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Key Points:
• A least-square fitting method has been used to evaluate the magnetic signatures disturbance dynamo electric fields
• Differences in the magnetic signatures of CME and high-speed solar wind streams generated magnetic storms are identified
• We have analyzed disturbance dynamo in three different longitudinal sectors, as affected by seasonal and longitudinal variations

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Abstract  Ionospheric disturbance dynamo is one of the main processes that causes perturbations in the upper atmosphere during a magnetic storm. We present a new method, based on the least square fitting, for estimation of the magnetic signatures associated with ionospheric disturbance currents. Using a wavelet semblance analysis, the durations of disturbance dynamo electric fields have been investigated at three longitudinal sectors. For that we have analyzed the disturbance dynamo (D_{dyn}) for 19 magnetic storms. It has been found that during CME generated storms magnetic signature of D_{dyn} may be observed—depending on strength of the storm as well as on the duration of interplanetary magnetic field (IMF) Bz southward—in one, two or all three longitudes. The Oscillatory behavior of IMF Bz during the high-speed solar wind streams (HSSWs) generates D_{dyn} globally and the corresponding effects are observed at all low latitude magnetic observatories. In this regard, the Joule heating estimation shows that CME and HSSWs generated storms have very different patterns. The D_{dyn} duration is found to be maximum for the storms occurring during equinox season. Moreover, the HSSWs events are more likely to cause—because of the oscillatory IMF Bz—long lasting D_{dyn} as compared to CME generated counterpart. This study presents a detailed analysis of disturbance dynamo as affected by longitudinal and seasonal variations. In this regard the difference in magnetic signatures, of CME and HSSWs originated storms, have been highlighted.

Plain Language Summary  Space weather activities significantly perturb the quiet time ionosphere through various coupling mechanisms. Ionospheric disturbance dynamo is one of the main processes that causes perturbations in the upper atmosphere during a magnetic storm. We present a new method for estimation of the magnetic signatures associated with ionospheric disturbance currents. The durations of disturbance dynamo electric fields have been investigated at three longitudinal sectors for 19 magnetic storms. It has been found that during CME generated storms magnetic signature of D_{dyn} may be observed in one, two or all three longitudes. The Oscillatory behavior of IMF Bz during the high speed solar wind streams (HSSWs) generates D_{dyn} globally and the corresponding effects are observed at all low latitude magnetic observatories. In this regard, the Joule heating estimation shows that CME and HSSWs generated storms have very different patterns. The D_{dyn} duration is found to be maximum for the storms occurring during equinox season. Moreover, the HSSWs events are more likely to cause long lasting D_{dyn} as compared to CME generated counterpart. This study presents a detailed analysis of disturbance dynamo of CME and HSSWs originated storms.

1. Introduction

It was in 1722, when Graham observed the regular variation of the Earth’s magnetic field. It was also noted that sometimes this variation gets disturbed (Stern, 2002). In 1808 Humboldt introduced the concept of magnetic storms to understand the magnetic field variations associated with solar disturbances (Botting, 1994). Balfour Stewart in 1880 presented a possible mechanism to explain the regular variation of the Earth’s magnetic field, where he proposed the circulation of electric currents above the Earth. The existence of such currents was confirmed by later studies (Stewart, 1880). In 1901, with the first transatlantic link, Marconi demonstrated the existence of ionosphere, in this regard Breit and Tuve carried a survey of the ionosphere in 1925 (Breit & Tuve, 1925).
With increasingly powerful magnetometers the measurements of the magnetic field, on Earth as well as on board satellites, have become more accurate and the corresponding magnetic data are interpreted in terms of equivalent electric currents. Incoherent scatter radars allow the measurements of ionospheric electric currents (Mazaudier, 1982; Mazaudier & Bernard, 1985; Mazaudier & Blanc, 1982), for example, the ones situated at Chatanika in the auroral zone (Brekke et al., 1974), in middle latitudes at Millstone-Hill/USA and Saint Santin/France (Carpenter & Kirchhoff, 1975; Mazaudier, 1982; Mazaudier & Bernard, 1985) and in low latitudes at Arecibo/USA (Harper, 1977). As such measurements are rare and very expensive, the magnetometer has remained a useful instrument for describing the real electric currents.

Using the theory of the ionospheric regular dynamo (Chapman & Bartels, 1940) it is possible to understand the regular variation of the Earth’s magnetic field as generated by the circulation of neutral atmosphere in the dynamo region (90–150 km). The positive ions are preferably driven by the collisions with neutrals which thus have a speed quite different from electrons, which are under the sole influence of a Lorentz force. Consequently, there is a creation of electric currents in the ionosphere (Balfour Stewart’s hypothesis; Stewart, 1880).

During a magnetic quiet period, the ionospheric regular dynamo is the origin of the Solar quiet (Sq) and Equatorial Electrojet (EEJ) current systems, respectively at middle and equatorial latitudes. Whereas for the periods of a robust magnetic activity, strong ionospheric electric currents develop in the auroral zone. These currents—named as auroral electrojets—dissipate energy by the Joule heating effect, which in turn modifies the temperature, pressure and movement of the thermosphere. The disturbed thermospheric winds spread toward mid and low latitudes and, by the dynamo effect, create disturbed ionospheric electric fields, that is, DDEF. Blanc and Richmond (1980) presented the first numerical simulation of the Ionospheric disturbance dynamo. In the present study we have focused on the magnetic signatures of this physical process. Mazaudier (1985) observed the disturbance winds—due to Joule heating—by using the data of incoherent scatter radar, their findings are consistent with predictions of the Blanc and Richmond model (1980).

Another solar wind and/or magnetosphere activity associated with auroral electrojets, and results in simultaneous penetration of ionospheric electric fields from high to low-latitudes at all longitudes, is the so-called prompt penetration of the electric field (PPEF) (Nishida, 1968). Vasyliunas (1970) established the first model of the penetration of magnetospheric convection by reproducing the two current cells of the DP2 equivalent current system. There are also electric currents in the magnetosphere (Cole, 1966; Fukushima & Kamide, 1973) which influence the magnetic observations around the globe and one needs to remove the effects of these currents while studying ionospheric dynamics. Thus, the magnetic signature of the disturbed ionospheric dynamo must be extracted from a complex magnetic signal, which is an integrated effect of different ionospheric and magnetospheric electric current systems circulating in the terrestrial environment.

