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EXPRESS LETTER

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Evidence for presence of a global quasi-resonant mode of oscillations during high-intensity long-duration continuous AE activity (HILDCAA) events

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Abstract

The responses of two High-Intensity Long-Duration Continuous AE Activity (HILDCAA) events are investigated using solar wind observations at L1, magnetospheric measurements at geosynchronous orbit, and changes in the global ionosphere. This study provides evidence of the existence of quasi-periodic oscillations (1.5–2 h) in the ionospheric electric field over low latitudes, total electron content at high latitudes, the magnetic field over the globe, energetic electron flux and magnetic field at geosynchronous orbit, geomagnetic indices (SYM-H, AE, and PC) and the Y-component of the interplanetary electric field (IEFy) during the HILDCAA events at all local times. Based on detailed wavelet and cross-spectrum analyses, it is shown that the quasi-periodic oscillation of 1.5–2 h in IEFy is the most effective one that controls the solar wind–magnetosphere–ionosphere coupling process during the HILDCAA events for several days. Therefore, this investigation for the first time, shows that the HILDCAA event affects the global magnetosphere–ionosphere system with a "quasi-resonant" mode of oscillation.

Keywords: HILDCAA, CIR, Prompt penetration electric field, Global oscillation, Magnetosphere–ionosphere coupling

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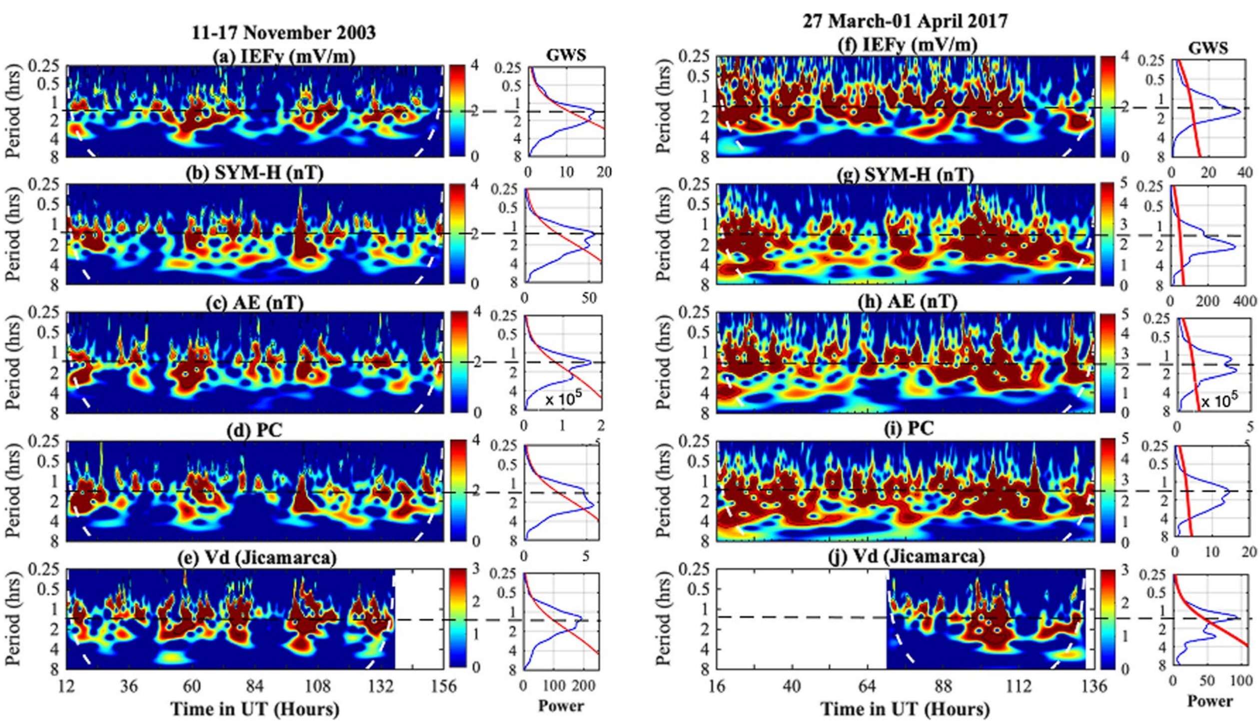
Graphical Abstract



Introduction

During the declining and minimum phase of the solar cycle, solar wind emanating from the coronal holes are the major source of space weather disturbance in the near-earth space environment. The fast solar wind (600–800 kms^{-1}) originating from coronal holes interacts with the background slow solar wind stream (300–400 kms^{-1}) in the interplanetary medium creating an interaction region generally known as a Corotating Interaction Regions (CIRs) (Belcher and Davis Jr. 1971; Smith and Wolfe 1976; Borovsky and Denton 2006; Tsurutani et al. 2006; Rout et al. 2017; Richardson 2018). The Alfvénic fluctuations in the north–south component of the interplanetary magnetic field (IMF Bz) associated with CIR drive weak to moderate recurrent geomagnetic storms with a prolonged recovery phase. Intense and long-duration (ranging from a few days to the Carrington rotation period) auroral activity has been observed during this kind of long-lasting recovery phase of geomagnetic storm, which is known as High-Intensity Long-Duration Continuous AE Activity (HILDCAA) (Tsurutani and Gonzalez 1987; Tsurutani et al. 1995, 2006; Hajra et al. 2014). HILDCAA events are mainly characterized by properties, such as: (i) the magnitude of peak AE index reaches more than 1000 nT at least once during the event, (ii) the event continues for at least 2 days, (iii) the AE index never drops below 200 nT for more than 2 h at a time, and (iv) the auroral activity occurs after the main phase of magnetic storms (Tsurutani and Gonzalez 1987; Hajra et al. 2013). However, these criteria are not rigid and it is also possible to consider a HILDCAA event without strictly following all the criteria (Tsurutani et al. 2004; Hajra et al. 2013). One of the major space weather phenomena during the HILDCAA events is the acceleration of relativistic electrons (~MeV) in the outer radiation belt (Tsurutani et al. 2009; Hajra et al. 2013), and it is these 'killer electrons' that can cause significant damage to sensitive satellite electronics (Hajra et al. 2014, 2015). Therefore, understanding HILDCAA events are crucial from the space weather application perspective.

