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RESEARCH ARTICLE

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Occurrence of meridional and easterly surges and their impact on Malaysian rainfall during the northeast monsoon: a climatology study

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Abstract

The cold surge or meridional surge (MS) is known to be one of the main features that contributes to extreme Malaysian rainfall events during the boreal winter or northeast monsoon. This study investigates other factors that contribute to the heavy rainfall, besides the cold surge, as well as their impacts on rainfall in the Malaysian region. Based on known methods, two additional types of surge are identified, namely the easterly surge (ES) and the mixed surge (MES), which is a mixture of both ES and MS. Daily average wind data from the European Centre for Medium-Range Weather Forecasts Reanalysis ERA-Interim for 37 seasons of the northeast monsoon (1979–1980 to 2016–2017, October–March) were used to identify the MSs, ESs and MESs. The impact of these surges on rainfall in the Malaysian region was investigated by using the rainfall data from the meteorological stations of the Malaysian Meteorological Department and the Tropical Rainfall Measuring Mission. The results showed that the MS plays an important role in modulating heavy rainfall in the early season over the east coast of Peninsular Malaysia. Meanwhile, the ES dominates the rainfall distribution over Sarawak in the late middle season. The rainfall modulated by the MES shows a higher intensity and concentrates over the southern part of the east coast of Peninsular Malaysia and Sabah. These findings provide a climatological view of the spatial and temporal distribution of heavy rainfall associated with different types of surge, which can be used as a forecasting tool for predicting surges and their impacts.

KEYWORDS

boreal winter, cold surge, easterly surge, impact on rainfall, meridional surge, mixed surge, northeast monsoon

1 | INTRODUCTION

Malaysia is geographically located in the western maritime continent region, as described by Ramage (1971). The monsoon regions delineated by Ramage (1971) show that Malaysia is included in the region marked with large seasonal variations in wind direction and therefore the aspects of the monsoon and its characteristics in Malaysia are largely influenced by the wind, rather than the rainfall distribution. This is why monsoon studies in Malaysia have placed more emphasis on wind rather than precipitation.

The boreal winter monsoon is referred to as the northeast monsoon (NEM) season in Malaysia due to its prevailing northeasterly winds and typical yearly occurrence from November until March. During this period, strong pressure gradients are established between the Siberian High and South China Sea (SCS) from time to time. As this pressure gradient increases, it can initiate low-level outbreaks of cold air mass (which is known as the cold surge [CS] by local meteorologists) from the East Asiatic landmass. This surge intensifies the northeasterly winds over the SCS and hence maximum winds are observed over the central SCS and downstream over the southern SCS. At the same time, the cyclonic vortices located within the monsoon trough get intensified due to increases in relative vorticity and mass convergence. This causes widespread torrential rainfall, lasting for a few days, that will affect the Malaysian coastal regions facing the SCS (Moten *et al.*, 2014). The CS has a significant impact on the weather over Malaysia as the east coast states of Peninsular Malaysia are known to receive about 70% of their total annual rainfall over the first half of the season (November–December) during active monsoon years (Moten *et al.*, 2014). In some cases, the northeasterlies penetrate anomalously far south. This caused the severe floods in mid-December 2006 to late January 2007 in the southern Peninsular Malaysia as described by Tangang *et al.* (2008). It was one of the worst floods of the century and was caused by three extreme precipitation episodes initiated by the CS.

In addition to the CS, there is another disturbance that contributes to the heavy rainfall over Malaysia during the NEM, which is known as the easterly surge (ES) (Hai *et al.*, 2017). Hai *et al.* (2017) defined the ES as the zonal wind surge due to the strengthening or equatorward movement of the subtropical ridge in the northwestern Pacific as a result of a Siberian High outbreak. They also revealed that the unusual heavy downpours and severe flooding in the inland and mountainous areas of the east coast of Peninsular Malaysia during December 2014 were caused by the ES. Two unusual extreme rainfall events, which lasted for 11 days and delivered more than 1,100 mm of precipitation, caused extensive damage and widespread floods in many inland areas.

The importance of both the CS and the ES were emphasized by Chang *et al.* (1979), Cheang (1980) and Chen *et al.* (2013). They addressed the ES as the westward propagation of easterly waves from the western Pacific Ocean. According to Chang *et al.* (1979), the interactions between the low-level northeasterly monsoon winds and the westward propagating wave can enhance low-level convergence and organized deep cumulus convection over the SCS. Cheang (1980) agreed that the different synoptic conditions and rainfall distribution in Malaysia depend very much on whether the CS and ES are in phase or out of phase. He classified the rainfall associated with the CS and ES into four types: (a) no widespread heavy rainfall when neither the CS nor the ES reach the SCS; (b) widespread and short-lived (1 or 2 days) heavy rainfall when the ES (without the CS) reach the SCS; (c) widespread torrential rainfall when both the CS and the ES reach the SCS; and (d) widespread heavy rainfall when the CS (without the ES) reach the SCS.

Chen *et al.* (2013) also pointed out a similar finding. They discovered that heavy rainfall occurred in Peninsular Malaysia in the early period (November–December) of the NEM, where two groups of disturbances related to the heavy rainfall events were highlighted: (a) the interaction of the ES with the CS; and (b) the interaction of the CS with the mountains between west Borneo and Kalimantan. Meanwhile, the NEM heavy rainfall events in Borneo occurred in the later period (December–February) of the NEM, where two groups of disturbances related to the heavy rainfall events were highlighted: (a) the ES that propagated to the SCS due to the location of a near-equatorial trough across northern Borneo in December or across central Borneo in January–February; and (b) the interaction of the CS with Borneo's orography.

Some findings from Cheang (1980) and Chen *et al.* (2013) have similar discussions to this study on the rainfall variability in Malaysia associated with the occurrence of the CS/ES. However, there are still some unanswered questions from the above findings, such as how the heavy rainfall based on the findings can be forecasted and where the exact locations of these heavy rainfall events are. This study was organized to answer the questions, focusing more on operational purposes and how the findings in this study applied in operational.

Recognizing the fact that the CS and the ES have a great impact on the occurrence of heavy rainfall events in Malaysia during the NEM, it is important to find a tool to guide forecasters to predict the events of heavy rain during the presence of the CS and the ES. Therefore, this study provides a general spatial temporal view of heavy rainfall due to the occurrence of surges, based on a climatological study. It can be used as one of the forecasting tools to monitor the surges and predict their impacts on the rainfall in the Malaysian region.

