Development Processes of Oceanic Convective Systems Inducing the Heavy Rainfall over the Western Coast of Sumatra on 28 October 2007

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Abstract

This study analyzed the oceanic convective systems that induced heavy rainfall over the western coast of Sumatra on 28 October 2007. The convective systems that satisfied the definition of a mesoscale convective complex (MCC), as identified by infrared satellite imagery, developed repeatedly for 16 hours over the Indian Ocean near Sumatra. The MCC developed from midnight on 27 October until the early morning of 28 October, and it was intensified by the land breeze from Sumatra. New convective systems around the decaying MCC were generated during the daytime of 28 October, and they propagated to the western coast of Sumatra in the evening because of a divergent outflow from a cold pool. The combination of the land breeze from Sumatra and cold pool outflows from the decaying MCC was a significant factor in the formation of the convective system that induced strong rainfall up to 46 mm h^{-1} over the western coast of Sumatra.

1. Introduction

The Indonesian Maritime Continent (IMC) is the area of greatest convective activity within the tropics, and it receives the largest amount of rainfall of anywhere in the world (Ramage 1968). Sumatra is one region within the IMC where deep convection occurs frequently (Yamanaka et al. 2008), generating the largest volumetric rainfall especially on the western coast of Sumatra (Hirose et al. 2009; Love et al. 2011). Mori et al. (2011) showed that average annual rainfall greater than 3,000 mm y^{-1} on 10-year period (1998-2007) was observed along the southwestern coast of Sumatra. Sumatra is the second region most frequently floods within Indonesia which approximately 1401 flood events recorded during the 13-year period from 2002 to 2014, and about 38.62% of those occurred on the western coast of Sumatra based on data from the National Board for Disaster Management (*source data: http://dibi.bnpb.go.id/).*

Many previous studies have described the characteristics and propagation of the diurnal convection near Sumatra (e.g., Mori et al. 2004; Sakurai et al. 2005). Mori et al. (2004) showed that diurnal convection, which develops over the western coast of Sumatra in the late evening, could migrate up to 400 km from the coastline under the influence of low-level westerly winds. Generally, diurnal convection develops over the mountainous region of Sumatra because of strong daytime surface heating, although larger-scale convective systems are sometimes organized by interactions between land and sea breeze circulations and large-scale environment flows (Nitta and Sekine 1994; Mori et al. 2004). Shibagaki et al. (2006) showed that westward-propagating meso-β-scale cloud clusters (horizontal scale of ~100 km) that develop in the eastern mountainous region of Sumatra, can act as triggers for the development of larger-scale systems, the so-called super cloud clusters (Nakazawa 1988). Houze et al. (1981) have documented that convection over the island of Borneo, related to sea breeze convergence, is able to aggregate and move off the coast to produce the greatest amount of precipitation during the morning over the oceans (Williams and Houze 1987).

There are several definitions of convective systems depending on the parameters used and several phrases used to describe them, e.g., mesoscale convective systems (MCSs), mesoscale convective complexes (MCCs), as the largest subclass of MCSs (Maddox 1980), and super cloud clusters (Nakazawa 1988). Here, for ease of comparison with previous studies, the definition of the MCC based on a universal rule using only satellite data. Several previous studies (e.g., Yuan and Houze 2010; Virts and

Houze 2015) have documented the climatology of the largest MCSs over the entire area of the tropics, including the IMC, and they have identified the existence of MCCs over the Indian Ocean. However, there have been few studies analyzing the surface winds around MCCs in the tropics because observations over the ocean are too sparse to detect the detailed surface wind distribution.

This study focused on the elucidation of the role of the MCC that occurred over the Indian Ocean near Sumatra on 27–28 October 2007 in inducing the generation of new convective systems that produce heavy rainfall on the western coast of Sumatra. Analysis of Cross Calibrated Multi Platform (CCMP) data was attempted to give a deeper insight into the mechanism of eastward-propagating convective systems, which previously have been reported to occur in the region (e.g., Mori et al. 2004). The effect of the cold pool from the decaying MCC and its interaction with the land and sea breeze circulations are the subjects of discussions in this article.

2. Data and study method

The equivalent black body temperature (T_{BB}), derived from the hourly infrared data of MTSAT-1R (Multi-functional Transport Satellite) with spatial resolution of 0.05° × 0.05°, was used to identify the MCCs and their physical characteristics based on the parameters given by Maddox (1980) as shown in Table 1. In addition, the convective index (C_I) was determined by taking the temperature below a threshold value if T_{BB} was smaller than the threshold value (C_I = threshold − T_{BB}, for T_{BB} < threshold) and making C_I equal to zero for T_{BB} values that were greater than or equal to the threshold value (C_I = 0, for T_{BB} ≥ threshold). In this study, the threshold value was set at 253 K as suggested by Adler and Negri (1988). The estimated rainfall data, corresponding to the MCCs, were obtained from the Tropical Rainfall Measuring Mission's (TRMM) 3B42 v6 data set, which has 3-hourly temporal resolution and 0.25° × 0.25° spatial resolution.

