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RESEARCH ARTICLE

Analysis of the Regional Ionospheric Disturbance Index During Geomagnetic Storm in 2012

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ABSTRACT The impacts of severe geomagnetic storms that occurred in 2012 on the emergence of large-scale ionospheric anomalies in the equatorial region of Malaysia was investigated in this study. The research analyzed three significant geomagnetic storms that happened on April 24 (−120 nT), July 16 (−113 nT), and October 01 (−122 nT) of 2012. Their effects were assessed across different locations identified by the latitudes and longitudes 4°N 99°E, 3.06°N 101.54°E, 4.18°N 102.04°E, 3.16°N 113.03°E, 6.07°N 116.07°E, and 6.30°N 99.78°E respectively. Total Electron Content (TEC) from the GPS network over Malaysia was assessed by comparing the TEC during the three main phases of geomagnetically disturbed days with the average profiles of TEC during the quiet period. To determine the level of perturbation, the log of TEC was calculated in relation to the quiet reference median of 15 quiet days prior to the observation days. To represent the influence of the geomagnetic storms on TEC in Malaysia, a disturbance index was utilized. The thresholds of the index were established to indicate the level of disturbance, with positive and negative signatures of ±1 representing a quiet state, and ±2 indicating a moderate disturbance. A moderate ionospheric storm was indicated by ±3, while a severe ionospheric storm was represented by ±4. Based on the three events chosen, the threshold of the disturbance index indicated a severe storm on April 23, 2012 at 1900 UT, which was early morning of April 24, in the Malaysian region, while the other two storms indicated no severe storm, with the index ranging from ±1 to ±3 only. The study found that positive and negative disturbances in the ionosphere were a common occurrence. The impact of the storms was observed to persist before and after the actual storm period. This emphasizes the importance of having a dedicated ionospheric weather index in addition to geomagnetic indices over the equatorial region to evaluate and predict the impact of space weather storms, thus enhancing the precision and reliability of radio systems that are vulnerable to ionospheric disruptions.

INDEX TERMS Geomagnetic storm, GPS, ionosphere, ionospheric disturbance index, equatorial region, total electron content (TEC), space weather, radio systems.

I. INTRODUCTION

The ionosphere is one of the atmospheric layers that is important in space weather conditions for users of radio-based systems, space-based navigation and HF communication systems. This is due to the dispersive nature of the ionosphere which can have an impact on these systems [1]. These effects can be particularly severe during storm periods. The ionosphere exhibits significant temporal and spatial variations, and when geomagnetic activity intensifies, the interplay between the magnetosphere, ionosphere, and thermosphere leads to dynamic changes in the distribution of ionospheric plasma, giving rise to ionospheric storms [2], [3]. During such storms, the plasma density in the ionosphere may experience significant increases or decreases over several hours to days compared to normal conditions. Notably, the characteristics

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of ionospheric storms can vary considerably during different geomagnetic storms. Moreover, even during periods of low geomagnetic activity, the ionospheric conditions can change significantly based on factors such as season, local time, and location [4], [5]. The variations in the equatorial ionization anomaly (EIA) and other ionospheric irregularities over the equatorial region such as Equatorial Plasma Bubble (EPB) or scintillations and equatorial electrojets have a particularly significant impact on ionospheric conditions at low latitude regions [6].

Understanding solar activity, geophysical parameters, and ionospheric conditions is essential for space weather monitoring. To provide a better understanding of space weather conditions globally, various countries have established their own space weather centers and index. One example is the Space Weather Prediction Centre at NOAA which has developed its own space weather scale. Geomagnetic storms (represented by the G scale), solar radiation storms (represented by the S scale), and radio blackouts (represented by the R scale) are all described using well-known scales that range from 1 to 5 (https://www.swpc.noaa.gov/). In the Southern Hemisphere, the Australian Space Weather Forecasting Centre uses solar wind speed and X-ray flux to describe solar activity. The K-index, pc3-index, Dst-index and the GIC-index are used to monitor the geophysical environment. Meanwhile, for monitoring the ionospheric conditions, they utilize a T index map derived from foF2 observations. All these will aid users in HF communication. Another index which is used by the center to describe conditions of the regional ionosphere is the TEC disturbance index. This index covers Australia and New Zealand, and it is used to determine whether the regional ionosphere is enhanced or depressed in the Australian region (https://www.sws.bom.gov.au/).

To monitor the status of the ionosphere, one can employ indices such as TEC, foF2, and other suitable measures that indicate the extent of disturbance in the electron density. TEC, in particular, offers a comprehensive overview of the ionosphere's dynamics and serves as a valuable metric in assessing its activity [7]. TEC, coupled with the consideration of ionospheric anomalies, is an essential ionospheric parameter for single-frequency Global Positioning Satellite (GPS) systems. Customers' judgments and algorithms may benefit greatly from the information provided by an ionospheric index, which is a proxy measure of the ionosphere's complex changes. These indices provide a realistic method to fill in the gaps in our understanding by reducing complicated disturbances, such ionospheric plasma bubbles, to single numbers. They are useful as inputs for application-specific algorithms and may be used directly for risk estimation. Non-scientific users who may not need or have a comprehensive understanding of the physical intricacies of the ionosphere are encouraged to use these indices as such indices offer a streamlined way for the users to comprehend the essential aspects that might be pertinent to their needs or interests.

It is challenging to construct an ionospheric storm scale due to the interplay of seasonal, daily, local temporal, and geographical impacts on ionospheric changes. Recent years have seen a rise in the demand for ionospheric data, prompting scientists to seek for real-time ionospheric indicators. Using a 27-day median value and comparing it to its standard deviation across latitude, local time, and season over a period of 18 years over Japan, [8] have established an ionospheric storm they call the "I-scale." This scale is independent of time of year, geographic location, or weather conditions.

Meanwhile, [9] proposed a novel ionospheric disturbance index based on weak and moderate geomagnetic storms that occurred over the northern and southern hemisphere on May 12, 2021 during the 25th solar cycle. The index showed significant anomaly changes during the moderate geomagnetic storm. Reference [10] proposed the ionospheric activity index (AI) which was calculated based on f_oF_2 measurements over Europe. The index covered data collected over 13-years which were obtained from a single European station, and it is used to investigate the seasonal dependence of ionospheric storms. The SRMTID index and the SSMTID index, proposed by [11] in 2006 offer real-time updates on the activity of Medium-Scale Travelling Ionospheric Disturbances (MSTIDs) at mid-latitude stations. These indices provide valuable information without the need for a local network. At a regional scale, the Along Arc TEC Rate (AATR) statistic may be used to pinpoint times of disruption that negatively impact GNSS performance. Dual-frequency GNSS observations allow for straightforward derivation of AATR [12].