2 | DATA AND METHODS

The present study applied the methods due to Chang *et al.* (2005) and Hai *et al.* (2017) with regard to use of the terms meridional surge (MS) and ES and the third type of surge, the mixed surge (MES), which is a mixture of both ES and MS. It used data from October to March, which represents the period of the NEM season in Malaysia, as defined by Moten *et al*. (2014).

The number and intensity of MSs in this study were determined based on the index definition from Chang *et al*. (2005). They were calculated as the average of 925 hPa meridional winds bounded by 110 ° E to 117.5 ° E along 15 ° N. Meanwhile, the number and intensity of ESs were adopted from the index definition by Hai *et al*. (2017). They were calculated as the average of 925 hPa zonal winds between 7.5 ° N and 15 ° N along 120 ° E. A MS/ES event was said to occur when this index exceeded 8 m/s. As for the third type of surge, the MES, it was considered when a MS and ES occurred concurrently. The region between 110 ° E and 117.5 ° E was used to cover the SCS region and the region along 15 ° N was used to capture all the CSs and ensure that the CS entering the SCS region originated from Siberia. Meanwhile, the region between 7.5 ° N and 15 ° N was used to capture the broad easterly winds from the West Pacific Ocean coming into the SCS region. The region along 120 ° N was used to capture the ES and ensure that the surge entering the SCS region originated from the West Pacific Ocean. The location of the regions used to calculate the MS and ES are shown graphically in Figure 1.

The daily average wind data at 925 hPa obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-Interim) for 37 seasons of the NEM (1979–1980 to 2016–2017, October–March) were used to determine the MS, ES and MES. They were available from January 1, 1979, until the present and had a spatial resolution of 0.75° × 0.75° (Dee *et al*., 2011).

The daily and monthly rainfall data from October to March 1951–2016 were obtained from the Malaysian Meteorological Department (MMD). The distribution of the average surge days was compared with the monthly rainfall from the MMD meteorological stations to investigate the impact of different kinds of surge on the rainfall distribution. Eight meteorological stations were selected to represent the regions in Peninsular Malaysia, Sabah and Sarawak. Peninsular Malaysia was divided into northern east coast and southern east coast regions and was represented by the Kota Bharu and Mersing stations, respectively. As for Sabah and Sarawak, they were each divided into three regions: eastern Sabah, northern Sabah, western Sabah, eastern Sarawak, central Sarawak and western Sarawak. They were represented by Sandakan, Kudat, Kota Kinabalu, Miri, Bintulu and Kuching stations, respectively. The regions are shown in Figure 1, while the details of the stations are summarized in Table 1. In this study, a heavy rainfall episode was said to have occurred if any of the stations recorded daily rainfall that exceeded 150 mm.

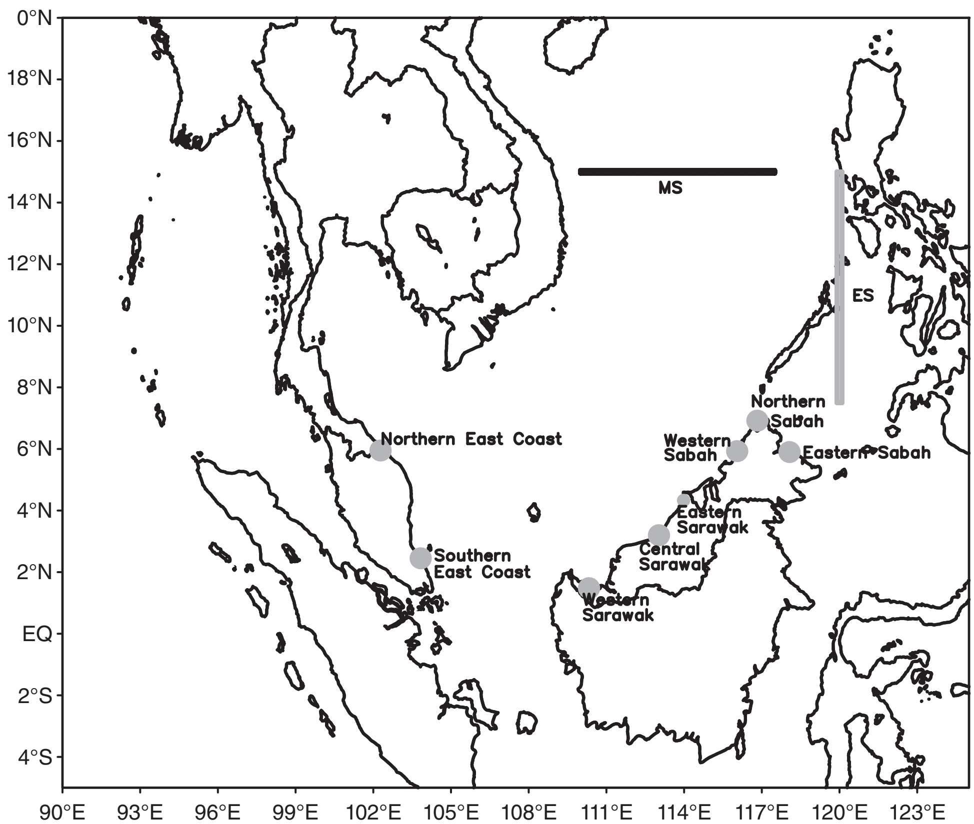

FIGURE 1 The geographical location of meteorological stations representing the region in Malaysia. The black region indicates the area used to calculate the meridional surge (MS), while the grey region indicates the area used to compute the easterly surge (ES)

A few studies on the NEM in Malaysia have used satellite observation data to describe the precipitation pattern and rainfall events, e.g. Chang *et al.* (2005), Tangang *et al.* (2008), Chen *et al.* (2013) and Hai *et al.* (2017). The present study also used satellite observation data to investigate the impact on rainfall due to the occurrence of surges. In this study, the daily averages of satellite data from the Tropical Rainfall Measuring Mission (TRMM), TRMM_3B42V7, for 20 NEM seasons (1997–1998 to 2016–2017, October–March) were used. This dataset was obtained from the Goddard Earth Sciences and Information Services Center (GES-DISC). It covered the latitude band 50 ° N to 50 ° S for the period from 1998 to the delayed present with a spatial resolution of $0.25° \times 0.25°$. The validation analysis of TRMM_3B42V7 over Malaysia and the neighbouring regions showed a very good correlation with the ground observed data as revealed in Roongroj and Long (2008), Varikoden *et al.* (2010), As-Syakur *et al.* (2011, 2013) and Jiang *et al.* (2016).