The surface wind data were obtained from the CCMP, which covers the global ocean for the period of 20-years with 6-hourly temporal resolution and 25-km spatial resolution. The dataset is produced using a variational analysis method to combine extensive cross-calibrated multiple satellite datasets with in situ data and ECMWF (European Centre for Medium-Range Weather Forecasts) analyses (Atlas et al. 2011). In order to identify the cloud-induced surface flows, wind vector anomalies were calculated by subtracting the resultant daily wind speed from the 6-hourly wind speed. The existence of cold pool was examined using the surface potential temperature from the ECMWF ERA-Interim analysis fields, which are available at 6-hourly intervals with 0.25° horizontal resolution (Dee et al. 2011).

The representativeness of the TRMM and ERA-Interim data over land were assessed by comparing with observational data obtained at Pulau Baai weather station in Bengkulu (3.47°S, 101.80°E) and synoptic data over Sumatra from several weather stations, i.e., at Tabing in Padang (0.53°S, 100.21°E), Simpang-tiga in Pekanbaru (0.28°N, 101.27°E), and Padang Kemiling in Bengkulu (3.53°S, 102.20°E) obtained from the OGIMET meteorological database (Valor and López 2014). The temporal trend of the global data was confirmed to be consistent with that of observations from the several weather stations over Sumatra that shows high correlations of more than 0.7. Over the ocean, comparison with data obtained from TRITON (Triangle Trans-Ocean buoy Network, Ando et al. 2005) buoy at (5°S, 95°E) shows high correlations of more than 0.7.

3. Results and discussion

3.1. Evolution of the development of the MCC

Figure 1 shows the evolution of the MCC that occurred near Sumatra on 27–28 October 2007. Cotton et al. (1989) have defined eight stages in the life cycle of an MCC: MCC-12 h, pre-MCC, initial, growth, mature, decay, dissipation, and post-MCC; however, the most important period for an MCC is from the initial to the dissipation stage. The MCC-12 h stage defines the condition of the MCC around 10–15 hours before the initial stage, as shown in Fig. 1a. In addition, the MCC developed under a large-scale environmental situation in which the Madden-Julian oscillation index (Wheeler and Hendon 2004) was positive but its amplitude was very weak.

The MCC that is the topic of this study began to develop from the pre-MCC stage at 2200 local time (LT) on 27 October 2007. At that time, small-scale clouds were located over the western coast of Sumatra and the nearby Indian Ocean, as shown in Fig. 1b. These groups of clouds grew rapidly until around midnight (0100 LT), which marked the onset of the initial stage (Fig. 1c). By 0400 LT on 28 October 2007 (Fig. 1d), during the growth stage of the MCC, the sizes of the clouds had increased further and they began merging with each other, such that the maximum extent of the MCC was attained at 0700 LT (Fig. 1e). During the mature stage, the MCC had a cloud shield with an area of around 319,083 km^2 and the interior cold cloud covered an area of around 211,059 km^2. The center of the MCC during this stage was around 3.21°S, 97.46°E with an eccentricity of around 0.76. At 1300 LT, during the decay stage, the MCC began to split and dissipated (Fig. 1f). During the dissipation stage in the late afternoon (1600 LT) (Fig. 1g) and by the post-MCC stage later that evening (1900 LT) (Fig. 1h), the

MCC had split into small-scale clouds that propagated eastward toward the western coast of Sumatra.

3.2. The Development of New Convective Systems

Figure 2a shows that some of the clouds mentioned in subsection 3.1 are convective clouds indicated by high C_I values. The convergent surface wind flow indicates that the land breeze triggered the development of some of the clouds over the western coast of Sumatra, whereas the westerly wind in the lower atmosphere triggered the development of some of the clouds over the nearby Indian Ocean. This is consistent with the findings of Mori et al. (2004) and Sakurai et al. (2005), who concluded that ocean convection occurs in the morning until noon, owing to the propagation of convective systems along the western coast of Sumatra, triggered by this strong land breeze, but in this study, the convective systems discussed are defined as MCC. During the mature stage of the MCC early in the morning (0700 LT) of 28 October, as shown in Fig. 2b, some of the clouds over the western coast of Sumatra and the nearby Indian Ocean merged to create the maximum extent of the MCC. The convergence of the land breeze and the westerly wind clearly supported the development of the MCC. The potential temperature at the center of the MCC was relatively low (at around 297.5 K) compared with the surrounding area (299–300 K). According to Engerer et al. (2008), this area is the so-called cold pool, which is an area of downdraft air cooled by evaporation that spreads out horizontally beneath a precipitating cloud. In addition, the cold pools were associated with potential temperature decreases (Tompkins 2001) and generated by these individual convective cells in an MCS typically spread out at the surface and combine to form a large mesoscale cold pool covering a contiguous area on the scale of the entire MCS (Houze 2004).