Reference [13] developed two indices, namely DfoF2-upper (Dfu) and DfoF2-lower (Dfl), to monitor global mid-latitude ionospheric disturbances. These indices were created using data from ionosondes and aimed to quantify the deviations of observed foF2 values from their monthly averages. Positive values are denoted as Dfu typically representing ionospheric disturbances, while negative values are denoted as Dfl. By comparing these two indices, valuable insights can be gained regarding the magnitude of ionospheric storm impacts at intermediate latitudes. Meanwhile, [14] introduced a disturbance ionospheric index named DIX, which was derived from GNSS measurement. Additionally, [15] and [16] introduced the W index which was built using f_oF_2 measurements and TEC over Europe. A logarithm of the modified ionospheric parameter was used as the definition of the W index which was then compared to the reference value obtained from a quiet environment. The criteria were set based on the frequency with which negative storms occurred at a single station. W indices were also computed for other places, and it was discovered that they increased correspondingly with northern latitude. In order to better comprehend how the ionosphere affects operational radio systems, a service that provides a real-time assessment of the level of TEC disruption at each grid point of the map, as indicated by the ionospheric W index, may be useful [16].

This index is currently available online and can be accessed via https://www.izmiran.ru/services/iweather/ind/My.

However, there is currently no recognized ionospheric storm scale based on direct ionospheric measurements over the equatorial region [17]. The ionosphere exhibits significant temporal and spatial variabilities, including variations related to season, day-to-day changes, local time, and location. These complexities pose challenges in defining a standardized ionospheric storm scale [3], [5].

Therefore, the primary purpose of this study was to create an index for regional ionospheric disturbances across the equatorial area, with a focus on Malaysia, using Gulyaeva's W-index. Three different geomagnetic storms that occurred on April 24, July 15, and October 01, 2012 were analysed in order to examine their effects across the Malaysian region, specifically in Selangor (3.06° N, 101.54° E), Pahang (4.18° N, 102.04° E), Sarawak (3.16° N, 113.03° E), Sabah (5.04° N, 118.33° E) and Langkawi (6.35° N, 99.8° E).

II. METHODOLOGY

A. METHOD FROM BERNESE GNSS SOFTWARE

Bernese GNSS Software (BGS) version 5.2 was used [18] to derive the TEC map by using the geometry-free (L4) linear combination which is represent by equation (1) below:

$$L_4 = L_2 - L_1 \tag{1}$$

where L_1 is the carrier phase with frequency of $f_1 = 1575.42$ MHz and L_2 is the carrier phase with the frequency of $f_2 = 1227.50$ MHz. the geometry-free linear combination equations for phase and pseudocode read as:

$$L_4 = -a\left(\frac{1}{f_1^2}\right) - \left(\frac{1}{f_2^2}\right) F_I(z)\, E(\beta, s) + B_4 \tag{2}$$

$$P_4 = +a\left(\frac{1}{f_1^2}\right) - \left(\frac{1}{f_2^2}\right) F_I(z)\, E(\beta, s) + b_4 \tag{3}$$

where L_4 and P_4 are the geometry-free phase and pseudocode observables, a is constant, $4.03 \times 10^{17} ms^{-2} TEC^{-1}$, f_1 and f_2 are the frequencies associated with the carriers L_1 and L_2. $F_I(z)$ is the mapping function evaluated at the zenith distance, z', $E(\beta, s)$ is the vertical TEC in TECU, where β is the geographic or geomagnetic latitude, and s is the sun fixed longitude, and $B_4 = \lambda_1\beta_1 - \lambda_2\beta_2$ is a constant bias due to the initial phase ambiguities B_1 and B_2 with their corresponding wavelengths λ_1 and λ_2.

Equations 2 and 3 are valid for zero-difference observations and were therefore used in this analysis. Phase leveling process was performed in order to resolve the unknown ambiguity-offset and infrequent cycle slips due to signal loss of lock in phase data. This leveling was performed by adjusting the continuous arcs of the TEC from phase to the mean value of the corresponding TEC from code values. The satellite biases were downloaded from the Centre for Orbit Determination in Europe (CODE) while the receiver biases and vertical TEC were calculated using the spherical harmonic expansion, as described in Equation 4, which was used in modeling the ionosphere in BGS:

$$E(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_{nm}(sin\beta)\left(a_{nm}\cos(ms) + b_{nm}\sin(ms)\right) \tag{4}$$

where, β is the geographic latitude, s is the sun-fixed longitude, n_{max} is the maximum degree of spherical harmonics expansion, and a_{nm} and b_{nm} are the unknown coefficients of the spherical harmonics. The normalized associated legendre functions of degree n and order m are given by $\tilde{P}_{nm} = \bigwedge(n, m) P_{nm}$ for a spherical harmonic expansion of degree n_{max}. The unknown parameters of the global ionospheric model are the TEC coefficients of the spherical harmonics, which may be derived from the normalized function $\bigwedge(n, m)$, and the legendre functions P_{nm} and a_{nm}, respectively.

At the ionospheric pierce point, a height of 450 km is used by the thin-shell elevation mapping function to convert slant TEC to vertical TEC. Using weighted least squares solution, the unknown coefficients were calculated.

B. SELECTION OF GPS DATA

For this research, archived data in RINEX format from 78 Global Positioning System (GPS) receivers were utilized. This regional map was generated to study TEC variations during quiet and disturbed days over Malaysia. The GPS receiver network used in this study is called the Malaysia Real-Time Kinematic Network (MyRTKnet), which is owned and managed by the Department of Mapping and Surveying Malaysia (DMSM). The GPS data was analyzed using the Bernese GPS Software 5.2. Figure 1 illustrates the geographical distribution of the GPS receivers utilized in this research across Malaysia.

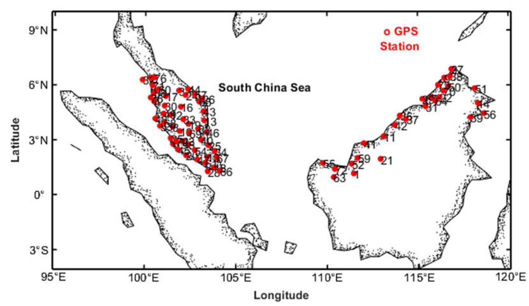

FIGURE 1. The distribution of GPS receivers obtained from MyRTKnet.