TABLE 1 The eight meteorological stations that represent the region in Malaysia

Area	Meteorological station	Region
Peninsular Malaysia	Kota Bharu	Northern east coast
	Mersing	Southern east coast
Sabah	Sandakan	Eastern Sabah
	Kudat	Northern Sabah
	Kota Kinabalu	Western Sabah
Sarawak	Miri	Eastern Sarawak
	Bintulu	Central Sarawak
	Kuching	Western Sarawak

To verify the performance of the MS/ES/MES indices, some case studies were analysed using daily average wind data at the 925 hPa level from the ECMWF ERA-Interim, the Global Forecast System (GFS) model analysis and the National Centers for Environmental Prediction (NCEP) Final (FNL) model analysis. The GFS and NCEP FNL models are weather forecast models produced by the NCEP. The FNL data are made with the same model which NCEP uses in the GFS but the FNL data are prepared about an hour or so after the GFS is initialized. The FNL data are delayed so that more observational data can be used. The GFS and NCEP FNL data have a spatial resolution of $0.5° \times 0.5°$ and $0.25° \times 0.25°$, respectively. In addition, daily average wind data at the 925 hPa level from the GFS model forecast of f0120 and satellite data of Feng Yun (FY-2G) from the China Meteorological Administration (CMA) were also used in this verification to compare the

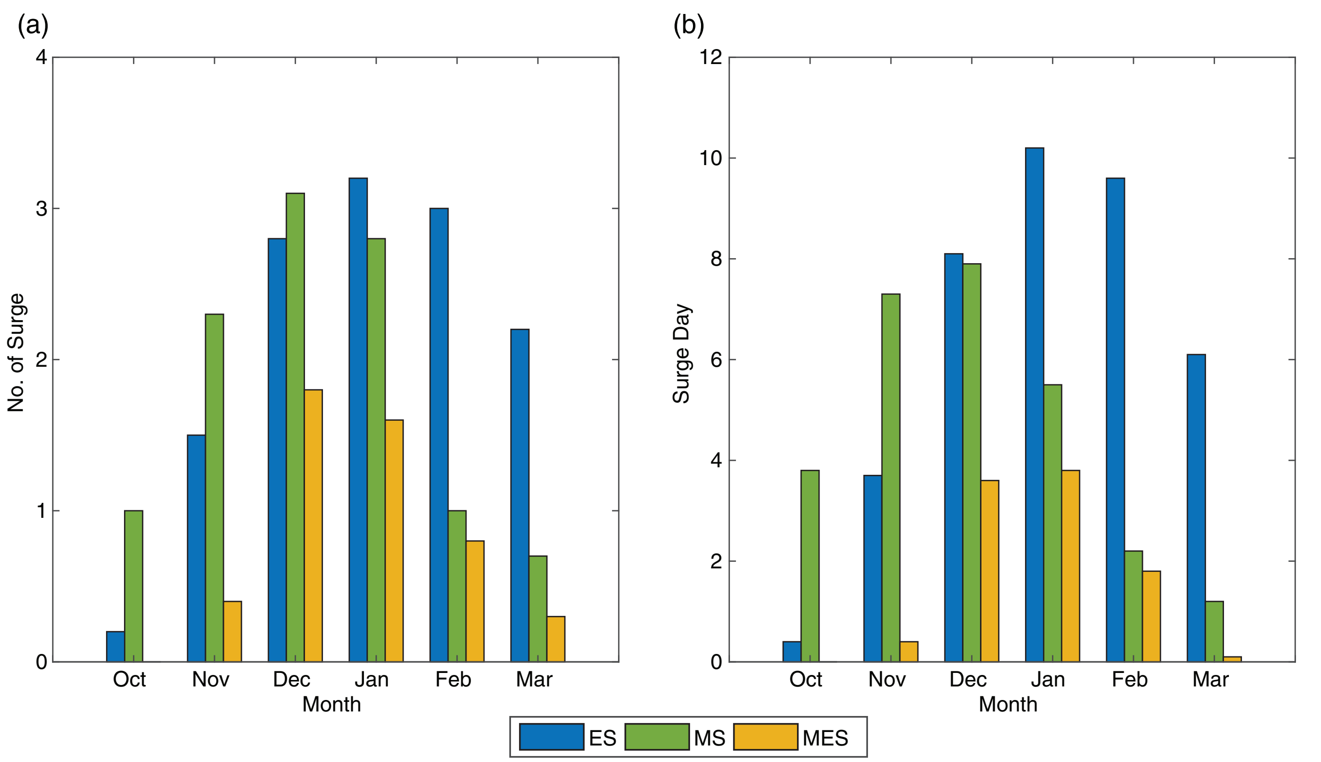

FIGURE 2 The monthly distribution of (a) the average number of surges and (b) the average number of surge days *per* season for meridional surges (MSs), easterly surges (ESs) and mixed surges (MESs). The averages are calculated based on the wind data for 37 seasons of the northeast monsoon (1979–1980 to 2016–2017, October–March)

results; f0120 is an initial time of the forecast data used to forecast 5 days (120 hr) ahead.

3 | RESULTS AND DISCUSSION

3.1 | The statistics of the MS, ES and MES

Based on 38 years of records, the average number of surges *per* season was 29, which consisted of 11 episodes of MS, 13 episodes of ES and five episodes of MES. The average surge days *per* season was 76, of which 28 days fell under MS, 38 days fell under ES and 10 days fell under MES. The average duration of surges *per* episode for MSs and ESs was 3 days, while for MES it was 2 days. The monthly distribution of the average number of surges and surge days *per* season for MSs, ESs and MESs is shown in Figure 2. Two different skews were perceived, where the highest frequency of MS and MES occurred during December and the highest frequency of ES occurred during January. The statistics of MS, ES and MES are depicted in Table 2. In the present study the first and last episodes of MS, ES and MES are normal if the surge fell within one standard deviation of the mean episodes. The mean and standard deviation values for the first episode of MS was 22 October and 13 days, while the mean and standard deviation values for the last episode of MS was 25 February and 23 days. Meanwhile, the mean and standard deviation values for the first episode of ES was 17 November and 16 days, while the mean and standard deviation values for the last episode of ES was 20 March and 11 days. As for the MES, the mean and standard deviation values for the first episode of MES was 7 December and 19 days, while the mean and standard deviation values for the last episode of MES was 10 February and 22 days, respectively.