Fejer et al. (1983) were the first to point out the effect of PPEF and DDEF on incoherent scatter radar data of Jicamarca. They observed the electric field due to the penetration of the magnetospheric convection (PPEF) on the day of a magnetic storm, and the electric field due to the disturbed ionospheric dynamo (DDEF) during the recovery phase of a storm. Likewise, Le Huy and Amory-Mazaudier (2005) in their study selected the cases having minimum auroral activity during the recovery phase of storm and thus highlighted the $D_{\text{dyn}}$, magnetic signature of the disturbed ionospheric dynamo. Zaka et al. (2010) presented the latitudinal variations of disturbance dynamo generated during the two events of 1993 and compared the results with DP2 disturbance. Fathy et al. (2014) analyzed the longitudinal variation of disturbance dynamo during the coronal hole event of April 2010. Fejer et al. (2017) summarized the recent progresses made to analyze the disturbance dynamo and its effect at middle and low latitudes. Nava et al. (2016), Zaouar et al. (2017), Bulusu et al. (2018) and Younas et al. (2020) studied the temporal variation of disturbance dynamo generated during different storms by applying the band pass filter techniques. However, the $D_{\text{dyn}}$ can have Sq like variations, which may not be considered as an effect of DDEF. Hence, applying simple band pass filters to $D_{\text{dyn}}$ may overestimate the duration of DDEF. Here, we have applied a new method, based on least square fitting, for the calculations of ionospheric disturbance current. Using a wavelet-based semblance analysis, we have estimated $D_{\text{dyn}}$ by separating only those periods which show truly anti-Sq variations. For that we have analyzed 19 different magnetic storms of various origins.
The rest of this article is organized as follows; Section 2 describes the methodology used in this study, while Section 3 presents five events of different categories. In Section 4, we have discussed $D_{\text{dyn}}$ variations with Joule heating. The summary and conclusion of the study is presented in Section 5.

2. Methodology

2.1. Interplanetary Data

Two of the key parameters, namely interplanetary magnetic field (IMF) and solar wind speed, characterizing the space weather activities are provided by Advanced Composition Explorer (http://www.srl.caltech.edu/ACE/) via OMNIWEB data center (https://omniweb.gsfc.nasa.gov/).

2.2. Magnetic Indices

The SYM-H, ASYM-H, and AE data is obtained from World Data Center for Geomagnetism, Kyoto Japan. Here SYM-H and ASYM-H indices are, respectively the estimation of symmetric and asymmetric part of storm-time ring currents, while AE is used to assess auroral currents (http://wdc.kugi.kyoto-u.ac.jp/).

2.3. Magnetic Observatories and Magnetic Data Analysis

For all the considered 19 magnetic storms, we have analyzed the magnetic data of observatories located at low latitude in Asian sector (Guam, GUA), African region (M’bour, MBO) and American sector (Kourou, KOU). For some of the cases we have also included the observations of Adis Ababa (AAE) and Bac Lieu (BCL). The geographical locations and coordinates of the considered magnetic observatories are shown, respectively in Figure 1 and Table 1. The magnetic data of these observatories is provided by INTERMAGNET (https://www.intermagnet.org/).

| Station ID | Sector | Latitude | Longitude | Magnetic dip |
|------------|--------|----------|-----------|--------------|
| GUA        | Asia   | 13.59    | 144.87    | 12.35        |
| BCL        | Asia   | 9.28     | 105.73    | 1.33         |
| AAE        | Africa | 9.03     | 38.76     | 0.43         |
| MBO        | Africa | 14.38    | -16.97    | 6.99         |
| KOU        | America| 5.21     | -52.93    | 15.25        |
| HUA        | America| -12.05   | -75.01    | 0.62         |

Table 1  
Geomagnetic and Geographic Coordinates of the Considered Magnetic Observatories

Figure 1. Location of the magnetic observatories.
The variation in the horizontal component of magnetic field (\(H\)) is used for estimating the ionospheric disturbance currents (\(D_{\text{iono}}\)). The H component of magnetic field is computed using the eastward (\(X\)) and northward (\(Y\)) components, that is,
\[
H = \sqrt{X^2 + Y^2}.
\]
During a magnetic storm, the \(H\) component of Earth’s magnetic field can be decomposed as the following superposition
\[
H = H_o + S_H + D_{\text{mag}} + D_{\text{iono}},
\]
or, equivalently
\[
D_{\text{iono}} = \left[ H - H_o - D_{\text{mag}} \right] - S_H.
\]
Here \(D_{\text{mag}}\) is the disturbance due to magnetospheric currents and \(\Delta H = H - H_o\) denoting the change in \(H\), after subtracting the corresponding five hours average of local midnight value \(H_o\). The disturbance in the \(H\) at low latitudes is mainly influenced by the zonally symmetric ring currents—whose strength is estimated by the high resolution (1-min) SYMH index. For an accurate investigation of ionospheric electric field, one needs to remove the effect of these magnetospheric currents from the magnetic data. For that Choudhary et al. (2011) and Yamazaki and Maute (2016) have proposed a least square technique that is, by fitting, at a given station, the linear trends to nighttime data of the \(H\) component and SYMH index. The fitting equation can be written as
\[
H^n = C_1 + C_2 T^n + C_3 \text{SYMH}^n,
\]
where \(T\) is the time in Julian days. Equation 2 is for five hours nighttime data of each day \(n\). The coefficients \(C_1\), \(C_2\), and \(C_3\) are determined by the method as described below. Consider the equation
\[
H^n = A^n \times M,
\]
where \(H^n\) contains the \(H\) data during the nighttime, that is,
\[
H^n = \begin{pmatrix}
H^n_1 \\
H^n_2 \\
\vdots \\
H^n_k
\end{pmatrix},
\]
with \(k\) denoting the total number of nighttime data points and \(A^n\) is a matrix contains the \(T\) and SYMH index, as follows
\[
A^n = \begin{pmatrix}
1 & T^n_1 & \text{SYMH}^n_1 \\
1 & T^n_2 & \text{SYMH}^n_2 \\
\vdots & \vdots & \vdots \\
1 & T^n_k & \text{SYMH}^n_k
\end{pmatrix}.
\]
The symbol \(M\) in Equation 3 depicts a vector which contain the fitting coefficient, namely
\[
M = \begin{pmatrix}
C_1 \\
C_2 \\
C_3
\end{pmatrix}.
\]
After calculating \(H^n\) and \(T^n\), the fitting coefficients can be determined using the least square estimation technique (Yamazaki & Maute, 2016). For that one can write
\[
M = \left( A^n \right)^T \left( A^n \right)^{-1} \times \left( A^n \right)^T \left( H^n \right)^{-1}.
\]
where $t$ denotes the transpose matrix operation. Once the coefficients $C_1$, $C_2$, and $C_3$ are known, the corrected variation in $H$ component can be found by the relation

$$\Delta H - D_{\text{map}} = H - \left( C_1 + C_2 \cdot T + C_3 \cdot \text{SYM}H \right).$$  \hfill (8)

The daily quiet variation ($S_q$) is calculated from $\Delta H$ over five quiet days ($j = 5$), that is,

$$S_j^H = \frac{1}{j} \sum_{i=1}^{j} \Delta H_i.$$

Finally, we can determine the desired ionospheric disturbance current ($D_{\text{iono}}$) by using Equations 8 and 9 in Equation 1.