C. SELECTION OF GEOMAGNETIC AND SOLAR ACTIVITY DATA

The indexes for periods of disturbed geomagnetic storms were obtained from the World Data Center for Geomagnetism, which is operated by the Data Analysis Center for Geomagnetism and Space Magnetism at Kyoto University, Japan. The center's website (http://swdcwww.kugi.kyoto-u.ac.jp/Dstae/index.html) provides access to these indexes.

TABLE 1. Geomagnetic storms with their observation parameters for 2012.

Source	Events	Date	Minimum Dst (nT)	Kp index
WDC OMNI	1	April 24, 2012	-120	6
	2	July 15, 2012	-139	7
	3	October 01, 2012	-122	6

Additionally, NASA's Space Data Facility (https://omniweb.gsfc.nasa.gov/form/dx1.html) maintains a database that includes hourly averaged measurements of the Interplanetary Magnetic Field (IMF Bz). Table 1 contains the minimum Dst and Kp index values for the geomagnetic storms examined in this study.

D. IONOSPHERIC DISTURBANCE INDEX

Previous research recommended utilizing characteristics such as the percentage difference between the present observables and the corresponding median at the same local time and place in order to characterize the ionospheric condition using TEC [15]. Studies conducted by [15] and [16] showed that a segmented logarithmatic scale of ionospheric weather index is suitable for assessing and defining the effect of geomagnetic storms on the TEC. Bahari et al. [19] developed the first Malaysia Ionospheric Disturbance Index, known as M-index, for geomagnetic storms that occurred in 2014 based on the same method created by Stanislawska and Gulyaeva [16] which is known as W-index. The disturbance index was calculated based on Eq. (5) to quantify the ionospheric variability in this study [18]:-

$$Dlog = \log\left(\frac{TEC}{TECmed}\right) \tag{5}$$

The logarithm of the disturbance index (Dlog) was segmented based on specific thresholds corresponding to percentage changes in the Total Electron Content (TEC), as detailed in Table 2. To measure the degree of perturbation, the TEC values were compared to a quiet reference level, which was determined as the daily hourly median for the 15 days preceding the observation period. The M-index was then calculated by categorizing the perturbations based on the relevant thresholds. Specifically, an M-index value of ±1 indicated a quiet condition, ±2 represented a moderate condition, ±3 denoted a moderate ionospheric storm, and ±4 indicated an intense ionospheric storm condition.

Locations used in this study for the disturbance index analysis are shown in Figure 2.

III. ANALYSIS OF THE RESULTS

To evaluate and enhance the ionospheric disturbance index in relation to geomagnetic storms, this study examined three different categories of geomagnetic storms which included two moderate G2 scale storms and one strong G3 scale storm that occurred in 2012. The selection of these three storms enabled analysis of their respective impacts over the Malaysian region under varying geomagnetic conditions.

TABLE 2. Ionospheric disturbance index displaying the relevant thresholds of logarithmic deviations corresponding to the changes in TEC [15].

Disturbance index	Dlog	Class
4	$0.301 < D_{log}$	Positive intense ionospheric storm
3	$0.155 < D_{log} \leq 0.301$	Positive moderate ionospheric storm
2	$0.046 < D_{log} \leq 0.155$	Positive moderate disturbance
1	$0 < D_{log} \leq 0.046$	Positive quiet state
-1	$0.046 \leq D_{log} < 0$	Negative quiet state
-2	$-0.155 \leq D_{log} < -0.046$	Negative moderate disturbance
-3	$-0.301 \leq D_{log} < -0.155$	Negative moderate ionospheric storm
-4	$D_{log} < -0.301$	Negative intense ionospheric storm

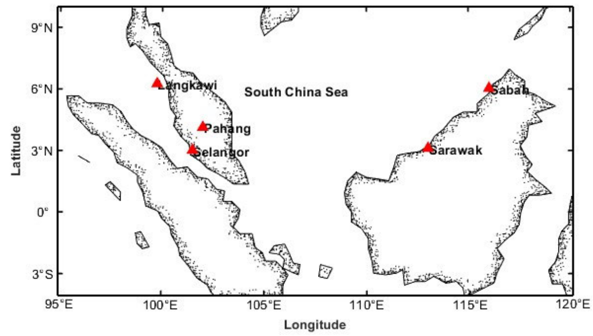

FIGURE 2. The geographical locations over Malaysia where the disturbance index was analyzed for this study.

A. EVENT 1: GEOMAGNETIC STORM OF APRIL 24, 2012

To develop and analyze the proposed ionospheric disturbance index, the geomagnetic storm that occurred on April 24, 2012 was chosen as Case 1 in this study. Figure 3 (a) shows IMF_Bz which was used to measure the storm's intensity.

Based on Figure 3 (a), a sudden storm commencement (SSC) occurred at 0500 UT (=UT+8 = 1300 LT, because LT is 8 hours heading to UT) on April 23, 2012, with a value of −8.3 nT. The maximum negative value was reached at 1800 UT with a value of −15.4 nT.

The Dst index began a rapid decrease at 0000 UT on April 24, 2012, reaching its minimum of −120 nT at 0400 UT, indicating the main phase of the geomagnetic storm. It briefly rebounded to a value of −103 nT and persisted for two more hours before reaching its minimum value of −120nT on April 24. The Dst index started to experience a recovery phase around 0800 UT, however the value remained negative and was more than -50 nT. A brief partial rebound was recorded,