TABLE 2 The statistics of meridional surges (MSs), easterly surges (ESs) and mixed surges (MESs) during the northeast monsoon season in Malaysia

MS	Climatology
Early occurrence of the first surges	1 October
Average occurrence of the first surges	22 October
Late occurrence of the first surges	20 November
Early occurrence of the last surges	24 December
Average occurrence of the last surges	25 February
Late occurrence of the last surges	28 March
Least no. of MSs	5
Average no. of MSs	11
Highest no. of MSs	18
Average days *per* season	28 days
Average days *per* episode	3 days
ES	
Early occurrence of the first surges	19 October
Average occurrence of the first surges	17 November
Late occurrence of the first surges	29 December
Early occurrence of the last surges	7 February
Average occurrence of the last surges	20 March
Late occurrence of the last surges	30 March
Least no. of ESs	8
Average no. of ESs	13
Highest no. of ESs	22
Average days *per* season	38 days
Average days *per* episode	3 days
MES	
Early occurrence of the first surges	4 November
Average occurrence of the first surges	7 December
Late occurrence of the first surges	26 January
Early occurrence of the last surges	6 January
Average occurrence of the last surges	10 February
Late occurrence of the last surges	23 March
Least no. of MESs	1
Average no. of MESs	5
Highest no. of MESs	9
Average days *per* season	10 days
Average days *per* episode	2 days

MS is derived from Chang *et al*. (2005) while ES is derived from Hai *et al*. (2017). MES is considered when both 8 m/s thresholds are crossed concurrently.

3.2 | The impact on rainfall due to the occurrence of MS, ES and MES

The impact on rainfall in the Malaysian region was investigated by using the rainfall data from meteorological stations of the MMD and the TRMM. The analysis is shown in Figures 3 and 4, respectively.

3.2.1 | Using the rainfall data from meteorological stations

The average amount of rainfall from the MMD meteorological stations and the average number of surge days for MS, ES and MES in Peninsular Malaysia are shown in Figure 3a–c, respectively. The results show that on the east coast of Peninsular Malaysia rainfall in both regions was distributed almost the same as MS and MES occurrences where both the rainfall amount and the number of MSs peak in December (Figure 3a–c). However, in the ES case, the maximum rainfall was not in phase with the maximum occurrence of all type ES cases (Figure 3b).

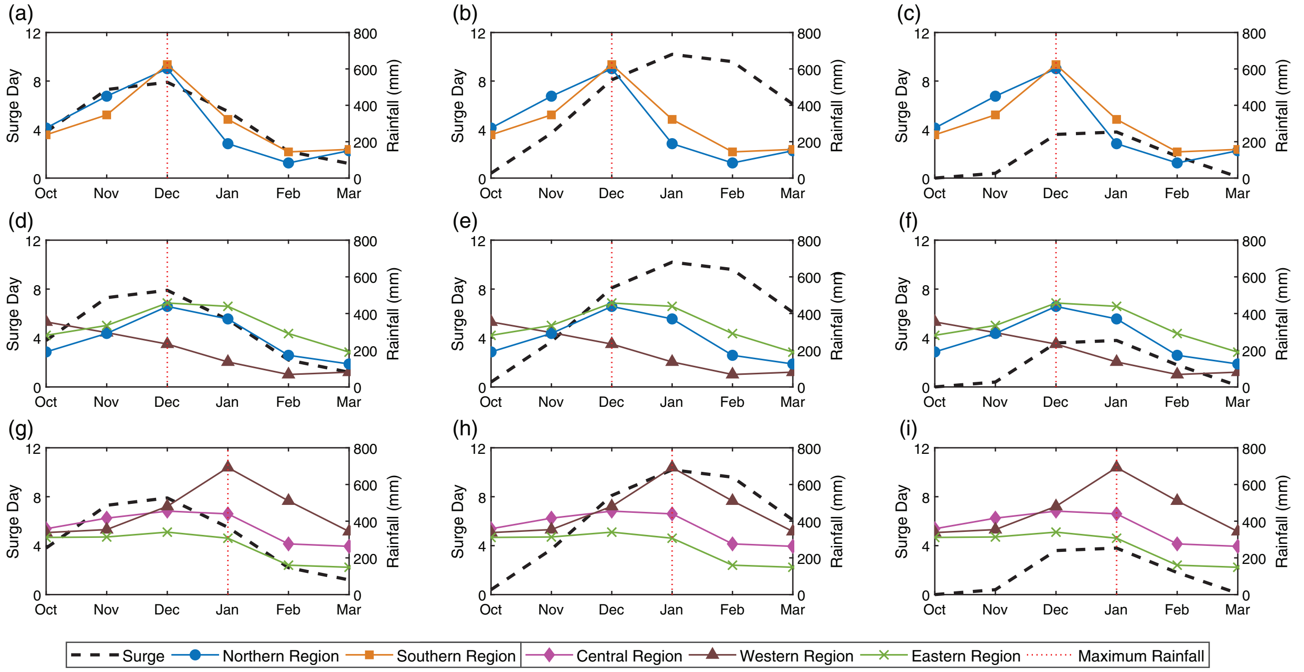

FIGURE 3 The average rainfall and number of surge days for (a) meridional surges (MSs) in Peninsular Malaysia, (b) easterly surges (ESs) in Peninsular Malaysia, (c) mixed surges (MESs) in Peninsular Malaysia, (d) MSs in Sabah, (e) ESs in Sabah, (f) MESs in Sabah, (g) MSs in Sarawak, (h) ESs in Sarawak and (i) MESs in Sarawak

The average rainfall and number of surge days for MS, ES and MES in Sabah are shown in Figure 3d–f, respectively. Like the rainfall distribution in Peninsular Malaysia, the rainfall in Sabah regions with the exception of the western region is distributed similarly to the MS and MES occurrence (Figure 3d,f). The rainfall in northern and eastern regions of Sabah is maximum in December, as well as the peak occurrence of MSs and MESs. As the peak occurrence of ESs is in January, the rainfall distribution in Sabah is not in phase with the occurrence of ESs (Figure 3e).