Periodic oscillations associated with Alfvénic waves of periods ranging from several tens of minutes to several hours are commonly observed in the solar wind magnetic field during the HILDCAA events (D'Amicis et al. 2007; Diego et al. 2005). The Alfvenic fluctuations in IMF Bz/IEFy can affect the rate of reconnection at the dayside magnetopause (Lu et al. 2002; Siscoe et al. 2011; Liu et al. 2018). This, in turn, affects the solar wind–magnetosphere–ionosphere coupling processes. A few studies report the effect of periodic oscillations in IMF Bz on the magnetosphere during the HILDCAA events (Marques de Souza et al. 2018; Marques de Souza Franco et al. 2019). By doing cross-wavelet and cross-correlation analyses between AE and IMF Bz, Marques de Souza et al. (2018) found that the solar wind–magnetosphere coupling during HILDCAA events is the most efficient in periods ≤ 8 h. Furthermore, the response of the magnetotail is investigated by using the Cluster measurements (Marques de Souza Franco et al. 2019) and it is shown that the magnetotail responds stronger to IMF Bz fluctuations at 2–4 h time scales during the HILDCAA events, which are typical substorm periods. However, these studies could not show whether the same fluctuation in IMF Bz also affects the equatorial ionosphere. To the best of these authors' knowledge, it is yet to be investigated whether the most dominant periodic component in IMF Bz/IEFy affects the global magnetosphere–ionosphere (MI) system simultaneously for several days during the HILDCAA events. Therefore, this investigation, for the first time, addresses this question directly and reveals that specific periodic fluctuations in IMF Bz associated with the HILDCAA events affect not only the particle injections at geosynchronous orbit but also the global ionosphere (from high to low latitude) continuously for several days.

Data and methodology

The solar wind parameters (IMF Bz, IEFy, flow speed, and dynamic pressure) and geomagnetic indices (symmetric component of ring current: SYM-H, auroral electrojet: AE, and polar cap index: PC) are taken from the NASA GSFC CDAWeb, wherein solar wind parameters are corrected for propagation lag until the nose of the bow shock. SYM-H and AE indices are used to identify the HILDCAA events, as described in the introduction section. To investigate the quasi-periodic oscillations during HILDCAA events from the solar wind to the equatorial ionosphere, it is important to have unambiguous and continuous measurements of the ionospheric electric field over the low latitude. It is to be noted here that equatorial electrojet strength is, in general, used to infer the electric field variation only during the daytime, whereas the vertical drift derived from digisonde, can be safely used in nighttime (Pandey et al. 2017). In addition to this, uncertainty associated with the ionosonde derived vertical drift (5–10 ms^{-1}) is, in general, much larger than the uncertainty in the ISR drift (Woodman et al. 2006). Therefore, the vertical drift measurements by ISR over Jicamarca (11.9°S,77°W) are used in the present work to enable us to draw unambiguous scientific inferences. The diurnal variations of the F-region vertical plasma drifts ($\mathbf{V_d} = (\mathbf{E} \times \mathbf{B})/B^2$) over the dip equator (averaged over 250–450 km altitude region) are obtained from the ISR, Jicamarca. To study the impact of the HILDCAA events in the magnetosphere, the Z-component of the magnetic field and the energetic electron flux measured at geosynchronous altitude by Geostationary Operational Environmental Satellites (GOES-10, and GOES-13) are considered. In addition, variations in the horizontal (H)-component of the geomagnetic field from the SuperMAG chain are also investigated to examine the changes in the magnetic field variations from the north pole to the equator. These stations are Resolute Bay (RES:Mag Lat: 82.54°N, Mag Long: 50.8°W), Ottaba (OTT: 54.8°N ,3.6°E), Kourou (KOU: 14.2°N,20.5°E), and Huancayo (HUA: 2.4°S,2.64°W). Furthermore, the Total Electron Content (TEC) measurements from the two high latitude stations: Fairbanks (FAIR: 57°N,149.8°W), and Baker (BAKE: 64°N,101.5°E) are also utilized to investigate the effects of HILDCAA on high latitude TEC change.

To study the periodic oscillations in the Solar wind–magnetosphere–ionosphere system during the HILDCAA events, wavelet analysis is performed using Morlet as the mother wavelet (Torrence and Compo 1998). It is to be noted here that the solar wind–magnetosphere coupling during HILDCAA events is more efficient at the period ≤ 4 h which are mostly driven by interplanetary Alfvén waves embedded in the high-speed solar wind streams (Belcher and Davis 1971; Marques de Souza Franco et al. 2019). Therefore, wavelet analyses are carried out using the residuals of fast fluctuating (period ≤ 4 h) components of all the parameters. The fast fluctuations (residuals) in all parameters during these events are extracted (by detrending) using the Savitzky–Golay smoothing algorithm (Savitzky and Golay 1964). Furthermore, the global wavelet spectra (GWS), i.e., the time-averaged wavelet spectrum are obtained to identify the most significant periods in the time series (Torrence and Compo 1998).

Observations and results

The response of the MI-system is investigated for two typical HILDCAA events that occurred during 09–17 November 2003 (Fig. 1 left panel), and 27 March–01 April 2017 (right panel). Figure 1 shows the variations in the solar wind, geomagnetic indices, and vertical plasma drift over low latitude ionosphere. From top to bottom, the panels show the variations in V, P, IMF Bz (black), and IEFy (red) in the GSM co-ordinate system, SYM-H, AE, PC index, V_d along with the reference quiet time drifts (red) obtained for the similar season and solar epoch (Scherliess and Fejer 1999). The horizontal blue line in the 4th panel indicates the duration of the HILDCAA events. Following the HILDCAA criteria as mentioned in the introduction section, the 2003 event continued for 6 days (from 12:00 UT, 11 November to 12:00 UT, 17 November 2003), and the 2017 event lasted for 5 days (from 16:00 UT, 27 March to 16:00 UT, 01 April 2017).