The magnetic disturbance $D_{\text{iono}}$ during a storm can be associated with two phenomena, namely DP2 and $D_{\text{dyn}}$. Here the former is a short period magnetic disturbance associated with PPEF (Nishida et al., 1966) and is simultaneously observed at all longitudes during the main phase of a magnetic storm (Nishida, 1968). Whereas the $D_{\text{dyn}}$ is associated with DDEF (Bulusu et al., 2018; Fathy et al., 2014; Le Huy & Amory-Mazaudier, 2005) and results in the anti Sq oscillations, which are often observed during the recovery phase. Moreover, the $D_{\text{iono}}$ has also contribution from other sources such as partial ring current during the early phase of a storm and sometime Sq-like oscillations during the recovery phase, which cannot be associated $D_{\text{dyn}}$ (Younas et al., 2020). Hence, simply applying filters to $D_{\text{iono}}$ for the estimation of $D_{\text{dyn}}$ may not provide an accurate information. Here, we propose a wavelet-based method, namely semblance analysis (Cooper & Cowan, 2008) for the extraction of anti-Sq oscillation. Semblance analysis compares the local phase relation between two data sets as function of time and wavelength. This can be done by performing a cross wavelet transform (CWT) of two time series (Torrence & Compo, 1998) which gives amplitude ($\alpha$) and the local phase ($\theta = \tan^{-1}\left( \text{Im(CWT)} / \text{Re(CWT)} \right)$), where Im and Re denotes the imaginary and real parts, respectively. The semblance is then evaluated as (Cooper & Cowan, 2008)

$$\text{Semblance} = \cos^n (\theta),$$  \hfill (10)

where $n$ is a positive odd integer. From above equation it is clear that the semblance ranges from $-1$ (anti-correlated) to 1 (positive correlated).

Finally, $D_{\text{dyn}}$ can be computed by comparing Sq variation of a station with corresponding $D_{\text{iono}}$ value, followed by the extraction of only those periods which are anti-correlated with Sq oscillation, that is,

$$D_{\text{dyn}} = \alpha \left[ \text{anticorr} \left( \text{semblance} \left( \text{Sq}, D_{\text{iono}} \right) \right) \right].$$  \hfill (11)

Here, the function semblance($\text{Sq}, D_{\text{iono}}$) determines the correlation between two signals. Since we are interested in anti-Sq signatures, thus the contributions having a positive correlation with Sq are neglected. The factor $\alpha$ in Equation 11 denotes a cross-wavelet power amplitude, which quantifies the strength of anti-correlated periods. The semblance analysis provides a phase correlation between two signals which ranges from $-1$ (anti-correlated) to 1 (positive correlated). However, it does not provide the strength of such correlation (or anti-correlation), for example, signals A and B can have semblance of $-1$, similarly A and C may also have the same semblance, but they can have very different strengths. Such difference of strength in two signals is quantified by the factor $\alpha$, as determined by CWT. Thus, the semblance is further multiplied by $\alpha$ to find the relative strength of anti-correlated periods (see Equation 9 of Cooper & Cowan, 2008). Duration of $D_{\text{dyn}}$ is estimated by considering the time interval from the start of disturbance till the semblance reduces to a threshold value 0.3, after which there is a weak anti-correlation and cannot be related to the signatures of $D_{\text{iono}}$. In principle, such weak signals remain non-zero for relatively longer duration.

### 2.4. Joule Heating of Upper Atmosphere

Joule heating ($J_H$) of upper atmosphere has been estimated through the Space Weather Modeling Framework (SWMF) version v20140611. We run the SWMF model remotely on Community Coordinated Modeling Center (CCMC) computers (http://ccmc.gsfc.nasa.gov) through various model runs. The corresponding Joule heating is calculated using height integrated total ionospheric current ($J$) and Pedersen conductance ($\sigma_P$) as follows (Kalafatoglu Eyiguler et al., 2018)
Here $J_x$, $J_y$, and $J_z$ are ionospheric currents flowing along East, North, and upward directions, respectively.

3. Results

3.1. Case 1

Figure 2a shows the global parameters, namely (from top to bottom) IMF (nT), Bz component of IMF (nT), solar wind speed (km/s), the AE index (nT), ASYM-H index (nT) and SYM-H index, from March 30, 2001 to April 05, 2001. The arrival of CME, as indicated by sudden storm commencement (SSC), is shown by a vertical dotted line on March 31 at 0052 UT. The IMF increases rapidly soon after the SSC and reaches its maximum value of 72 nT at 0122 UT, followed by a gradual decrease during the late hours of April 02 and eventually returns to its pre-storm value. The CME is associated with an enhancement in IMF (5.54–21.97 nT) as well as in the Bz component of IMF (1.52–18.9 nT). Solar wind speed increases from 420 to 650 km/s, similar trends are observed in SYM-H (−9–124 nT) and ASYM-H (10–128 nT). During this storm, the IMF Bz has started oscillating after the SSC and at 0530 UT turned southward for a long duration (till 0820 UT) having a minimum value of −49 nT at 0624 UT. The second phase of southward directed Bz started at 1430 UT and remained there till 2210 UT with a minimum value of −36 nT. The main phase (MP) has started at 0440 UT and lasted till 0810 UT with a minimum value of SYM-H index to be −437 nT. During the MP, the AE index has shown a large increase with a maximum value of 1,200 nT. The recovery phase (RP) of this storm started at 0812 UT and lasted till the April 04 with a long period southward directed IMF Bz from 1430 to 2210 UT on March 31, 2001. The AE index shows multiple peaks during the RP with its maximum value 2,407 nT observed at 1711 UT on March 31.

Figure 2b shows the magnetic variation at (from top to bottom) GUA (Asia), MBO (Africa) and KOU (America) from March 31 to April 04, 2001. Each panel represents $D_{\text{iono}}$ (red), Sq (blue), and SYM-H index (black). We can observe an anti-Sq signature in $D_{\text{iono}}$ at all the stations on March 31 and April 01, 2001.

In Figure 2c, we present $D_{\text{dyn}}$, computed using the method as described in Equation 11, at the three magnetic observatories, namely GUA, MBO and KOU (top to bottom) from March 30 to April 04, 2001. Vertical axis presents period of oscillations, where the color bar corresponds to the normalized strength of $D_{\text{dyn}}$ disturbance at each station. A large enhancement is observed in $D_{\text{dyn}}$ first in America followed by Asia and Africa. At the Asian sector, $D_{\text{dyn}}$ has started on April 1 around 0930 UT and lasted till 1145 UT of April 03 with a temporal duration of 2.1 days. Whereas, at the African (American) sector, $D_{\text{dyn}}$ started around 0521 UT April 01 (0650 UT on March 31) and lasted till 1350 UT (1800 UT) April 03 having a temporal duration of around 2.4 (3.5) days. Moreover, we note that the period of $D_{\text{dyn}}$ disturbance is centered around 20–28 h.