In this case study, the cold pool began to develop during the mature stage and it spread increasingly until the decay stage, as shown in Fig. 2c. The difference in potential temperature could have acted as a trigger for the development of new convective systems to form along the leading edge of the cold pool, as in frontal theory (Fig. 2c), which is consistent with the findings of Wilson and Schreber (1986). Such new convective systems, which are generated over the ocean in the daytime, eastward-propagating to the western coast of Sumatra due to of the divergent outflow of the cold pool, in conjunction with the evening sea breeze. Convective activities over Sumatra are more extensive during the evening (1900 LT) due to the new convective systems induce the land convection over the western coast of Sumatra (Fig. 2d). Therefore, this study give a deeper insight into the mechanism of eastward-propagating convective systems, which previously have been reported to occur in the region (e.g., Mori et al. 2004). The structure and evolution of MCCs over the Indian Ocean are related to the diurnal convective activities over Sumatra.

3.3. Diurnal rainfall variation during the MCC event

Figure 3 shows the horizontal distribution of rainfall during the studied MCC event. During the initial stage at 0100 LT (Fig. 3a), only light rainfall (<6 mm h^{-1}) was observed over the Indian Ocean. However, the observed early morning (0700 LT) maximum occurred because of the increase in the number of convective clouds (Fig. 2a), rather than because of the increase in extent of the coverage of the MCC during the mature stage (Fig. 3b). The rainfall system began to propagate slowly eastward from the Indian Ocean toward the western coast of Sumatra (Fig. 3c) during the new convective systems which generated by MCC propagate eastward to the western coast of Sumatra at the decay stages at the daytime (1300 LT), and the peak rainfall on the western coast of Sumatra began in the evening at 1600 LT (Fig. 3d) until 1900 LT (Fig. 3e) is caused by the interaction of new convective systems with land convection which make the convective activity becomes intense on the western coast of Sumatra during the dissipation stages until post-MCC stages. Compared with the observational data, the rainfall intensity increased significantly, especially during the dissipation and the post-MCC stages over some parts of western Sumatra, as shown in Fig. 4. Heavy rainfall occurred over southwestern coastal ocean at Pulau Baai (Bengkulu) from 1400–1900 LT, which reached a maximum intensity of around 35 mm hr^{-1} at 1600–1700 LT during the dissipation stage of the MCC. During the post-MCC stage at 1900 LT, a significant increase in rainfall (up to 46 mm h^{-1}) occurred over southwestern coastal land at Padang Kemiling (Bengkulu). Rainfall also occurred over northwestern coastal land at Tabing (Padang) and over inland at Simpang-tiga (Pekanbaru) but it was only light in intensity because of the weaker effect of the MCC compared with the area around Bengkulu. The diurnal rainfall associated with the MCC had a similar pattern. The rainfall over the Indian Ocean occurred when the MCC started developing and it reached a maximum when the MCC began to decay, at which time, the rain started to move toward the western coast of Sumatra. This is consistent with previous studies, which have stated that MCCs possess the potential to exert considerable impact on regional rainfall patterns, as mentioned in section 1.

Schematic representations of the MCCs evolution and migration over the Indian Ocean, related to the diurnal variation of rainfall over the western coast of Sumatra, are shown in Fig. 5 based on the results described above. Figure 5a shows the initial stage of the MCC at around midnight on 28 October 2007. The development of the MCC over the Indian Ocean began from several convective clouds generated by the land breeze and westerly wind. Figure 5b shows the mature stage of the MCC in the early morning on 28 October. The MCC reached its maximum extent and the peak rainfall occurred over the Indian Ocean because of the propagation and merging of several areas of convective cloud, triggered by the convergence between the land breeze and the westerly wind. Figure 5c shows the decay and dissipation stages of the MCC, which occurred during the daytime through to the evening. The MCC began to dissipate and new convective systems were generated owing to the development of the cold pool. The new convective system generated over the Indian Ocean during the daytime propagated to the western coast of Sumatra because of the divergent outflow of the cold pool, in conjunction with the evening sea breeze.

This evolutionary scheme differs from the scenarios outlined previously by Mori et al. (2004) and Shibagaki et al. (2006), who described the westward propagation of developing convective systems over Sumatra, as mentioned at the second paragraph in section 1. However, the convective systems described by Houze et al. (1981) are similar and they share common features with those of the present study. Houze et al. (1981) showed that the convective systems over the South China Sea begin to develop around midnight and mature in the early morning, helped by the land breeze from the island of Borneo to the east. This study presented a more detailed evolution of the MCCs in the IMC region and a description of the convective systems generated by the interaction of the cold pool outflow and the land breeze, based on high-resolution surface wind data retrieved by the CCMP and the ERA-interim temperature field.