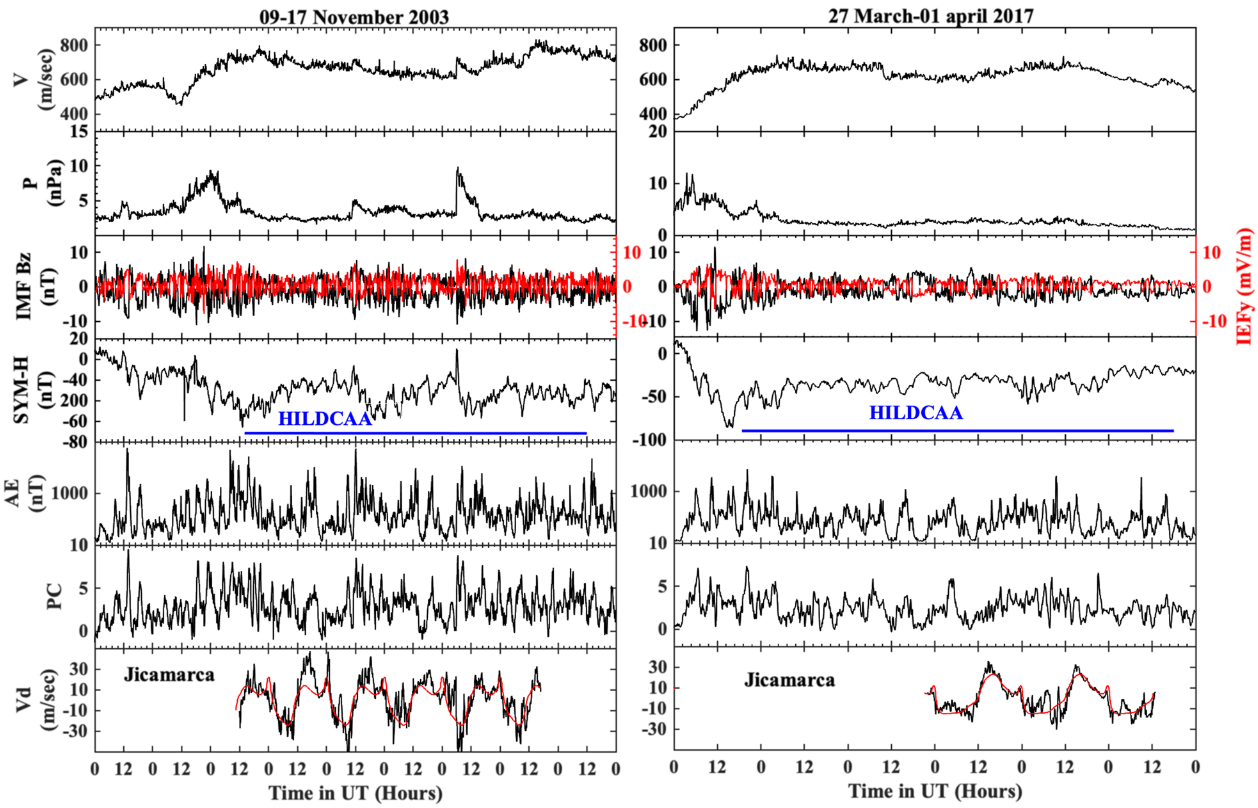


Fig. 1 Solar wind, geomagnetic and ionospheric drift measurements over low-latitude during two HILDCAA events on 09–17 November 2003 (left panel) and 27 March-01 April 2017(right panel). From top to bottom, the panels show the temporal variations of solar wind velocity (V), dynamic pressure (P), IMF Bz, and IEFy in GSM co-ordinate system, SYM-H, AE, PC index, and vertical drift over Jicamarca (V_d) with the quiet time variation (red). The horizontal blue lines in the 4th panel indicate the duration of the HILDCAA events

The high-speed solar wind stream started at ~12:00 UT on 10 November 2003 to a high value of ~ 800 kms^{-1} and continued throughout the event. Similarly, the high-speed stream started at ~06:00 UT on 27 March and remained steady at ~700 kms^{-1} for several hours during the 2017 event. It can be seen that IMF Bz and IEFy are highly fluctuating for both the events due to Alfvénic waves associated with it. For the 2003 event, IMF Bz and IEFy fluctuate around the zero with amplitudes of ~ ±10 nT and ~ ±7mV/m, respectively, whereas these amplitudes are ~ ±5 nT and ~ ±3 mV/m for the 2017 event. The minimum values of SYM-H are −66 nT and −86 nT for the 2003 and 2017 events, respectively. This implies that the CIRs did not drive very strong geomagnetic storms in either case. However, there was considerable geomagnetic activity over the high latitude ionosphere as indicated by the large values of AE and PC indices. It may be noted that the AE crossed above 1000 nT several times during both events. It can be clearly seen that on the event days, the variations in V_d over the equatorial ionosphere are significantly different from the quiet day variations (red line). The small-scale fluctuations are more prominent during the HILDCAA period. Unfortunately, the drift data is only available from 12:00 UT, 11 November to 17:00 UT, 16 November 2003 (total 125 h) and from 22:00 UT, 29 March to 13:00 UT, 01 April 2017 (total 63 h) for the respective events.

