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Review of the Northeast Monsoon 2021/2022 in Malaysia

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and Nursalleh K Chang

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CONTENTS

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Summary

The 2021/2022 Northeast Monsoon (NEM) season started on 1 November 2021 and ended on 15 March 2022. This season recorded 16 surges, and most of the significant rainfall events are mainly associated with mixed surges. The season saw two tropical cyclones, with Typhoon Rai causing heavy rainfall in Peninsular Malaysia (PM). The Madden-Julian Oscillation (MJO) played a key role in influencing rainfall, contributing to wet weather in the Maritime Continent (MC) in November, enhancing rainfall in the Northwest Pacific (NWP) in December, and bringing wetter conditions to the MC again in March after spending time in the Indian Ocean (IO).

1.0 Introduction

Surges have a significant impact on Malaysia's weather and can be classified into three types: Meridional Surge (MS), Easterly Surge (ES), and Mixed Surge (MES) (Fakaruddin et al. 2019). The MS commonly referred to as a cold surge (CS) is associated with the outbreak of cold air mass due to the strong pressure gradient between Siberian and South China Sea (SCS). This surge intensifies the northeasterly winds and amplifies the cyclonic vortices located within the monsoon trough, often leading to widespread torrential rainfall (Moten et al. 2014). Conversely, the ES begins when the subtropical ridge in the NWP strengthens or moves closer to the equator. According to Cheang (1977), 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. As for the MES, it is identified when both a MS and an ES occur concurrently.

Previous studies have shown that the MJO has a significant influence on Malaysia's weather during the NEM. According to Chang et al. (2005) the frequency of CS can be influenced by the phase of the MJO. The frequency of CS is reduced during the suppressed and suppressed-to-active transition phases. Lim et al. (2017) reveals that during the enhanced convection phase of the MJO, the rainfall event associated with the CS is often enhanced and has the potential to trigger extreme rainfall events. This is because the MJO convection phase moistens the environment and increases the atmosphere's conditional instability.

On the inter-annual time scale, ENSO plays an important role in modulating the weather in Malaysia. During the NEM 2021/2022 season, the Pacific is experiencing La Nina conditions, with sea surface temperatures (SST) cooler than average, and trade winds stronger than average in the western and central equatorial Pacific Ocean. The presence of La Nina can result in heightened rainfall and a significantly stronger monsoon season.

This report aims to provide an overview of the 2021/2022 NEM season features. They include monsoon onset and withdrawal dates, surges occurrence, rainfall distribution, and also brief synoptic analysis. Furthermore, the report also includes the influence of the MJO, ENSO, and the presence of NWP tropical cyclones during this period.

2.0 Data and Method

This study used daily rainfall data from the Malaysian Meteorological Department (MET Malaysia). Wind data at the 925-hPa and 850-hPa levels, along with mean sea level pressure (MSLP), were obtained from the ECMWF ERA5 reanalysis. Daily large-scale precipitation data came from the Global Precipitation Mission (GPM). Additionally, the Madden-Julian Oscillation (MJO) and El Niño-Southern Oscillation (ENSO) data were sourced from the Australian Government Bureau of Meteorology website (http://www.bom.gov.au/climate). Tropical cyclone data and tracks were obtained from the Digital Typhoon database, accessible at http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en.

2.1 Definition of Onset and Withdrawal of the NEM

The onset and withdrawal of the NEM for the 2021/2022 season are determined using methods described by (Moten et al. 2014), commonly referred to as the Northeast Monsoon Index (named NEMI from here on). NEMI is obtained by using the average zonal wind component at 925-hPa and 850-hPa within the blue box region as shown in **Figure 1**. The onset of NEM occurs if the easterly wind component is sustained for at least seven days, with at least one day wind speed greater than 5 knots (2.5 m/s). The withdrawal of the NEM is said to have taken place when the easterly wind component has weakened to less than 2.5 m/s for seven consecutive days and the westerly wind component (positive value) starts to penetrate the Malaysian region (Moten et al. 2014).

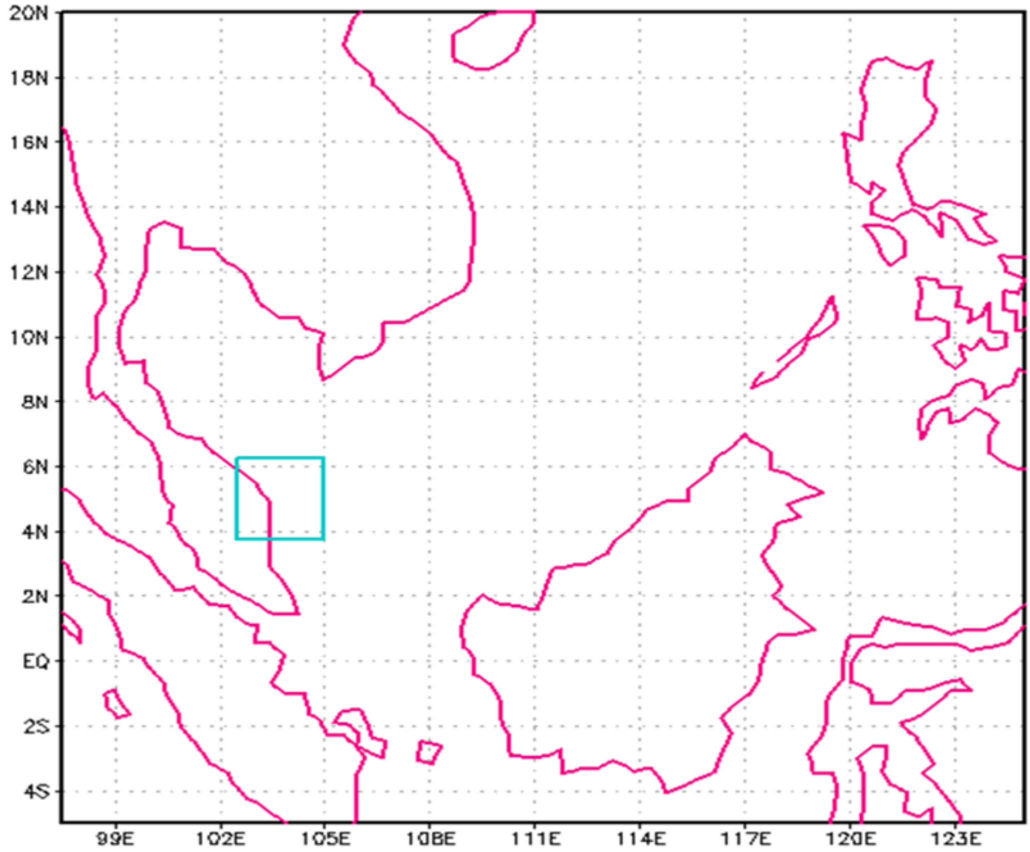

Figure 1: Blue box area at 3.75 °N to 6.25 °N and 102.50 °E to 105.00 °E used for computing the onset and withdrawal of NEM (Moten et al. 2014)

2.2 Definition of Monsoon Surges (MESI)

MS is said to have occurred when the average 925 hPa meridional winds bounded by 110 °E to 117.5 °E along 15 °N exceeded 8 m/s for at least three consecutive days. Similarly, the Easterly Surge (ES) occurs when the average of 925 hPa zonal winds between 7.5 °N and 15 °N along 120 °E exceed 8 m/s for at least three consecutive days (Chang et al. 2005, Ooi et al. 2017, and Fakaruddin et al. 2019). The MES is defined as when MS and ES occur simultaneously for at least two consecutive days.

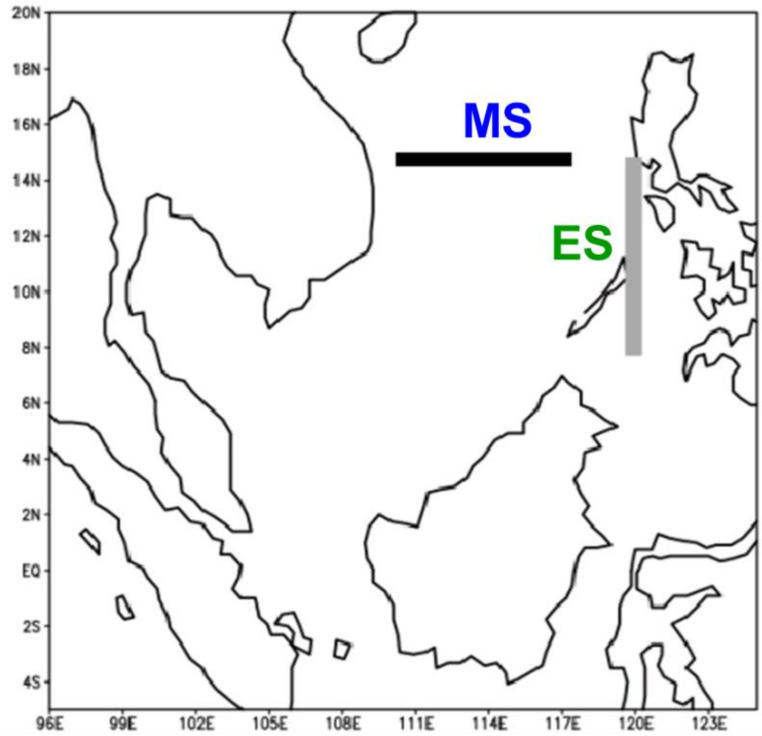

Figure 2: The black line represents the region to calculate the MS wind index and the grey line represents the region to calculate the ES wind index.

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3.0 Results and Discussion

3.1 Onset and Withdrawal NEM 2021/2022

The onset and withdrawal of NEM 2021/2022 were both determined using the NEMI. The onset and withdrawal dates for the NEM 2021/2022 season were **1 November 2021** and **15 March 2022**, respectively as shown in **Figure 3**. These onset and withdrawal dates fall within the normal range of the climatological **(Figure 4)**. **Figure 5 (a)** and **(b)** show the low-level winds during the first 5 days after the onset and withdrawal. During the onset pentad, low-level northeasterly (NE) winds dominate the SCS region. These NE winds originated from the East Asian continent and the trough was located around 3° N in the SCS region. In the withdrawal pentad, the trough shifted poleward and located around 5° N in the Malaysian region and 15° N in the Indian Ocean (IO) region. The westerly winds penetrated the Malaysian region as the northeasterly winds in the region retreated northward.

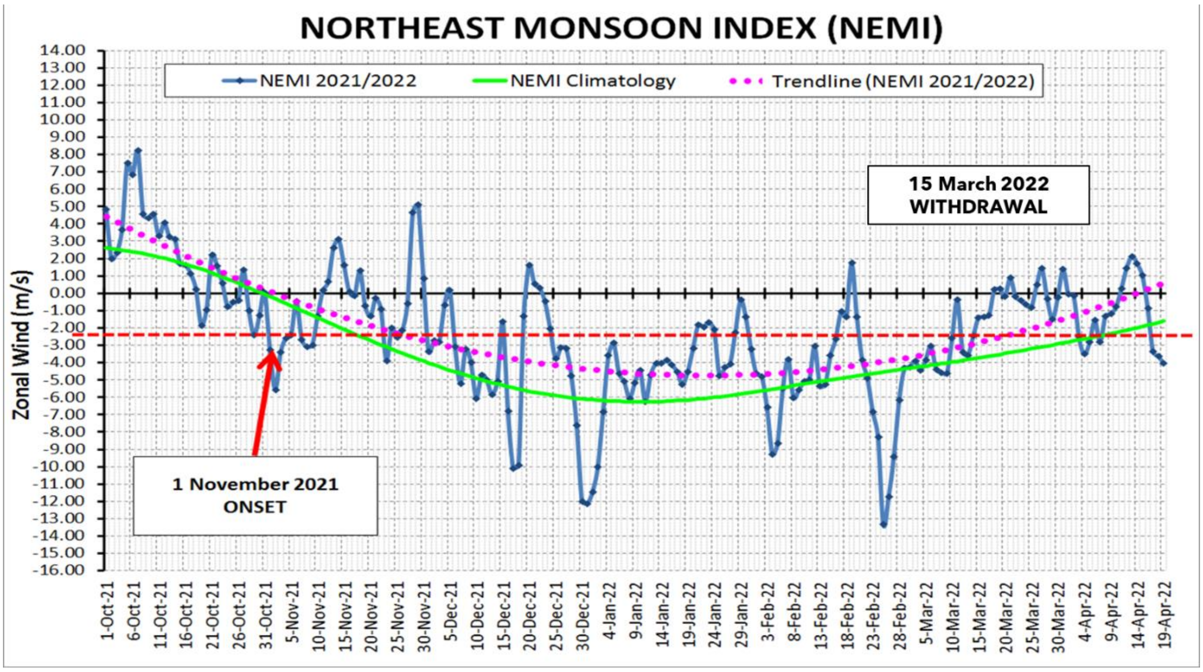
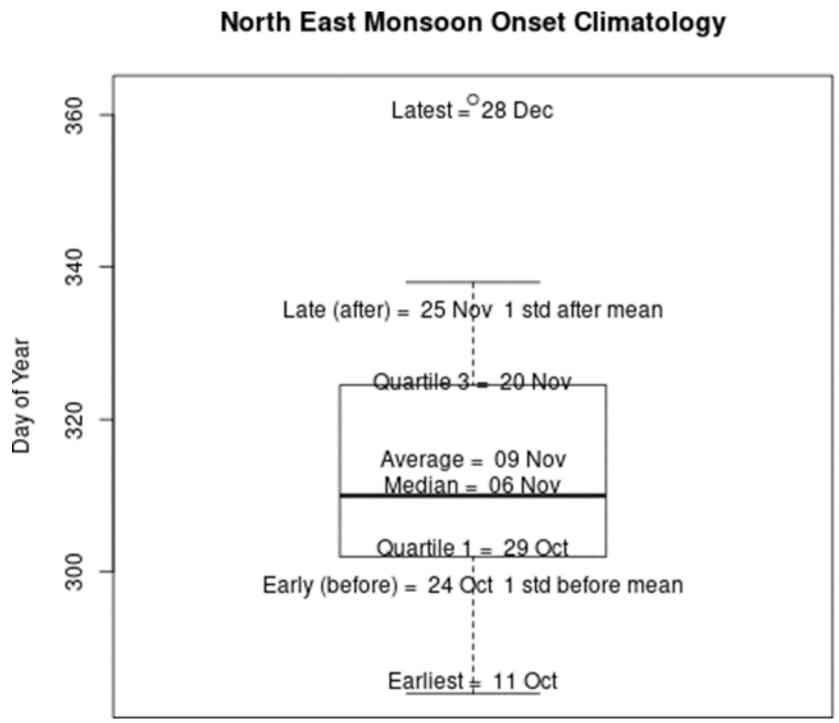