3.2. Case 2

Figure 3a presents the same analysis as in Figure 2a for a period March 15–20, 2013. The CME strikes the Earth on March 17 at 0545 UT as indicated by a vertical dotted line. The compressional phase (CP) of storm has lasted for 1.5 h with SYM-H index having a maximum value of 33 nT. The MP started around 0715 UT and lasted till 2244 UT and SYM-H index reaches a minimum value of −129 nT. The ASYM-H index depicts a large increase with a maximum value of 171 nT at 1230 UT on March 17, 2013. The IMF shows an increasing trend from 4 to 22 nT, while Bz component of IMF starts oscillating in the southward direction and remains there till 2100 UT. The solar wind speed increases from 420 to 750 km/s while AE index shows a major auroral activity after the CME with a maximum peak (2,690 nT) observed at 1650 UT.

In Figure 3b, we present the same analysis as we did for Figure 2b but from March 15 to March 20, 2015. This CME strikes at 0545 UT, thus during the MP of the considered storm GUA was on the night side. The $D_{\text{iono}}$ shows large positive values at GUA. An anti-Sq trend is evident at MBO and KOU on March 17 and 18, 2013, respectively.
Figure 2.
Figure 3c is the same as Figure 2c for the period March 15–18, 2013. The Asian sector (GUA) does not show any evidence of $D_{\text{dyn}}$, whereas we can observe a period of $D_{\text{dyn}}$ disturbance at MBO and KOU, respectively on March 17 and 18, 2013. Temporal duration of $D_{\text{dyn}}$ at MBO and KOU is 1.5 and 1.2 days, orderly.

3.3. Case 3

Figure 4a is the same as Figure 2a but from September 25–30, 2001. The shock of CME, as detected by SSC, is indicated by a vertical line on September 25 at 1945 UT. The CP of this storm has lasted till 2230 UT (3.5 h) during which the value of IMF increases from 04 to 36 nT, solar wind speed changes from 360 to 660 km/s and ASYM-H index enhances from 20 to 173 nT. The MP has lasted till 0117 UT with SYM-H taking its minimum value of $-115$ nT. The auroral activity remains high till the mid-day of September 26, 2001 with a maximum peak of 2,500 nT at 2215 UT on September 25.

Figure 4b is same as Figure 2b for a period September 25–30, 2001. The anti-Sq trend is detected at GUA station only on September 26, while MBO and KOU have not shown any anti-Sq oscillation during the RP. This fact is consistent with Figure 4c which shows that for this particular storm the $D_{\text{dyn}}$ disturbance is found only in the Asian sector (GUA). The duration of $D_{\text{dyn}}$ at GUA is about 1.8 days (from September 25 1900 UT to September 25 1700 UT).

3.4. Case 4

Figure 5 corresponds to the space weather event of April 4–10, 2010. This case has a weak CME at the beginning with streams of HSSWs lasting till April 10, 2010. In Figure 5a, we present the same analysis as in Figure 2a but for the period April 4–10, 2010. The arrival of a weak CME is marked by dotted vertical line on April 5, 2010 at 0740 UT. This CME is associated with an increase in IMF (4–21 nT), IMF Bz (3–18 nT) and the solar wind speed reaches 500 to 810 km/s. Then, IMF Bz starts oscillating till April 10, 2010 which is a key indicator of the HSSW streams. The AE index remained high (1,000 nT>) till April 10, 2010. In Figure 5b the anti-Sq oscillation in $D_{\text{iono}}$ is observed at all three stations for the whole considered period, which is also confirmed in $D_{\text{dyn}}$ plots, generated by semblance analysis, in Figure 5c. The duration of $D_{\text{dyn}}$ is different at all three longitudes, for example, the longest $D_{\text{dyn}}$ disturbance is observed at Africa with the duration of 4.5 days followed by America and Asia lasting, respectively for 4.2 and 3.9 days.

3.5. Case 5

Figure 6 corresponds to the case of HSSWs that occurred in August 2010. Various global parameters describing the geomagnetic activity are presented in Figure 6a which is the same as Figure 2a but from August 20 to August 31, 2010. The arrival of HSSWs is marked by a vertical line dotted line on August 23 at 2313 UT. This event is associated with an increase in IMF (6–22 nT), Bz component of IMF (0–16.7 nT), solar wind speed (285 km/s to 700 km/s), and SYM-H index (18–59 nT). The Earth remains under the influence of HSSWs from August 23 to August 30, 2010 as indicated by solar wind speed and oscillatory IMF Bz during a considered period.

Figure 6b is the same as Figure 2b but for a period August 20–29, 2010. Here one can observe the presence of anti-Sq signature at all the stations till August 29. Figure 5c corresponds to $D_{\text{dyn}}$ at three low latitude stations (GUA, MBO, KOU) located at three longitudinal sectors (Asia, Africa, America) from August 22 to August 30, 2010. The $D_{\text{dyn}}$ disturbance starts first in the Asian sector followed by Africa and America, respectively. This apparent difference in the response of different sectors might be due to the local time of the stations. The temporal duration of $D_{\text{dyn}}$ is maximum in Asia, followed successively by Africa and America.

Figure 2. (a) Global Parameters, (from top to bottom): IMF in nano tesla, Bz component of IMF in nano tesla, solar wind speed in km/s, AE index in nano tesla, ASYM-H index in nano tesla, and SYM-H in nano tesla from March 30 to April 05, 2001. (b) Magnetic variations at three observatories located in three regions (from top to bottom): GUA (Asia), MBO (Africa), and KOU (America) from March 30 to April 04, 2001. On each panel Delta H (black), Sq variation (blue) and disturbed ionospheric current $D_{\text{iono}}$ is superimposed. (c) Disturbance dynamo ($D_{\text{dyn}}$) estimated using wavelet based semblance analysis during March 30 to April 04, 2001. The vertical dashed line corresponds to the arrival of CME.
Figure 3. (a) Same as Figure 2a but from March 15–19, 2013, (b) Same as Figure 2b March but 15–19, 2013, (c) Same as Figure 2c but March 15–18, 2013.
Figure 4. (a) Same as Figure 2a but from September 25–30, 2001, (b) Same as Figure 2b but from September 25–29, 2001, (c) Same as Figure 2c but September 25–29, 2001.
Figure 5. (a) Same as Figure 2a but April 4–10, 2010, (b) Same as Figure 2b but April 04–10, 2010, (c) Same as Figure 2c but April 04–10, 2010.
Figure 6. (a) Same as Figure 2a but August 20–31, 2010, (b) Same as Figure 2b but August 20–29, 2010, (c) Same as Figure 2c but August 22–30, 2010.
### 3.6. Comparison Among the Five Cases

In Sections 3.1–3.5, we have described the geomagnetic activity during the five space weather events (one from each category). In this regard cases 1, 2, and 3 correspond to CMEs with $D_{\text{dyn}}$ observed, respectively at three, two, and one sectors, respectively. Whereas the other two cases, namely 4 and 5, describe the space weather events of CME + HSSWs and HSSWs, respectively. In this section, we look at the possible reasons to explain the observed trends in $D_{\text{dyn}}$ during these events.