To study the periodic oscillations during these HILDCAA events, wavelet spectra for IEFy, SYM-H, AE, PC, and V_d over Jicamarca are given in Fig. 2. Figure 2 (left panel) shows the wavelet analysis from 12:00 UT, 11 November to 12:00 UT, 17 November for the 2003 event. The right panels show the wavelet spectra of corresponding parameters from 16:00 UT, 27 March to 16:00 UT, 01 April for the 2017 event. The X-axis shows the Universal Time (UT) in hours and Y-axis represents the period in hours. The corresponding power and global wavelet spectrum (GWS) are also shown in each panel. The cone of influence (COI) is indicated by white-dashed lines. COI is the region, where the edge effects become important and the results outside the COI are not reliable. The red line in the GWS represents the 95% significance level. The black dashed-line is marked at 1.5 h periodicity. It can be clearly seen that the wavelet spectra for SYM-H,

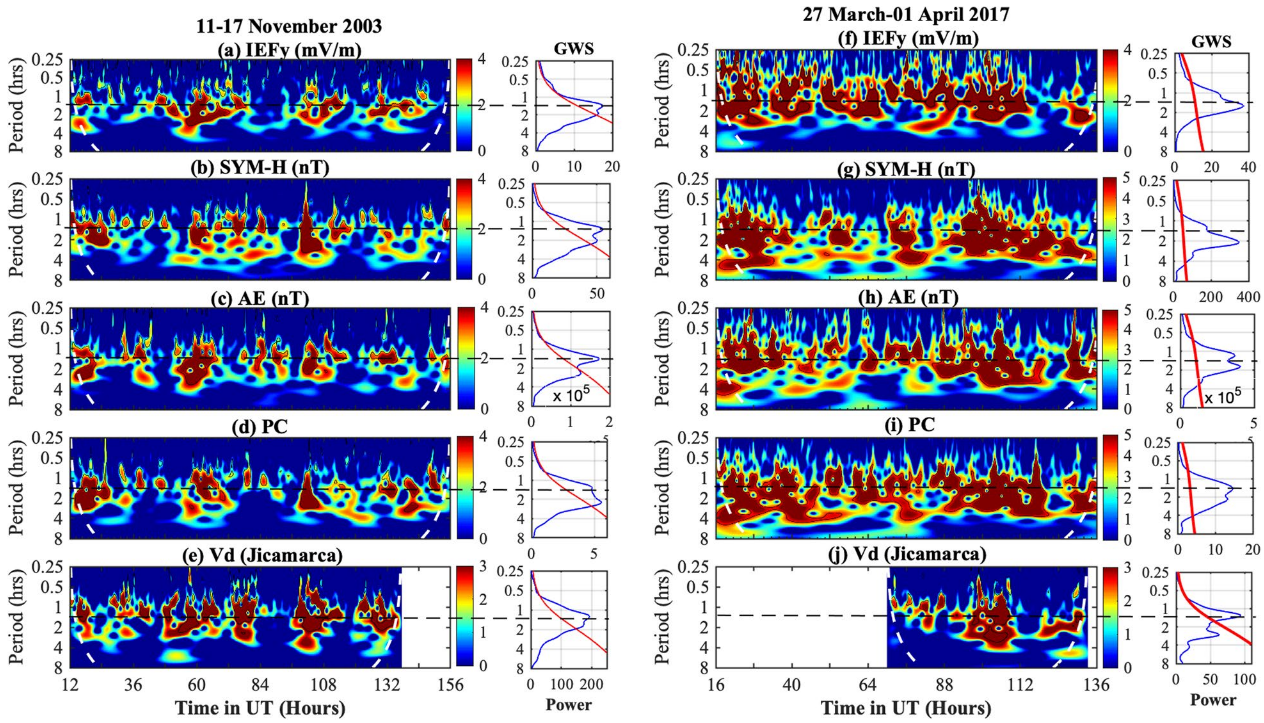


Fig. 2 Wavelet power spectra of time series of **a** IEFy, **b** SYM-H, **c** AE, **d** PC, and **e** V_d from 12:00 UT, 11 November to 12:00 UT, 17 November 2003. The right panels show the wavelet spectra of corresponding parameters from 16:00 UT, 27 March to 16:00 UT, 01 April 2017. The corresponding power and GWS are also shown in each panel with 95% significance level (red line). The cone of influence (COI) is indicated by white-dashed lines. It is to be noted that the wavelet spectra for both events show the highest peak in the GWS at ~1.5–2 h. The black dashed-line is marked at 1.5 h period. The concomitant occurrence of the 1.5–2 h periodicity in IEFy, SYM-H, AE, PC, and V_d implies possible global oscillations during the HILDCAA events

AE, PC, and V_d for both events show a common peak in the GWS at ~1.5–2 h. Furthermore, the wavelet power of IEFy for the 2003 event (Fig. 2a) shows strong ~1.5 h oscillations for almost the entire duration excluding a small interval of 81–91 h on 14 November 2003. On the other hand, in the case of the 2017 event, the wavelet spectra of IEFy (Fig. 2f) show the presence of ~1.5–2 h oscillations for the entire duration. It is striking to note that a common periodic oscillation of ~1.5–2 h in V_d is found nearly simultaneously with the IEF_y and other geomagnetic indices for both events.

To establish the causal relationship between the IEF_y and V_d during the HILDCAA events, harmonic analyses are performed using the standard algorithm of Schulz and Stattegger (1997). Harmonic analyses are carried out using the residuals of fast fluctuating components of IEFy, and Vd. The fast fluctuating components (residuals) are extracted using the Savitzk–Golay smoothing algorithm (Savitzky and Golay 1964). The advantage of the Savitzk–Golay algorithm is its ability to suppress the noise with minimum distortion (Rout et al. 2019). Furthermore, to establish the causal relationship between two time series at a given periodicity, cross-spectrum analyses are performed. The left panel of Fig. 3 depicts the results obtained from the harmonic analysis of IEFy and vertical drift during 12:00 UT, 11 November-17:00 UT, 16 November 2003 (total 125 h). Similarly, the right panel shows the results of harmonic analysis during 22:00 UT, 29 March-13:00 UT, 01 April 2017 (total 63 h). The left panel of Fig. 3 shows the periodic components of (a) IEFy, (b) Vd along with (c) the squared coherency (black) and phase spectra (red) between IEFy and Vd for the 2003 event. Similarly, the right panel shows the harmonic analysis of the 2017 event. The dashed black horizontal lines in Fig. 3 (a, b, d, and e) are marked at the confidence level of 95%. Periodicity of 1.5 h is found to be significant and present in both the parameters for the 2003 event, whereas the periodicity of 1.7 h is found to be significant for the 2017 event (marked by gray shaded box). The black horizontal dashed line in Fig. 3c, f are marked at a 90% false alarm level. It can be noticed that several periodicities in IEFy and Vd are above the significance level. Among these, a periodicity of 1.5 h is common in IEFy, and Vd for the 2003 event, whereas it is 1.7 h for the 2017 event. It is to be noted that to establish the causal relationship between two time series, it is necessary to have