Figure 3g–i shows the average rainfall and number of surge days for MS, ES and MES respectively in Sarawak. Unlike the rainfall distribution in Peninsular Malaysia and Sabah where the rain peaks were in December, the maximum rainfall in Sarawak was observed in January. This suggests that there might be a different mechanism influencing the rainfall distribution in this region. Figure 3h,i shows that, except in the eastern region, the rainfall in Sarawak was distributed similarly to the ES and MES occurrence distributions. However, the rainfall distributions in these regions were not similar to the MS occurrence distribution (Figure 3g).

Overall, the rainfall distribution in Peninsular Malaysia and Sabah (all regions except the western region) during the NEM season was mostly influenced by the occurrence of MSs in the early period of the season. This was evident with the maximum rainfall due to the occurrence of MS in December. As the number of ES days increased and reached its maximum during January, the rainfall distribution over these regions was largely modulated by mixed events of MSs and ESs or simply MESs. Therefore, the distribution of MESs was more spread and had a broad maximum peak in December and January. Meanwhile, the impact on rainfall due to the occurrence of ESs was more significant over the western and central regions of Sarawak, with the maximum rainfall due to the occurrence of ESs in January. The occurrence of MSs, ESs and MESs did not influence the rainfall distribution in the western region of Sabah and the eastern region of Sarawak. Cheang (1980) showed that the rainfall amount in these two regions was influenced by the southwest monsoon (summer monsoon) rather than the NEM.

Generally, these results are consistent with the findings of Chen *et al.* (2013), which also revealed that the interaction of ESs with CSs caused heavy rainfall events in Peninsular Malaysia. Meanwhile, in Borneo, heavy rainfall was caused by interaction of the propagation of ESs to the SCS due to the location of a near-equatorial trough across northern Borneo/across central Borneo and interaction of CSs with Borneo's orography.

3.2.2 | Using the rainfall data from the TRMM

The rainfall distribution due to the occurrence of MSs, ESs and MESs by using the TRMM is described in the composite plot of monthly wind and precipitation in Figure 4. The

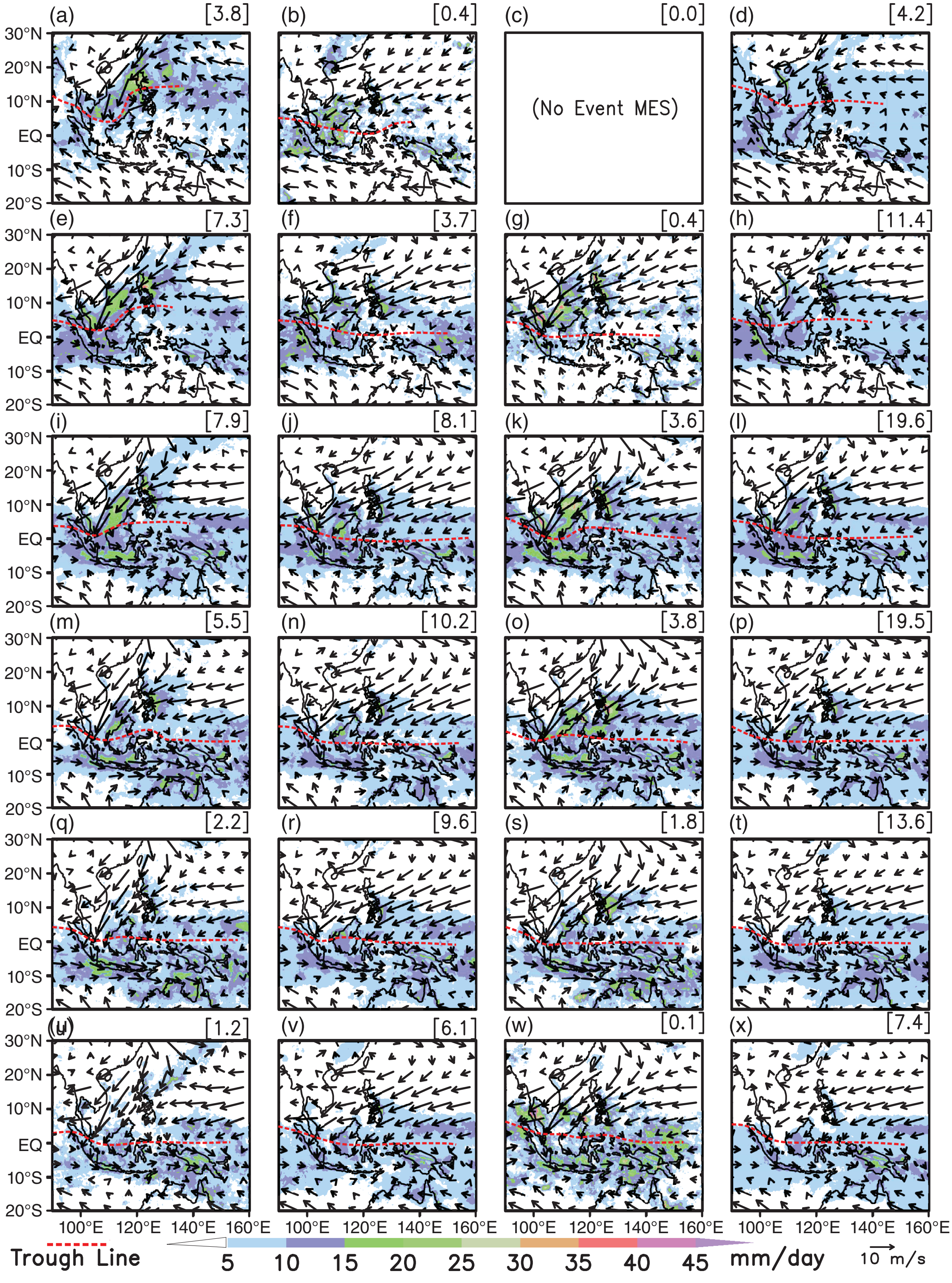

FIGURE 4 The composite plots of rainfall during surge occurrence for (a) a meridional surge (MS) in October, (b) an easterly surge (ES) in October, (c) a mixed surge (MES) in October, (d) climatology in October, (e) MS in November, (f) ES in November, (g) MES in November, (h) climatology in November, (i) MS in December, (j) ES in December, (k) MES in December, (l) climatology in December, (m) MS in January, (n) ES in January, (o) MES in January, (p) climatology in January, (q) MS in February, (r) ES in February, (s) MES in February, (t) climatology in February, (u) MS in March, (v) ES in March, (w) MES in March and (x) climatology in March. The average surge days *per* season (as shown in Figure 2) is shown in brackets at the top-right corner

composite wind and rainfall data were taken for 20 seasons of the NEM (1997–1998 to 2016–20/17, October–March).