4. Summary

This study analyzed the oceanic convective system that caused heavy rainfall over the western coast of Sumatra on 28 October 2007. The convective system satisfied the criteria for an MCC, as defined by Maddox (1980), and followed the developmental stages outlined by Cotton et al. (1989). The MCC developed from around midnight on 27 October until the early morning of 28 October. Several convective systems were generated during the decay stage of the MCC because of convergence between the land breeze and westerly wind. The new convective systems around the decaying MCC were generated during the daytime on 28 October, and they propagated toward the western coast of Sumatra during the evening of 28 October because of the divergent outflow from the cold pool. The combination of the land breeze from Sumatra and the cold pool outflow from the decaying MCC was a significant factor in the formation of the convective system that caused the heavy rainfall up to 46 mm h^{-1} over the western coast of Sumatra.

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Figure Captions

Fig. 1. Horizontal distribution of black body temperature (T_{BB}) for Mesoscale Convective Complex (MCC) criteria from infrared data obtained by MTSAT-1R over the Indian Ocean near Sumatra on 27–28 October 2007, showing the eight stages of MCC evolution: (a) MCC-12h stage (1000 local time (LT)), 27 October 2007; (b) pre-MCC stage (2200 LT), 27 October 2007; (c) initial stage (0100 LT), 28 October 2007; (d) growth stage (0400 LT), 28 October 2007; (e) mature stage (0700 LT), 28 October 2007; (f) decay stage (1300 LT), 28 October 2007; (g) dissipation stage (1600 LT), 28 October 2007; (h) post-MCC stage (1900 LT), 28 October 2007. Red color indicates interior cold cloud with $T_{BB} \leq 221$ K and blue color indicates cloud shield with $T_{BB} \leq 241$ K. Tb, ST, PB and PK are respectively Tabing, Simpang-tiga, Pulau Baai and Padang Kemiling shows the location of weather stations.

Fig. 2. Horizontal distribution of convective index (C_I) (shaded) from infrared data of MTSAT-1R, wind surface vector anomaly (vector) from Cross-Calibrated Multi-Platform (CCMP) data, and potential temperature (contour) from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim data during the occurrence of the Mesoscale Convective Complex (MCC) over the Indian

Ocean near Sumatra on28 October 2007: (a) initial stage (0100 local time (LT)), showing merging of some convective clouds to create the MCC; (b) mature stage (0700 LT), showing cold pool area forming in the center of the MCC, as indicated by the low potential temperature; (c) decay stage (1300 LT), showing several new convective systems forming on the leading edge of the cold pool; (d) post-MCC stage (1900 LT), showing the new convective systems migrating from over the Indian Ocean near Sumatra toward the western coast of Sumatra. Tb, ST, PB and PK are respectively Tabing, Simpang-tiga, Pulau Baai and Padang Kemiling shows the location of weather stations.

Fig. 3. Horizontal distribution of rainfall from Tropical Rainfall Measuring Mission (TRMM) 3B42 v6 data (shaded) and wind vector anomaly (vector) from Cross-Calibrated Multi-Platform (CCMP) data during the occurrence of the Mesoscale Convective Complex (MCC) over the Indian Ocean near Sumatra on 28 October 2007: (a) initial stage (0100 local time (LT)); (b) mature stage (0700 LT); (c) decay stage (1300 LT); (d) dissipation stage (1600 LT) but when wind data were not available; and (e) post-MCC stage (1900 LT). Tb, ST, PB and PK are respectively Tabing, Simpang-tiga, Pulau Baai and Padang Kemiling shows the location of weather stations.

Fig. 4. Rainfall observational data during the occurrence of the Mesoscale Convective Complex (MCC) over the Indian Ocean near Sumatra on 28 October 2007 (1300–2400 local time (LT)) at specific sites on the western coast of Sumatra: Pulau Baai weather station in Bengkulu, Tabing weather station in Padang, Simpang-tiga

weather station in Pekanbaru, and Padang Kemiling weather station in Bengkulu. The figure panel shows the location of weather stations.

Fig. 5. Schematic representations of the evolution and migration of the mesoscale convective complex (MCC) over the Indian Ocean near Sumatra related to the diurnal rainfall variation over the western coast of Sumatra. (a) MCC initial stage around midnight; (b) MCC mature stage during the morning; (c) MCC decay stage during the daytime; and (d) MCC dissipation stage during the evening. Light and dark gray areas indicate the MCC cloud shield and convective clouds, respectively. Cores of heavy rainfall are represented by green circles. Convergent and divergent flows are indicated by the blue and red arrows, respectively. The cold pools in (b) and (c) are indicated by blue ellipses.