Figure 3: Onset and withdrawal date calculated based on Northeast Monsoon Index (NEMI) only



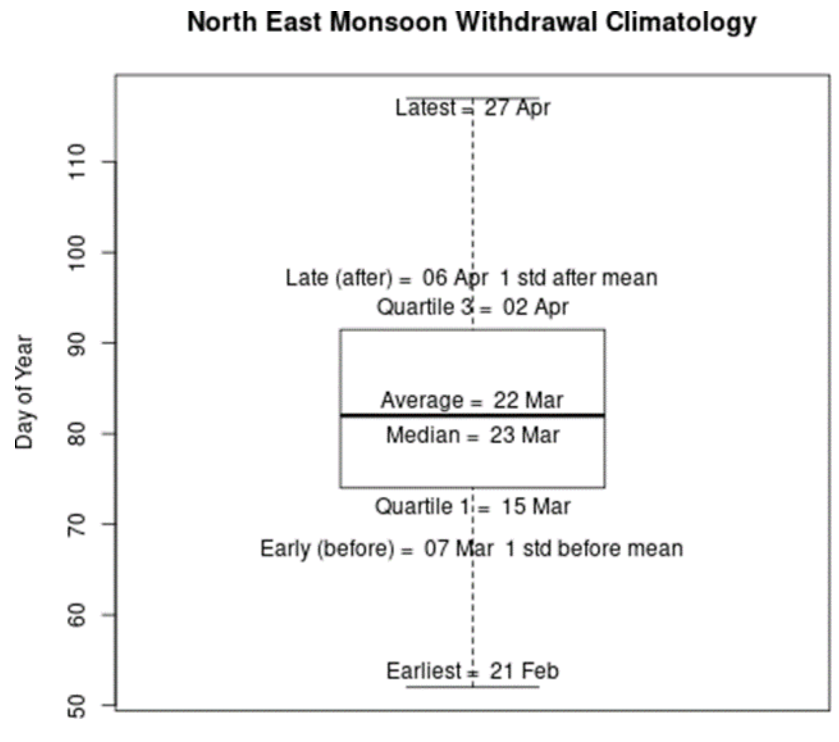


Figure 4: NEM onset date distribution (top) and NEM withdrawal date distribution (bottom)

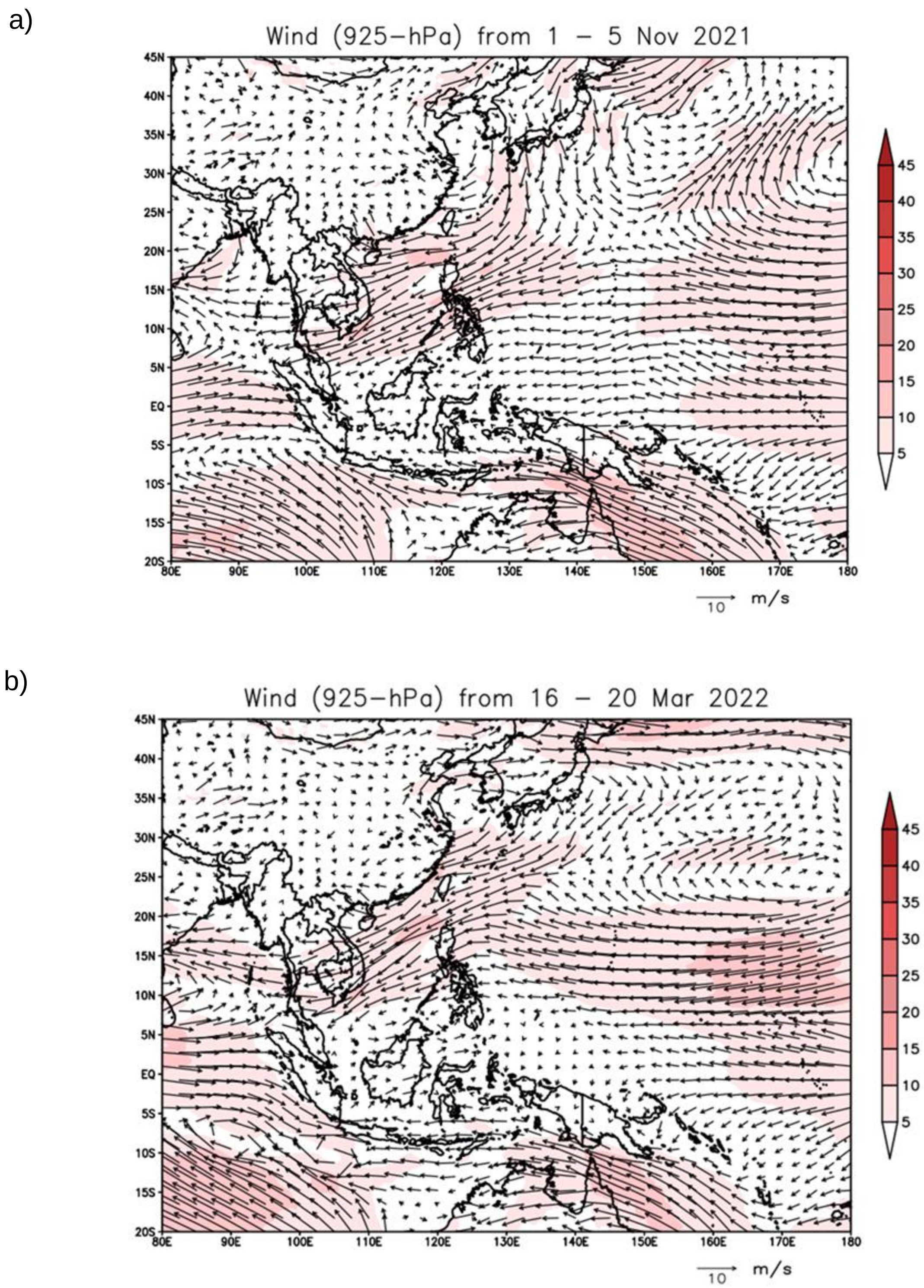


Figure 5: 925 hPa winds during (a) onset pentad of NEM 2021/2022 (1-5 Nov 2021); (b) one pentad after withdrawal of NEM 2021/2022 (16-20 Nov 2021). Shaded contours indicate wind speed.

3.2 Monsoon Surges of NEM 2021/2022

The date and period of monsoon surges were determined using MESI. A total of **16 surges** were observed during NEM 2021/2022. Of the 16 surges, 4 were categorized as MS, 7 were categorized as ES, and 5 as MES. The longest surge duration was 7 days, which occurred in the 2nd episode of MS and MES, Meanwhile, the shortest surge duration was 3 days. They were observed in episodes 3 and 4 of the MS, episodes 1 and 3 of the ES, and, episode 4 of MES. The summary of the surges during the NEM 2021/2022 is provided in Table 1. Table 2 compares the number of surges and the total day of surges between the climatological and NEM 2021/2022. The NEM 2021/2022 saw fewer surges compared to the climatology but the total days of surges are comparable. This indicates the surges in the NEM 2021/2022 season were generally longer.

Meridional Surge (MS)		**Easterly Surge (ES)**		**Mixed Surge (MES)**	
Episode	Date	Episode	Date	Episode	Date
1.	22 – 26 Nov 2021	1.	1 – 3 Nov 2021	1.	8 – 11 Nov 2021
2.	30 Nov – 6 Dec 2021	2.	25 – 29 Dec 2021	2.	8 – 14 Dec 2021
3.	16 – 18 Dec 2021	3.	3 – 5 Jan 2022	3.	30 Dec – 2 Jan 2022
4.	11 – 13 Jan 2022	4.	14 – 17 Jan 2022	4.	4 – 6 Feb 2022
		5.	31 Jan – 3 Feb 2022	5.	23 – 27 Feb 2022
		6.	7 – 12 Feb 2022		
		7.	28 Feb – 3 Mac 2022		
Total MS days = 18 days		Total ES days = 29 days		Total MES days = 23 days	

Table 1: Meridional, Easterly, and Mixed Surge during NEM 2021/2022

	Climatology	NEM 2021/2022
Total number of surges	29	16
Total surge days	76	70

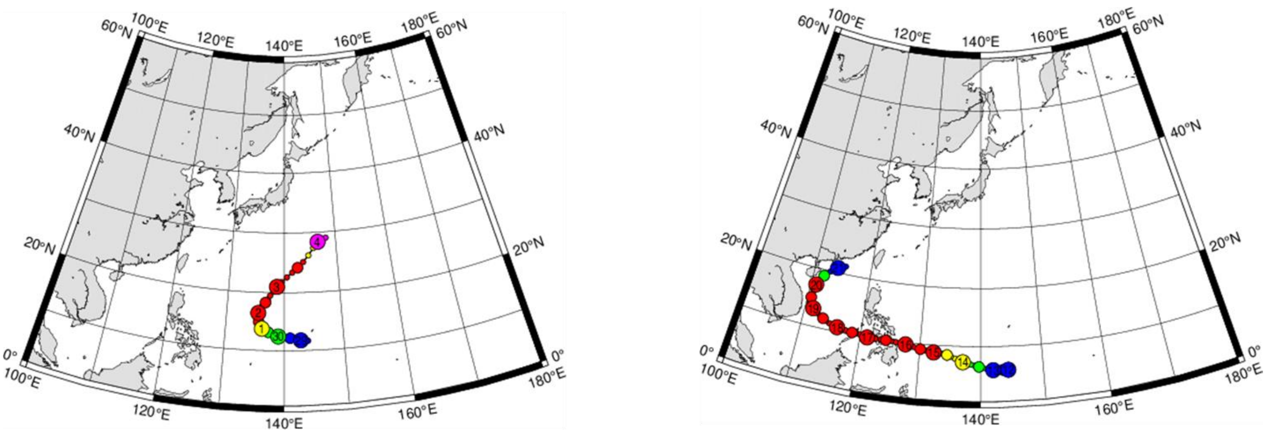
Table 2: The total surges during NEM season and NEM 2021/2022

3.3 Tropical Cyclone (TC) Occurrence during NEM 2021/2022

Tropical cyclones (TCs) in the Western North Pacific (WNP) or the South China Sea (SCS) can alter synoptic circulation patterns and influence weather in the Asian monsoon region, depending on the TC's intensity and location (Munirah Ariffin and Subramaniam Moten 2009). The strongest TC of 2021 was Typhoon Rai, with maximum winds recorded at 105 knots. There were two TCs during the Northeast Monsoon (NEM) 2021/2022, as listed in Table 3.

No.	Name of TC	Date of TC
1.	Nyatoh	30 Nov 2021 – 4 Dec 2021
2.	Rai	13 – 20 Dec 2021

Table 3: List of TC during NEM 2021/2022 that has an impact on the weather patterns in Malaysia



Taufan Nyatoh **Taufan Rai**

Figure 6: TC Nyatoh and TC Rai track and intensity

3.4 Episode of Surges during NEM 2021/2022

3.4.1 Episode 1: 1 November – 3 November 2021

The first surge of the season was an ES. It occurred from 1 – 3 November 2021. **Figure 7** shows the low-level wind circulation and rainfall before, during, and after the first episode of the surge. During this period, winds in the Malaysian region were predominantly easterly and originated from the western Pacific Ocean.

Two days before the ES, on October 30, 2021 **(Figure 7(a))**, a pair of vortices were observed in the eastern equatorial Indian Ocean (IO). Westerly winds were present around the equatorial region between the vortices. In the Straits of Malacca, convergence occurred between the westerlies from the northern hemisphere vortex and the southeasterlies from the southern hemisphere, leading to heavy rain. At the same time, there was a vortex over the equatorial western Pacific, with heavy rain located on the northern side of the vortex. Elsewhere, heavy rain was observed on the windward side of the southern Philippines and Indochina.

One day before the ES **(Figure 7(b))**, the vortex over the equatorial western Pacific weakened and therefore the rainfall around the vortex became disorganized. A vortex developed in the Borneo and this led to the deepening of the trough, which extended from IO to Borneo. The presence of the vortex allowed the easterly winds to blow parallel along the coast of Borneo. This led to rain observed along the Borneo coast and also near the southwestern quadrant of the vortex. Due to wind diffluent, there was no significant weather in Peninsular Malaysia.

On the surge day (1st November 2021) **(Figure 7(c))**, the trough in the region remained stationary from its previous day position, extending from IO to Borneo. Confluence winds from the northern SCS brought heavy rain over the southern SCS. An easterly wave was observed over the equatorial western Pacific near the southern Philippines. Heavy rain was observed on the windward side of this region.

Figure 7(d) depicts the circulation on the 2nd November 2021. The cyclonic vortex shifted westward and entered SCS. The previously zonally oriented trough observed a day earlier was now tilted northwest-southeast. With this tilting of the trough, the northeasterly winds penetrated westward into the Malaysian region, causing heavy rain there. A large expansion of rain was observed in the SCS with heavy rain concentrated on the east coast of Peninsular Malaysia. In the easterly wave region, the wave further developed. Convergence behind its inverted trough became pronounced, leading to the development of heavy rain.

On the 3rd of November 2021 **(Figure 7(e))**, the vortex in southern SCS shifted northward, allowing southwesterly winds to blow parallel to the Borneo coast. This shift and the combination of frictional convergence along the Borneo coast resulted in heavy rain over the coastal region of Sarawak. Simultaneously, the confluence of easterly winds also contributed to heavy rain over the SCS. The easterly wave propagated further westward, causing heavy rain over the Philippine Sea.

