Earth’s geomagnetic response to solar wind changes associated with solar events at low latitude regions at the TRE MAGDAS Station

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Abstract. The Sun's magnetic activity influences disturbances that perturb interplanetary space by producing large fluxes of energetic protons, triggering geomagnetic storms and affecting the ground geomagnetic field. The effect of two solar events, namely Coronal Mass Ejection (CME) and Coronal Holes, on geomagnetic indices (SYM/H), solar wind parameters and ground geomagnetic fields has provided magnetic ground data, which were extracted from the Terengganu (TRE, -4.21°N, 175.91°E) Magnetometer (MAGDAS) station, and investigated in this study. Results show that the physical dynamic mechanism in the Earth's magnetosphere is triggered by various solar wind parameters associated with CMEs and Coronal hole events during the minimum solar cycle of 24 at low latitudes. It is important to study solar wind-magnetosphere coupling because it has an impact on ground-based technological systems and human activities.

Keywords: Earth geomagnetic field, solar wind, geomagnetic indices, CME, coronal holes

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1. Introduction

Activities of the Sun, solar winds, magnetosphere, ionosphere, and thermosphere are defined as space weather that influences the performance of space-borne, human health and ground-based technologies [1]. Geomagnetic storms are caused by a variety of solar wind variables associated with solar activity, such as solar flares, coronal mass ejections (CMEs), coronal hole, high solar wind speed and solar energy particles. The increase in solar activity causes large fluxes of energetic protons that form a super
geomagnetic storm [2]. CMEs is a solar phenomenon that contributes to the largest geomagnetic storm caused by high-density plasma when it is associated with the southward Bz component [4]. The formation of CMEs causes regional reconnections in the solar corona where light isotopes and plasmas in the solar corona are spread throughout the solar magnetic field [5]. Kilpua et al. (2019) found that high-speed CMEs are most likely preceded by geoeffective sheaths in the form of high-speed ejection sheaths that possess average high solar wind speeds and magnetic fields, and consequently, intense driving electric fields [6]. The occurrence of geomagnetic storms is mainly caused by CMEs driven by solar winds penetrating into Earth’s magnetospheric system [7][8]. The coronal hole region has open magnetic fields that extend into interplanetary space; thus, high-speed solar winds can escape and interact with the magnetosphere resulting in magnetic storms. Recent studies on the coronal hole region have detected the geo-effectiveness of high wind speeds propagating in interplanetary space [9][10]. Meanwhile, observations have revealed the effect of solar winds and the orientation of interplanetary space on ground geomagnetic fields associated with solar activity. The ground horizontal component has a significant effect on the enhanced solar wind-magnetosphere coupling process. [11][12][13]. The main objective of this paper is to investigate the effects on solar wind parameters, geomagnetic storms and ground horizontal geomagnetic components caused by the occurrence of CMEs and coronal events during solar cycle of 24.

2. Methodology

This study investigated the effects of CMEs and coronal hole activity on solar wind changes, geomagnetic storms and Earth’s horizontal geomagnetic field in low-latitude regions. The geomagnetic storm that measures the symmetric part of the magnetospheric ring current activity at the equator is SYM/H. The Disturbance storm time (Dst) index and SYM/H are similar parameters, while the comparison of Dst Index and SYMH was only time interval. The Dst index was gauged every 3 hours and SYM H was gauged per minute/data. Geomagnetic storms are classified according to weak (-30 < Dst < -50 nT), moderate (-50< Dst < -100 nT), intense (-200< Dst < -100 nT) and super storm (Dst < -200) stages. This study considered four solar wind parameters, such as solar wind speed (V), solar wind dynamic pressure (P), solar wind input energy (IE) and interplanetary magnetic field (IMF-Bz). Solar wind input energy is indicated as Epsilon (ε) and calculated using the original Akasofu parameter, as shown in Equation (1) [14]. Data concerning coronal hole and CME events were obtained from the SolarHam website (https://www.solarham.net/regions.htm), Solar and Heliospheric Observatory (SOHO) website (https://cdaw.gsfc.nasa.gov/CME_list/) and space weather live (https://www.spaceweatherlive.com/). Meanwhile, the SYM/H and solar wind parameters data were acquired from the OMNI website (https://omniweb.gsfc.nasa.gov/form/omni_min.html), which was provided by the Space Physics Data Facility (SPDF) based at NASA’s Goddard Space Flight Center in Greenbelt, MD U.S.A. The data used were high resolution with a one-minute interval.

Solar wind input energy $= \frac{4\pi}{\nu_0} VB^2 \sin^4 \left( \frac{\Theta}{2} \right) I_s 2 \text{ (erg/s)}$ (1)

where, $V$= solar wind speed (kms$^{-1}$), $B$ = magnitude of IMF (nT) and $I_s$ are the 7 Earth radii. The polar angle of the IMF vector ($\Theta$), projected onto the Y-Z plane, namely; $[\tan^{-1} (B_y/B_z)]$ for $B_z > 0$ and $[180^o - \tan^{-1} (B_y/B_z)]$ for $B_z < 0$.