Table 1. Physical characteristics of MCCs (Maddox 1980)

Size:	A-Cloud shield with continuously low $T_{BB} \leq$ - 32ºC (241 K) must have an area $\geq$ 100,000 km^2 B-Interior cold cloud region with $T_{BB} \leq$ - 52ºC (221 K) must have an area $\geq$ 50,000 km^2
Initiate:	Size definitions A and B are first satisfied
Duration:	Size definition A and B must be met for a period of $\geq$ 6 hours
Maximum extent:	Contiguous cold cloud shield ($T_{BB} \leq$ - 32ºC (241 K)) reaches a maximum size
Shape:	Eccentricity (minor axis/major axis) $\geq$ 0.7 at time of maximum extent
Terminate:	Size definitions A and B no longer satisfied

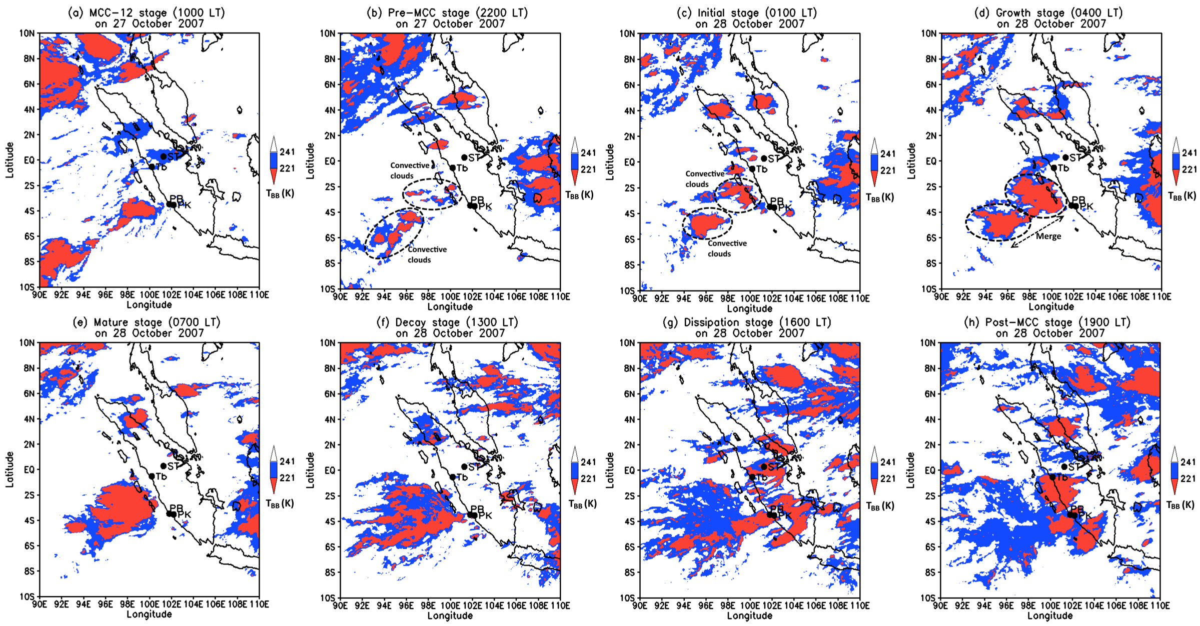

Fig. 1. Horizontal distribution of black body temperature (T_{BB}) for Mesoscale Convective Complex (MCC) criteria from infrared data obtained by MTSAT-1R over the Indian Ocean near Sumatra on 27–28 October 2007, showing the eight stages of MCC evolution: (a) MCC-12h stage (1000 local time (LT)), 27 October 2007; (b) pre-MCC stage (2200 LT), 27 October 2007; (c) initial stage (0100 LT), 28 October 2007; (d) growth stage (0400 LT), 28 October 2007; (e) mature stage (0700 LT), 28 October 2007; (f) decay stage (1300 LT), 28 October 2007; (g) dissipation stage (1600 LT), 28 October 2007; (h) post-MCC stage (1900 LT), 28 October 2007. Red color indicates interior cold cloud with $T_{BB} \leq 221$ K and blue color indicates cloud shield with $T_{BB} \leq 241$ K. Tb, ST, PB and PK are respectively Tabing, Simpang-tiga, Pulau Baai and Padang Kemiling shows the location of weather stations.

