

# Magnetotail response to corotating interaction region driven geomagnetic storms: Cluster observations

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## Key Points:

- The HILDCAA events that occur during the storm recovery phases could cause a spread of energy to periodicities of 2 to 12 h in the auroral region.
- During both phases of geomagnetic storms driven by CIRs, cyclic substorm periods ( $\leq 4$  hours) were found as dominant in the coupling between solar wind- magnetotail ( $IMF B_z \times$  magnetotail  $B_x$ ), solar wind-auroral region ( $IMF B_z \times AE$  index) and magnetotail- auroral region (magnetotail  $B_x \times AE$  index).
- Spectral index results suggest a strong turbulence in the magnetotail and auroral regions during recovery phases.

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## Abstract

In this work we have selected 40 corotating/stream interaction (CIR) driven geomagnetic storms that occurred between 2001 and 2016, and statistically studied their impacts on the magnetotail. The wavelet transform was applied to the interplanetary magnetic field (IMF)  $B_z$  component, magnetotail  $B_x$  component, and the auroral electrojet (AE) index during geomagnetic storms. The cross-wavelet technique was applied to determine the periods of higher correlation between the IMF  $B_z \times$  magnetotail  $B_x$ , IMF  $B_z \times$  AE index and magnetotail  $B_x \times$  AE index. More than 80% of the most energetic periods in the IMF  $B_z$  and magnetotail  $B_x$  are found to be shorter than 4 hours, independently of the storm phase. The AE index presented the range between 2-4 hours as the most common with energetic periods for both storm main and recovery phases. In the recovery phase, periodicities in the AE index are more spread ( $\leq 12$  hours) than for the main phase ( $\leq 8$  hours) probably due to the presence of high-intensity long-duration continuous AE activities (HILDCAAs). From the cross-wavelet analysis (IMF  $B_z \times$  magnetotail  $B_x$ , IMF  $B_z \times$  AE index and magnetotail  $B_x \times$  AE index), periods  $\leq 4$  hours are found to be dominant in both storm phases, which coincide with the cyclic substorm periods. The power spectral analysis showed that the IMF  $B_z$  and magnetotail  $B_x$  time series follow the Kolmogorov (-5/3) power law. Additionally, the mean values of the spectral indices for the magnetotail  $B_x$  and AE index are higher during the recovery phase than the main phase. This suggests that turbulence is more pronounced during the recovery phase of geomagnetic storms driven by CIRs.

## 1 Introduction

A magnetized plasma is continuously emitted from the solar corona, known as the solar wind (Parker, 1958). This plasma propagates away from the Sun filling the interplanetary medium, with supermagnetosonic speed and carrying with it the solar magnetic field, called the interplanetary magnetic field (IMF) (Hundhausen, 1995). The IMF has a typical magnitude of the order of 5 to 10 nT near Earth's orbit (Baumjohann & Nakamura, 2007). As of today, the solar wind is broadly classified into two groups: high-speed streams (HSS) and slow streams (Schwenn, 2006). The slow speed streams have typical speed  $V_{sw}$  of  $\sim 350 - 450 \text{ km s}^{-1}$ , and originated mainly from the helmet streamers of the Sun (Gosling et al., 1981; Suess et al., 2009; Abbo et al., 2016). HSSs, on the other hand, with  $V_{sw}$  in the range of  $\sim 750-850 \text{ km s}^{-1}$  (Phillips et al., 1995; Tsurutani et al., 2006) emanate from solar coronal holes (Krieger et al., 1973). When an HSS overtakes the ambient slower solar wind, a region of compressed plasma with an intense and fluctuating IMF is formed, called stream interaction regions (SIRs) or, if they persist for several solar rotations, corotating interaction region (CIR) (Smith & Wolfe, 1976; Tsurutani et al., 1995; Sanchez-Garcia, 2023, Chian et al., 2024). For brevity and consistency with earlier works we will call all events studied here as CIRs.

In the CIRs there is compression and acceleration of plasma in the slow solar wind streams in the opposite direction to the Sun, and compression and deceleration of the fast solar wind streams towards the Sun. At 1 AU (Astronomical Unit = distance from Earth to the Sun  $\approx 150$  million kilometers), CIRs, in general, do not present well-developed shocks (Smith and Wolfe, 1976; Tsurutani et al., 1995). However they can lead to the occurrence of geomagnetic storms and other significant geomagnetic activity occurrence (Tsurutani et al., 1995, 2006; Alves et al., 2006). The geoeffectiveness of CIRs is related to fluctuations caused by Alfvén waves that can result in intervals of southward IMF (Richardson, 2006). They are usually followed by moderate storms with smaller percentages of CIRs leading to intense storms (Alves et al., 2006; Echer et al., 2008, 2013). Another type of geomagnetic activity, high-intensity long-duration continuous *AE* activities (HILDCAA) events, have their main cause associated to alfvénic fluctuations in HSS originating from coronal holes (Tsurutani and Gonzalez, 1987), since most of the events occurred during CIRs (Hajra et al., 2013, Souza et al.