The horizontal geomagnetic field (H-component) was extracted from MAGDAS magnetometer with one-second data interval, which were then recorded and transferred to Japan. Data were collected from the MAGDAS magnetometer (MAGDAS-II) at TRE station, which is located at the East Coast Environmental Research Institute (ESERI) in Universiti Sultan Zainal Abidin, Terengganu, Malaysia. Details of selected MAGDAS magnetometer stations are listed in Table 1. The MAGDAS magnetometer is a ring core-type fluxgate magnetometer that measures three components in the geomagnetic field in the ground, namely the horizontal component (H), declination component (D) and the vertical component (Z).

The data were collected from the MAGDAS magnetometer (MAGDAS-II) at TRE station, which is located at the East Coast Environmental Research Institute (ESERI) in Universiti Sultan Zainal Abidin, Terengganu, Malaysia. Details of selected MAGDAS magnetometer stations are listed in Table 1. The MAGDAS magnetometer is a ring core-type fluxgate magnetometer that measures three components in the geomagnetic field in the ground, namely the horizontal component (H), declination component (D) and the vertical component (Z).
3. Result and Discussion

This section presents an analysis of the dependence of solar wind changes on the Earth’s horizontal geomagnetic field (H-component) at low latitude regions with data obtained from a selected MAGDAS magnetometer station, which is the TRE station. Figure 1 depicts the variety of solar wind changes and its effects on ground geomagnetic field (H-component) from 1st March to 30th March 2017. On 1st March 2017, the IMF-Bz, V, P, and IE responded to the occurrence of a moderate geomagnetic storm (SYM-H = -70 nT). High solar wind pressure (P = 3-14 nPa) and high solar wind speed (V = 400-700 km s⁻¹) carrying input energy (0.3-3.3 x10¹⁹ ergs) reacted to the moderate geomagnetic storm on 1st March 2017 in a strong southward Bz condition (5 to -7 nT). This moderate storm corresponded to a change in the H-component, which reached values of (4.150-4.142 x10⁴ nT) at the same time.

The weak geomagnetic storm (SYM/H = -30 nT) occurred in the middle of the 14th of March 2017 as a result of CME-associated coronal hole events on the 12th of March 2017. The weak storm was caused by by a weak solar wind pressure (P =2-3 nPa) with low solar wind speed (V=350-320 km s⁻¹) in southward Bz orientation (0 to -5 nT) as well as low solar wind energy measuring (0-0.6 x10¹⁹ ergs) conveyed into Earth’s magnetosphere. The influence of solar wind parameters and CME-associated coronal hole events on the H-component is not shown in Figure 1 due to instantaneous fluctuations during the same period caused by artificial noise.

In addition, it is noticeable that increases in solar wind speed (V =500-600 km s⁻¹), solar wind dynamic pressure (P =4-2 nPa) and solar wind input energy (1.5-0.5x10¹⁹ ergs) caused a weak geomagnetic storm (SYM/H = -50 nT) on 22nd March 2017 with a weak southward Bz orientation (4 to -3 nT). As shown in Figure 2, the H-component decreased as the solar wind changed with a value of (4.148 - 4.140 x10⁴ nT). In the early part of 28th March 2017, there was a moderate geomagnetic storm (SYM/H = -60 nT) caused by solar wind changes with a high solar wind speed (V=600-750 km s⁻¹) associated with dynamic pressure (2-5 nPa), a strong southward Bz condition (10 to -10 nT) and a high energy transfer rate of (0-2 x10¹⁹ ergs). The analysis also indicated a moderate geomagnetic storm as well as change of the H-component on 28th March 2017, as shown in Figure 2 (f). The H-component is decreased with values varying (4.150-4.140 x10⁴ nT). At the end of March, the Bz component showed a weak antiparallel orientation to Earth’s magnetic field with values ranging from (0 to -6 nT), in response to a weak geomagnetic storm (SYM H¹ = -30 nT) on 30th March 2017. At the same time, there was a slight increasing trend in solar wind speed (V =580-620 km s⁻¹) and dynamic pressure (P =1-3 nPa) with solar wind input energy varying from (IE =0.3-0.6 x10¹⁹ ergs). As shown in Figures 1(e) and (f), the drop in SYM/H is equivalent to a very small decline in the H-component, which varied from (4.150 4.148 x10⁴ nT).