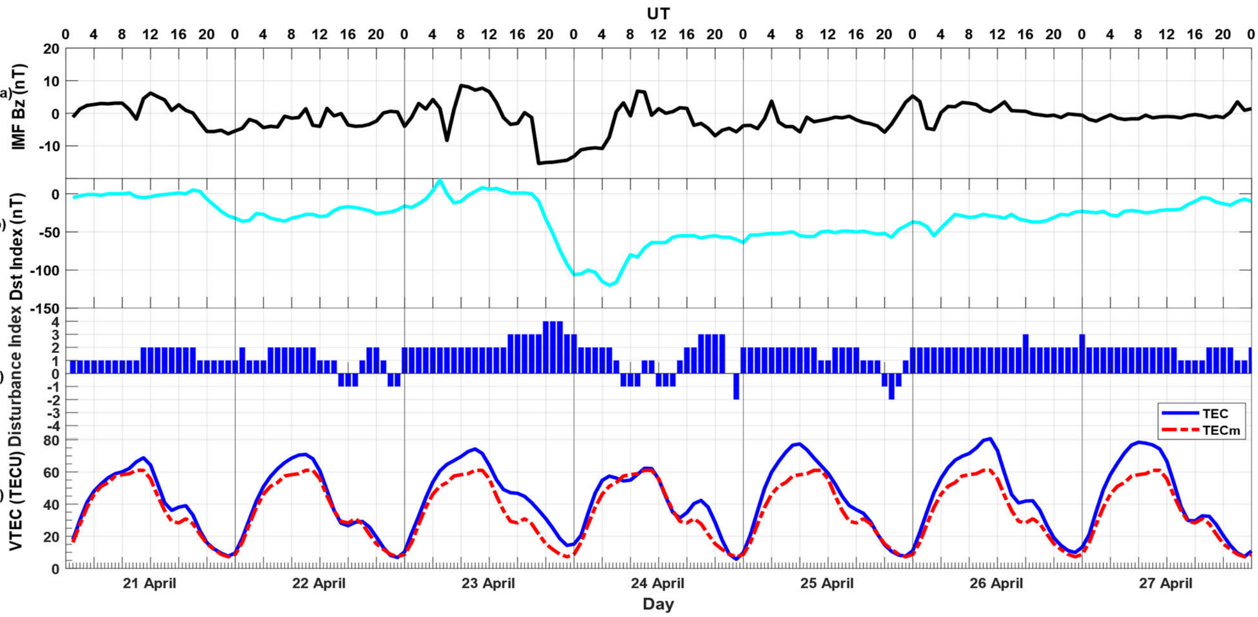

FIGURE 3. Geomagnetic conditions based on the disturbance index analysis with (a) IMF_Bz index, (b) Dst index, (c) ionospheric disturbance index, and (d) TEC variations with median TEC (TEC_m) (red dashed line) and, observed TEC (solid blue line) from April 21-27, 2012 for the location (4.0°N, 99.0°E).

and this was then followed by a second minimum Dst on April 25, 2012 [20].

To analyze and develop the ionospheric disturbance index, TEC data for location (4.0°N, 99.0°E) from April 21 to 27, 2012 were examined along with the median quiet day patterns (denoted by red dashed line), calculated using the data for the 15 quietest days of the month. It should be noted that on April 24, there were peaks of TEC observed around 0500 UT, 1000 UT and 1800 UT. These peaks corresponded to the variations of Dst where two fluctuations were recorded. Additionally, these peaks occurred during the recovery phases of the geomagnetic storms.

The first stage indicated intense storm conditions which started at 0000 UT and lasted until 0500 UT with Dst value of (−105 nT to −116 nT), while the second stage indicated moderate storm conditions which occurred from 0600 UT until 2300 UT with Dst value of (−97 nT to −64 nT). It can be seen in Figure 3 (d) that on April 24, 2012, three peaks of TEC were observed at 0500 UT (value of 56.20 TECU), 1000 UT (value of 62.10 TECU), and 1800 UT (value of 38.10 TECU). Low-latitude ionospheric stations have a daily pattern of TEC that rises from dawn to an afternoon maximum and then falls to a minimum after sunset [3]. This is a major problem in prediction and navigation since the TEC curves indicate significant day-to-day changes in TEC, especially around midday [1], [21]. Solar activity causes this fluctuation, where TEC fluctuations during daytime are large while changes during night-time are practically consistent.

The ionospheric disturbance index was calculated from Equation (1) which is the equation utilized for region of Malaysia. Figure 3 (c) shows that the ionospheric disturbance started at 2000 UT on April 23 and continued until the early morning of April 24, which was the main phase of the storm. As can be observed in Figure 3 (c), the disturbance index indicated that the normal state began on April 21 and continued until 1700 UT on April 23. The index reached positive moderate storm (+3) at 1400 UT and continued until 2000 UT on April 23, in between the period the index showed positive intense ionospheric storm (+4) from 2000 UT to 2200 UT. On April 24, 2012 the index indicated a positive moderate ionospheric storm (+3) starting from 0000 UT until 0100 UT. No negative ionospheric storm was observed during this event.

The behavior of the ionosphere in response to the geomagnetic storms varied depending on the local time and longitude. The effects of the ionospheric disturbances were examined at various locations during the storms, as depicted in Figure 4. Different locations were chosen based on various longitudes including Selangor (3.06°N, 101.54°E), Pahang (4.18°N, 102.04°E), Sarawak (3.16°N, 113.03°E), Sabah (5.04°N, 118.33°E), and Langkawi (6.35°N, 99.8°E). Positive storms were prominent around latitude 3.06° N, 4.18° N, 3.16° N, 5.04° N, and 6.35° N with longitude around 101.54°E, 102.04°E, 113.03°E, 118.33°E and 99.8°E for April 23. Negative ionospheric storms were found mostly on April 24 and April 25. Positive ionospheric storm continued to occur from April 26 until April 27. This might be due to the recovery phase of the geomagnetic storm on April 24, 2012.

Based on Figure 4, severe storms were found in three locations namely- Pahang, Sabah and Langkawi, which varied in their latitude and longitudes. In light of SSC that occurred at 0500 UT on April 23, no prominent changes were found