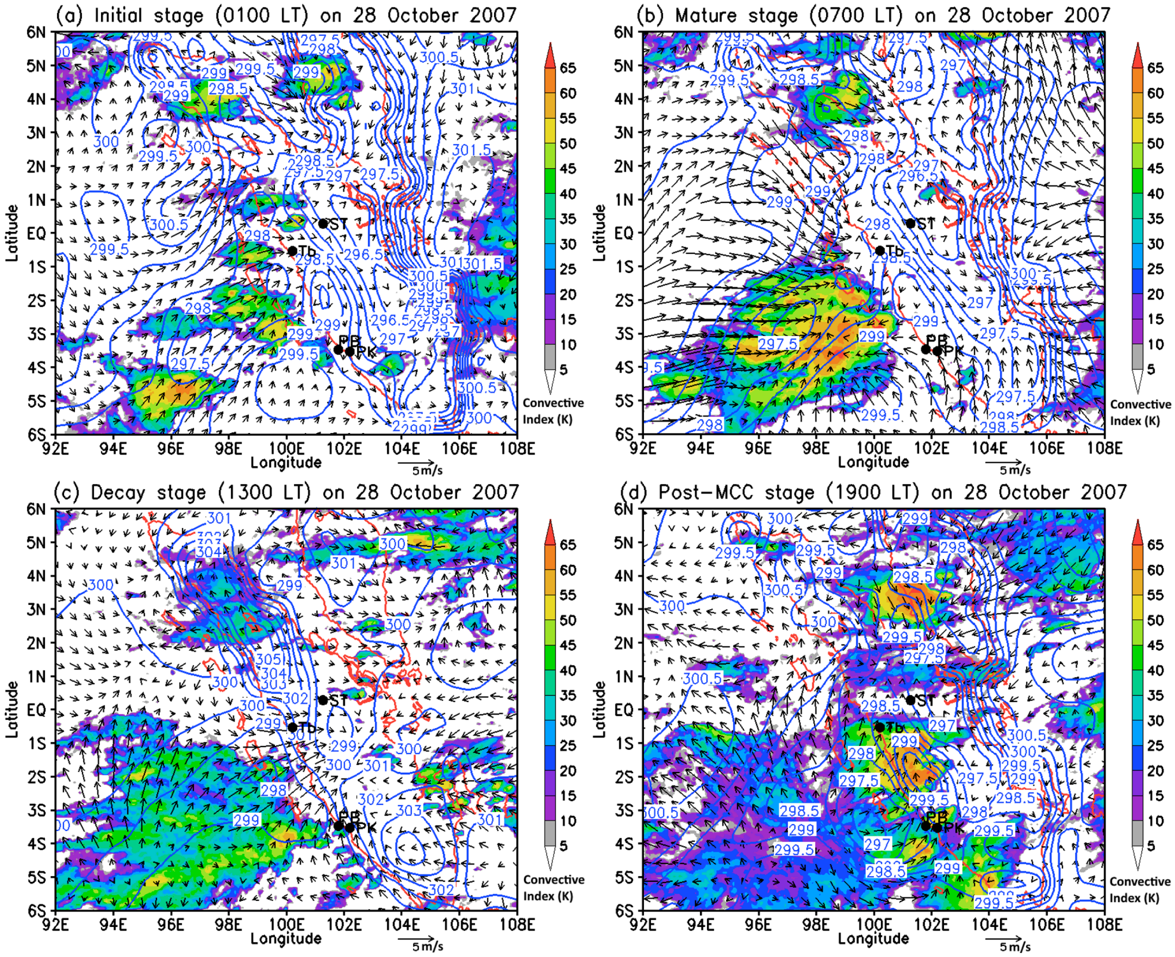

Fig. 2. Horizontal distribution of convective index (C_I) (shaded) from infrared data of MTSAT-1R, wind surface vector anomaly (vector) from Cross-Calibrated Multi-Platform (CCMP) data, and potential temperature (contour) from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim data during the occurrence of the Mesoscale Convective Complex (MCC) over the Indian Ocean near Sumatra on28 October 2007: (a) initial stage (0100 local time (LT)), showing merging of some convective clouds to create the MCC; (b) mature stage (0700 LT), showing cold pool area forming in the center of the MCC, as indicated by the low potential temperature; (c) decay stage (1300 LT), showing several new convective systems forming on the leading

edge of the cold pool; (d) post-MCC stage (1900 LT), showing the new convective systems migrating from over the Indian Ocean near Sumatra toward the western coast of Sumatra. Tb, ST, PB and PK are respectively Tabing, Simpang-tiga, Pulau Baai and Padang Kemiling shows the location of weather stations.

