during MJO phases 1 and 2 over the South China Sea. These anomalous winds weaken or inhibit the development and southward progression of cold surges. However, the conditions during the 2006/07 precipitation episodes were exceptional as an MJO disturbance emerged over the Indian Ocean during mid-December 2006 and propagated eastwards across the Maritime Continent.

[10] As shown by the 30 to 60 days filtered outgoing long-wave radiation (OLR) anomaly (Figure 3a), an enhanced deep convection emerged over the Indian Ocean and propagated towards the Maritime Continent. However, the MJO weakened considerably as it approached the western side of the Maritime Continent. Nevertheless, we postulate that the MJO played an important role in the extreme precipitation episodes by interacting with the northeasterly winds over the South China Sea. During the first episode, the center of the enhanced deep convection region was located over the central Indian Ocean (not shown). The strong easterly winds south of Java and south-western Sumatra are consistent with the *Chang et al.* [2005] composite of phase 1 of MJO. Strong easterly winds over Java during this period helped inhibit the counter-clockwise turning of the northeasterly winds and indirectly inhibited the formation of the Borneo vortex. The strong easterly winds over the western Pacific helped strengthen the northeasterly winds over the southern South China Sea. Hence we hypothesize that the presence of the MJO over the Indian Ocean contributed to the first episode of precipitation in two ways. First, the presence of the MJO helped to strengthen the northeasterly wind over the South China Sea although the cold surge outburst from the north was the prime cause of the strong northeasterly wind. Secondly, the existence of strong easterly winds south of Java opposed the penetration of the cross-equatorial winds from the southern part of the South China Sea. As a result, the counter-clockwise turning of the northeasterly winds was inhibited leading to the direct penetration of northeasterly winds into the southern Peninsular and Sumatra. Indirectly, this condition also inhibited the formation of the Borneo vortex.

[11] The large-scale circulation over an area west of Sumatra during the second episode was markedly different compared to that during the first episode. During this period, the circulation was dominated by twin cyclones west of Sumatra with strong westerly winds in between the cyclones [*Perreira et al.*, 1996]. As the system approached Sumatra and southern Peninsular Malaysia, the strong westerly jet in between the twin-cyclones eventually triggered strong westerly winds over an area north of Java. This led to the counter-clockwise turning of the northeasterly winds over the southern South China Sea and helped to form the Borneo vortex and strong cross-equatorial flows (Figure 2b). These circulations eventually helped intercept and transport the low-level moisture to the western and southern parts of Borneo. During this period, deep convection over Sumatra and southern Peninsular Malaysia was reduced while that over western and southern parts of Borneo was enhanced.

[12] For a period of about two weeks after the second episode (i.e. from 29 December 2006–10 January 2007), there was no significant heavy precipitation recorded over southern Peninsular Malaysia. During this period the remnant of the MJO was over the Maritime Continent (not shown). However, the strong westerly winds over and north of Java during this period promoted the counter-clockwise turning of the northeasterly winds and avoided direct penetration of the northeasterly winds to southern Peninsular Malaysia and Sumatra. The formation of the Borneo vortex during this period helped to shift the enhanced deep convection region to western and north Borneo. It was reported that certain locations in northern Borneo were affected by floods during this period. However, during the third episode of the extreme precipitation event, the remnant