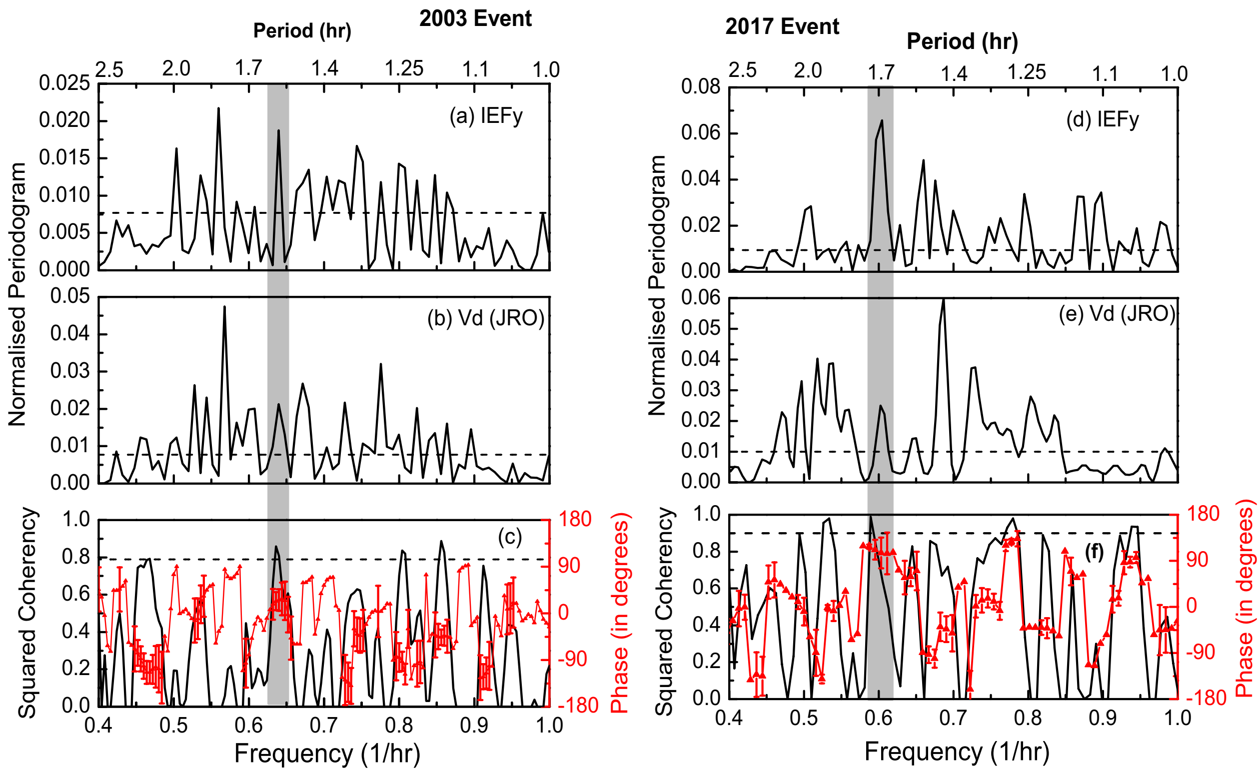


Fig. 3 Harmonic analyses of 2003 (left panel) and 2017 (right panel) events. Top three panel show the Lomb–Scargle normalized periodograms for **a** IEFy, and **b** Vd, where the black dashed horizontal line shows the 95% confidence limit. The 3rd panel represents the squared coherency (black) with the phase spectra (red) between two time series **c** IEFy and Vd. The horizontal black dashed lines in **c**, f are marked at 90% false alarm level. The rectangular grey box is marked to show the common periodic components, where the time series of IEFy, and Vd show significant coherency with stable phase relationship (essential to infer causal relationship). JRO, Jicamarca Radio Observatory

high coherency with a stable phase at the common periodicities (Chakrabarty et al. 2008; Rout et al. 2017). Therefore, the periodicities of 1.5 and 1.7 h in Vd are found to be causally connected with IEFy for the 2003 and 2017 events, respectively. The causally connected periodicities are highlighted with gray-colored boxes in Fig. 3. Therefore, this analyses strongly suggest that the 1.5–2 h periodic components in Vd are due to corresponding variations in IEFy during these HILDCAA events.

The globally distributed magnetometers and TEC data are explored to further investigate the presence of periodic fluctuations during these HILDCAA events. Figure 4 is the same as Fig. 2, but it reveals the wavelet spectra of the geomagnetic field and TEC variations for the 2003 and 2017 events. Figure 4a shows the variations of the H-component of the geomagnetic field for three latitudinally well-separated stations RES (black), OTT (blue), and KOU (red) for the 2003 event, and the corresponding wavelet spectra are also shown. Figure 4c shows the variations of the H-component of magnetic field for RES (black), OTT (blue), and HUA (red) for the 2017 event. The corresponding GWS are also provided in the same panel. From these analyses, quasi-periodic oscillations of ~1.5–2 h are observed in all the globally distributed magnetic field measurements from high to low latitudes during the HILDCAA events. In addition to these magnetometer observations, the TEC data are also analyzed from two typical high latitude stations (FAIR and BAKE) for the 2003 and 2017 events, respectively. Figure 4b, d shows the variations of VTEC and the corresponding GWS are shown for the respective events. The wavelet spectra clearly reveal the presence of 1.5–2 h quasi-periodic oscillations in the TEC measurements over high latitude ionosphere during the HILDCAA events. However, it is to be noted that the same periodic oscillations are not observed on low and mid-latitude TEC data (not shown here).