During the case of March 31, 2001, CME strikes the Earth at 0050 UT. The observed $D_{\text{dyn}}$ is generated as a result of the Joule heating at high latitudes. Figure 7a (black) shows the Joule heat—as estimated by SWMF/BATRUS model—for a period March 30 to April 02, 2001, moreover Figure 7a (red) represents the AE index superimposed on the JH. Here we note the two large sections of Joule heating with a first peak of 4880 GW as observed on March 31 at 0440 UT and a second peak (3320 GW) at 1713 UT. These strong periods of JH generate disturbance dynamo at global scale and consequently we can observe the anti-Sq signature at all three sectors as indicated in Figure 2c.

For the event of March 2013, the CME commenced on March 17 at 0406 UT. Figure 7b (red) indicates the variation in JH of upper atmosphere during this space weather event, while the black curve in the same figure presents AE index variations from March 16 to March 19, 2013. The JH begin to increase soon after the SSC and remained high till the end of the day (March 17). The maximum estimated value of JH, using the BATRUS model, is 1180 GW around 1000 UT. Heating of upper atmosphere for long duration generates disturbance dynamo that is, observed at low latitudes in two sectors as indicated in Figure 2c.

During the magnetic storm of September 2001, CME commenced on 25th at 1900 UT. Here we note that there is a short section of JH having a maximum value of 1600 GW at 2230 UT as depicted in Figure 7c. This weak JH could not generate disturbance dynamo at global level and is confined to only a particular sector (as in Figure 3c).

For the case 4, there is a HSSWs during the recovery phase as indicated by high solar wind speed and oscillatory IMF $B_z$. The arrival of CME is indicated by a vertical line in Figure 4 on April 05 0740 UT. During

![Figure 7. Comparison between AE and Joule heating for the five selected events.](image-url)
this event there are two main episodes of JH of upper atmosphere as shown in Figure 7d. The first (second) peak occurred at 0900 (1305) UT having a maximum value of 990 (018) GW. Apart from these two peaks JH remains relatively high till the mid of April 08, 2010, which is due to the presence of HSSWs during the recovery phase, which allows energy input for long durations. This JH has enhanced the duration of $D_{\text{dyn}}$ at three sectors as observed in Figure 4c, that is, the disturbance lasts for 3.9, 4.5, and 4.2 days, respectively.

The last scenario that is, case 5 corresponds to a purely HSSWs event, where the AE index depicts multiple peaks of energy inputs from August 24 to August 28, 2010. Figure 7e shows the JH estimation during the HSSWs this event. Both JH and AE indicate that there is a large energy input from August 23 to August 29, 2010, however magnitude of JH in this case is smaller as compared to the CME events discussed earlier. The $D_{\text{dyn}}$ started first at Asian sector followed by African and American counterparts. The temporal duration of observed $D_{\text{dyn}}$ is maximum at Asia and subsequently Africa and America, respectively. Analysis of these five typical storms shows that during the CME events disturbance lasts for 1–2 days, whereas in case of HSSWs, we see that duration of $D_{\text{dyn}}$ may last for more than 04 days. The oscillatory IMF Bz for long time, during the HSSWs events, allow long period of Joule heating in the auroral zone. Furthermore, whenever there is HSSWs along with the CME, $D_{\text{dyn}}$ disturbance is intensified and lasts for several days after the storm.

### 3.7. Generalization to 19 Storms

We have computed $D_{\text{dyn}}$ for 19 different space weather events. These considered storms, depending on the sources (CME/HSSW/CME + HSSW/Several CMEs), are of several categories. Moreover, the CME events are further categorized with $D_{\text{dyn}}$ observed in 1, 2, or 3 sectors. In Table 2 we have grouped the cases according to the different categories of events (CMEs, CMEs + HSSW’s, HSSWs, Several CMEs).

Table 3, based on the data of Guam, M’Bour and Kourou, presents the results of our analysis for 19 selected events. In the same table columns 1 to 6 show, respectively the type of storm, SSC time in UT, time of max CP with duration, MP with duration, AE peaks with time in UT and duration of recovery phase. Columns 7 and 8 present the strength and duration of $D_{\text{dyn}}$ at Asian, African, and American sectors, respectively and highest value of $D_{\text{dyn}}$ during each case is highlighted with bold text. Figure 8a depicts the maximum duration of the observed $D_{\text{dyn}}$ for each storm (from left to right) corresponding to CME only, CME + HSSWs and HSSWs events, orderly. Here we note that $D_{\text{dyn}}$ duration is largest (from 19 selected events) for the storm 06 (an HSSWs event). However, it can be inferred from the same figure that duration of $D_{\text{dyn}}$ for HSSWs and CME + HSSWs events is relatively long as compared to CME (only) events. The mean and standard deviation are 2.25 days and 0.81 for CME, 4.30 days and 0.72 for CME + HSSW’s and 4.30 days and 1.69 for HSSWs. Figure 8b presents the maximum strength of $D_{\text{dyn}}$ for each storm (from left to right: CME only, CME + HSSWs, and HSSWs only, respectively). The strength of $D_{\text{dyn}}$ at a station is estimated by following Le Huy and Amory Mazaudier (2008), namely from minimum of $D_{\text{iono}}$ when it is anti-phase to $S_{\text{q}}$.