On the first day of the surge termination, **(Figure 7(f))**, an anticyclone over the East China Sea (ESC) moved south. Meanwhile, the vortex in the SCS shifted toward Peninsular Malaysia and weakened. Despite the weakening, light winds still flow cyclonically around the vortex. Easterly winds moved westward and entered the Philippines, resulting in heavy rain there.

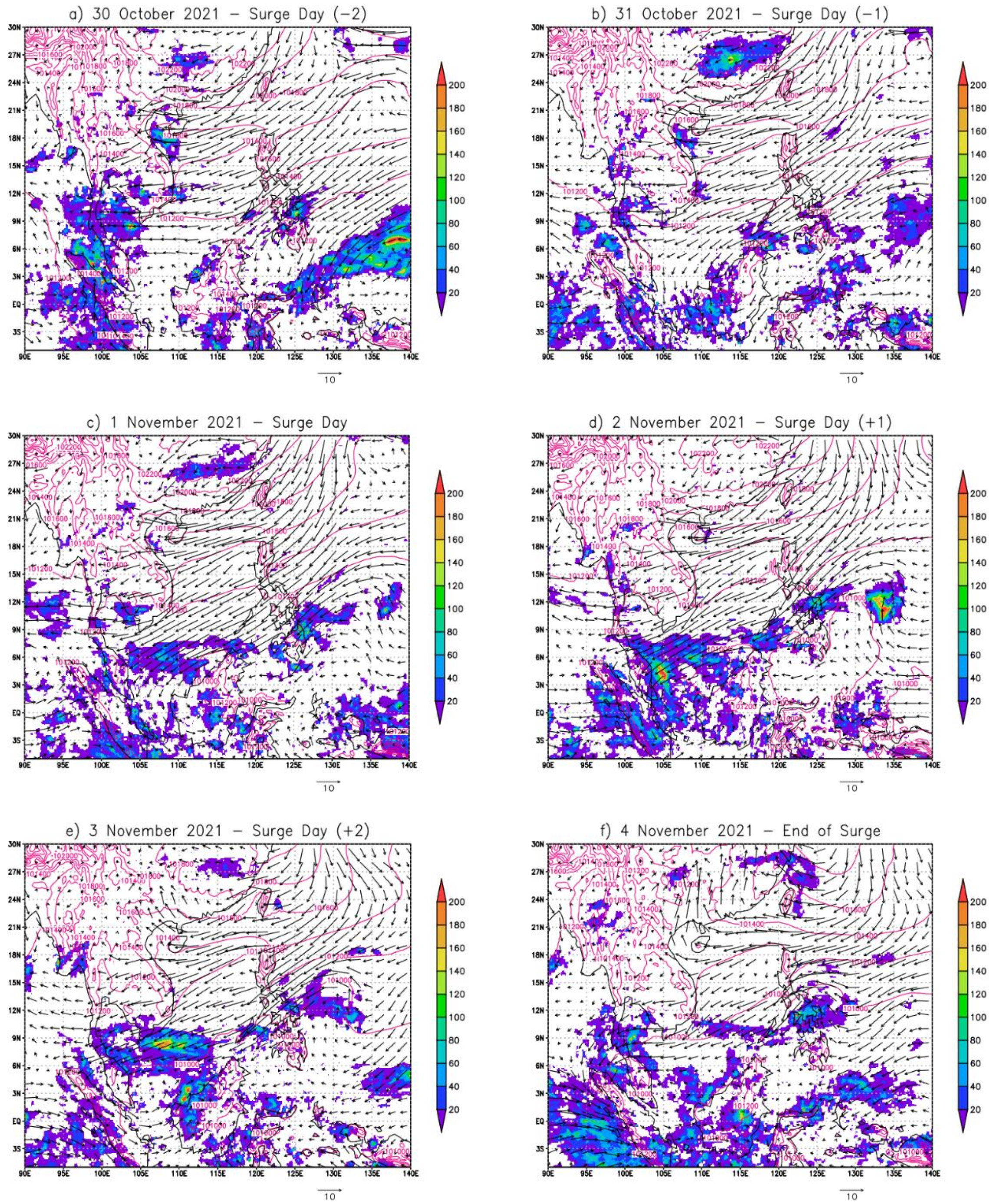


Figure 7 (a-f): 925hPa wind circulation (vector), GPM rain (shaded contour) and MSLP (line contour) before, during, and after the surge.

The surge occurred from 1-3 November 2021.

3.4.2 Episode 2: 8 November – 11 November 2021

The second surge came only five days after the first surge. The second surge occurred from 8 – 11 November 2021 and was identified as MES. **Figure 8** shows the large-scale circulation before, during and after the second episode of the surge.

One day before the surge **(Figure 8(a))**, easterly winds dominated the SCS, while light and variable winds were observed in the Malaysian region. Heavy rain was observed on the windward side of Sumatra. A pair of vortices was located in the eastern equatorial IO. This led to the westerly winds to penetrate Sumatra before turning southeasterly over the Straits of Malacca. The convergence of these southeasterlies with easterly winds caused heavy rain to occur on the northern coast of Peninsular Malaysia. Additionally, heavy rain was observed on the windward side of the eastern Philippines.

Figure 8(b) shows that on the surge day, the convergence of strong northeasterly winds from mainland China and easterly winds from the west Pacific Ocean led to heavy rain over the SCS. The winds diverged as they entered in Peninsular Malaysia region, therefore causing lesser weather activity there. In Sarawak, rain was observed around the vortex. At the same time, the presence of frictional convergence brought heavy rain over the Celebes Sea.

The northeasterly and easterly winds converged in the southern SCS and led to heavy rain over southern SCS, the east coast of Peninsular Malaysia and the Gulf of Thailand on 9th November 2021 **(Figure 8(c))**. The easterly winds converged in speed as they penetrated the Philippines, bringing heavy rain over the Sulu Sea and the northern part of Sabah. As the easterly winds entered the southern SCS region, it turned northerlies, and deepened the vortex in the Borneo, bringing heavy rain to the coastal and interior region of Sarawak.

On the subsequent day **(Figure 8(d)**), winds from the northern SCS converged in the southern SCS and caused heavy rain there. The northeasterly winds penetrated the Malaysian region and flowed cyclonically around the vortex, causing heavy rain at the turning point of the vortex. Over the Philippine Sea, northwesterly winds turned northeasterly and converged with easterly winds, causing heavy rains in the northeastern part of the Philippines.

Northeasterlies and easterly winds strengthened over the northern SCS and the western Pacific Ocean on the 11th November 2021 **(Figure 8(e))**. As the vortex in

SCS became stronger, a band of heavy rain was observed in the southern Indochina and Gulf of Siam. At the same time, with the strengthening of the vortex, southwesterly winds were observed running parallel to the Borneo Coast, causing heavy rain.

After the surge day ended, **(Figure 8(f))**, as the northeasterly winds weakened, the vortex also gradually weakened. A large expand of rain was observed in the SCS with heavy rain concentrated in the Gulf of Thailand and the southeastern quadrant of the vortex. At the same time, heavy rain was observed on the windward side of the Philippines.

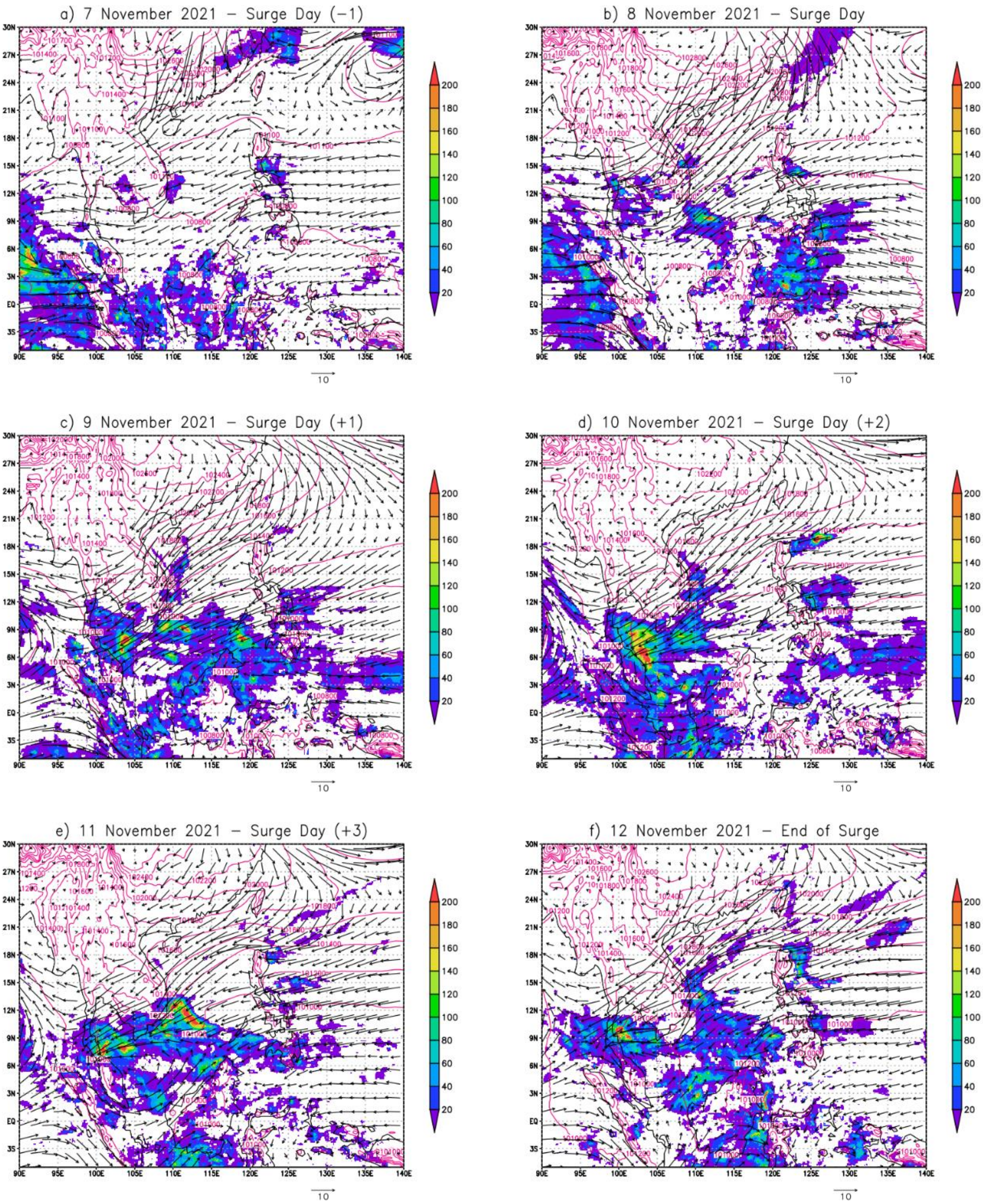


Figure 8 (a-f): same as Figure 7 except for the surge occurring from 8-11 November 2021

3.4.3 Episode 3: 22 November – 26 November 2021

The third episode of surge for the season which lasted for 5 days occurred from 22 – 26 November 2021. It was identified as MS type of surge. Before surge day **(Figure 9(a))**, a cyclonic vortex was detected in the southern SCS and another in the equatorial western Pacific. These two vortices were embedded within the monsoon trough, which spanned from north Sumatra to the equatorial western Pacific. The cyclonic vortex in the southern SCS caused heavy rainfall. During this period, a weak easterly wave was observed over the SCS.

The easterly wave weakened considerably on the surge day **(Figure 9(b))** while the cyclonic vortex in the southern SCS dissipated. In Peninsular Malaysia, winds became generally light and variable. The cyclonic vortex in the equatorial western Pacific propagated westward. Heavy rain was observed in the western quadrant of the vortex. Horizontal wind shear caused heavy rain in the SCS and northeastern Peninsular Malaysia.

Figure 9(c) and Figure 9(d) show an outbreak of CS in SCS, strengthening the northeasterly winds in the region. The confluence of northeasterlies and easterlies winds entering SCS and Malaysia region resulted in an elongated band of rain along the windward side of Peninsular Malaysia. This northwest-southwest tilt rain band extended into the southern hemisphere on the second day of the surge. The southern hemisphere rain band dissipated on the following day when the cross-equatorial northeasterly winds ceased. A cyclonic vortex began to form over Borneo. Confluence winds in the northeastern IO caused heavy rain in the region. At the same time, the cyclonic vortex over the equatorial western Pacific Ocean weakened, and the trough became less established.

The cyclonic vortex in Borneo intensified as it moved over the ocean **(Figure 9(e)),** exhibiting close circulation. The convergence of northeasterly and easterly winds, coupled with horizontal shear, resulted in heavy rain in the SCS and Peninsular Malaysia. Heavy rain was also observed on the windward side of the Philippines.

On the first day after the surge ended **(Figure 9(f))**, the cyclonic vortex in southern SCS intensified and developed into a low-pressure system with center pressure registering 1008 hPa. The convergence zone at the northern quadrant of the low-pressure system caused heavy rain. At the same time, a steep pressure gradient caused strong winds in the East China Sea to penetrate the SCS. The narrow passage between Taiwan and the Philippines caused these winds to converge and resulted in heavy rain there.