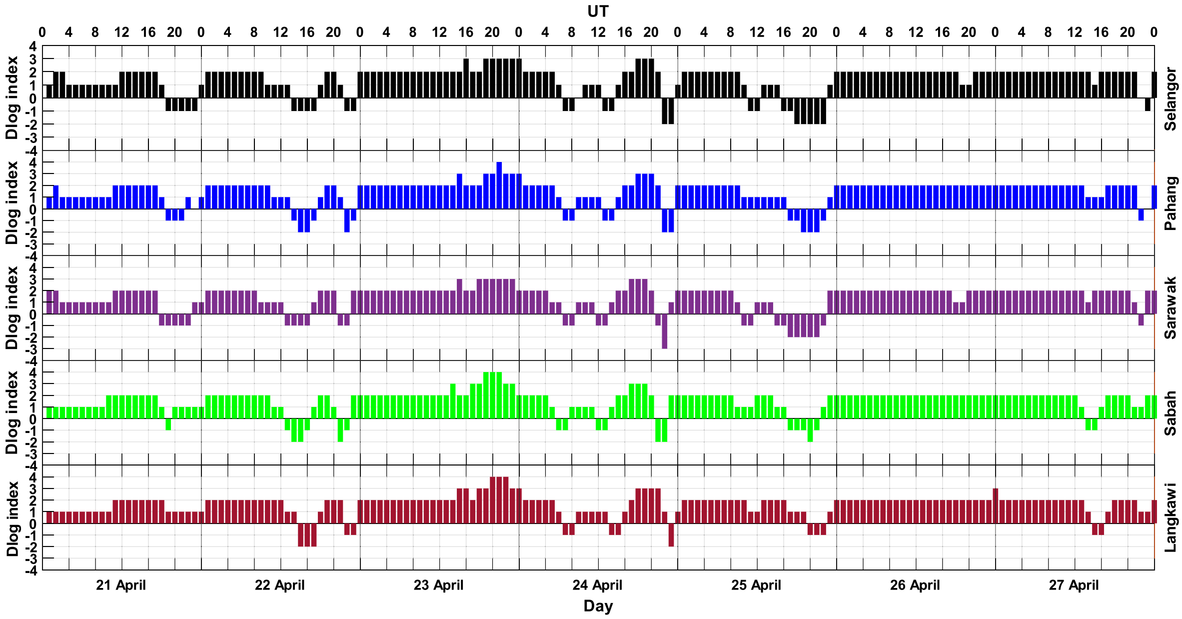

FIGURE 4. Ionospheric Disturbance Index Analysis of different locations over Malaysia from April 21-27, 2012. Black color shows the analysis for Selangor (3.06°N, 101.54°E), blue for Pahang (4.18°N, 102.04°E), purple for Sarawak (3.16°N, 113.03°E), green for Sabah (5.04°N, 118.33°E), and red for Langkawi (6.35°N, 99.8°E).

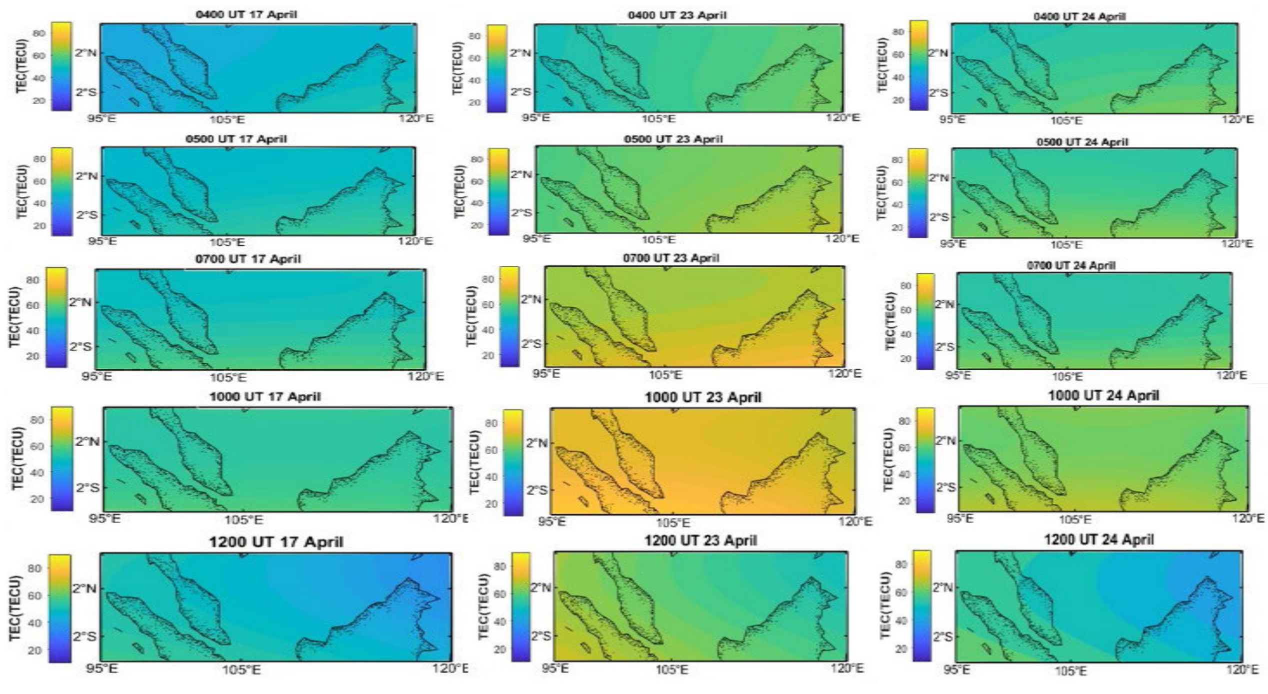

FIGURE 5. The VTEC map for April 17 (quiet day), April 23 and April 24 (disturbed days), 2012 at 0400 UT, 0500 UT, 0700 UT, 1000 UT, and 1200 UT.

for all these locations, however a moderate disturbance was detected around 1800 UT which continued until 2300 UT.

Analysis showed that severe ionospheric storms occured in three locations namely- Pahang, Sabah and Langkawi, which varied with their latitudes and longitudes. From the results it can be seen that the most significant positive storms were found only over Sarawak, Sabah and Langkawi. This could be attributed to their specific geographical locations for instance, Langkawi is situated near the geomagnetic dip of the equator [22].

Figure 5 shows an example of vertical TEC map for April 17 (quiet day), April 23 and April 24 (disturbed days), 2012 at 0400 UT, 0500 UT, 0700 UT, 1000 UT and 1200 UT. The variations of TEC for the latitudes 0°N to 8°N and the