2016).

Interplanetary Coronal Mass Ejections (ICMEs) are the main geomagnetic storm drivers during solar maximum and rising phases and tend to cause more intense events (Gonzalez et al., 2007; Echer et al., 2008; Rawat et al. 2018). On the other hand, in the declining phase, CIRs occur more often and become more important in the interaction between solar wind and the magnetosphere (Gonzalez et al., 1999, 2007). CIR driven geomagnetic storms are mostly moderate ( $-50 \text{ nT} \geq Dst > -100 \text{ nT}$ ), but they show to have a higher integrated energy and therefore a long-term higher effectiveness in the solar wind- magnetosphere coupling than geomagnetic storms driven by ICMEs (Turner et al., 2006). Thus they also present risks for space technology, communication power and transportation systems (Strugarek et al., 2014).

Koller et al. (2022) studied the relation between jets in the magnetosheath and large-scale structures from the solar wind, ICMEs and SIRs/CIRs using THEMIS observations. Their results suggest that SIR/CIRs and HSS can enhance the number of geoeffective jets in the magnetosheath.

Denton et al. (2006) have found that CIR-driven geomagnetic storms produce a more significant modulation in the plasma sheet temperature than events caused by ICMEs.

The response of the ionosphere to 79 CIR events during 2004-2009 using GPS-derived ionospheric total electron content (TEC) values was investigated by Chen et al. (2015). Those authors considered latitude, longitude, local time and storm onset time dependence. The daytime TEC response to CIR storms appeared to be different from that of ionospheric F2 peak densities at high and middle latitudes. The ionospheric peak density seems to present long periods of negative response of about 2-3 days while the TEC response seems to be mostly positive. Further, a positive response from the electron density in the daytime can be observed, whereas the subauroral region showed a negative response (Chen et al., 2015).

Korth et al. (2006; 2011) studied the response of the magnetotail and polar cusps to CIRs using wavelet and cross-wavelet analysis. Their results showed periods of 2-3 hours of higher correlation between solar wind and magnetotail plasma parameters (Korth et al. 2006), while for the cusps, the periods found were around 15–25 minutes (Korth et al., 2011). The effects in the interior of the Earth's cusp and the

recurrent substorm activity are due to the Alfvén waves present in the HSS (Korth et al. 2011).

Echer et al. (2017) studied the magnetosphere response, including magnetotail, to CIR and their HSS occurred in September to October 2003 during HSS-driven storms and substorms. It was found in that work that the magnetosphere exhibits a periodic response in the range 1.8 to 3 hours to solar wind HSS fluctuations. These responses were found to be globally consistent in the magnetotail, geosynchronous orbit, auroral region and ground-based magnetometers.

Typical ionospheric disturbances and magnetotail signatures of a magnetospheric substorm are observed during the passage of CIRs and HSS by Earth. Further, the aurora related to CIRs also showed similar signatures of substorms, with localized onset and expansion toward the pole and both longitudinal directions (Despirak et al., 2013; Despirak et al., 2014). Nevertheless, while auroras formed by substorms are confined to a small region, usually located in the midnight sector, auroras with large sizes were observed during CIR passages (Despirak et al., 2014).

The higher effectiveness of CIR-driven geomagnetic storms in the magnetosphere-ionosphere system is due to the fact that, although the CIR driven geomagnetic storms tend to be weaker than the storms caused by ICMEs, they usually have a longer recovery phase duration. Then CIR-driven storms show a larger value of integrated energy dissipated in the magnetosphere during its duration (Turner et al., 2009).

The main aim of this work is to investigate the response of the magnetotail to geomagnetic storms caused by CIRs using statistical analysis. We intend to identify the dominant periods of IMF and magnetosphere fluctuations in the solar wind, magnetotail and auroral region for Cluster magnetotail's intervals and also find the periods of higher correlation between them. The characteristic energy distribution during the magnetotail interval of these events, as well as correlation distributions were also investigated. In our study we have also divided the Cluster magnetotail's crossings in intervals of main and recovery phases, with the aim to search for differences and similarities between them.