Prior to calculating the minimum of $D_{\text{iono}}$, a moving average filter is applied by following the methodology of Fathy et al., 2014. In this way effect of DP2 magnetic perturbations are averaged out. The strength of $D_{\text{dyn}}$
| No | SSC [UT] | UT Time and Max. of CP [Positive SYMH[nT]] + duration | UT Time and Max. of MP (negative SYMH) [nT] + duration | Duration of the RP [Days] | \( D_{\text{ap}} \) duration with Start and end time in UT | Maximum Strength of \( D_{\text{ap}} \) with UT time in each Sector |
|----|----------|-----------------------------------------------------|-----------------------------------------------------|--------------------------|-----------------------------------------------------|-----------------------------------------------------|
| Storm 1 CME + HSSW | 2015-03-17-0445 UT Asia [12:00 LT] Africa [03:30 LT] America [01:15 UT] | 0448 UT (67) 02 Hours 2245 UT (-230 nT) 16 Hours | 20150317-0830 (770) 20150317-1430 (1570) 20150317-1830 (1260) 20150317-2330 (1170) | 7.5 Days | 17/03 1600 UT 19/03 0500 UT 1.5 Days | Asia 18/03 0300 UT Africa 22/03 1300 UT 4.5 Days America 18/03 0200 UT 22/03 1300 UT 4.5 Days |
| Storm 2 CME + HSSW | 2015-06-22-1822 UT Asia [01:00 LT] Africa [17:00 LT] America [15:45 LT] | 0622 UT (85) 01 Hours 06230425 UT (-207 nT) 10 Hours | 20150622-1830 (1636) 20150622-1230 (1346) | 7.5 Days | 23/06 0600 UT 27/06 0100 UT 3.8 Days | Asia 23/6 0200 UT 26/06 0500 UT 23/06 0150 UT 1400 UT | Africa -25nT America -45.7nT -96nT -79nT |
| Storm 3 CME + HSSW | 2018-08-25 0750 UT Asia [14:00 LT] Africa [06:00 LT] | 0825 UT 27 09 Hours 08260711 UT (-206 nT) 17 Hours | NA | 7.5 Days | 26/08 2200 27/08 1500 0.8 Days | Asia 26/08 1600 30/08 0200 3.5 Days America 26/08 1200 28/08 2300 2.5 Days |

| 26/08/18 | 1755UT | 1639UT | -42.8nT | -37.61nT |
| Storm 4 | CME | HSSW | UT | 06:04 UT | 14:19 | 02:10 UT | 05:10 UT | 10:04 LT | 13:09 LT | 15:55 LT | 06:04 LT | 10:04 LT | 15:55 LT | 06:04 LT |
|---------|-----|------|----|----------|------|----------|----------|--------|--------|---------|----------|----------|---------|----------|
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| 2010-04-05 | [14] | [28] | [19] | 59      | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    | -397.8nT | 60    |
| Storm 8 CME | 2012-04-23-0310 UT | Asia [11:00 LT] | Africa [01:40 LT] | America [23:50 LT] | America [12:00 LT] | 2304 0423 | 2405 0330 | 20120412-1930 (990) | 3.8 Days | 25/04 1600 | 29/04 1000 | 24/04 1300 | 24/04 0900 | 24/04/12 | 25/04/12 | 24/04/12 | 24/04/12 |
| Storm 9 CME | 2001-09-25-1945 UT | Asia [03:00 LT] | Africa [18:30 LT] | America [23:50 LT] | America [15:15 LT] | 2509 2200 | 2609 0110 | 20010925-2230 (1753) | 4.8 Days | 25/09 1900 | 27/09 1700 | NA | NA | 25/09/01 | 2310UT | NA | NA |
| Storm 10 CME | 2001-11-06-0153 UT | Asia [20:00 LT] | Asia [00:30 LT] | America [22:30 LT] | America [23:50 LT] | 0611 0154 | 0611 0406 | 20011106-0430 (1990) | 4.9 Days | NA | 06/11 1600 | 06/11 1800 | 06/11/01 | 06/11/01 | 07/11/01 | 06/11/01 | 1810UT | -21nT |
| Storm 11 CME | 2006-12-14-1400 UT | Asia [07:00 LT] | Africa [12:30 LT] | America [10:30 LT] | America [23:30 LT] | 1412 2110 | 1512 0055 | 20061214-1530 (1616) | 6 Days | 14/12 1800 | 14/12 1900 | 14/12 1900 | 14/12 1900 | 15/12/06 | 15/12/06 | 15/12/06 | 15/12/06 |
| Storm 12 Multiple | 2004-11-07-1740 UT | America [10:30 LT] | America [10:30 LT] | America [23:30 LT] | America [23:30 LT] | 0711 1940 | 0811 0555 UT | 20041107-0130 (1303) | 6 Days | 08/11 0600 | 08/11 0500 | 08/11 0500 | 10/11/04 | 09/11/04 | 09/11/04 | 09/11/04 | 2120UT | 2120UT |
| CME  | Asia [0700 LT] | Africa [0930 UT] | America [1440 LT] | S1 | 08 Hours | 02 Hours | 06 Hours |
|------|---------------|------------------|-------------------|---|----------|----------|----------|
| Storm 13 | 2004/01.048 | 0955 UT | 0935 UT | 2004/01.070 | 0935 UT | 0935 UT | 0935 UT |
| Multiple | CME | Africa [0630 LT] | America [0530 LT] | S1 | 08 Hours | 02 Hours | 06 Hours |
| Storm 14 | 2003/08.136 | 0935 UT | 0935 UT | 2003/08.136 | 0935 UT | 0935 UT | 0935 UT |
| Storm 15 | 2003/11.204 | 0935 UT | 0935 UT | 2003/11.204 | 0935 UT | 0935 UT | 0935 UT |
| Storm 16 | 2000/10.03 | 0935 UT | 0935 UT | 2000/10.03 | 0935 UT | 0935 UT | 0935 UT |
| Storm 17 CME | 2001-11-24-0445 UT | 24/11 0600 UT | 24/11 1430-230 nT 8.5 Hours | 20011224-0630 (2006) | 04 Days | 24/11 1500 25/11 1700 1.1 Days | 24/11 0500 25/11 0700 1.4 Days | 24/11 0500 24/11/01 1210UT -60.64nT | 24/11/01 1514UT -111nT | 24/11/01 1624UT -77.79 nT |
| Storm 18 CME | 2013-03-17-0406 UT | 17/3 0605 UT | 2013/03/17-1630 UT -127 nT 11 Hours | 20130317-1630 (1820) | 03 days | NA 17/03 0500 18/03 1800 1.5 Days | 17/03 0500 18/03 1500 1.4 Days | 19/03/13 0340UT -13.4nT | 17/03/13 1944UT -87.3nT | 17/03/13 2010UT -83.4nT |
| Storm 19 HSSW | 2005-04-12,0540 UT | 11/4 1634UT 09 hours | 200504120330 (875) 200504121930 (855) 200504131230 (960) 200504131630 (1100) | 06 days | 12/4 2200 17/4 0000 3.1 Days | 13/4 / 0100 15/4 0800 2.3 Days | 12/4 1600 15/4 0300 2.5 Days | 14/04/05 0245UT -22nT | 14/04/05 0900UT -48.58nT | 13/04/05 1730UT -24.5nT |

Note: Highest value of $D_{sys}$ during each case is highlighted with bold text.
Figure 8. (a) Maximum duration of $D_{\text{dyn}}$ during each of the selected storm: (from left to right) CME, CME + HSSWs and HSSWs events respectively. (b) Maximum strength of $D_{\text{dyn}}$ observed during each storm.
is generally high for CME events, for example, it is large values for storms 5 and 15. The mean strength and standard deviation are $-113.52$ and $86.16$ nT for CME, $-83.16$ and $14.68$ nT for CME + HSSWs, and $-50$ and $26.27$ nT for HSSWs. Analysis of Table 3 leads to the following comments.