Based on the surge dates during this period, there was no MES during October (Figure 4c). Two maximum rainfall centres associated with a MS were observed during October, in the SCS and on the windward side of the Philippines (Figure 4a). The monsoon trough was oriented in the northeast–southwest direction over the SCS and zonally oriented west of the trough axis at 7 ° N. The south equatorial trough can be seen intruding into the northern hemisphere. The October climatological monsoon trough was located at around 7 ° N (Figure 4d). In contrast to the MS event, the monsoon trough was zonal and located at around 3 ° N. Intense rainfall can be seen in the Malaysian and southern SCS regions due to the occurrence of an ES (Figure 4b). This clearly shows that, even though MSs may happen in October, because of the orientation and position of the trough Peninsular Malaysia is still under the influence of westerly winds and such MSs do not bring rainfall to the Malaysian region.

In November, the climatological monsoon trough has migrated south to around 3 ° N to 5 ° N and is zonally positioned west of Borneo, while in the Borneo region its position runs parallel to the coast of Borneo (Figure 4h). Due to the occurrence of MSs, three major rainfall areas are observed in the northeast–southwest orientation, with the most northward rain centre located in eastern Luzon and the most southward rainfall area located in the east coast region of Peninsular Malaysia. Between these two areas is the rainfall area, locating the southeastern region of the coast of Indochina Peninsular and the central region of the southern SCS. Interestingly, these rainfall areas are all located facing the prevailing northeasterly winds. Within these prevailing northeasterly winds is the monsoon trough, located zonally at around 5 ° N, west of the prevailing northeasterly wind axis (Figure 4e). The monsoon trough is located slightly equatorward at around 3 ° N in the ES events. Embedded in this trough is the vortex located in Borneo, which is known as the Borneo vortex (BV). Three rainfall areas with the same locations but weaker rainfall intensity than the MS events are also observed during ES events (Figure 4f). Another rainfall was observed, confined to the vicinity of the BV. The combination of MS and ES or MES events showed heavy intensities in rainfall areas. The trough is located more or less zonally at around 3 ° N (Figure 4g).

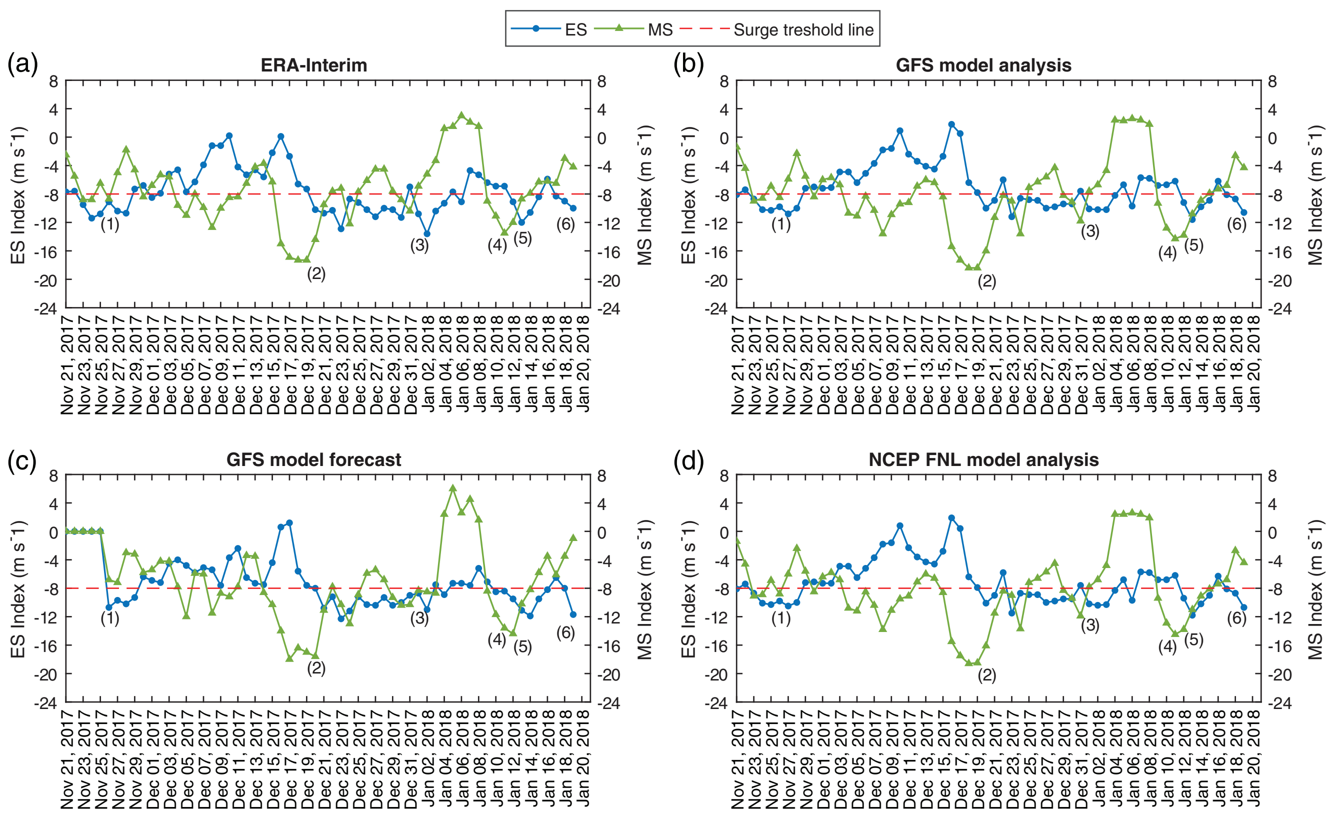

FIGURE 5 Analysis of case studies using the daily average wind data at 925 hPa of (a) ERA-interim, (b) GFS model analysis, (c) GFS model forecast and (d) NCEP FNL model analysis. Six case studies were selected: (1) mixed surge (MES) on November 26, 2017; (2) meridional surge (MS) on December 19, 2017; (3) easterly surge (ES) on January 1, 2018; (4) MS on January 10, 2018; (5) MES on January 12, 2018; (6) ES on January 19, 2018