## 2 Data and Methodology of analysis

## 2.1 Data sources

In this study we have used data from the IMF  $B_z$  component, magnetotail  $B_x$  component and from the auroral electrojet index ( $AE$ ). The IMF data were obtained from NASA's OMNI database (<https://omniweb.gsfc.nasa.gov/>) with a time resolution of 1 minute. The geomagnetic field  $B_x$  component data were obtained from the magnetometer onboard the SC1 spacecraft of the Cluster constellation from the European Space Agency (ESA) website (<https://www.cosmos.esa.int/web/csa/access>). We used 1 minute averaged Cluster magnetic field data in this work. The  $B_x$  component was used here because it can be an indicator of the geometry and large-scale dynamics of the magnetotail current sheet, providing signatures of processes like thinning, reconnection, and flapping, which can be useful in understanding the magnetotail's response to CIR-driven storms (McPherron et al., 1973, Korth et al., 2006). In order to remove long-term effects observed in the geomagnetic field  $B_x$ , a technique of long-term trend extraction using the Haar wavelet function was applied in the data (Bolzan et al., 2020).

The auroral electrojet ( $AE$ ) index was proposed by Davis and Sugiura in 1966 (Davis & Sugiura, 1966) and is used to measure geomagnetic activity in the auroral zone (Rostoker, 1972). The 1 minute  $AE$  index data are provided by the World Data Center for Geomagnetism (WDC), Kyoto, Japan (<https://wdc.kugi.kyoto-u.ac.jp/>). For the storm phase classification into main and recovery phases, we have used storm time disturbance indices  $Dst$  and  $SYM-H$  with temporal resolutions of 1-hour and 1-minute respectively from WDC Kyoto (Sugiura, 1964; Iyemori 1990; Gonzalez et al., 1999). The storm main phase was marked between the times when sharp depression in  $SYM-H$  ( $Dst$ ) was noted until the minimum value was attained while the recovery phase was defined as the period between time of minimum  $SYM-H$  ( $Dst$ ) and recovery to pre-storm levels. The selection criterion followed the classification proposed by Gonzalez et al. (1994), where a moderate geomagnetic storm is defined by a minimum  $Dst$  value in the range  $-100\text{nT} \leq Dst \leq -50\text{ nT}$ .

In Table 1 the 40 CIR-driven geomagnetic storms that were found between 2001 and 2016 are presented. In addition to the date of occurrence, the  $Dst$ ,  $V_{sw}$ ,  $B_s$  (southward IMF  $B_z$ ) and  $E_y$  (y-component of the electric field) values are also shown. From Table 1 it is noted that the event number 17 exhibited double minimum in  $Dst$ . The event

occurred on 28 July, 2005, and the first *Dst* minimum (-50 nT) could be attributed to the CIR whereas HSS caused the second, smaller depression in *Dst* (minimum *Dst* = - 41 nT). Alfvénic fluctuations in IMF  $B_z$  associated with HSS are distinctly visible. The density enhancements indicate the compression region of CIRs.