Figure 5 depicts the periodic fluctuations in the magnetosphere by (a) the variations of the Z-component of the magnetic field in the GSM co-ordinate system, and (b) energetic electron flux (>0.6 MeV) at geosynchronous

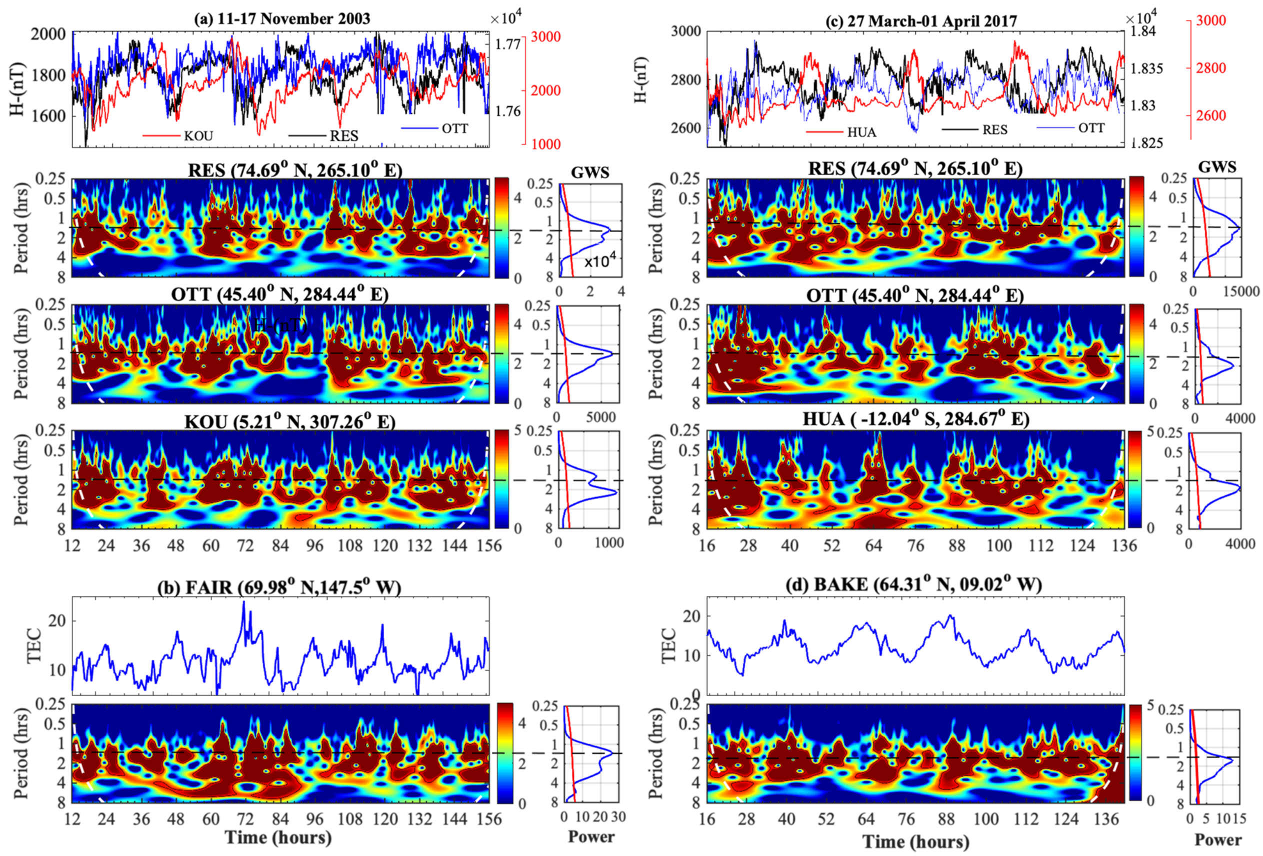


Fig. 4 This figure is similar to Fig. 2, but for the magnetic field and TEC measurements. The top left panel shows **a** the temporal variations in the H-component of the geomagnetic field for three latitudinally well-separated stations RES (black), OTT (blue), and KOU (red) for the 2003 event. The top right panel shows the **c** variations of the H-component of magnetic field for the stations' RES (black), OTT (blue), and HUA (red) for the 2017 event. The corresponding wavelet spectra are provided in the middle panels for the similar period, as mentioned in Fig. 2. The bottom panels show the temporal variations of VTEC **b** FAIR, and **d** BAKE stations, and the corresponding wavelet spectra are also provided in the bottom panel

orbit measured by the GOES-10 satellite, and the corresponding wavelet spectra are also provided in Fig. 5c, d for 2003 event. It is to be noted here that the magnetic field measurement of the GOES-13 satellite is not available for the 2017 events. Hence, only the variation of available electron flux for 475 KeV energy channel, and its wavelet spectra are shown in Fig. 5e, f. As can be seen from Fig. 5a, b, the Z-component of magnetic field and electron fluxes are showing very similar variations with each other. It is interesting to note that the quasi-periodic oscillations of 1.5–2 h are clearly seen in the Z-component of the magnetic field for the 2003 event and electron fluxes at geosynchronous orbit for both the events.