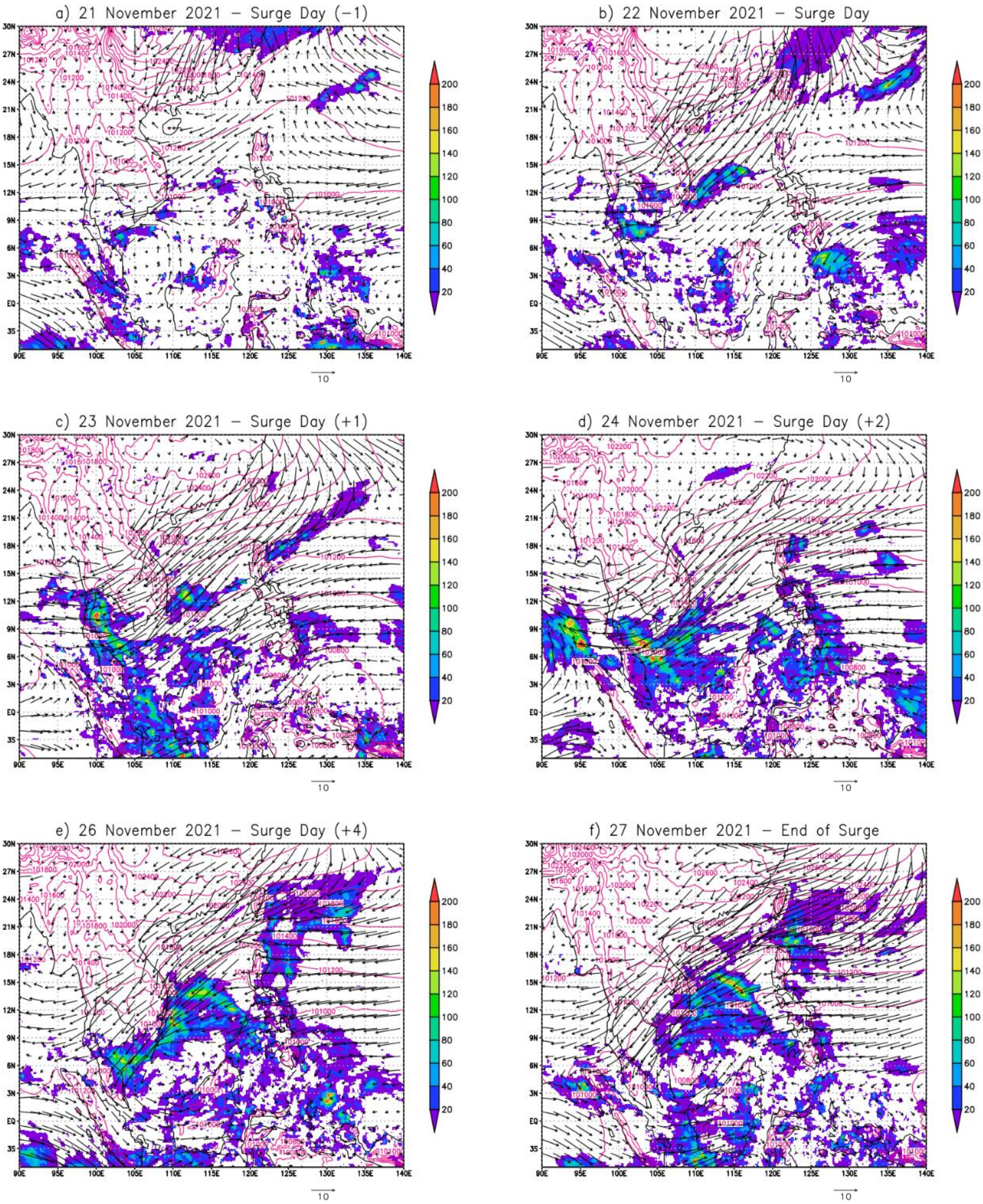


Figure 9 (a-f): same as Figure 7 except for the surge occurring from 22 - 26 November 2021

3.4.4 Episode 4 - 6: 30 November – 18 December 2021

Episodes four through six of the surges lasted continuously for 16 days, each showcasing different types of surges. It started with MS, followed by MES, and ended with MS. On the first day of episode four (30 November 2021), strong northeasterly winds from mainland China were observed in the SCS region. These winds converged into a low-pressure system in the Andaman Sea causing rainfall along the southern coast of the Indochina Peninsular and the Andaman Sea **(Figure 10(a))**. At the same time, Typhoon Nyatoh moved into the western Pacific Ocean, with strong winds swirling around its low center of 1002 hPa.

Typhoon Nyatoh intensified the following day (1 December, 2021) in the Northwestern Pacific (NWP) basin **(Figure 10(b))**, with its core pressure dropping to 1000 hPa. Its presence resulted in northeasterly winds spanning from the SCS to the Pacific Ocean. Frictional convergence caused heavy rain in the SCS, while horizontal shear brought heavy rain to the east coast of Malaysia and Thailand. Additionally, heavy rain was observed in the northern quadrant of the cyclonic vortex in the Andaman Sea.

Figures 10(c) and **10(d)** show Typhoon Nyatoh tracked north/northeastward, curving around the high-pressure area in the Northern Pacific Ocean. The monsoon trough extended from the western Pacific Ocean to Peninsular Malaysia, tilted southwest-northeast between 0°N and 10°N. This tilting allowed the northeasterly winds to converge, causing heavy rain behind the trough.

The monsoon trough remained in the same location as the previous day **(Figure 10(e))**, while a cyclonic vortex embedded within the trough moved westward over the western Pacific Ocean. Meanwhile, Typhoon Nyatoh tracked northeastward and dissipated by 4 December 2021 **(Figure 6)**. As the high-pressure system in mainland China moved westward, the cold surges (CSs) penetrated further east and extended towards the equator.

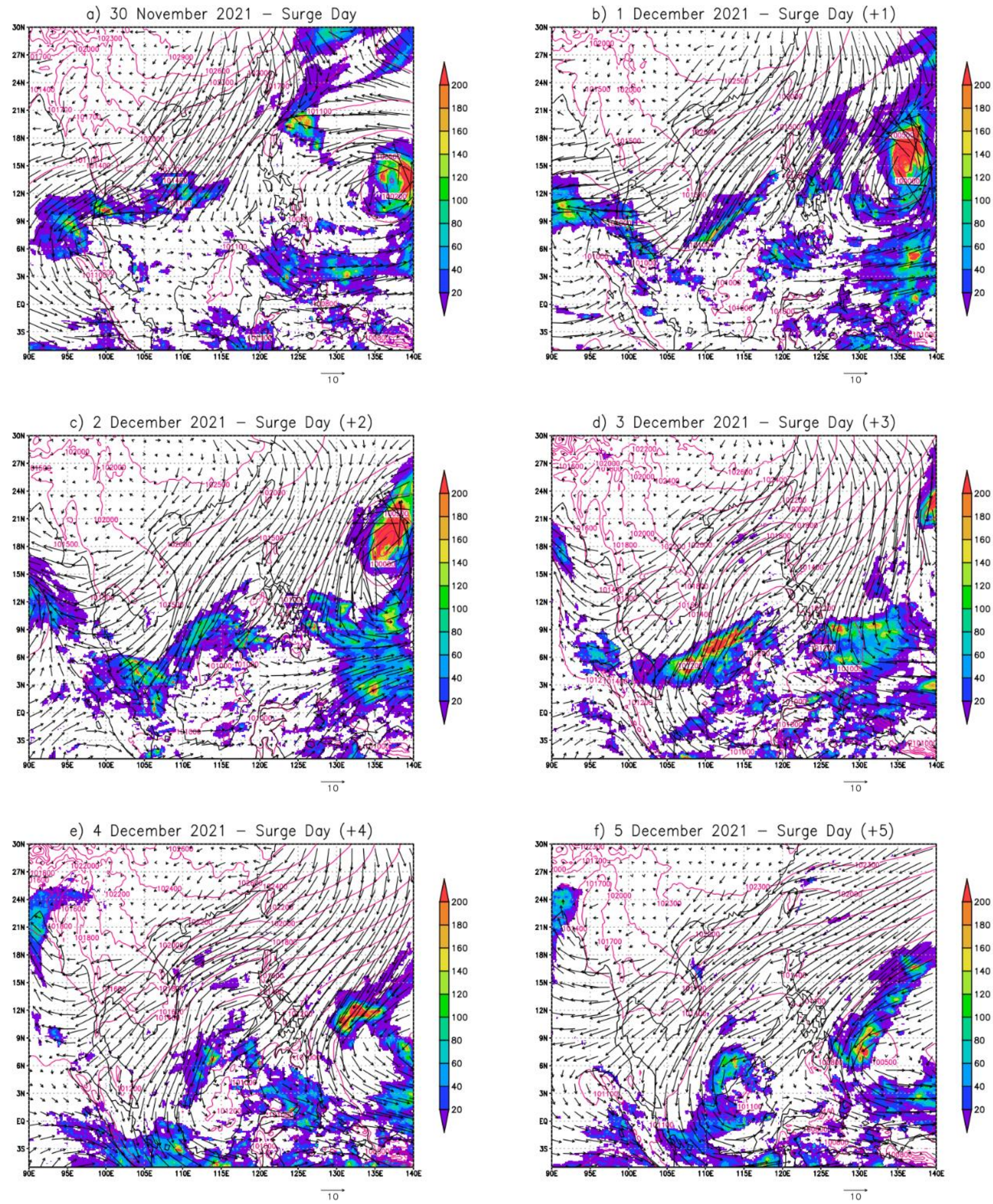


Figure 10 (a–f): same as Figure 7 except for the surge occurring from 30 November – 6 December 2021

On 5 December 2021 **(Figure 10(f))**, the monsoon trough remained quasi-stationary with two embedded vortices. Heavy rain was observed in the northwestern part of these vortices. The MS ended on 7 December 2021 **(Figure 10(g))**, and was followed by MES on 8 December 2021 (Episode 5). The confluence of winds in the Pacific Ocean brought heavy rain to the windward side of the Philippines **(Figure 10(h))**. Four days after the surge, a tropical depression formed around the equatorial Pacific Ocean **(Figure 10(i))**, which later developed into Typhoon Rai on 13 December 2021 **(Figure 10(j))**.

On 14 December 2021, the high-pressure system in the ECS directed eastward winds into both Typhoon Rai and the cyclonic vortex in the SCS, leading to heavy rainfall near Typhoon Rai and the northern part of the cyclonic vortex **(Figure 10(k))**. The MES concluded on 15 December, followed by the resumption of an MS on 16 December (Episode 6) **(Figure 10(l))**, coinciding with the ongoing activity of Typhoon Rai in the Philippines.

During the surge period, heavy rainfall occurred on the east coast of Peninsular Malaysia, resulting in prolonged periods of heavy rain in the states of Kelantan, Terengganu, and Pahang **(Table 4) (Figure 10(m))**. The monsoon trough extended from the Philippines to Sumatra in a southwest-northeast orientation between 0°N and 10°N. The slanting of the trough allowed northeasterly winds from the Pacific Ocean to converge, causing heavy rainfall in the cyclonic region of the trough.

On 17 December (**Figure 10(n))**, Typhoon Rai strengthened upon entering the SCS after passing through the Palawan. The typhoon was fueled by confluent winds from mainland China and the Pacific Ocean. Diffluent winds over downstream of the SCS caused one branch to enter PM, where it converged with westerly winds from Sumatra, bringing heavy rainfall to the Straits of Malacca. Meanwhile, another branch extended into East Borneo, resulting clear weather in the region.

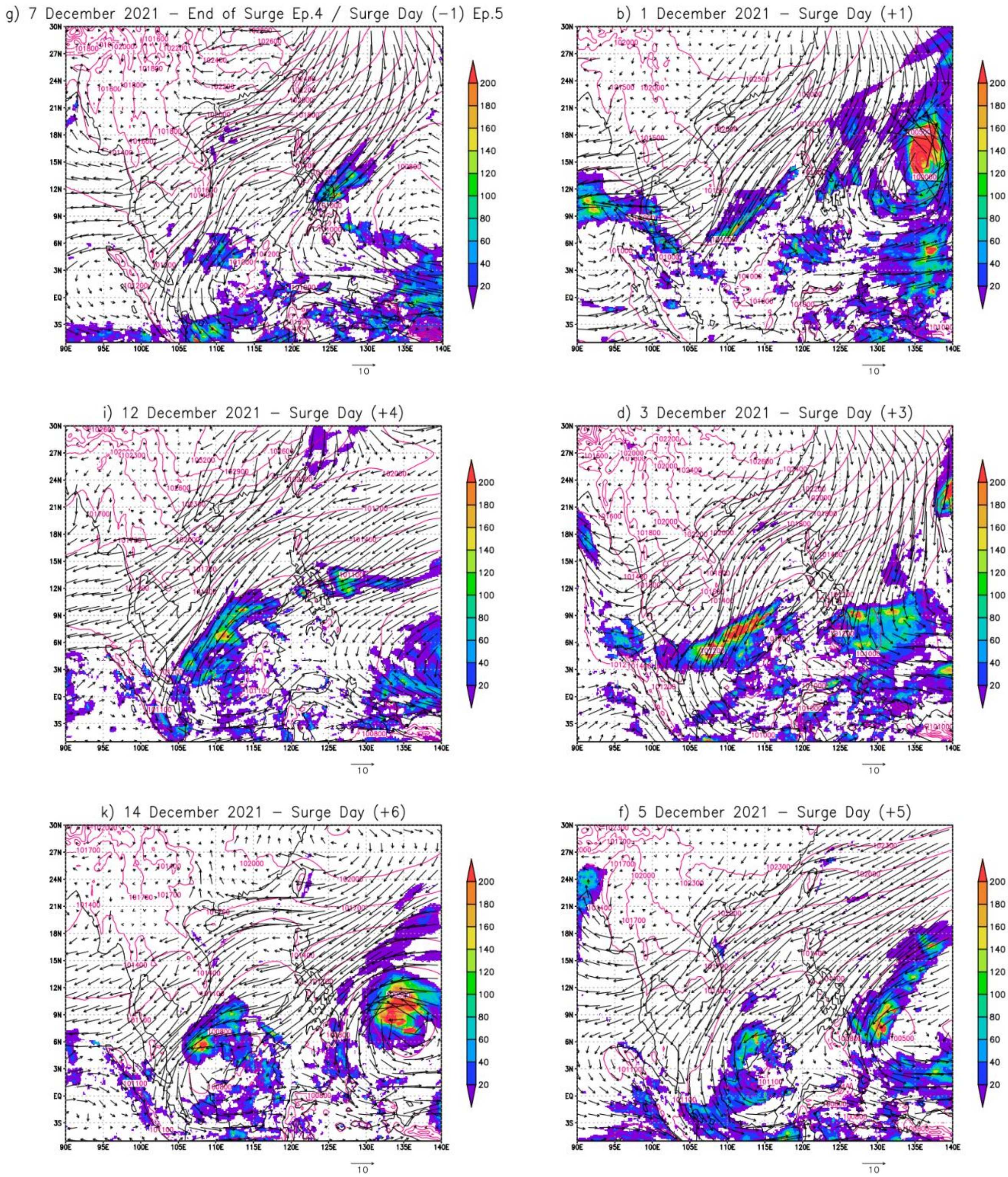


Figure 10 (Figure g–l): same as Figure 7 except for the surge occurring from 8 – 14 December 2021