**Table 1.** CIR-driven geomagnetic storms during 2001–2016.

| No. | Date       | Minimum<br><i>Dst</i><br>(nT) | Peak $V_{sw}$<br>(km s <sup>-1</sup> ) | Peak $B_s$<br>(nT) | Peak $E_y$<br>(mV m <sup>-1</sup> ) |
|-----|------------|-------------------------------|----------------------------------------|--------------------|-------------------------------------|
| 01  | 2001-09-23 | -73                           | 568                                    | 9                  | 4.7                                 |
| 02  | 2001-10-09 | -64                           | 468                                    | 5.7                | 2.6                                 |
| 03  | 2002-09-04 | -109                          | 415                                    | 18.3               | 6.8                                 |
| 04  | 2002-10-07 | -115                          | 373                                    | 8.4                | 3                                   |
| 05  | 2002-10-14 | -100                          | 356                                    | 13.6               | 4.6                                 |
| 06  | 2002-10-24 | -98                           | 733                                    | 7.4                | 4.5                                 |
| 07  | 2002-10-31 | -52                           | 513                                    | 5.7                | 2.9                                 |
| 08  | 2002-11-03 | -75                           | 484                                    | 6.3                | 3                                   |
| 09  | 2003-07-12 | -105                          | 595                                    | 12.5               | 7.4                                 |
| 10  | 2003-07-16 | -90                           | 609                                    | 10.2               | 6.1                                 |
| 11  | 2003-07-27 | -57                           | 773                                    | 14.3               | 6.3                                 |
| 12  | 2003-08-06 | -60                           | 481                                    | 11.3               | 5.0                                 |
| 13  | 2003-08-07 | -61                           | 641                                    | 8.6                | 5.4                                 |
| 14  | 2003-10-14 | -85                           | 724                                    | 8.6                | 5.3                                 |
| 15  | 2004-10-13 | -63                           | 431                                    | 8.6                | 3.5                                 |
| 16  | 2005-07-10 | -92                           | 484                                    | 19.6               | 9.1                                 |
| 17  | 2005-07-28 | -50 (-41)                     | 419                                    | 5.2                | 2.2                                 |
| 18  | 2005-08-31 | -131                          | 412                                    | 16                 | 6.3                                 |
| 19  | 2005-09-10 | -73                           | 748                                    | 5.1                | 3.6                                 |
| 20  | 2006-09-24 | -56                           | 667                                    | 7.3                | 2.9                                 |
| 21  | 2007-10-25 | -51                           | 694                                    | 4                  | 2.3                                 |
| 22  | 2008-09-04 | -51                           | 488                                    | 8.7                | 4.3                                 |
| 23  | 2008-10-11 | -60                           | 421                                    | 11                 | 3.9                                 |
| 24  | 2009-07-22 | -83                           | 359                                    | 14.5               | 4.9                                 |
| 25  | 2010-10-11 | -75                           | 360                                    | 11.6               | 4.2                                 |
| 26  | 2011-09-10 | -55                           | 554                                    | 17.1               | 8.2                                 |
| 27  | 2013-08-27 | -54                           | 411                                    | 10                 | 4.1                                 |
| 28  | 2015-07-05 | -68                           | 575                                    | 14                 | 6.7                                 |
| 29  | 2015-07-23 | -64                           | 459                                    | 11                 | 4.8                                 |
| 30  | 2015-09-07 | -71                           | 602                                    | 10.1               | 5.9                                 |
| 31  | 2015-09-11 | -82                           | 641                                    | 10.8               | 5.3                                 |
| 32  | 2015-10-04 | -56                           | 456                                    | 7.7                | 3.4                                 |
| 33  | 2015-10-07 | -93                           | 462                                    | 8.7                | 4.0                                 |
| 34  | 2015-10-08 | -58                           | 758                                    | 3.2                | 2.3                                 |
| 35  | 2015-10-10 | -50                           | 611                                    | 3.1                | 1.7                                 |
| 36  | 2016-08-23 | -74                           | 451                                    | 11.1               | 4.7                                 |
| 37  | 2016-09-01 | -59                           | 433                                    | 7.5                | 3.2                                 |
| 38  | 2016-09-03 | -50                           | 666                                    | 2.6                | 1.7                                 |
| 39  | 2016-09-29 | -66                           | 705                                    | 5.2                | 3.7                                 |
| 40  | 2016-10-25 | -60                           | 721                                    | 6.6                | 4.1                                 |

## 2.2 Methodology of analysis

In this section the methodologies used for developing this work are presented: wavelet and Fourier transforms.

### 2.2.1 Wavelet and cross-wavelet transform

In order to determine the main periodicities occurring in HSS and in the magnetotail and auroral regions, the wavelet transform (WT) was employed to the IMF, magnetotail and auroral data.

The WT allows us to investigate how the energy is distributed in time and period or frequency ranges in non-stationary time series (Torrence and Compo, 1998). The wavelet functions (known as "daughter wavelets") are generated from a simple generating function (called wavelet-mother):

$$\psi_{a,b} = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right)$$

for  $a, b \in \mathbb{Z}$  and  $a \neq 0$ , which undergoes expansions/contractions and translations in time. The WT transforms the signal  $f(t)$  into a function with two variables (scale and time), represented by  $WT(a, b)$  from Eq. (1):

$$WT(a, b) = \int_{-\infty}^{\infty} f(t) \psi_{a,b}^*(t) dt, \quad (1)$$

where  $a$  is the dilation coefficient,  $b$  is the coefficient of translation in time, and  $\psi_{a,b}^*(t)$  represents the complex conjugate of the mother-wavelet function.

The Cross-Wavelet Transform (XWT) (2) is constructed from two continuous WT of the variable time series (Grinsted et al., 2004; Bolzan, 2005) and can be obtained by Eq. (2).

$$XWT(a, b) = WT(a, b) WT'(a, b)^* \quad (2)$$

In Eq. (2),  $W^x$  and  $W^y$  represent the WT applied to the time series  $x(t)$  and  $y(t)$ , and  $(*)$  represents the complex conjugate of the WT.