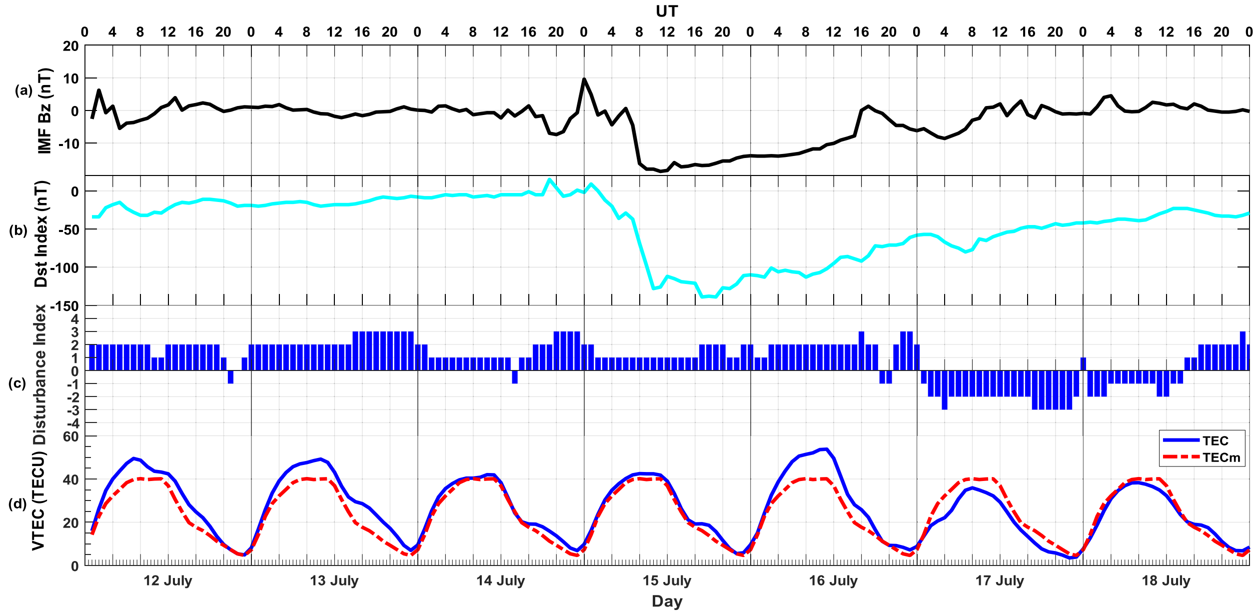

FIGURE 6. Geomagnetic conditions based on the Disturbance Index Analysis with (a) IMF_Bz index, (b) Dst index, (c) ionospheric disturbance index, and (d) TEC variations with median TEC (TECm) (red dashed line) and, observed TEC (solid blue line) from July 12-18, 2012 for the location (4.0°N, 99.0°E).

longitudes 95°E to 120°E are presented for the period before during and after the storm. It can be observed from Figure 5 that the anomaly on the quiet day of April 17, 2012, was fairly smooth and uniform over the different time periods. Contrastingly, on April 23, 2012, with the sudden commencement of Event 1 storm, a pronounced TEC variation could be observed at 0700 UT and 1000 UT compared to the quiet day. Notably, it could be observed that the TEC variations fluctuated with the increase in longitudes. On April 24, the TEC variations were slightly different compared to April 23, 2012. At 0700 UT, the TEC values decreased with the increase of latitudes and at 1200 UT, the TEC values decreased with the increase of longitudes.

The maximum TEC value of 80.3 TECU was recorded at 1000 UT on April 23, 2012. In contrast, on the day of Event 1 storm, which was on April 24, 2012, the maximum value of TEC was 69.90 TECU at 1000 UT. Based on the VTEC map, it could be said that Event 1 storm was quite a pre-storm in the Malaysian region [7]. According to [23], strong pre-magnetic storm indicators have been observed in NmF2 with percentage deviations ranging from −91% to 500% across the equatorial, low, and mid-latitudes, where the maximum values were noted at the equator.

B. EVENT 2: GEOMAGNETIC STORM OF JULY 15, 2012

To describe Event 2, IMF_Bz, Dst, ionospheric disturbance index and VTEC were plotted in Figures 6 (a) to (d), respectively for the period of July 12-18, 2012. The Dst profile shown in Figure 6 (b) was the main phase of this event, where on July 15, an intense geomagnetic storm (minimum Dst = −128 nT at 0900 UT) continued until 2300 UT (minimum Dst = −110 nT). A moderate storm occurred at 0700 UT and 0800 UT with Dst values of – 69 nT and −98 nT respectively. It then reached a state of intense storm again at 0900 UT with a Dst value of −128 nT and continued until 1000 UT on the next day, reaching a Dst value of −102nT. Reference [24] observed that most strong storms occur in two stages during the main phase, similar to the storm event of April 24, 2012.

The reaction of the ionosphere to the commencement of a magnetic storm during the local daytime is typical for mid- and low-latitude regions [15]. where, the positive phase of the ionospheric storm was observed during the local night-time on the previous day, on July 13, 2012. Malaysia was mostly unaffected by the geomagnetic storm of July 15, 2012. On July 17, 2012, a negative phase was detected during the local midday. Event 2 storm produced both positive and negative effects. However, the negative impacts were largely detected during the local early morning and midday, while the positive impacts were detected at local noon and night-time.

No intense storm was detected for Event 2 as shown in Figure 6 (c). Moderate positive disturbances (+3) were found before and after the storm day. From the result, it appears that the Malaysian region was mostly unaffected by this storm. This could be due to the seasonal variations in the equatorial region; in July, which corresponds to the summer solstice, the mean TEC was observed to be lower compared to March and April [31].

Figure 7 shows the effects of the geomagnetic storms which occurred on July 12-18, 2012 across different locations over Malaysia. For this geomagnetic event, no severe storm was found in any of the locations.

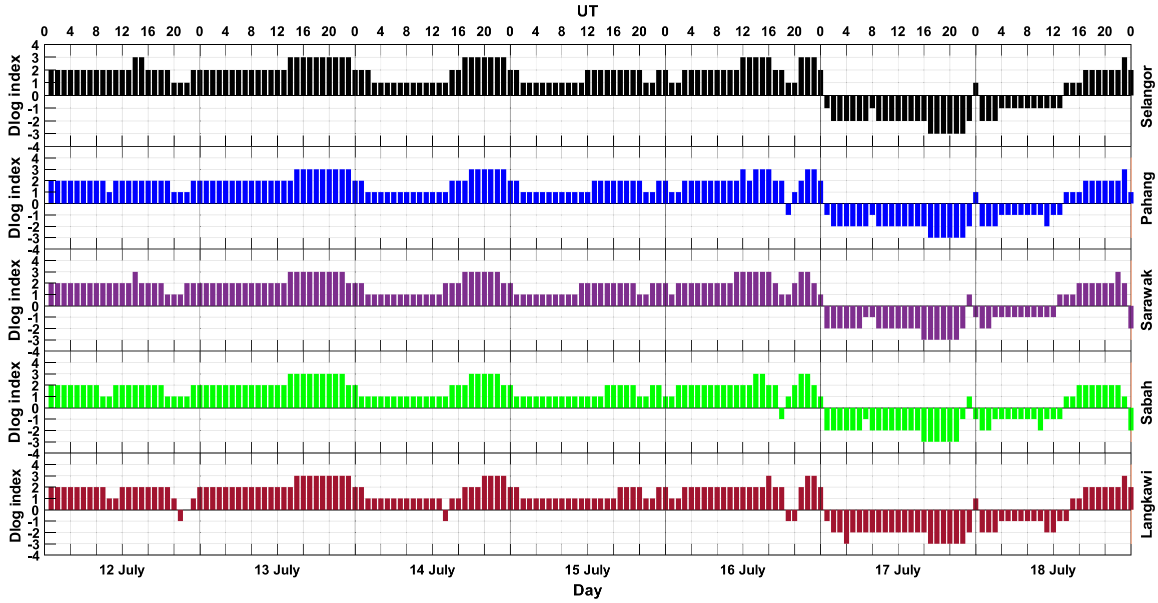

FIGURE 7. Ionospheric Disturbance Index Analysis of different locations over Malaysia from July 12-18, 2012. Black color shows the analysis for Selangor (3.06°N, 101.54°E), blue for Pahang (4.18°N, 102.04°E), purple for Sarawak (3.16°N, 113.03°E), green for Sabah (5.04°N, 118.33°E), and red for Langkawi (6.35°N, 99.8°E).