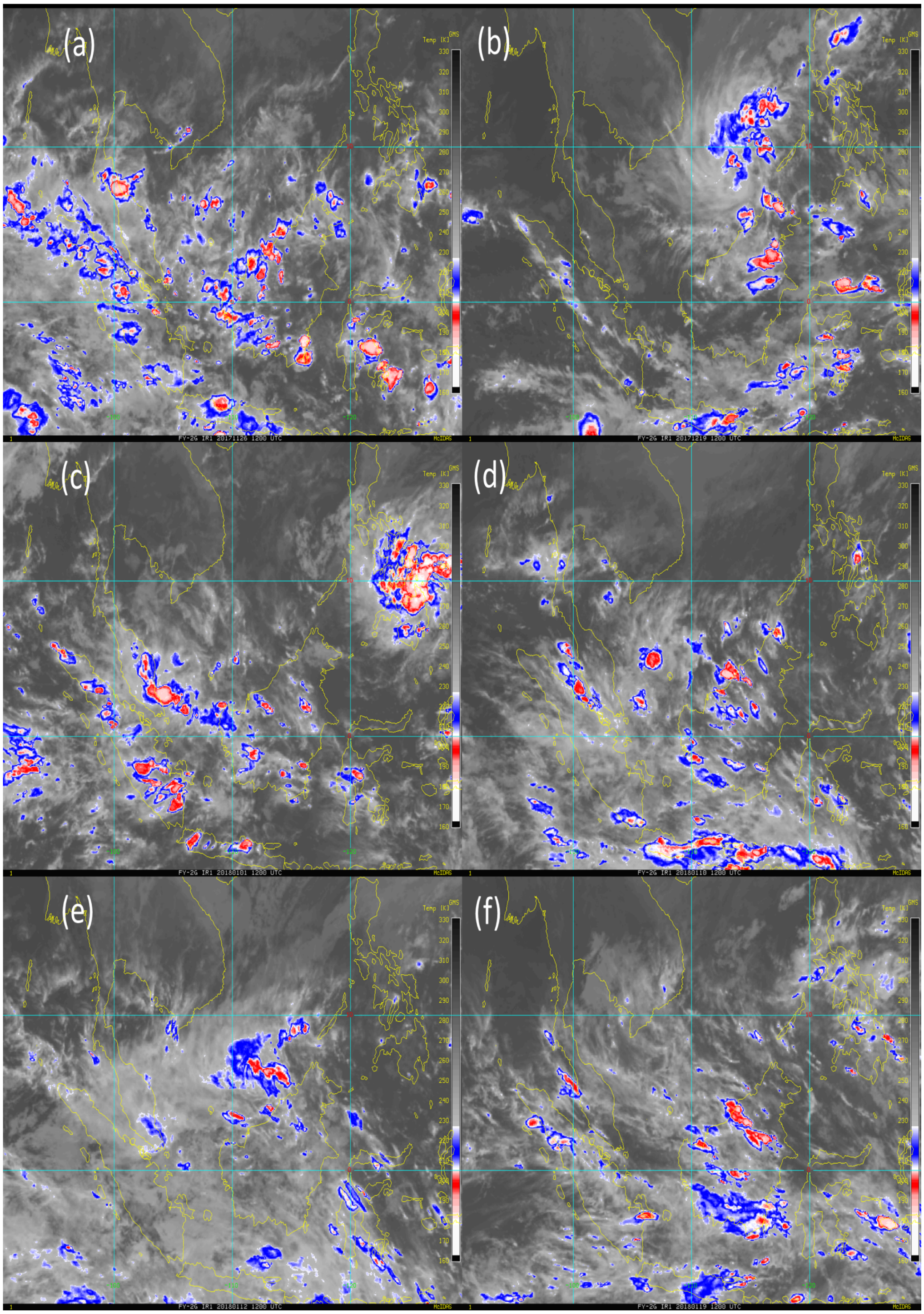

FIGURE 6 The satellite image of FY-2G at 1200 UTC in the selected case studies: (a) mixed surge (MES) on November 26, 2017; (b) meridional surge (MS) on December 19, 2017; (c) easterly surge (ES) on January 1, 2018; (d) MS on January 10, 2018; (e) MES on January 12, 2018; (f) ES on January 19, 2018

By December, the climatological monsoon trough is located at around 3 ° N and the northeast–southwest oriented trough in Borneo strengthens. During this time (where MS occurrences peak), strong northeasterly winds are observed in the SCS region (Figure 4l). The monsoon trough in the MS events is tilted in a northeast–southwest direction, almost parallel to the Borneo coast. Because of this, the northeasterly winds penetrate further south and this gives rise to the strong cyclonic shear in this region. At the same time, diffluence of the northeasterly winds was observed in the northern part of the east coast of Peninsular Malaysia. Therefore, rainfall can be found over the strong cyclonic shear region, over the southern part of the east coast of Peninsular Malaysia, the central and western part of Sarawak and the central southern SCS (Figure 4i). The same conditions are observed during ES events ((Figure 4j). Due to the peak occurrence of MS and an increasing number of ESs during December, the occurrence of the MES will have a great impact on the rainfall over the east coast of Peninsular Malaysia, Sabah, Sarawak and the SCS (Figure 4k).

By January the climatological trough moves further south and is located at around 2 ° N to the west of Peninsular Malaysia and the northeast–southwest orientation trough located in the Borneo region deepens (Figure 4p). Even though MSs still occur during this time, they will not bring much rainfall to Peninsular Malaysia due to the diffluence of the wind which is an unfavourable condition for convection to take place in this region. However, within the northeast–southwest trough, strong cyclonic shear is present and this can induce the BV. Convection often forms in the northwestern part of the vortex (Figure 4m). With the intensification of low-level anticyclonic circulation on the southeastern coast of China, the number of ES events peaks in this month. During ES events, the trough is more zonally oriented in the Borneo region, and thus rainfall and the BV are formed closer to the island. During these events, rains are also seen in the southern part of the east coast of Peninsular Malaysia and the northern part of Borneo (Figure 4n). When a MES occurs during this period, the rainfall pattern is similar to the sum of the MS and ES (Figure 4o).