The periods with high energy or with higher correlation can be detected using the Global Wavelet Spectrum (GWS), which can be computed by

236  $\int |\varphi(\tau, \tau)|^2 d\tau$  for the main periodicities. For the identification of the periods  
 237 with higher correlation, the GWS is obtained by  $\varphi = \frac{\sigma_x^2 \sigma_y^2}{\sigma_x^2 + \sigma_y^2} \int |\varphi(\tau, \tau)|^2 d\tau$ ,  
 238 where  $\sigma_x^2$  and  $\sigma_y^2$  represent the variances of the time series,  $x(t)$  and  $y(t)$ , respectively.

239

### 240 2.2.1.1 Energy distribution Classification

241 The wavelet power persistence can be classified into four types: Local,  
 242 Intermittent, Quasi-Continuous, and Continuous, based on their temporal duration and  
 243 physical significance. Local distribution indicates power restricted to short intervals,  
 244 representing transient phenomena like bursty bulk flows. The Intermittent characteristic  
 245 describes features appearing and disappearing at intervals, reflecting recurrent or  
 246 stochastic processes. The Quasi-continuous distribution denotes signals present for  
 247 most of the duration, suggesting a sustained but modulated response to solar wind  
 248 drivers. Continuous classification refers to power persisting throughout the entire interval,  
 249 signifying a steady-state, stable coupling between the solar wind and the magnetosphere  
 250 (Souza et al., 2016).

251

### 252 2.2.2 Fourier Transform

253 In order to study the turbulence of space plasmas, one powerful technique is  
 254 to apply Fourier transform to the data and obtain a power law spectrum for different  
 255 frequency ranges. The Fourier spectrum of a time series is fitted by a power-law function  
 256 as  $P(f) = c f^{-\alpha}$ , where  $P(f)$  is the Fourier spectral power,  $c$  is a constant,  $f$  is the  
 257 frequency, and the  $\alpha$  exponent is the power law index (Bolzan & Echer, 2014). While the  
 258 spectral power gives an indication of the amplitude of turbulence fluctuations in different  
 259 regions and frequency ranges, the power law index indicates how steep is the spectrum,  
 260 i.e., how fast it changes with frequency, and how the rate of energy is transferred from  
 261 large to small scales (Bruno et al., 2005). In this study, the Fourier analysis was used in  
 262 order to obtain the spectral index from the solar wind, magnetotail and auroral index data.

263

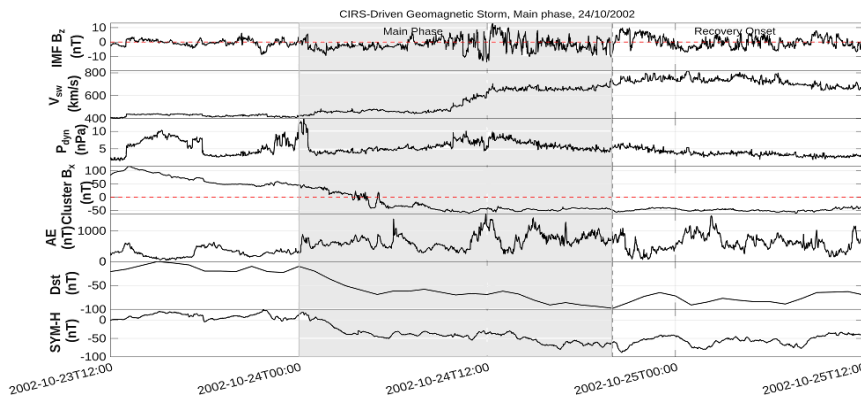
## 264 3 Results and Discussions

265 In this section, the wavelet, cross-wavelet and Fourier power law analysis  
 266 results are shown for the main and recovery phases of CIR-driven geomagnetic storms

267 during Cluster magnetotail intervals.

268 As expected, for CIR-driven geomagnetic storms, the majority of the events  
 269 are moderate storms. From the 40 events (Table 1), 87.5 % corresponds to moderate  
 270 storm classification ( $-50 \text{ nT} \geq Dst > -100 \text{ nT}$ ) while only 12.5 % (5 events) were intense  
 271 storms ( $-100 \text{ nT} \geq Dst > -250 \text{ nT}$ ). Weak and super intense storms were not identified  
 272 in this dataset.