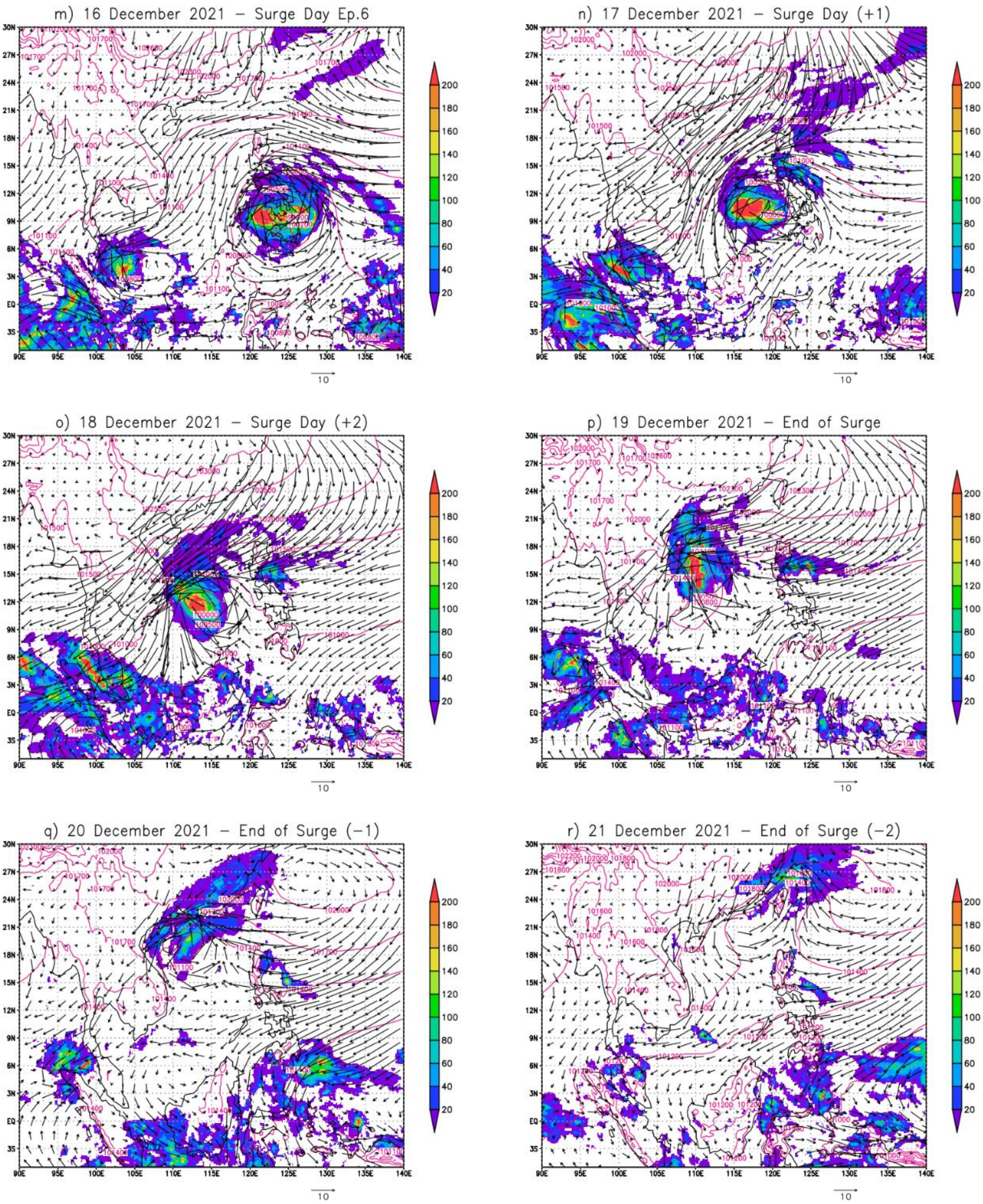


Figure 10 (m–r): same as Figure 7 except for the surge occurring from 16 – 18 December 2021

Typhoon Rai moved westward before unexpectedly re-intensifying into a Category 5-equivalent typhoon by 18 December **(Figure 10(o))** as it neared Vietnam. The northeast wind penetrated the PM and converged with the southwest wind, resulting in heavy rainfall in the Malacca Straits. On the next day, the typhoon weakened, leading to a deceleration of the northeasterly winds in SCS. The presence of light and variable winds in the SCS contributed to less weather in PM. This signaled the termination of MS 19 December 19. Along with this development, the easterly winds from the Pacific Ocean began to dominate the SCS, leading to wind divergence in the region **(Figure 10(p))**. Typhoon Rai remained active in the Indochina waters and heavy rainfall was observed around the typhoon. Heavy rainfall was also seen on the windward side of Sumatra.

Typhoon Rai made landfall in Hong Kong on 20 December **(Figure 10(q))**. As Typhoon Rai weakened, it led to a decrease in wind speeds across the SCS. The convergence of winds from the NE and SW resulted in heavy rainfall in the northern regions of the Straits of Malacca and Sumatra. The subsequent day saw Typhoon Rai underwent another phase of weakening, ultimately dissipating on 21 December in the southeast of Hong Kong **(Figure 10(r))**. Heavy rainfall and strong and gusty winds impacted several areas around the storm’s path.

3.4.5 Episode 7 - 9: 25 December 2021 – 5 January 2022

The ES occurred in the season's seventh surge episode, from 25 to 29 December 2021. One day before the ES **(Figure 11(a))**, strong easterly winds over the western Pacific turned northeasterly in the southern SCS and channelled towards the equator. These low-level northeasterly winds interacted with the region's terrain, resulting in the strong counter-clockwise and led to the formation of the Borneo Vortex (BV).

Strong northeasterly winds during the surge day turned counter-clockwise, strengthening the BV and increasing the rainfall over the interior regions of Sabah and Sarawak. (**Figure 11(b)).** Additionally, the presence of westerly winds over Sumatra also contributed to the counterclockwise rotation of northeasterly winds and the formation of BVs during this period (Tangang et al, 2008). During this period, the lack of heavy rainfall over Peninsular Malaysia indicated that the BV intercepted the low-level moisture transport.

On the next day **(Figure 11(c))**, the axis of the cold surge shifted slightly eastward, causing heavy rainfall across the windward side of the Philippines, the east coast of China, and the central SCS. This eastward shift, along with rainfall over the Philippines and clear weather in Peninsular Malaysia and western MC, suggested that the surge can be identified as the Philippines Sea type of surge (PHS) (Compo et al. 1999). The clear weather in the western MC can also be partly attributed to the large-scale subsidence in the region, as an active MJO was located in WPO during this time. Such conditions remained until day+2 of the surge (Figure 11(d)).

On 29 December 2021 **(Figure 11(e))**, the northeasterly winds weakened and the easterly wind penetrated Peninsular Malaysia region. Heavy rainfall was observed on the windward side of the Philippines, the central SCS, and the interior Sabah and Sarawak. During this time, three vortices were embedded in the monsoon trough, which was located at the equator. The end of this ES was followed by the 8th episode surge in the season when the northerly winds strengthened **(Figure 11(f))**. This surge occurred from 30 December 2021- 2 January 2022 and was identified as MES. The monsoon trough remained quasi-stationary, with three embedded vortices that caused heavy rain around the vortices.

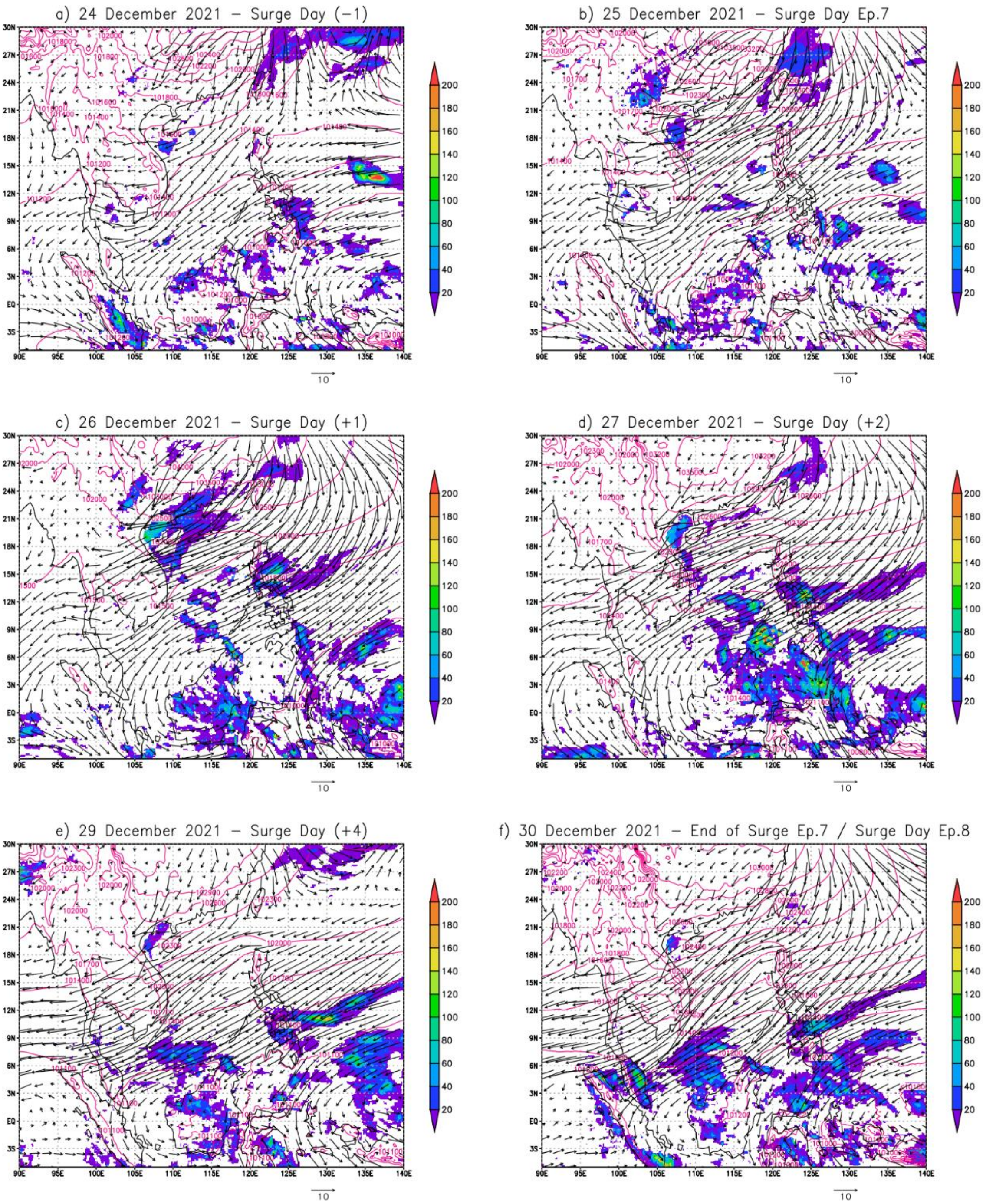


Figure 11 (a-f): same as Figure 7 except for the surge occurring from 25 – 29 December 2021

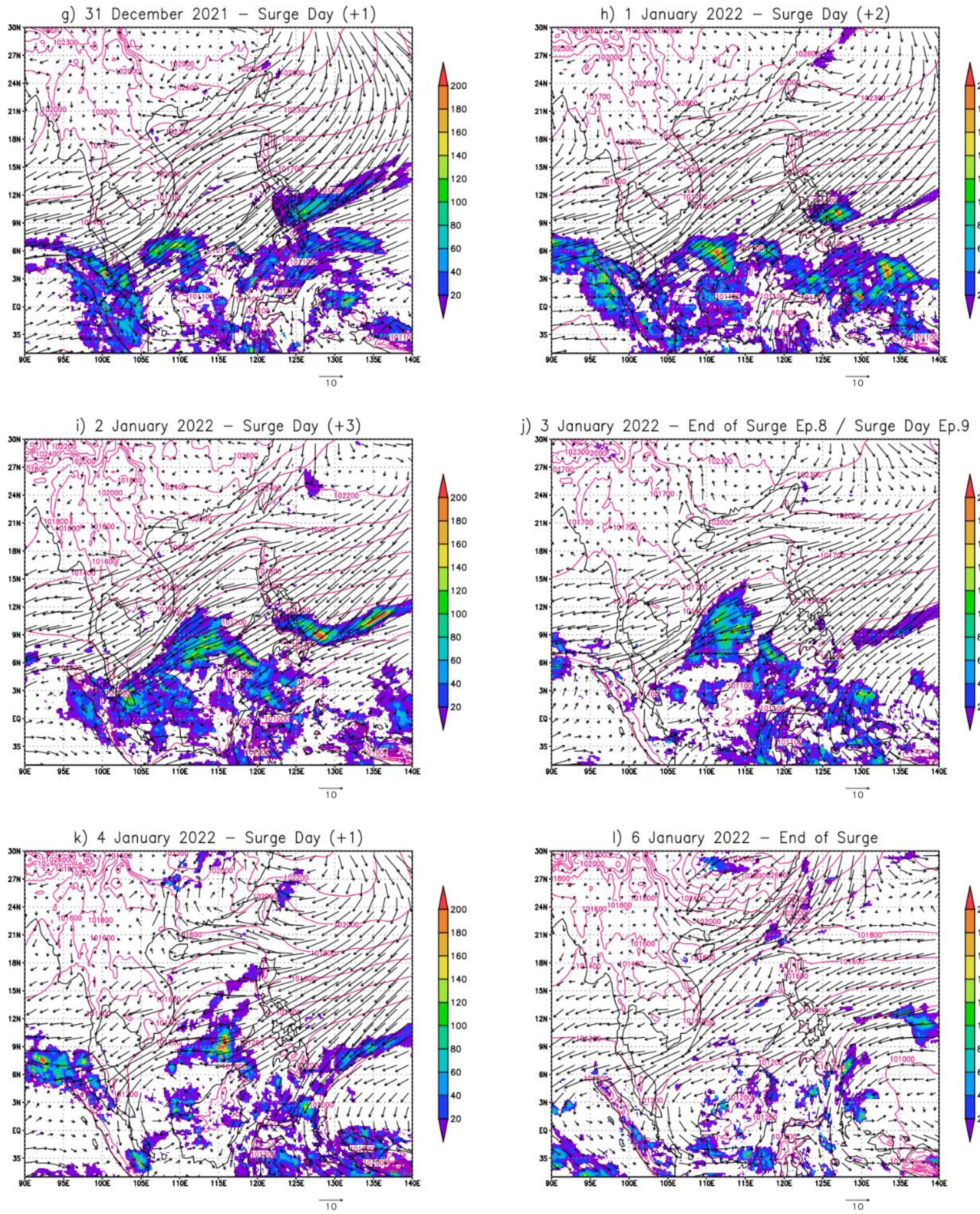


Figure 11 (g-l): same as Figure 7 except for the surges occurring from 30 December 2021 – 2 January 2022 and 3 – 5 January 2022

The northeasterly winds strengthened over the following two days **(Figure 11(g-h))**, penetrating further south into southern Peninsular Malaysia and the Sumatra region. Heavy rainfall was observed in this equatorial area. Additionally, the westerly winds in the southern hemisphere intensified the vortices at the equator, causing heavy rainfall around them.