By February and March, the monsoon trough is located near the equator and a strong cross-equatorial flow exists in the Malaysian region (Figure 4t,x). With the northern winter gradually coming to an end, the number of MS and ES events decreases (Figure 4q,r,u,v). However, in the presence of a MES, rainfall can be seen in the northern region of Peninsular Malaysia and the eastern maritime continent (Figure 4s,w).

3.3 | Monitoring the surges and their impact on rainfall in the MMD

The method of MS and ES indices that was discussed in the previous section was implemented and operationalized in the MMD as one of the forecasting tools in monitoring surges during the NEM season. The indices were calculated based on the grid point values from the GFS to monitor and forecast a possible surge in the Malaysian region beginning in the NEM 2017–2018 season.

To observe the performance of MS/ES/MES indices, some case studies were analysed using daily average wind data at the 925 hPa level from the ERA-Interim, GFS model analysis and NCEP FNL model analysis. The GFS model forecast of f0120 and the satellite image of FY-2G at 1200 UTC were also added to this analysis to compare the results. Six case studies were selected: (a) MES on November 26, 2017; (b) MS on December 19, 2017; (c) ES on January 1, 2018; (d) MS on January 10, 2018; (e) MES on January 12, 2018; and (f) ES on January 19, 2018. The results of the method with the ERA-Interim data, GFS model analysis, GFS model forecast and NCEP FNL model analysis are depicted in Figure 5.

As observed in Figure 5, generally the method can capture surges very well within this period. The same surge events were captured by all the indices using ERA-Interim data, GFS model analysis and NCEP FNL model analysis in Figure 5a,b,d, respectively. Meanwhile, different surges were captured by the indices using the GFS model forecast in some of the selected cases (as observed in Figure 5c). These analyses show that the performance of the method is good as it can capture the surge events pretty well, including the analysis using the GFS model forecast, where it can still capture the surge events even though they are different types of surges.

The satellite image of FY-2G at 1200 UTC in the selected case studies is depicted in Figure 6. Based on case 1, the MES event on November 26, 2017 (Figure 6a), the rainfall was concentrated over the northern region of Peninsular Malaysia, the coastal region of Sarawak and the eastern region of Sabah. This result shows a similar pattern to the rainfall distribution from the analysis in Figure 4g which indicated the MES event in November. Based on case 2, the MS event on December 19, 2017 (Figure 6b), the rainfall was concentrated over the eastern region of Sarawak and the western and eastern regions of Sabah. This result shows a similar pattern to the rainfall distribution from the analysis in Figure 4i which indicated the MS event in December. Based on case 3, the ES event on January 1, 2018 (Figure 6c), the rainfall was concentrated over the southern region of Peninsular Malaysia and the western region of Sarawak. This result also shows a similar pattern to the rainfall distribution from the analysis in Figure 4n which indicated the ES event in January.

Based on case 4, the MS event on January 10, 2018 (Figure 6d), and case 5, the MES event on January 12, 2018 (Figure 6e), the rainfall was concentrated over the southern region of Peninsular Malaysia, the central and eastern regions of Sarawak and the western region of Sabah in both events. These results show a similar pattern to the rainfall distribution from the analysis in Figure 4m which indicated the MS event in January and Figure 4o which indicated the MES event in January. Meanwhile, based on case 6, the ES event on January 19, 2018 (Figure 6f), the rainfall was concentrated over Sarawak. This result also shows a similar pattern to the rainfall distribution from the analysis in Figure 4n which indicated the ES event in January.

The similar pattern of satellite images with the rainfall distributions from the analyses in Figure 4 proves that the method can be implemented as a guidance in monitoring surges. It also proves that the climatology analysis of the occurrence of surges and their impact on rainfall as represented in Figure 4 can give a general view of the areas that can be expected to experience heavy rainfall, based on surge occurrence.

4 | SUMMARY

This study reveals that the rainfall distribution in the Malaysian region during the northeast monsoon (NEM) is mostly influenced by the occurrence of the meridional surge (MS), the easterly surge (ES) and the mixed surge (MES). The rainfall is largely modulated by the MS from October until January with peak occurrence of the MS in December. During this month, the MS modulates the rainfall over the South China Sea, the northern region of the east coast of Peninsular Malaysia and the eastern and northern regions of Sabah. As the occurrence of the ES increases and reaches its maximum in January, the rainfall is largely influenced by the ES, especially over the central and western regions of Sarawak until the end of the season. The MES develops higher rainfall intensity, especially over the southern part of the east coast of Peninsular Malaysia and Sabah, with the most intense rainfall caused by the MES occurring mainly in December and January.

Based on the statistics, the average number of surges during NEM seasons was 29 *per* season, which consisted of 11 episodes of MS, 13 episodes of ES and five episodes of MES. The average surge days *per* season was 76 days, which consisted of 28 days of MSs, 38 days of ESs and 10 days of MESs, respectively. The average duration of surge *per* episode for MSs and ESs was 3 days, while for MESs it was 2 days.

Some findings from Cheang (1980) and Chen *et al.* (2013) have similar discussions to this study on the rainfall variability in Malaysia associated with the occurrence of the cold surge (CS)/ES. However, there are still a few questions that cannot be answered from the above findings, such as how the heavy rainfall based on findings can be forecasted and where the exact locations of these heavy rainfall events are. This study was organized to answer the questions, and it focuses more on operational purposes and how the findings in this study were operationalized.

Recognizing that CSs and ESs have a great impact on the occurrence of heavy rainfall events in Malaysia during the NEM, it is important to find a tool to guide forecasters to predict the events of heavy rain during the presence of CSs and ESs. The results from the analyses show that the method can capture the surge events well. There is also a fairly similar pattern of rainfall distribution from satellite images with the analysis of rainfall by climatology during these events. This suggests that the method can be implemented in monitoring the surges. The findings in this study are also important to provide a general view of areas that can be expected to experience heavy rainfall due to the occurrence of surges based on their climatological rainfall impact. It can be used as one of the forecasting tools in monitoring surges and predicting their impacts on the rainfall in the Malaysian region.

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