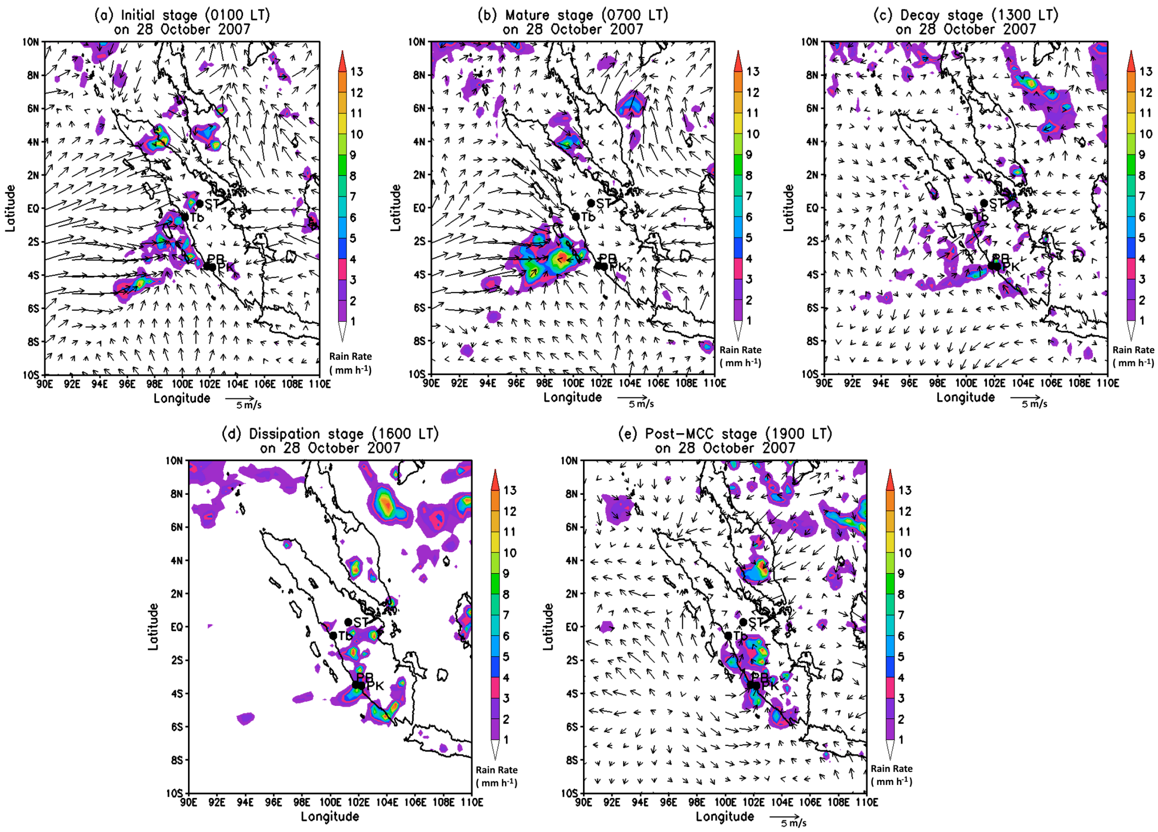

Fig. 3. Horizontal distribution of rainfall from Tropical Rainfall Measuring Mission (TRMM) 3B42 v6 data (shaded) and wind vector anomaly (vector) from Cross-Calibrated Multi-Platform (CCMP) data during the occurrence of the Mesoscale Convective Complex (MCC) over the Indian Ocean near Sumatra on 28 October 2007: (a) initial stage (0100 local time (LT)); (b) mature stage (0700 LT); (c) decay stage (1300 LT); (d) dissipation stage (1600 LT) but when wind data were not available; and (e) post-MCC stage (1900 LT). Tb, ST, PB and PK are respectively Tabing, Simpang-

tiga, Pulau Baai and Padang Kemiling shows the location of weather stations.