On 2 January 2022 **(Figure 11(i))**, the midlatitude high-pressure system propagated eastward. Along with this shift, the axis of strong northeasterly winds was located in the Philippines Sea (PHS) causing heavy rain on the windward side of southern Philippines. In the western MC, the southern hemisphere westerly winds were weak during this time causing the winds near the equator to be light and variable. The MES was replaced by ES (the 9th surge episode of the season) on the following day **(Figure 11(j)).** Pockets of heavy rain were still found in the SCS, PHS, and Celebes Sea. As the easterly winds became stronger and more dominant **(Figure 11(k and l))** in the SCS, a divergence flow formed across northern Peninsular Malaysia. One branch of this flow flowed southward into the southern hemisphere trough, while another branch flowed westward. Consequently, less weather activity was observed near the equator during this time.

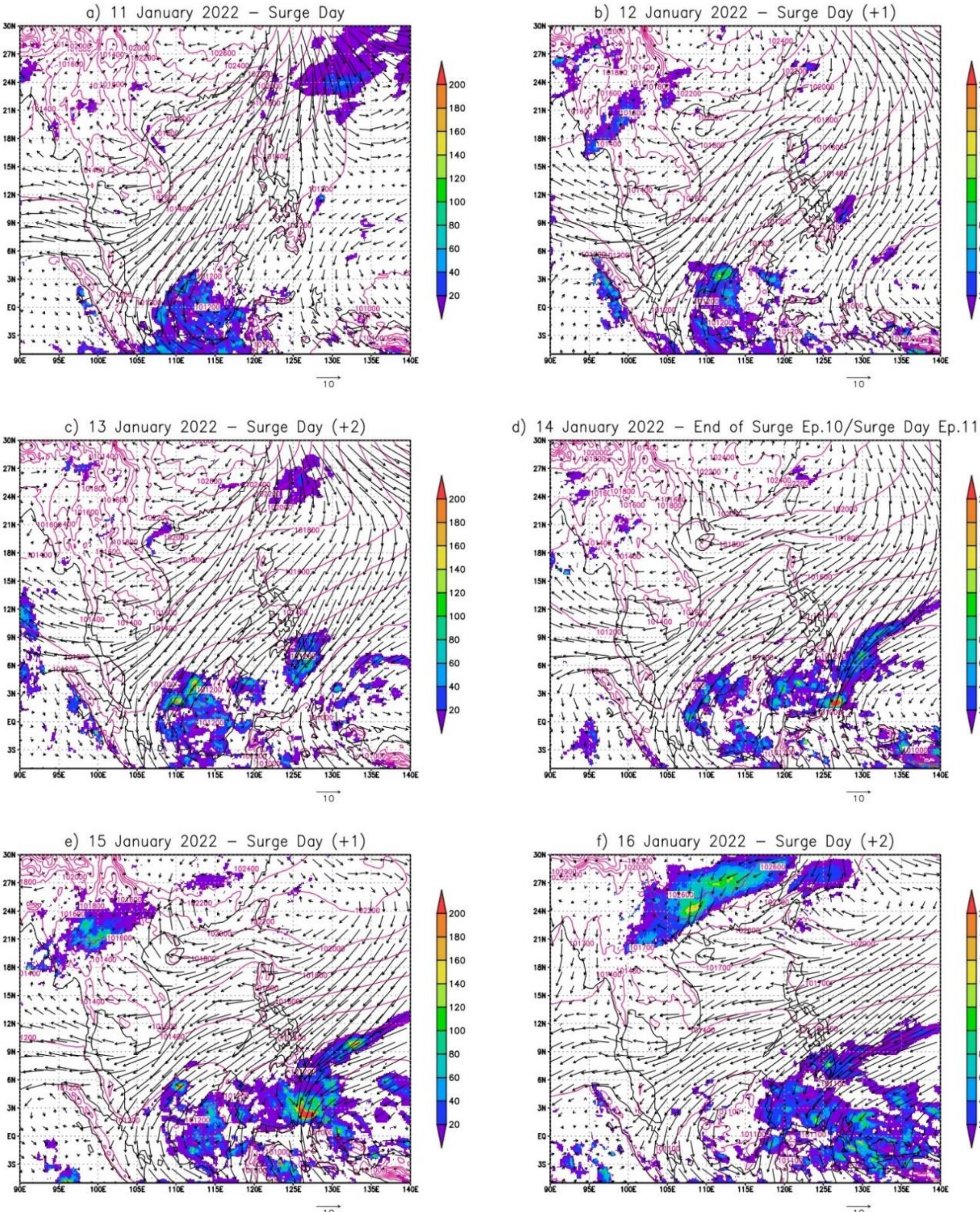
3.4.6 Episode 10-11: 11 – 17 Jan 2022

The tenth episode of the season was identified as a MS. It occurred after a five-day pause following the previous surge episode. This MS caused northeasterly winds to penetrate across the SCS toward the equator. These northeasterly winds then turned northwesterly in the southern hemisphere. The cyclonic shear facilitated the formation of a vortex over Borneo, accompanied by heavy rainfall around the vortex area **(Figure 12(a))**.

In the following days **(Figure 12 (b-d))**, the northeast-southeast tilt of the near-equatorial trough over Borneo caused the northeasterly winds to diverge near the east coast of Peninsular Malaysia. This divergence led to one branch flowing westward across the northern part of the peninsula and another turning northwest towards East Malaysia. The latter branch enhanced the cyclonic shear and caused heavy rain in East Malaysia. Consequently, due to the divergence flow over Peninsular Malaysia, the weather remained clear in the region.

The conclusion of the MS marked the onset of the eleventh surge episode of the season. This surge was identified as the ES. During this period, the near equatorial trough maintained its northeast-southwest tilt across Borneo. This tilting allowed the northeasterly winds to converge, resulting in heavy rain in East Malaysia, Kalimantan and Sulawesi **Figure 12 (e))**. On the following day, the rainfall in East Malaysia weakened but heavy rain was still seen in the south Philippine and Celebes Seas **(Figure 12 (f))**.

On 17 January **(Figure 12(g))**, westerly winds were observed over the Java Sea, and at the same time the northeasterly winds were observed over the SCS. Heavy rain was observed in the area where these northeasterly and westerly winds converged. By the end of the surge day **(Figure 12(h))**, the westerly winds had further intensified over the Java Sea, and their confluence resulted in heavy rain along the west coast of Sumatra. Meanwhile, the divergence of winds in Peninsular Malaysia contributed to the lack of rainfall.


a) 11 January 2022 – Surge Day
b) 12 January 2022 – Surge Day (+1)
c) 13 January 2022 – Surge Day (+2)
d) 14 January 2022 – End of Surge Ep.10/Surge Day Ep.11
e) 15 January 2022 – Surge Day (+1)
f) 16 January 2022 – Surge Day (+2)

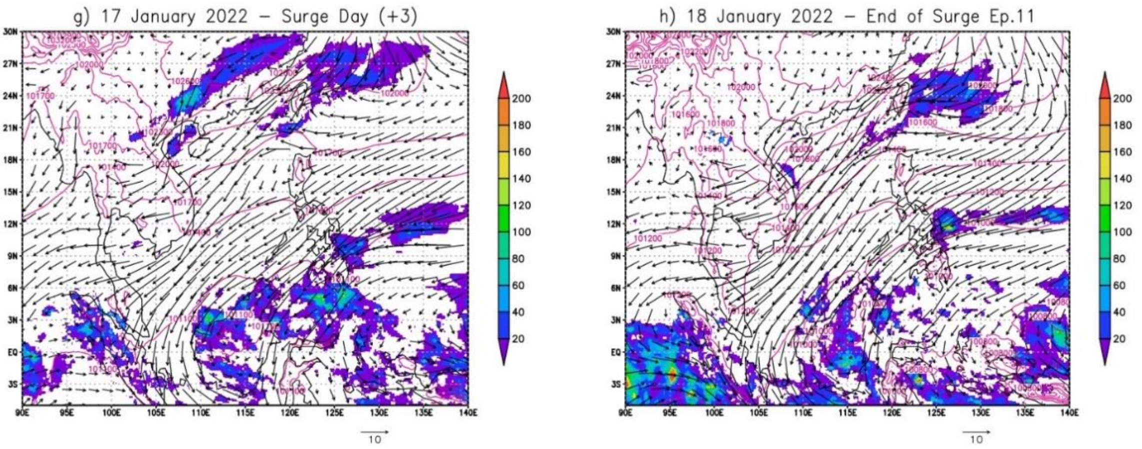


Figure 12 (a-h): same as Figure 7 except for the surges occurring from 11 – 13 January 2022 and 14 – 17 January 2022

3.4.7 Episode 12-14: 31 Jan – 12 Feb 2022

The twelfth to fourteenth episodes of the surge occurred consecutively for 13 days. The twelfth episode of the surge, known as ES, took place from 31 January to 3 February 2022, lasting four days. **Figure 13 (a)** shows that the axis of surge located seaward in the ECS. As a result, more easterly wind components were directed into the maritime equatorial during this episode. Upon approaching the equator, the easterly winds diverged over Peninsular Malaysia, with one branch heading westward and then northwest in the eastern Indian Ocean, while the other branch turned towards the interior of Borneo, resulting in heavy rainfall there. On 2 February 2022, the high-pressure system in the ECS shifted southeastward. The southern branch of this high-pressure system caused stronger easterly wind components to penetrate the SCS **(Figure 13(b))**. Heavy rains were observed in the waters off Peninsular Malaysia's east coast and the southern part of Sarawak.

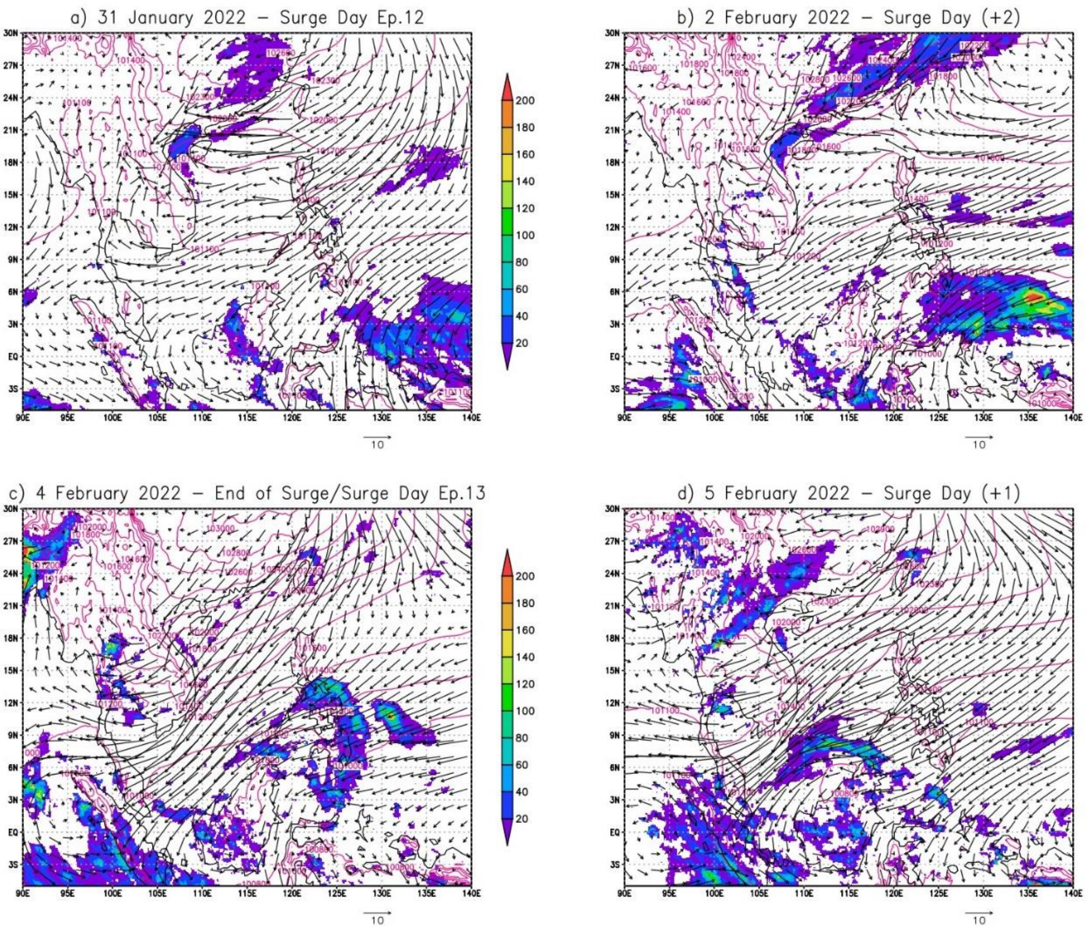
The end of the ES marked the onset of the MES **(Figure 13(c-d))**. The monsoon trough was located between 5°N and 5°S throughout this period. Cross-equatorial extended from Peninsular Malaysia to Borneo. Strong northeasterly winds swept across the SCS towards the equator. Two cyclonic vortices embedded in the trough, leading to heavy rainfall around both vortices.