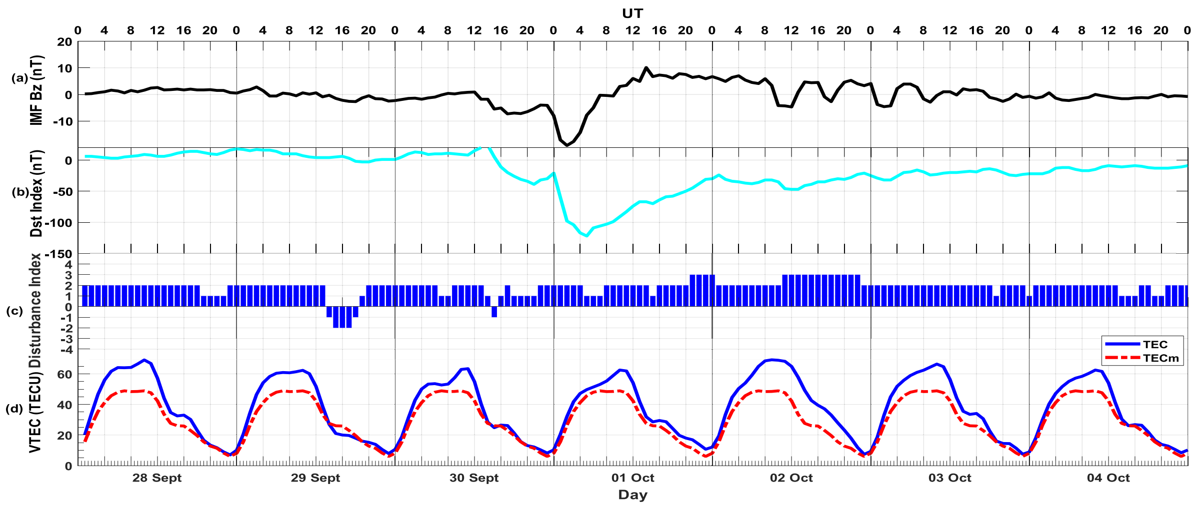

FIGURE 8. Geomagnetic conditions based on Disturbance Index Analysis with (a) IMF_Bz index, (b) Dst index, (c) ionospheric disturbance index, and (d) TEC variations with median TEC (TECm) (red dashed line) and, observed TEC (solid blue line) from September 28- October 04, 2012 for the location (4.0°N, 99.0°E).

However, the ionospheric disturbance hours were quite different from one location to another, as can be seen in Figure 7.

C. EVENT 3: GEOMAGNETIC STORM OF OCTOBER 1, 2012

In order to describe Event 3, IMF_Bz, Dst, ionospheric disturbance index, VTEC and median TEC were plotted and displayed in Figures 8 (a) to (d), respectively for the period of September 28 to October 03, 2012. The largest minimum Dst value was recorded at 0400 UT with a value of -122 nT. The Dst profile showed that the main phase of this geomagnetic storm event began on October 01, 2012, where an intense storm with a Dst value of -98nT began at 0200 UT and continued until 1900 UT. After 2000 UT, it returned to the normal ionospheric state. However, this storm did not have much impact over the Malaysian region compared to the previous event patterns. The ionosphere returned to its normal state on October 03, 2012. This storm event began at 0000 UT on October 01, 2012 and lasted for a few hours only, and was over at 0500 UT.

As can be seen in Figure 8 (c), the ionospheric disturbance index did not indicate any intense storm for the location 4.0°N, 99.0°E. Positive ionospheric moderate storm (+3) occurred on October 01 and 02, 2012 at 2000 UT and 1200 UT, respectively. The storm of Event 3 had both positive and negative impacts; however, the impacts detected

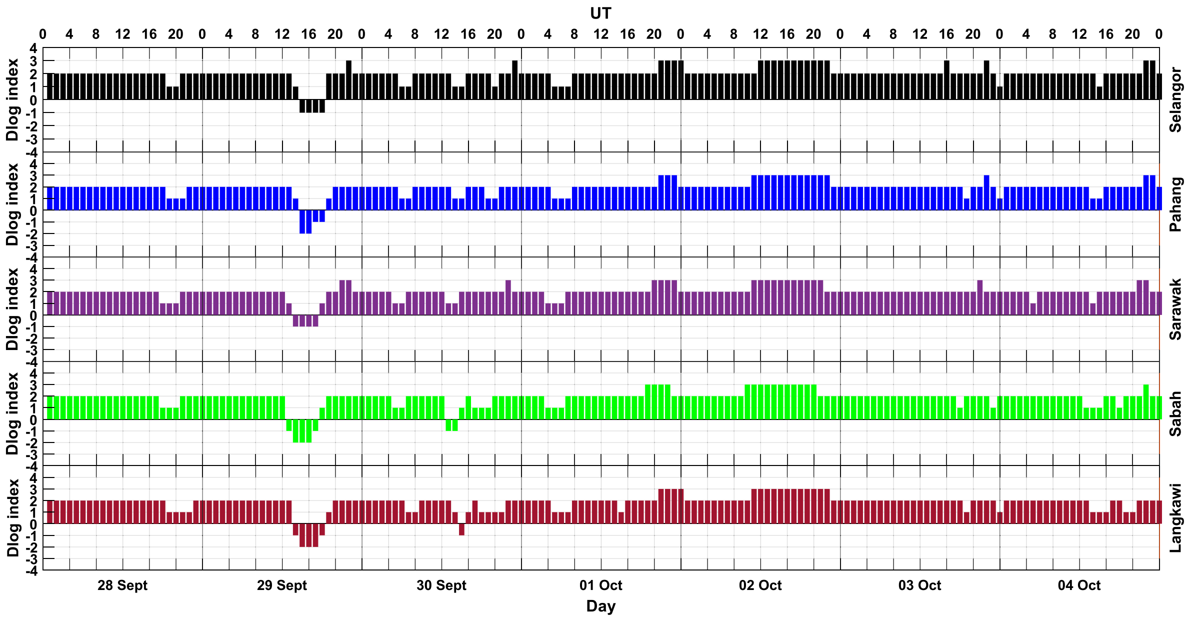

FIGURE 9. Ionospheric disturbance index analysis of different locations over Malaysia from September 28- October 04, 2012. Black color shows the analysis for Selangor (3.06°N, 101.54°E), blue for Pahang (4.18°N, 102.04°E), purple for Sarawak (3.16°N, 113.03°E), green for Sabah (5.04°N, 118.33°E), and red for Langkawi (6.35°N, 99.8°E).