1. For most of the considered cases, that is, 14 out of 19, the $D_{\text{dyn}}$ disturbance is observed in the three sectors.
2. When there is an HSSW (alone or with a CME) $D_{\text{dyn}}$ is observed in the three sectors of longitude, in all the events and the duration of the $D_{\text{dyn}}$ disturbance is longer.
3. We also note that for the cases of HSSW the peaks of AE are weaker (AE $< 1,000$ nT) than for CME instances (AE from $1,200$ to $2,006$ nT), however they last for long periods and hence are more effective in producing $D_{\text{dyn}}$.

3.8. Comparison With Le Huy and Amory-Mazaudier (2005)

Le Huy and Amory-Mazaudier have analyzed six magnetic storms (shown in gray in Table 3), by using three (different) magnetic observatories (Huancayo in America, Adis Ababa in Africa and Bac Lieu in Asia). While comparing our findings with the said study, we note that three of the considered storms, namely 5, 9, and 17 depict the same trends as reported by Le Huy & Amory-Mazaudier, 2005. However, for the events 10, 14, and 16 there are major differences in Asian and American sectors. Thus, we need to analyze these storms for all the available observatories (Guam, Bac Lieu, Adis Ababa, Mbour, Kourou, and Huancayo) as follows.

Figure 9a presents the $D_{\text{dyn}}$ at from top to bottom BCL, GUA, AAE, MBO, and KOU during November 5–8, 2001 (storm 10 of Table 3) for which Le Huy and Amory-Mazaudier observed the $D_{\text{dyn}}$ signatures at Asian and African sectors. Figure 9a shows the signatures of $D_{\text{dyn}}$ at all longitudinal sectors. Moreover, the stations BCL and GUA—belonging to the same longitudinal sector, namely Asia—have a different response. This might be due to the fact that Sq varies, as caused by the planetary waves, on a daily basis and can affect the evaluation of $D_{\text{dyn}}$ magnetic signatures. At the station AAE we observe long, as compared to MBO, $D_{\text{dyn}}$ signature. This is probably due to the fact that AAE lies within EEJ region and has contributions from other physical processes such as enhanced Cowling conductivity (Cowling, 1932). In the equatorial region due to the fact that the Earth’s magnetic field is almost horizontal—the conductivity is increased and is called the Cowling’s conductivity. Grodgi et al., 2017 described the relations between the various electrodynamic parameters at the equator. In contrast to Le Huy and Amory-Mazaudier (2005) we have observed signature of $D_{\text{dyn}}$ in the American sector (HUA), this can be due to the use of a different observatory, namely KOU in the same sector.

Figure 9b shows the $D_{\text{dyn}}$ (from top to bottom) at GUA, MBO, AAE, KOU, and HUA during the storm 14 of Table 3. Here one notes a different signature of $D_{\text{dyn}}$ as compared to Le Huy and Amory-Mazaudier (2005). There are two possible reasons; first we have employed a different method to extract $D_{\text{dyn}}$ and second, the use of different observatories in the two studies. Moreover, Le Huy and Amory-Mazaudier have considered the anti-Sq signature only on the day after the storm.

4. Discussion

Fejer et al., in 1983 studied the signatures of disturbance dynamo electric field over Jicamarca in F-region during a magnetic quiet day just after a storm, when there was no prompt penetration of the magnetospheric convection electric field. In the said analysis, they have found perturbed electric fields around 16–24 h after the onset of the storm. In a similar study Le Huy and Amory-Mazaudier considered the ionospheric disturbance dynamo from magnetic data, during a magnetic quiet day and found the anti-Sq oscillations during the recovery phase.

Fathy et al. (2014) studied the disturbance dynamo $D_{\text{dyn}}$ during the coronal hole event of April 2005 and separated the $D_{\text{dyn}}$ perturbation due to the ionospheric disturbance dynamo (Blanc & Richmond, 1980) from DP2 perturbation (Nishida, 1968) which is caused by penetration of the magnetospheric convection (Vasyliunas, 1970). The separation was achieved by using 4 h rolling average with a 1-h step to eliminate the effect of DP2. More recently Zaourar et al. (2017) and Nava et al. (2016) performed a wavelet analysis...
Figure 9. The $D_{\text{dyn}}$ disturbance (a) Storm of November 6, 2001 and (b) Storm of September 25, 2001.
on ionospheric disturbance current to estimate the $D_{\text{dyn}}$ perturbation and found that the main disturbance associated with $D_{\text{dyn}}$ has a periodicity of around 20–28 h. Younas et al. (2020) recently considered the asymmetric disturbances in the magnetic storm of August 2018. In this work we have proposed a new approach for the estimation of ionospheric disturbance current and analyzed 19 storms due to different solar perturbations, that is, CME, CME + HSSW and HSSW.

Our study reveals several interesting features, which are summarized as following.

4.1. Effect of Onset Time (UT) and Strength of Storm for Detection of $D_{\text{dyn}}$ During CME Generated Storms

Figures 8a and 8b (left) shows duration and strength of $D_{\text{dyn}}$ during the CME generated storms. Here one notes that, in contrast to HSSWs generated activity, the disturbance dynamo effects are not always observed at all longitudes. Accordingly, we have divided the CME generated storms in three categories as depicted in Table 2. In Figures 2–4, we have presented storms from each category. Figure 7 describes the Joule heating estimation and the corresponding AE index. During the CME generated storm—depending on its strength—IMF Bz turns southward for long durations and thus allowing large energy transfer into the magnetosphere. This behavior is quite different from HSSWs generated storm in which IMF Bz remains oscillatory. In our case the Joule heating estimates for the three selected storms have different patterns. For case 3, there is a sharp pulse of Joule heating, which quickly drops down to the normal values, while for cases 1 and 2 Joule heating remains for much longer intervals. Hence, for the third case, the said sharp pulse could not generate the dynamo effect globally while during the first two cases the large energy input for long time periods generates thermospheric winds globally. Consequently, the disturbance dynamo becomes strong enough and can be detected at all three longitudes. Hence, during the CME generated storm duration of IMF Bz is crucial in generating $D_{\text{dyn}}$ globally.