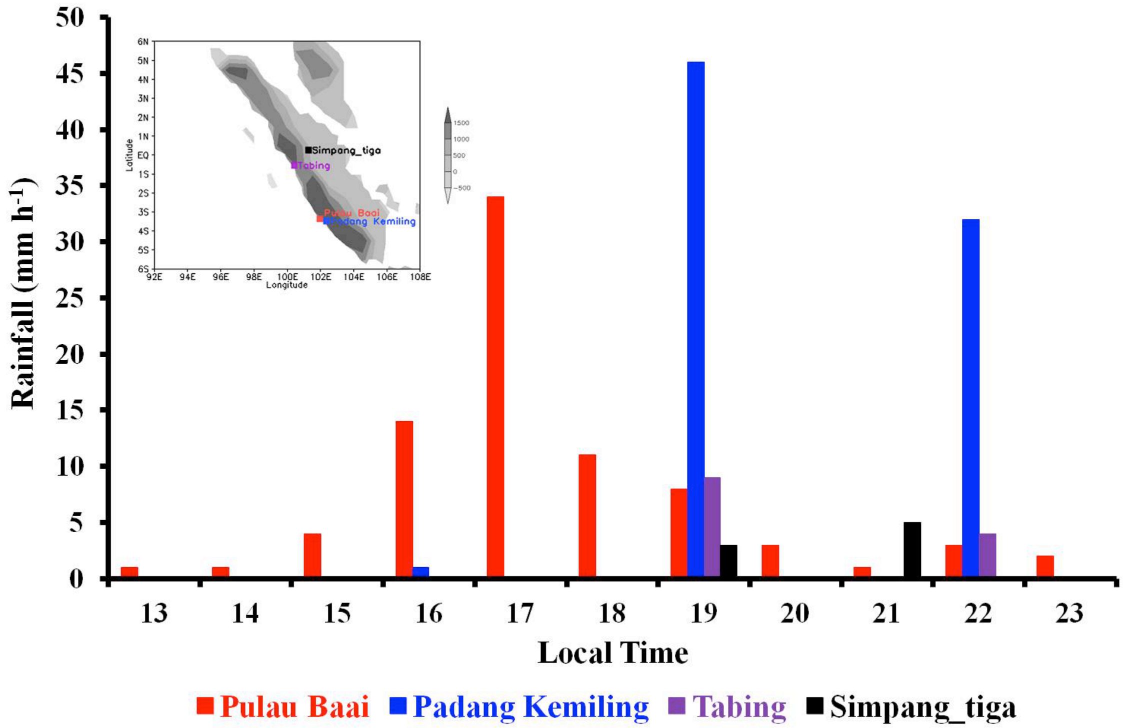

Fig. 4. Rainfall observational data during the occurrence of the Mesoscale Convective Complex (MCC) over the Indian Ocean near Sumatra on 28 October 2007 (1300–2400 local time (LT)) at specific sites on the western coast of Sumatra: Pulau Baai weather station in Bengkulu, Tabing weather station in Padang, Simpang Tiga weather station in Pekanbaru, and Padang Kemiling weather station in Bengkulu. The figure panel shows the location of weather stations.

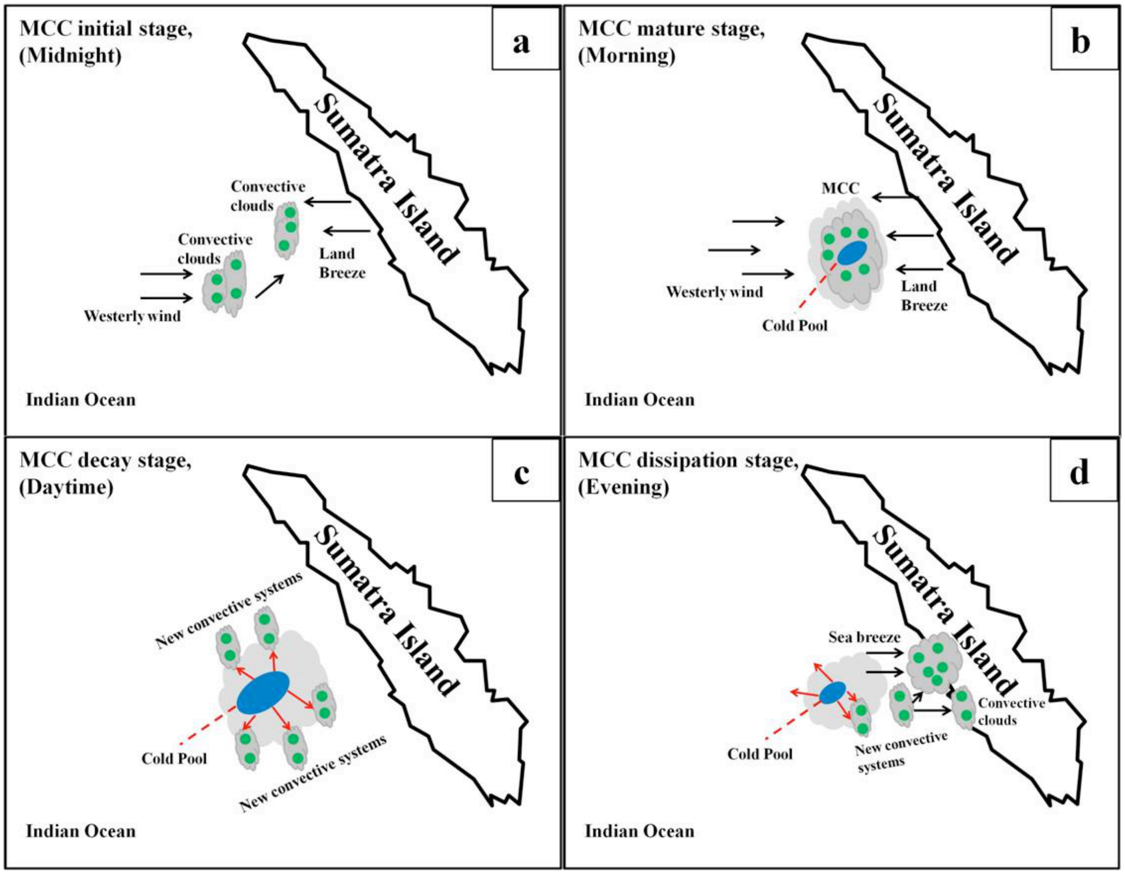

Fig. 5. Schematic representations of the evolution and migration of the mesoscale convective complex (MCC) over the Indian Ocean near Sumatra related to the diurnal rainfall variation over the western coast of Sumatra. (a) MCC initial stage around midnight; (b) MCC mature stage during the morning; (c) MCC decay stage during the daytime; and (d) MCC dissipation stage during the evening. Light and dark gray areas indicate the MCC cloud shield and convective clouds, respectively. Cores of heavy rainfall are represented by green circles. Convergent and divergent flows are indicated by the blue and red arrows, respectively. The cold pools in (b) and (c) are indicated by blue ellipses.