Discussion

This study reveals, for the first time, that the quasi-periodic oscillations of 1.5–2 h in solar wind electric field (IEF_y) drive similar periodic perturbations in the MI-system during HILDCAA events. The energy transfer from the solar wind to the MI-system during HILDCAA events is known to occur by magnetic reconnection (Dungey 1961) that in turn, strongly depends on the orientation of IMF Bz/IEFy (Hajra et al. 2014). In addition to magnetic reconnection, the viscous interaction between the solar wind and Earth's magnetosphere (Axford and Hines 1961; Tsurutani et al. 1990) and the cross-field diffusion by resonant wave–particle interactions at the dayside magnetopause (Tsurutani et al. 1981, 2006) also significantly contribute the transfer of energy from the solar wind to the MI-system. The Alfvenic fluctuations in the IMF Bz result in the continuous sporadic injection of particles into the ring current region thus maintaining a depressed Dst and inhibiting the decay of the ring current during HILDCAA events(Søraas et al. 2004). The major source of particle injection during the HILDCAA events that

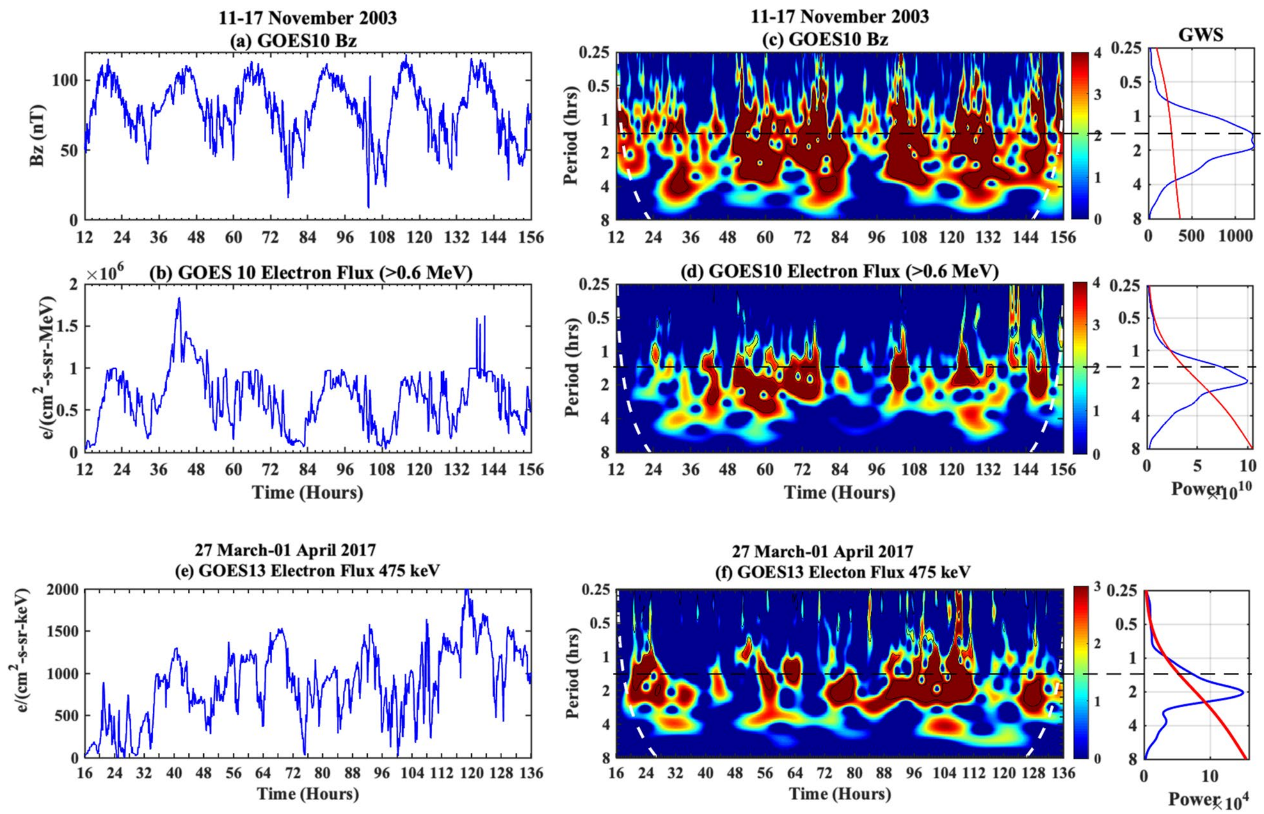


Fig. 5 This figure is similar to Fig. 2, but for the GOES measurements. **a** The temporal variations of the Z-component of the magnetic field, and **b** energetic electron flux (>0.6 MeV) at geosynchronous orbit measured by GOES-10 satellite and the corresponding wavelet spectra are provided on the right panel (**c** and **d**) for the 2003 event. **e** The temporal variations of electron flux for 475 KeV energy channel, and **f** its wavelet spectra for the 2017 event

come from the outer regions of the magnetosphere/plasmasheet towards the Earth due to the convection/dawn–dusk electric field (IEFy) (Gonzalez et al. 1994; Tsurutani et al. 2004). The periodic changes in IMF Bz/IEFy can cause the periodic changes in the ring current (SYM-H) index during the HILDCAA events which is clearly evident from Fig. 2.

This study also finds similar quasi-periodic oscillations of 1.5–2 h in IEFy, AE, and magnetic field and electron flux measurements at geosynchronous orbit. Auroral electrojet has two components. The eastward electrojet is primarily dominated by the electric field, whereas the westward electrojet is dominated by conductivity (Kamide and Kokubun 1996). It is suggested by Tsurutani et al. (2004) that AE activity during HILDCAA events does not necessarily mean the substorm activity, whereas Kim et al. (2008) observed a significant fraction of HILDCAA-time repetitive particle injections are associated with substorms. We note that, in the present case, the quasi-resonant periodicity of 1.5–2.0 h is slightly lower than the typical substorm lifetime of 2–3 h (Tsurutani et al. 1990; Newell and Gjerloev 2011; Ebihara 2019). Therefore, the role of substorms during HILDCAA events is complicated. Furthermore, it is to be noted that substorms can be triggered spontaneously by the many factors which are not necessarily related to external changes in the solar wind drivers (Henderson et al. 1996). These internal triggerings are random in nature and driven by self-organized criticality (Klimas et al. 2000; Tsurutani et al. 2004). Therefore, it is difficult to associate the periodicity of substorm occurrence with the fluctuations in the IMF Bz/IEFy periodicity. On the other hand, the fluctuations in IEFy can pave the way for recurring reconnections in the magnetotail during HILDCAA events leading to the enhanced particle precipitation into the auroral ionosphere(Tsurutani et al. 2004). The same fluctuating IEFy can penetrate from high to low latitude ionosphere during the HILDCAA events.