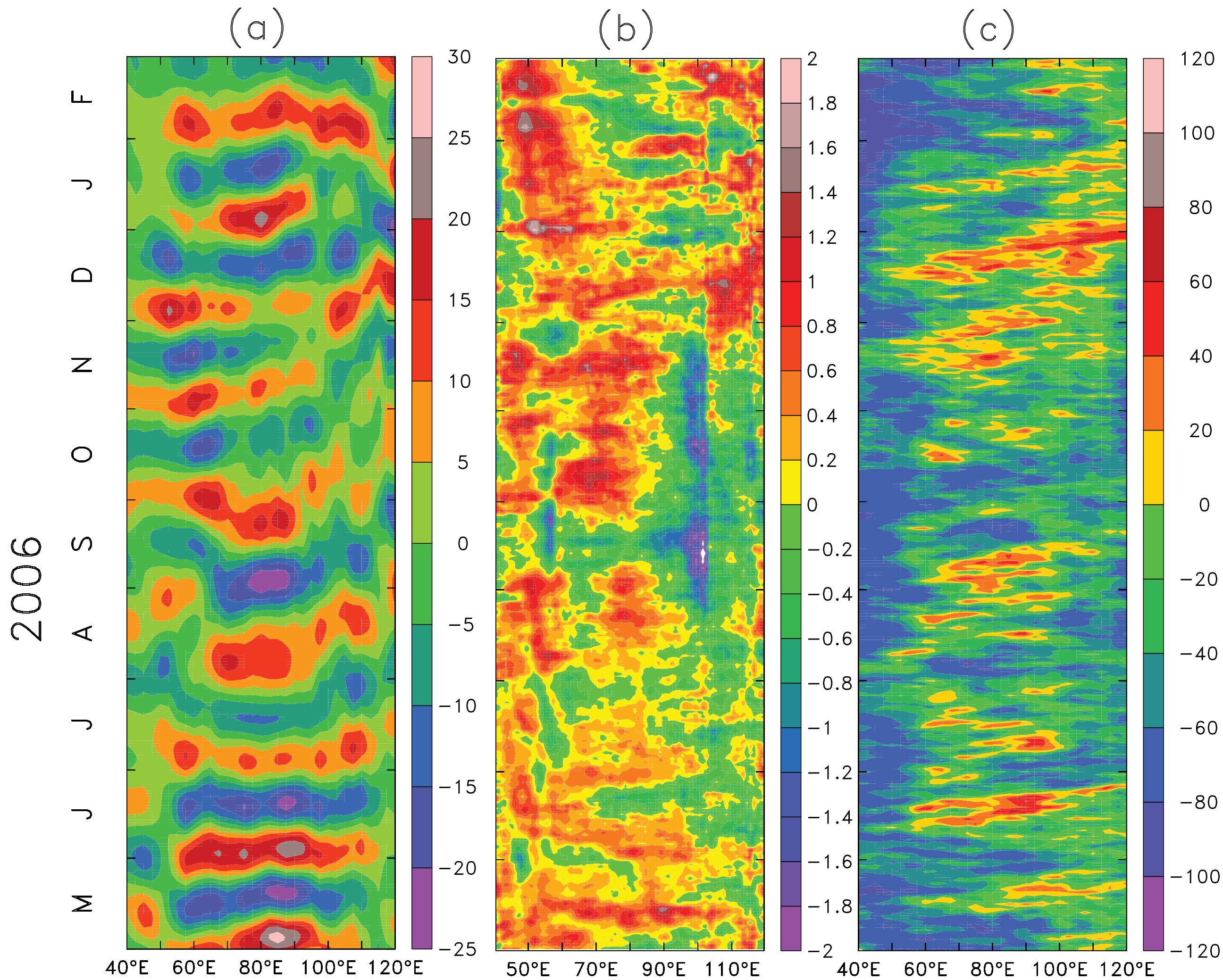

Figure 3. Time – longitude plot of the 5°S–5°N averaged of (a) 30 to 60 day band pass filtered OLR anomalies (Wm^{-2}). The daily anomalies of OLR were filtered using a Lanczos filter with 121 weights. (b) Daily TMI SST anomaly (°C), (c) The difference of the daily mean interpolated OLR from a value of 200 Wm^{-2}. Red indicates enhanced convection.

of the MJO was over the eastern edge of the Maritime Continent (not shown). The strong northeasterly wind over the central South China Sea originated mostly from a strong easterly component over the western Pacific. Over and north of Java, the westerly winds were considerably weaker than that during 00Z 30 December 2006 and such a condition was favorable for a direct penetration of northeasterly winds to the southern Peninsular Malaysia, hence producing similar conditions to that during the first episode.

3.4. The Role of the Termination of the 2006 Indian Ocean Dipole

[13] The anomalous conditions during the extreme episodes could also be related to the abrupt termination of the 2006 IOD. The anomalously cooler sea surface temperature (SSTA) of the southeastern Indian Ocean associated with this event was at its peak in September-October-November 2006 (Figure 3b). However, the negative anomaly was abruptly eroded in December 2006. In fact, during this period the entire equatorial Indian Ocean and regional seas surrounding the Maritime Continent were warmer than usual. Associated with this change was the eastward propagation of the active deep convection (Figure 3c). During November 2006, the active deep convection was confined to the Indian Ocean. However, during December 2006, the active convection spread over the entire equatorial Indian Ocean and the Maritime Continent, indicating an eastward propagation (Figure 3c). Interestingly, in normal years, during this period, the active convection is mostly confined in the east. The prolonged convection was most probably due to the warm SST anomalies that persisted in the west. As suggested by Figure 3c, the convective phase continued until mid-January and failed to switch to a non-convective phase. The role of convection from Indian Ocean, however, only had a secondary role in the extreme precipitation episodes. It was the northeast cold surge that interacted with the MJO related circulation that mostly contributed to the extreme events. Convection over the warmer SST in the entire equatorial Indian Ocean provided a favorable condition for these events to occur.

4. Summary

[14] The 2006/2007 flood over Peninsular Malaysia was caused by extreme precipitation events which occurred in three episodes i.e., between 17–20 December 2006, 24–

28 December 2006 and 11–14 January 2007. These extreme precipitation episodes were mainly due to the strong northeasterly winds over the South China Sea that interacted with the large-scale circulation associated with the MJO. In all cases, strong northeasterly winds penetrated anomalously far south to southern Peninsular Malaysia and Sumatra in a straight trajectory. The blocking effect of the elevated terrain of Sumatra caused low-level convergence and enhanced deep convection over southern Peninsular Malaysia and hence the flood. The lack of counter-clockwise turning of the northeasterly winds and the absence of Borneo vortex were mainly due to the enhanced easterly over and north of Java. These enhanced easterly winds over this region and also north of Australia and in the western Pacific were associated with Rossby wave-type of responses to the MJO deep convection over the Indian Ocean and were most pronounced during the first episode. The scenario during the second episode was similar to that of the first. However, the circulation west of Sumatra was dominated by the presence of twin-cyclones over the region. The presence of strong westerly jets over the equator in between the twin-cyclones eventually promoted the counter-clockwise turning of the northeasterly winds and the formation of the Borneo vortex. The circulation associated with the vortex helped to intercept low-level moisture from the regions of Sumatra and southern Peninsular Malaysia to western and southern parts of Borneo. During the third episode, the remnants of MJO disturbances were at the eastern edge of the Maritime Continent. During this period, the enhanced deep convection was also associated with the direct penetration of northeasterly winds to a region of elevated terrains over Sumatra and Peninsular Malaysia. The abrupt termination of the IOD in December 2006 also played a role. The anomalously cooler SST in southeastern Indian Ocean was at its peak in September-October-November 2006. However, in December 2006 these negative anomalies eroded abruptly. Warmer SST in the equatorial Indian Ocean helped in the MJO formation.

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