On 6 February **(Figure 13(e))**, the axis of the surge was position offshore in the subtropics. Strong easterly winds from the western Pacific merged with the northerly surge, further intensifying the northeasterly winds over the SCS. As a result, these strong northeasterly winds extended deeper into the Southern Hemisphere. These strong northeasterly winds turned anticlockwise upon crossing the equator and became westerly/northwesterly winds. These westerly winds intensified the vortex in Borneo and led to heavy rain in the interior Borneo dan Karimata Strait.

The end of MES marked the beginning of 14^{th} surge episode of the season **(Figure 13 (f))**. During this ES, easterly winds extended westward into to PM. Heavy rainfall was observed on the windward side of the Philippines, downstream of SCS, and the whole PM. Heavy rainfall also observed at the turning point of cross equatorial surge. On the next day **(Figure 13 (g))**, the easterly winds strengthened in the SCS. Heavy rainfall was observed near equator region.

On the 10 February 2022 **(Figure 13 (h-i))**, strong easterly winds converge near the Luzon Strait. As they traversed through this narrow passage, the winds split into two main branches: one moved northward towards Hong Kong and southern China, and another branch continued northeastward into the SCS. These strong northeasterly winds carried moisture and brought heavy rainfall downstream of SCS, including PM and East Malaysia. Heavy rainfall was also observed at the Karimata Strait, where the confluence winds of cross equatorial and westerly winds occurred.

The end of ES occurred when strong easterly winds diverged over the West Pacific Ocean **(Figure 13 (j))**, with one branch heading north and another passing through the Philippines before entering the SCS. The easterly winds moved further west across the PM, towards the vortex located west of the Sumatra. Less weather was observed across Malaysia.



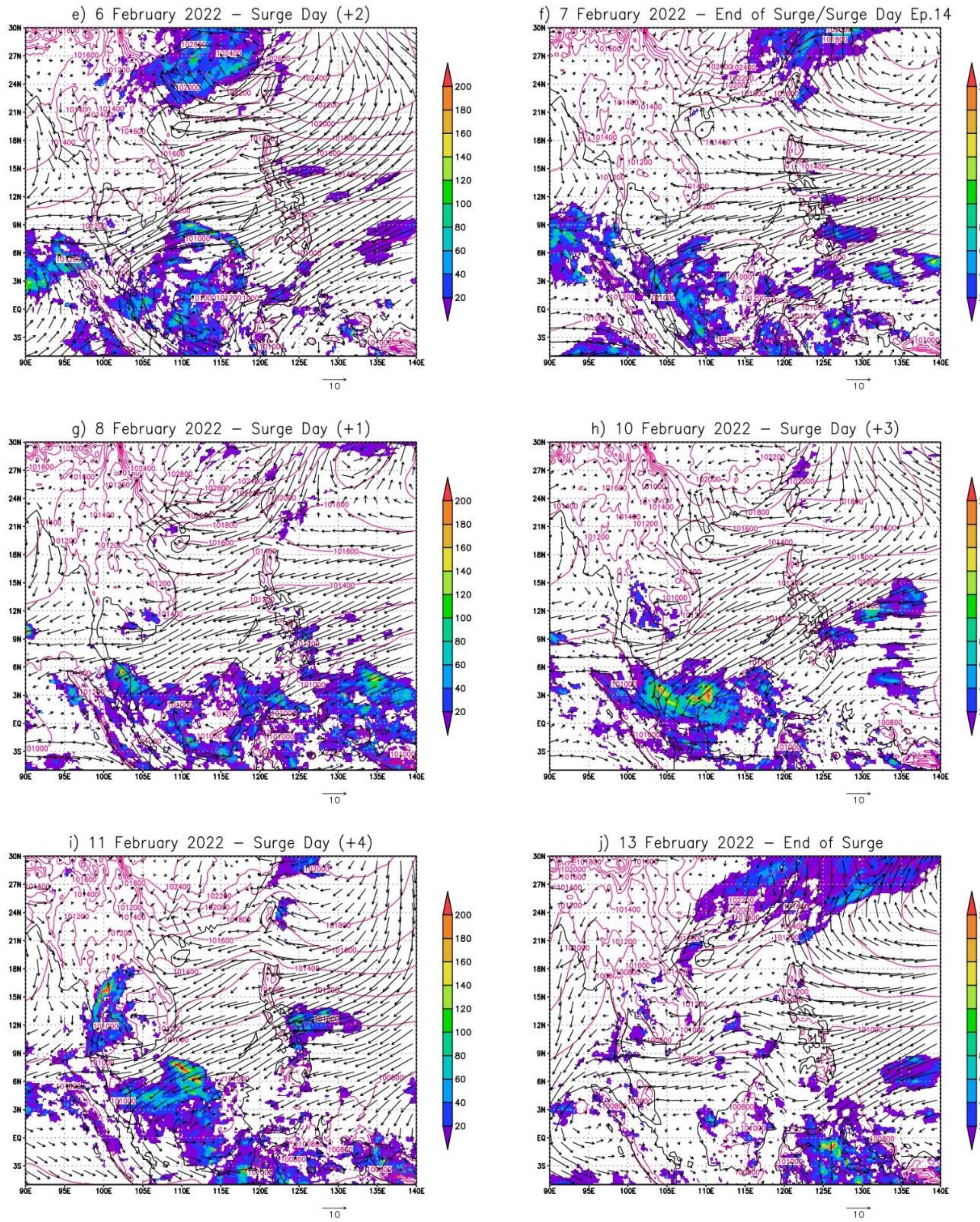


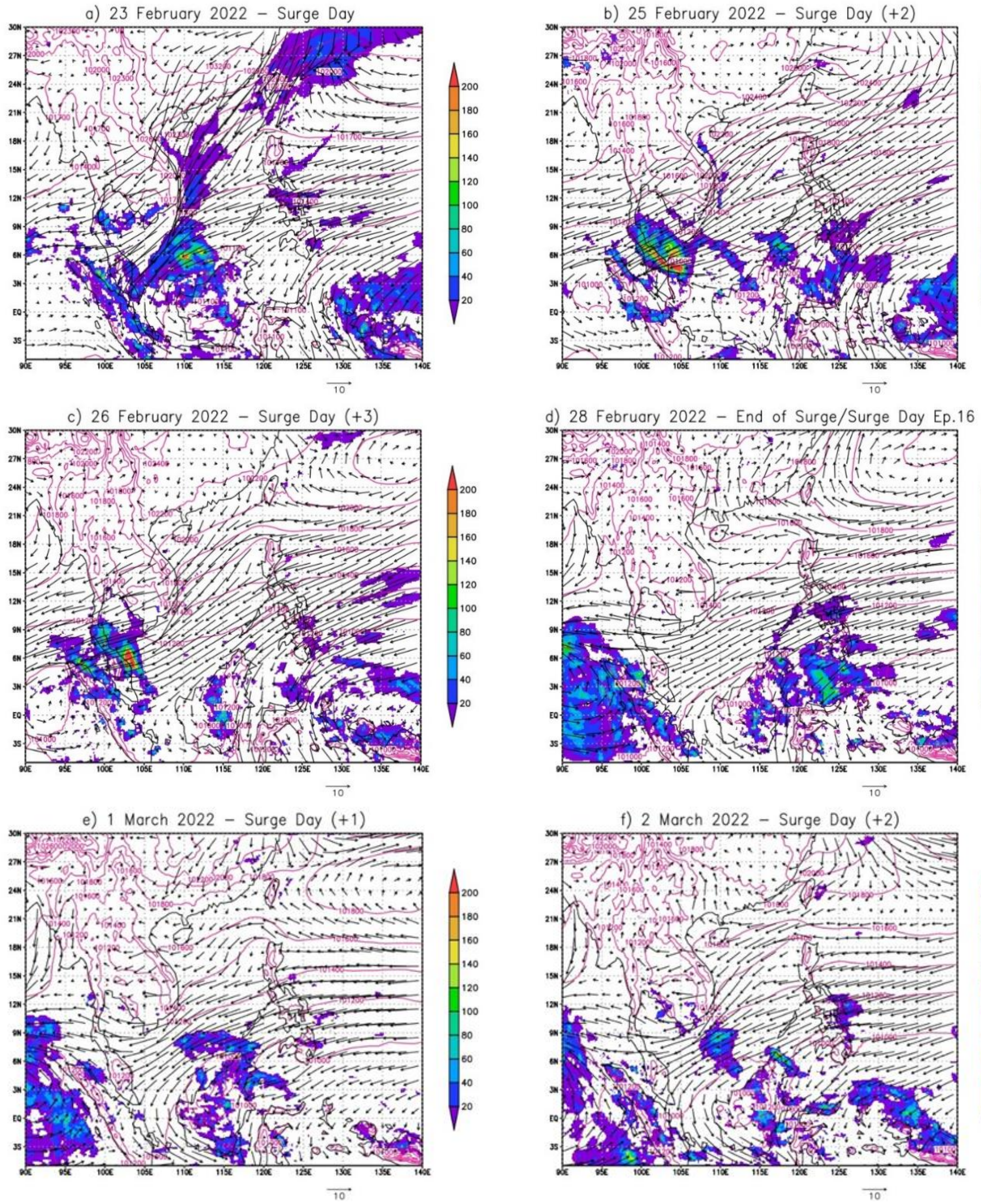
Figure 13 (a-j): same as Figure 7 except for the surges occurring from 31 January 2022 – 3 February 2022, 4 – 6 February 2023 and 7 – 12 February 2022

3.4.8 Episode 15 – 16: 23 Feb 2022 – 3 March 2022

The 15th episode of the surge was identified as MES. It occurred from 23 February to 27 February 2022, lasting five days. On the surge day **(Figure 14(a))**, strong northeasterly and easterly winds converged over the SCS, causing widespread rainfall. These confluence winds accelerated as they traversed over the small stretch of the SCS, eventually feeding into the BV and intensified it. Heavy rainfall was observed around the BV.

Two days after the onset of the surge, an anticyclone was observed in ECS **(Figure 14(b))**. This shifted the surge axis seaward, directing strong northeasterly winds into the SCS and the Philippine Sea. These winds converged downstream, causing heavy rain in eastern Peninsular Malaysia and the Gulf of Thailand. On the following day **(Figure 14(c))**, the anticyclone over the ESC strengthened and propagated eastward, causing the surge axis to tilt east-northeast. This reorientation of the axis directed the winds along this new path towards PM and the Gulf of Thailand. This brought heavy rain to these areas. Additionally, some of these winds penetrated PM, resulting heavy rain in the Strait of Malacca.

On 28 February **(Figure 14(d))**, the anticyclone in the ECS shifted southward, causing the winds in the equatorial region to become more zonally. This marked the end of MES and the beginning of ES. The strong easterly winds pushed moisture westward into the vortex located in the IO, where rain was observed in its vicinity. This condition persisted well into the following day **(Figure 14(e))**. On 2 March, northeasterly winds originating from the Asia continent were observed in the SCS region, accompanied by rain in the region **(Figure 14 (f))**. The rainfall in the IO vortex began to dissipate. By 3 March **(Figure 14 (g))**, rainfall was only observed in the southern IO. In the SCS, the rainband was pushed nearer to PM by strong easterly winds. These easterly winds induced cyclonic shear in the Borneo region, leading to the formation of BV. As the anticyclone in ECS moved further east on 4 March 2022 **(Figure 14(h))**, the easterly winds weakened considerably, marking the end of ES. The BV strengthened, and rainfall continued to be observed in the Borneo region.


a) 23 February 2022 – Surge Day
b) 25 February 2022 – Surge Day (+2)
c) 26 February 2022 – Surge Day (+3)
d) 28 February 2022 – End of Surge/Surge Day Ep.16
e) 1 March 2022 – Surge Day (+1)
f) 2 March 2022 – Surge Day (+2)
200
180
160
140
120
100
80
60
40
20
10

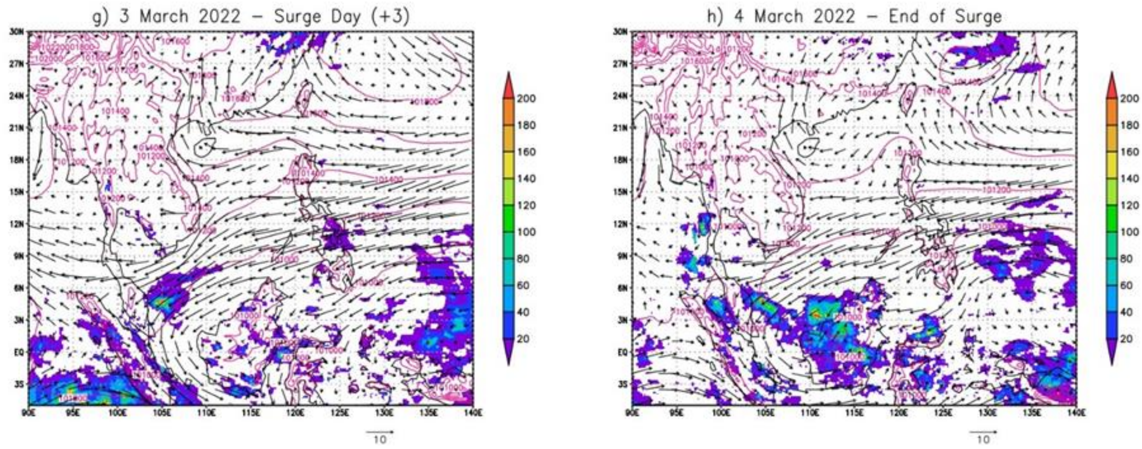


Figure 14 (a-h): same as Figure 7 except for the surges occurring from 23 – 27 February 2022 and 28 February – 3 March 2022

3.5 Rainfall Episode during NEM 2021/2022

During NEM 2021/2022, there were 16 episodes of surge consisting of ES, MS, and MES. However, out of these 16 surges, only six episodes were associated with heavy rainfall. A heavy rainfall episode is defined as a day when the daily accumulated rainfall at any principal stations exceeded 150 mm/day. Table 4 summarizes the heavy rainfall episodes on surge days.