Another important aspect that emerges out of the present investigation is the concomitant occurrence of the 1.5–2 h periodicity in IEFy, PC, V_d, and geomagnetic field that implies a possible effect of penetration electric field from the high–low latitude ionosphere for several days. Under suitable conditions, the dawn–dusk component of IEF (IEF_y) penetrates from the high–low latitude ionosphere (Kelley et al. 2003). The periodic changes in penetration electric field during the long duration penetration events are mostly associated with DP2-type electric field perturbations, where the magnetometers show a similar magnetic variation from high to low latitude as the IEF_y oscillates between dawn and dusk-ward (Nishida 1968; Yizengaw et al. 2016; Huang 2020). This is clearly observed from Fig. 4, where the magnetometers show a strong 1.5–2 h oscillation throughout the events. A wide range of periodicities of 25–35 min (Hanumath Sastri et al. 2000; Singh and Sripathi 2021), 30–40 min (Kikuchi et al. 1996; Chakrabarty et al. 2015; Rout et al. 2018), 60 min (Chakrabarty et al. 2008; Rout et al. 2019) were reported in the past that were associated with DP2-type electric field perturbations. Given this background, the observed quasi-periodic oscillation of 1.5–2 h during both the HILDCAA events is slightly on the higher side. This indicates that the shielding region is conditioned differently during HILDCAA events, and in this context, the additional roles played by particle injection/substorms triggered during HILDCAA events can play important roles. The hot plasma injected into the inner magnetosphere during HILDCAA events can change the plasma pressure in the plasma sheet that eventually changes the shielding time constants to the higher side (Gkioulidou et al. 2009) and hence higher periodicities are penetrated. It has been observed that the shielding does not get sufficient time to develop during the fast-varying IMF Bz conditions, the effect of convection electric field in the ionosphere can last for several hours due to multiple magnetic reconnections at dayside magnetopause that gives rise to multiple short-lived penetrations (Maruyama et al. 2007; Wei et al. 2008; Huang 2019). The periodic changes in TEC over high latitude are expected due to the particle precipitation during geomagnetically disturbed conditions (Sato et al. 2018; Chernyshov et al. 2020). Recently, Birch and Hargreaves (2020) reported that the quasi-periodic oscillations of 25–27 min in the F-region electron content at high latitude, the magnetic field at geosynchronous orbit are caused by the solar wind pressure and IMF. Using the Coupled Magnetosphere–Ionosphere–Thermosphere Model (CITM), Liu et al. (2018) and Zhang et al. (2019) showed that the energy flow from the solar wind to MI-system strongly depends on the temporal changes in IMF Bz and it also controls the Joule heating, cross polar cap potential, auroral peak electron flux, the vertical plasma drift, and ionospheric F2 peak density variations globally. They also found that the coupling efficiency significantly increases when the IMF Bz oscillates for $\geq$ 60 min. As far as the periodicities are concerned, the present finding of 1.5–2 h oscillations over low latitude ionospheric electric field during the HILDCAA events is consistent with the work of Manoj et al. (2008, 2013) which showed the coherence between the IEF_y and the equatorial electric field peaks ~1.5–2 h. However, the fundamental difference, in this case, is the evidence of a global oscillation right from the solar wind to the magnetosphere and eventually to the low latitude ionosphere suggesting the presence of a "quasi-resonant" mode of oscillation during HILDCAA events for several days. Although the present investigation brings out the 1.5–2.0 h as the preferred quasi-periodic oscillation mode for the two HILDCAA events, further investigations are needed to confirm whether this is the preferred quasi-resonant mode for all the events. This can open up possibilities to investigate the properties of the solar wind–magnetosphere and global ionosphere as a big system.

Summary

It is empirically demonstrated that a quasi-periodic oscillation of 1.5–2 h in IMF Bz/IEFy drives the periodic changes in the magnetic field and electron flux at geosynchronous orbit, geomagnetic indices (SYM-H, AE, and PC), geomagnetic field on Earth (from high to low latitude), TEC over high latitude, and vertical plasma drift over the equator for several days during the HILDCAA events. It seems that HILDCAA events can cause global perturbations with a "quasi-resonant frequency" which is most dominant in both magnetosphere and ionosphere for several days. These results are important not only to evaluate the solar wind–magnetosphere–ionosphere coupling process during the HILDCAA events but can also help to build up a forecasting strategy in the future.

Abbreviations

ICME:: Interplanetary Coronal mass ejection; CIR:: Co-rotating Interaction Region; HILDCAA:: High-Intensity Long-Duration Continuous AE Activity; JRO:: Jicamarca Radio Observatory; TEC:: Total electron content; SYM-H:: Symmetric component of ring current; PC:: Polar cap index; AE:: Auroral electrojet index.

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Author contributions

DR conceptualized the idea. DR, RS and KP analyzed data and DR wrote the first draft. RS, KP, TP, CS, DC, ST, and TB helped in the discussions and contributed to improve the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The ionospheric plasma drift data over Jicamarca used in this work are taken from Madrigal Database at Jicamarca Radio Observatory (http://madrigal.haystack.mit.edu/madrigal/). The Jicamarca Radio Observatory is a facility of the Instituto Geofisico del Peru operated with support from the NSF AGS-1433968 through Cornell University. The geomagnetic indices, solar wind and GOES data are obtained from NASA GSFC CDAWeb (https://cdaweb.gsfc.nasa.gov/index.html/). The geomagnetic data are taken from SuperMAG (https://supermag.jhuapl.edu/mag/?fidelity=low). The TEC data are taken from International Center for Theoretical Physics (https://arplsrv.ictp.it).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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