### Table 1. Details of selected MAGDAS magnetometer location.

| Stations  | Abbreviation | Geographic Latitude (°) | Geographic Longitude (°) | Geomagnetic Latitude (°) | Geomagnetic Longitude (°) | Region |
|-----------|--------------|-------------------------|--------------------------|--------------------------|--------------------------|--------|
| Terengganu| TRE          | 5.23                    | 103.04                   | -4.21                    | 175.91                   | Malaysia |


Figure 1. The variations in solar wind parameters a) IMF-Bz b) speed c) dynamic pressure d) solar wind input energy and geomagnetic storm e) SYM/H and ground geomagnetic field f) H-component of TRE magnetometer station.
Table 2. List of selected CMEs and Coronal hole.

| Date             | CME speed (km s\(^{-1}\)) | Time (UT)  | Coronal Hole | Time (UT) |
|------------------|-----------------------------|------------|--------------|-----------|
| 28\(^{th}\) February 2017 | 118                         | 23:12:12   | YES          | 10:26:17  |
| 12\(^{th}\) March 2017     | 444                         | 00:48:00   | YES          | 10:24:10  |
| 20\(^{th}\) March 2017     | 176                         | 00:48:01   | YES          | 10:25:53  |
| 27\(^{th}\) March 2017     | 338                         | 12:00:00   | YES          | 10:40:29  |

According to Table 2, the association between CMEs and coronal hole events on 28\(^{th}\) February 2017 responded to changes in solar winds, resulting in a weak geomagnetic storm on 1\(^{st}\) March, 2017. Large amounts of plasma ejected from the CME event had driven the high solar wind to interact with the Earth’s magnetic field, resulting in a geomagnetic disturbance [15]. This analysis shows that high dynamic pressure had compressed the Earth’s magnetosphere with plasma ejections resulting in strong magnetic reconnection and moderate geomagnetic storms [16]. The plasma ejection is driven by a high solar wind speed in a southward Bz condition that transferred high input energy in the magnetosphere. These solar wind changes associated with CME and coronal hole events influenced the physical processes in the magnetosphere, causing a decrease in the H-component [17]. On 14\(^{th}\) March 2017, a weak geomagnetic storm was also generated. According to the analysis, small coronal holes with weak solar wind pressure had contributed to low magnetosphere reconnection associated with southward Bz rotation, which caused low plasma densities and magnetic flux ejected into the inner magnetosphere. Tokumaru et al. [19] had supported this finding [18]. Figure 3 depicts the image of selected coronal hole events. However, disturbance in the ground caused by changes in solar winds was not shown due to artificial noise, which could be caused by man-made noise. Based on Figure 2, this is consistent with a short fluctuation in the H-component difference (diff-H) plot during the same period. The diff-H plot is used to estimate artificial noise on the ground in the ULF range.

The occurrence of a weak geomagnetic storm on 22\(^{nd}\) March, 2017 is indicated by a slow magnetosphere reconnection and low plasma injection process caused by the low solar wind’s dynamic pressure in a weak southward Bz condition. At same time, it affected solar wind speed and conveyed a low energy density magnetic reconnection. Meanwhile, high solar wind changes associated with CME and coronal hole events on 27\(^{th}\) March 2017 contributed to a moderate geomagnetic storm on 28\(^{th}\) March 2017. This can be explained by high plasma densities caused by CME expansion and the expansion of high solar wind speed flow-out from coronal holes injected into the magnetosphere by solar wind pressure in strong southward Bz condition [19]. According to Abuninna et al. [21], northern and southern holes produced enhanced geomagnetic activity, as shown in Figure 2. The coronal hole area on 27\(^{th}\) March 2017 was in the southern hemisphere [20]. The high magnetic reconnection in magnetosphere resulted in moderate storm, which was followed by a variation in the ground geomagnetic field with a decrease in the H-component. Finally, the analysis concluded that the wake of a weak storm on 30\(^{th}\) March 2017 was triggered by the low effect of CME and coronal hole events on 27\(^{th}\) March 2017, which contributed to a low acceleration of solar winds to Earth, resulting in a poor plasma environment in the magnetosphere [21]. Concurrently, the ground geomagnetic field had shown a decreasing trend in weak storms, indicating that the magnetosphere-ionosphere response was in action.
4. Conclusion
The analysis in this study shows that CME and coronal hole events have an impact on the occurrence of weak and moderate geomagnetic storms during the minimum solar cycle of 24. The huge plasma cloud from the CMEs driven by high solar winds with compressed energy were ejected into the magnetosphere due to high solar wind pressure in a strong southward Bz condition, thus, generating a moderate geomagnetic storm on 1st March 2017 and 27th March 2017. In addition, the analysis suggested that the expansion of high solar wind speed flow-out from coronal holes in the southern hemisphere injected into the magnetosphere by high solar wind pressure also contributed to a moderate storm. In this study, a small coronal hole on 12th March 2017 had caused low solar wind speeds and weak solar wind pressure, which ejected fewer ions and particles into the magnetospheric system, implying a weak storm on 14th March 2017. The development of a weak storm on 22nd March 2017 is explained by a weak southward Bz condition with weak solar wind pressure that caused lesser plasma densities ejected into the magnetosphere, resulting in a slow magnetic reconnection process. Following that, solar wind changes
associated with CME and coronal hole events had revealed the response to geomagnetic storms and the current system that penetrate the ground, resulting in a reduction of H-component at the TRE station. It has been found that a high reduction in the H-component corresponds to a moderate storm occurrence compared to a decreased H-component during a weak storm. However, changes in the H-component during a weak storm on 14th March 2017 did not occur, resulting in a rapid fluctuation caused by artificial noise on the ground.

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