were mostly positive. Negative impact was only detected on September 29, 2012 during the local night-time.

Figure 9 shows the ionospheric disturbance index of different locations for Event 3. This geomagnetic storm had no severe storm effects on the different locations across Malaysia.

IV. DISCUSSION

Result presented in Sections III-A, III-B, and III-C, demonstrated that the disturbance index has a stronger relationship with the 15-day quiet day median. If quiet days are carefully picked, the proposed disturbance index will have a higher degree of correlation. Despite the fact that ionospheric storms are often triggered by geomagnetic storms, the changes in the ionosphere may also be driven by other variables, such as variations in the equatorial ionization anomaly (EIA) and thermospheric wind and composition. As the ionosphere has already been lifted to high elevations by the prompt penetration electric field (PPEF) and the mechanical impacts of the equatorward neutral wind, the composition of change is often ineffectual during the main phase [25]. At sundown, the penetrating electric field and amplified equatorial plasma fountain generate an increase in density that may be felt in the mid-latitude storm. Recent modeling studies have shown that a positive storm may be generated by coupling the penetration electric field with an equatorward neutral wind either during a quiet phase or a storm phase. If this does not occur, plasma that has to excessively high altitudes around the equator will eventually diffuse down to low altitudes, where it will face considerable chemical loss.

Table 3 summarizes the significant storm anomalies which were found over Malaysia based on the new ionospheric disturbance index approach. The time period was converted from UT hour to LT hour to observe the regional effects. Most of the disturbances happened late night from 1800 LT to 2400 LT and during early in the morning namely between 0000 LT to 0600 LT. Event 1 consisted of a powerful storm with positive phase signatures which struck the local area early in the morning, and had a significant change in different locations as described in Section III-A. This effect could have been exacerbated by ionospheric penetration, disturbance dynamo, shielding electric fields, and alterations to the neutral thermosphere. It is likely that the cause of neutral wind during a storm is the rise in O/N2 effects that is brought about by the wind itself as a result of a mechanical or compositional change, with or without electric field penetration [26]. Energy deposited during storms in the upper atmosphere at high latitudes causes thermospheric upwelling to occur there and thermospheric downwelling in the middle and low latitudes. Both the increase in O/N2 and the favorable ionospheric response may be traced back to the downwelling [27].

One or two days prior to the storm's arrival, the negative signs were mostly seen in the afternoon and evening. The disturbance dynamo effect may explain these traits. The disturbance dynamo electric field, which is the reverse of the quiet time field, may form at high latitudes several hours after the storm has deposited energy and momentum, lasting 1-2 days. The downward $\mathbf{E} \times \mathbf{B}$ drift caused by the disturbance dynamo effect inhibits the equatorial plasma fountain, which in turn generates negative storm signatures on the day of the storm on the next day [28], [29].

Events 2 and 3 showed negative signs 2-3 days after the storm. Negative signs imply composition disruption. Neutral

TABLE 3. Summary of significant geomagnetic storm signatures based on the ionospheric disturbance index in the local time period.

Storm Events (2012)	Storm Type	Time period (LT)				
		(00-06) LT	(06-12) LT	(12-18) LT	(18-24) LT	Total (hour)
Event 1 (April 24)	Intense Storm	0	0	0	3	= 3
	Moderate Storm	6	0	0	5	= 11
Event 2 (July 15)	Intense Storm	0	0	0	0	= 0
	Moderate Storm	11	0	0	8	= 19
Event 3 (October 01)	Intense Storm	0	0	0	0	= 0
	Moderate Storm	3	0	3	6	= 12

wind may carry the neutral composition disturbance from high-latitudes to the equatorial areas in the midnight-dawn sector until midday, generating a negative storm effect.

Based on the results presented in Sections III-A, III-B, and III-C, positive storm signatures came first and negative ones subsequently. The major phase of the geomagnetic storms was generated by PPEF and the mechanical impacts of the equatorward winds, while the recovery phase was caused by neutral composition shift. The moderate geomagnetic storms also postponed the onset of negative storms. Intense storms may slow neutral composition transition [30]. Ionospheric storms may have unknown mechanisms. However, experimental findings may guide the development of theoretical explanations.

This ionospheric disturbance index is applicable for high latitude, mid latitude and low mid latitude, as observed by Stanislawska and Gulyaeva [16]. Based on our results, this index is also applicable for other low latitude regions. However, due to the variations of the ionosphere which varies with latitude and longitude, further analysis involving other low latitude regions should be performed.

V. CONCLUSION

Space weather, such as solar storms and geomagnetic disturbances, can reduce the accuracy of GNSS ionospheric models and negatively impair navigation and location systems. The ionosphere responds differently to space weather elements, depending on time and location. In light of this, an ionospheric disturbance index is required for practical purposes. This research therefore examined the ionosphere at low latitudes across different locations during severe and moderate geomagnetic storms in 2012 to establish its perturbation features and its effects. A severe storm was detected in Malaysia on April 24, 2012, with a real storm time delay. Meanwhile, the other two storms which occurred on July 15 and October 01, 2012 over the Malaysian region had no strong effects compared to their actual characteristics. These two storms had positive and negative impacts both before and after the occurrence of the storms. As Malaysia is close to the equator, this index appears to be more relevant to the IMF_Bz (By, GSM, nT). The index is easy to compute and requires no sophisticated technique, and users may specify the suggested ionospheric disturbance index locally, regionally, or globally. Since ionospheric disturbance near equatorial regions shows complex behavior, which is not understandable for many researchers, more study and analysis will therefore be necessary to establish an ionospheric disturbance index with higher accuracy rate for the Malaysian region.

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