Heavy Rainfall Episode	Date	Surges	Daily Accumulated Rainfall (mm)	Meteorological Station	State
1.	10 Nov 2021	MES	386	Kota Bharu	Kelantan
2.	9 Dec 2021	MES	155	Sandakan	Sabah
	11 Dec 2021		156	Sandakan	Sabah
	12 Dec 2021		166	Mersing	Johor
3.	16 Dec 2021	MS	144	Kerteh	Terengganu
	16 Dec 2021		144	Kuala Krai	Kelantan
	16 Dec 2021		134	Gong Kedak	Terengganu
	17 Dec 2021		188	KLIA	Selangor
	17 Dec 2021		261	Kuantan	Pahang
	18 Dec 2021		339	Kuantan	Pahang
	18 Dec 2021		153	Temerloh	Pahang
	18 Dec 2021		253	Subang	Selangor
	18 Dec 2021		201	Petaling Jaya	Selangor
4.	30 Dec 2021	MES	162	Kuala Krai	Kelantan
	30 Dec 2021		116	Kuantan	Pahang
	1 Jan 2022		102	Kuantan	Pahang
	2 Jan 2022		135	Kuantan	Pahang
	2 Jan 2022		219	Muadzham Shah	Pahang
	2 Jan 2022		142	Mersing	Johor
5.	6 Feb 22	MES	221	Kudat	Sabah
6.	24 Feb 22	MES	181	Mersing	Johor
	25 Feb 22		197	Kerteh	Terengganu

	25 Feb 22		230	Kuala Krai	Kelantan
	26 Feb 22		264	Kuala Terengganu	Terengganu
	26 Feb 22		188	Gong Kedak	Terengganu
	27 Feb 22		174	Kuala Krai	Kelantan

Table 4: Daily Accumulated Rainfall exceeding 150 mm for certain surge episodes

3.6 Madden Julian Oscillation (MJO) during NEM 2021/2022

The MJO is a large-scale atmospheric phenomenon that moves eastward along the equator over a 30- to 60-day period. It is characterized by a coupled pattern of deep convection and atmospheric circulation anomalies. The MJO moves eastward from the IO, across the MC, and into the western Pacific Ocean, with two main phases: convectively active phase and convectively suppressed phase. During the convectively active phase, there is heightened convective activity, heavy rainfall, increased cloudiness, and associated atmospheric disturbances. In contrast, the convectively suppressed phase is marked by reduced convection, drier conditions, and clearer skies.

Figures 15 and **16** show the strength and progression of the MJO through 8 different areas (8 phases) along the equator around the globe during the 2021/2022 NEM season (October 2021 till March 2022). The MJO's position is shown in a phase space defined by two components, RMM1 and RMM2, which are derived from a combination of winds at different levels and outgoing longwave radiation (OLR). The distance from the center of the diagram indicates the amplitude of the MJO. A greater distance implies a stronger MJO.

In October 2021, the MJO was inactive. However, it became active in phases 3 and 4 during November 2021. By December 2021, as indicated by the blue line, the MJO had significantly strengthened, moving outward into phases 6 and 7, which suggests a strong influence over the Western Pacific region. The active phase of the MJO in these areas is associated with upward motion, while subsidence (downward motion) over the MC results in suppressed convective activity, leading to drier conditions and less frequent rainfall.

In early January 2022, the MJO remained primarily active in the Western Pacific, but began shifting towards the Western Hemisphere by mid-January. The MJO's influence weakened towards the end of the month. In February 2022, the MJO transitioned through phases 3 and 4, affecting the IO and MC regions. Its amplitude was relatively weak for most of the month, as reflected by its proximity to the center of the phase space diagram. By mid-March 2022, the MJO became slightly more active over the Maritime Continent and South China Sea regions, potentially enhancing weather development in these areas during this period.

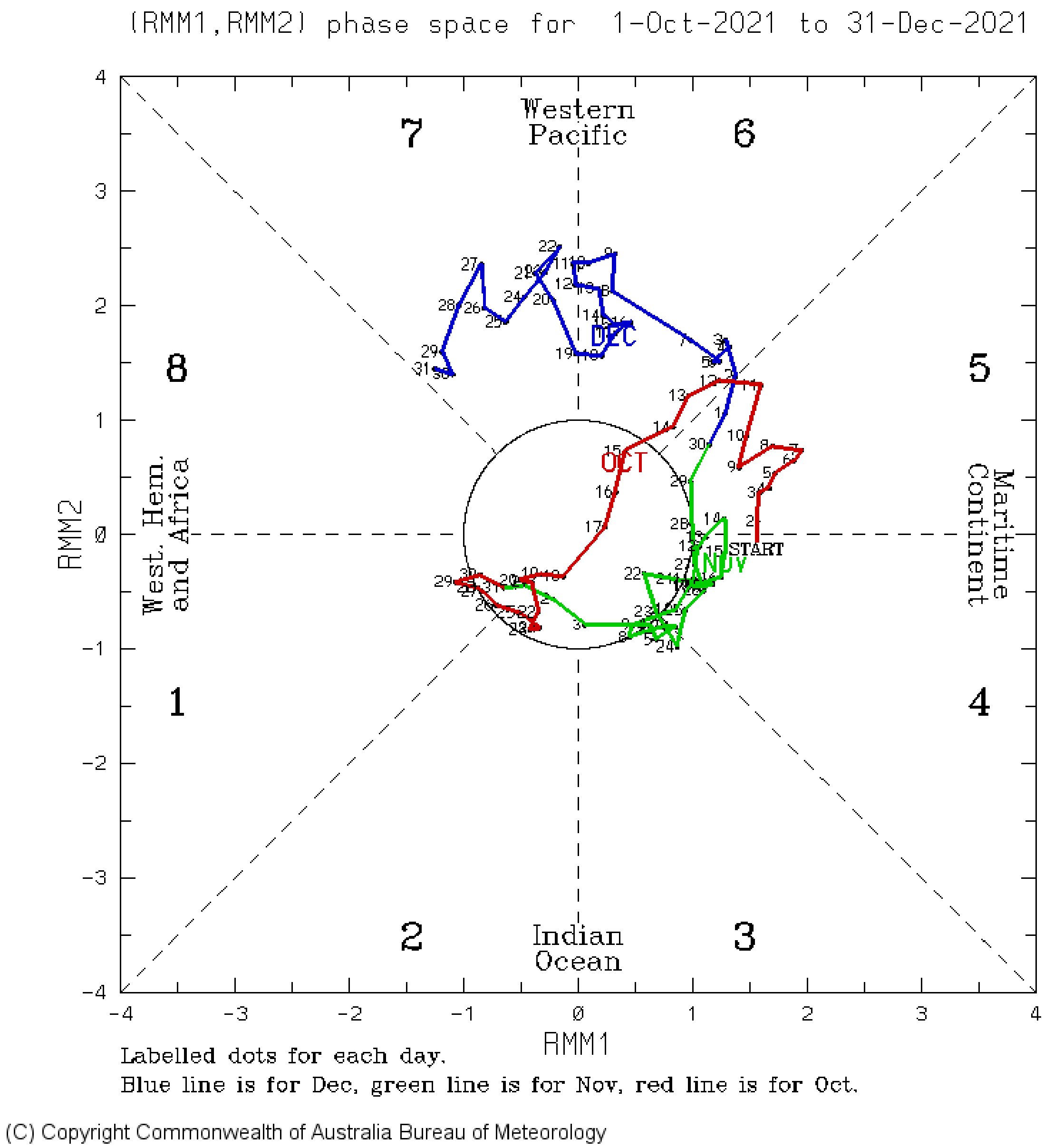


Figure 15: RMM1 and RMM2 phase diagram from October to December 2021.

(Figure from Australia Bureau of Meteorology)

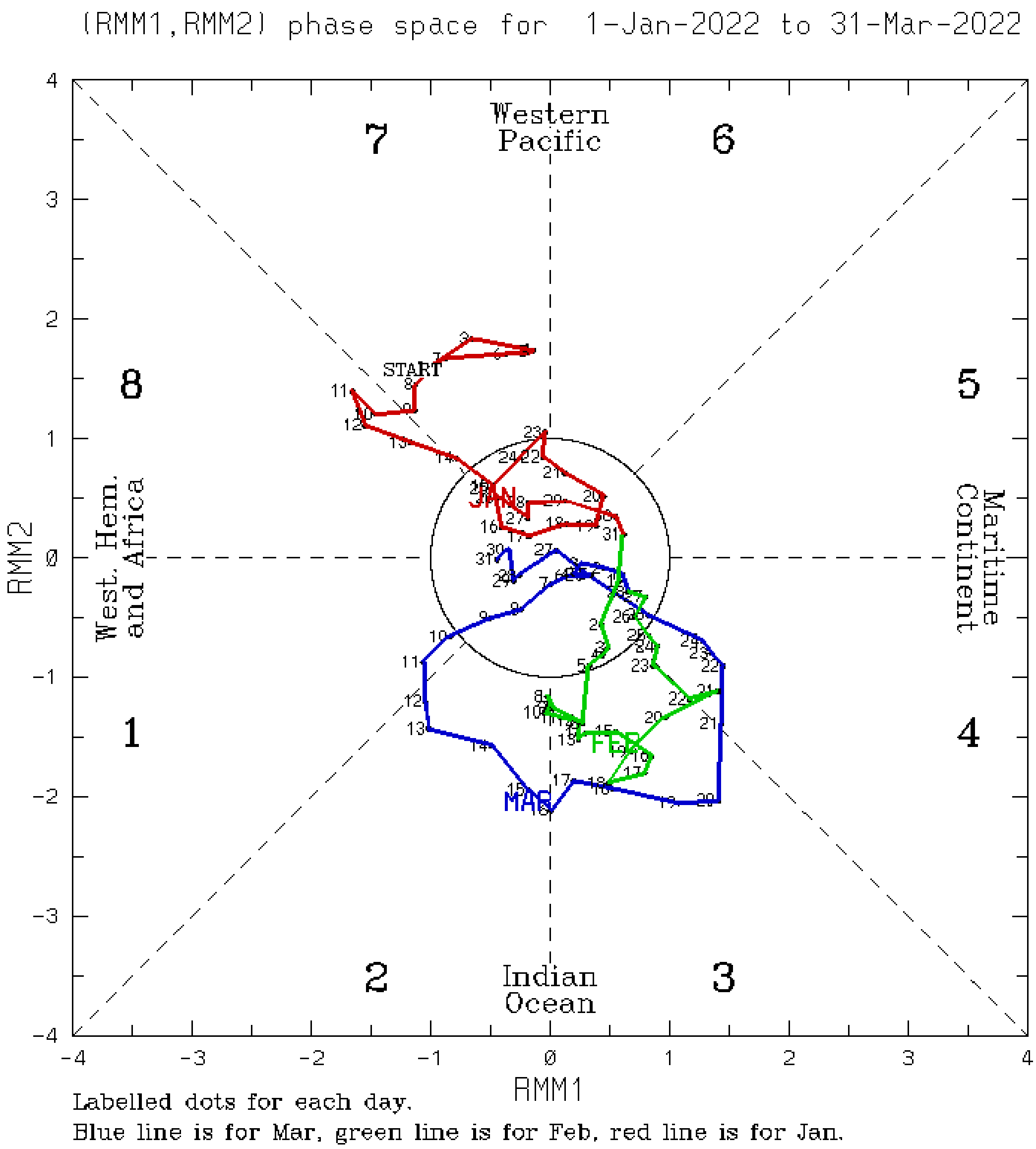


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Figure 16: same as Figure 15 except for January to March 2022.

(Figure from Australia Bureau of Meteorology)

4.0 CONCLUSION

The 2021/2022 NEM season onset and withdrawal dates fell within the normal climatological period. The onset date was 1 November 2021, while the withdrawal date was 15 March 2022. These dates align with the typical range for the NEM season. During the 2021/2022 NEM season, 16 surges were recorded. These surges included four MS, seven ES, and five MES. Only six of these surges resulted in heavy rainfall, with daily accumulated rainfall exceeding 150 mm at certain stations. These heavy rainfall episodes were reported during the first episode of the MS and in all of the MES episodes.

There were two TCs detected in the 2021/2022 NEM season. The strongest TC of the year was Typhoon Rai, which recorded maximum winds of 105 knots. As Typhoon Rai tracked westward into the SCS region, coupled with the presence of CS, heavy rainfall was observed around Malaysian region. Meanwhile, Typhoon Nyatoh was located further eastward in the NWP. During this time heavy rainfall was observed in SCS. The presence of TCs in the region, along with their interaction with CSs may influence the rainfall distribution, which needs further investigation.

The MJO is active in the MC during the early part of the NEM 2021/2022 season. In mid to late November 2021, wet weather in the MC may be contributed by the presence of MJO in the region. This MJO the propagated into the NWP in the following month which enhanced rainfall in this region. As the large-scale subsidence associated with the MJO occurred in the MC region during this time, less weather was expected even with the presence of the monsoon surge. In March 2022, MJO was mostly active in the IO and propagated into the MC towards the end of the month and bring wetter weather with it.

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