4.2. Longitudinal Variation of HSSW-Generated Storms

We have analyzed two HSSW events (storms 06 and 19), in this regard Figure 8a shows that, from all the 19 events, storm 06 has the longest duration of $D_{\text{dyn}}$. However, the strength of HSSWs is not comparable to the CME generated counterparts (Figure 8b). Both storms have caused $D_{\text{dyn}}$ effect at all longitudes, hence interestingly the HSSW-generated storms have long duration of disturbance dynamo. It looks that oscillatory IMF Bz frequency plays a key role in the observed signatures of HSSWs generated storms. As indicated by SYM-H index, the HSSWs events could not generate strong ring currents. Furthermore, during the HSSWs events IMF Bz remains oscillatory from the start till the end of a magnetic storm, which allows energy to be transferred from solar wind to the magnetosphere in short impulses and lasting for several days. Thus, strong ring current could not develop during these events. During a CME—in comparison with HSSWs—there is a sudden increase in auroral activity, which lasts for a short duration and hence may not produce disturbance dynamo globally. Whereas the continues energy input to auroral ionosphere, during the HSSWs, effectively heats the polar region and resulting in the signatures of DDEF at all longitudes (Rodriguez Zulaga et al., 2016).

4.3. Comparison of Results With Le Huy and Amory-Mazaudier (2005)

We have also presented the comparison of our findings with an earlier study by Le Huy and Amory-Mazaudier (2005) as depicted in Table 3 (gray). For the storms 5, 9, and 17 we have found similar trends, however for the storms 10, 14, and 16 our findings are quite different. This disagreement is due to the different methodology and observatories used by Le Huy and Amory-Mazaudier (2005), who have selected the events for which there was no auroral activity on the day after a magnetic storm. That means that the associated disturbance DP2, due to the penetration of the electric field, was zero and only the $D_{\text{dyn}}$ disturbance—due to the disturbed ionospheric dynamo—was present. Thus, there was no effect of DP2 and no filtering was required, but this method is only valid for the day after a storm in certain special cases. However, $D_{\text{dyn}}$ disturbance can also take place on the day of storm (some hour after SSC) and is considered in our study.
4.4. Effect of Season on the Duration of Storm

The storms 1, 2, and 3 of Table 3 occurred in different seasons during the same descending phase of solar cycle 24. These storms have almost the same origin, that is, CME with streams of high-speed winds during the recovery phase. Maximum duration of $D_{dyn}$, as observed from magnetic data, for storms 1, 2, and 3 is 5.2, 3.5, and 04 days, respectively. And the maximum strength of $D_{dyn}$ for these storms is, orderly $-96$, $-95.0$, and $-42$ nT. This shows that the storms occurring in equinox season are most likely to have strong and long-lasting disturbance dynamo, which agrees with the theoretical prediction of Huang (2013). During a magnetic storm large amount of energy deposition, at polar regions, heats the thermosphere and disturbance thermospheric neutrals winds are generated which flow toward the equator (Blanc & Richmond, 1980). During the solstice season, there is a background wind flowing from summer to winter hemisphere which is enhanced during a disturbed period. Consequently, the equatorward generated storm winds penetrate the winter hemisphere, the resulting disturbance currents from each hemisphere are not comparable to each other. However, for the equinox season there is no background wind flowing between the two hemispheres and the disturbed winds in both hemispheres are comparable, which causes a strong change accumulation at the equator and thus resulting in strong and long-lasting disturbance dynamo.

During the storm 1, AE index reaches a maximum value of 2,298 nT on March 17, 2015 at 1358 UT and remained high (>1,000 nT) till the end of March 22. However, for the storm 2, AE index shows a maximum value of 2,698 nT on June 22 at 2009 UT and remained high till June 24. For the storm 3, AE index has a maximum value of 2,250 nT on August 26, 2018 at 0800 UT and remained high till the end of August 27, 2018. This indicates that for storm 1, energy inputs to ionosphere-thermosphere system, as indicated by AE index, remains high for relatively long duration as compared to storms 2 and 3, which causes a strong and long-lasting disturbance dynamo in the equinox season (storm 1) in comparison with storms occurring in solstice season (storms 2 and 3).

4.5. Main Difference in the Response to CME, HSSWs, and CME + HSSWs Generated Storms

The $D_{dyn}$ may be observed in one, two or all sectors depending on the strength, season and starting UT time of a storm. However, we have found that storm with HSSWs followed by CME or only HSSWs have shown the effect of $D_{dyn}$ at all the longitudes, thus making it global. This difference in the response of CME and HSSWs can be associated with oscillatory IMF $B_z$ which allows continuous energy input to the magnetosphere-ionosphere system and thus heating of the upper atmosphere. Whereas, during the CME events, IMF $B_z$ turns southward and thus allowing large energy transfer. However, in contrast to HSSWs, such events last for short durations and hence do not generate enough Joule heating to cause a global $D_{dyn}$. This effect is evident during the weak CME events as illustrated in Table 3.

5. Conclusion

To conclude, we have analyzed the magnetic signatures of ionospheric disturbance dynamo ($D_{dyn}$) with a new method. In this regard the analysis has been performed for 19 different space weather events, for which we have found some interesting features of $D_{dyn}$ which are summarized as follows.

1. The period of $D_{dyn}$ oscillations is found to be between 16 and 28 h, which agrees with some earlier theoretical predictions (Huang, 2013; Rodríguez-Zuluaga et al., 2016).
2. The $D_{dyn}$ during the CME generated storms may be observed, depending on the strength of storm, in one, two or three longitudinal sectors. This fact can be related to southward excursion of IMF $B_z$. The storm with very long period of IMF $B_z$, or more than one episode of southward directed IMF $B_z$, may result in a global generation of $D_{dyn}$, which generates the observed magnetic signatures at all longitudes.
3. In contrast to CME generated event, the $D_{dyn}$ during HSSWs or CME + HSSWs is detected at all longitudes. This effect is related with the oscillatory behavior of IMF $B_z$ during the HSSWs, which allows continuous energy to build up in the thermosphere. Furthermore, the HSSWs generated storms are most likely to have long duration of $D_{dyn}$.
4. Our analysis of three magnetic storms, having almost the same global variations, reveals that the storms occurring in the equinox season are expected to have a strong $D_{dyn}$ as compared to events in other seasons.
5. The magnetic storms with multiple CMEs show multiple episodes of $D_{dyn}$ and can be associated with corresponding episodes of IMF Bz southward.

6. Joule heating analysis from AE index and BATRUS model indicates that the CME, HSSWs and CME + HSSW events have quite different heating patterns of the upper atmosphere. The CME events that have $D_{dyn}$ in only one longitude show sharp and short duration of high energy input. Conversely, the HSSW and CME + HSSW-generated storms have long duration of Joule heating. Probably, this is the reason why HSSW-generated storms tend to have long duration of $D_{dyn}$.

This study emphasizes that HSSW-driven events usually could not develop strong ring currents which is a proxy to measure the strength of a magnetic storm. However, these events may cause significant perturbation in the ionosphere-thermosphere through penetration of electric fields from high to low latitudes for several days. Hence, HSSWs should be taken into account while modeling and estimating ionospheric response during disturbed periods.

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