273 Figure 1 shows the time series of the IMF  $B_z$  (left upper panel), solar wind  
 274 speed (left second panel), solar wind pressure (left third panel), magnetotail  $B_x$  (left fourth  
 275 panel),  $AE$  index (left fifth panel),  $Dst$  index (left sixth panel), and  $SYM-H$  index (left  
 276 bottom panel) for the interval when the Cluster remained in the magnetotail during part  
 277 of the geomagnetic storm caused by a CIR that is identified as event 6 from Table 1. The  
 278 main phase is indicated by the gray area and corresponds to the interval between 00:00  
 279 UT and 19:09 UT, 24 October 2002. From Fig. 1 one can notice that oscillations in the IMF  
 280  $B_z$  increase after 08:00 UT, while in the magnetotail  $B_x$  data, high amplitude oscillations  
 281 are observed from 04:00 UT to 06:00 UT. These oscillations are related to the southward  
 282 IMF  $B_z$  extended interval seen from about 01:00 to 06:00 UT. Several quasi-periodic  
 283 oscillations in the  $B_x$  data can be seen from 06:00 to 18:00 UT. This seems to be related  
 284 to the high amplitude IMF  $B_z$  fluctuations noted after about 10:00 UT. In the  $AE$  index we  
 285 can observe peaks higher than 1000 nT in intervals close to both time ranges, as well as  
 286 a low (0.31) anti-correlation with the oscillations of IMF  $B_z$  with a lag of 22 minutes.  
 287 Lower values are observed around 12:00 UT in the IMF  $B_z$ , followed by peaks around  
 288 13:00 UT, which decreases after 14:00 UT. While the opposite behavior is observed in  
 289 the  $AE$  index, where we have peaks around 12:00 UT, lower values observed around  
 290 13:00 UT and other peaks are seen after 14:00 UT. There are several substorm events  
 291 noted in the  $AE$  index. One group seems to be associated with the first interval of  
 292 negative  $B_z$ , while the second group of substorms is related to the fluctuating IMF  $B_z$   
 293 interval. In the  $Dst$  index, the characteristic sharp decrease that occurs during the  
 294 geomagnetic storm main phase due to the increase of ionized particles being “trapped”  
 295 in the magnetic field lines can be observed. The minimum  $Dst$  ( $-98 \text{ nT}$ ) is reached at the  
 296 end of the time series (19:09 UT on 24 October 2002). The typical signature of the main  
 297 phase of the geomagnetic storm can be also seen in the  $SYM-H$  index time series  
 298 (bottom-left panel). The right panel shows the Cluster orbit, where the interval that covers  
 299 the gray region from the time series is marked in pink.



Cluster orbit 2002 296 (10/23) 08:40 UT to 2002 298 (10/25) 17:45 UT

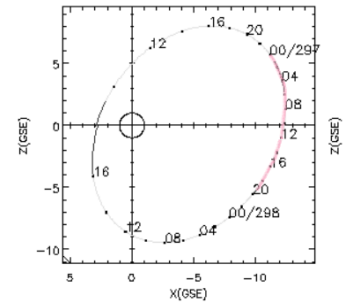
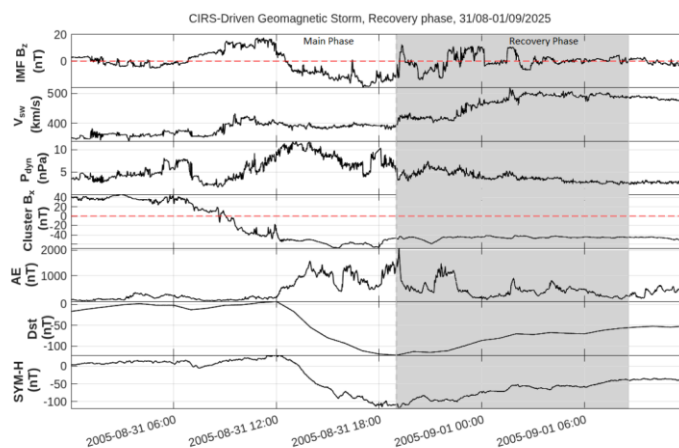


Figure 1. (left) Temporal variations of IMF  $B_z$ , solar wind speed ( $V_{sw}$ ), solar wind pressure ( $P_{dyn}$ ), magnetotail  $B_x$ , AE index,  $Dst$ , and SYM- $H$  indices during the main phase of a geomagnetic storm caused by a CIR on 24 October 2002. The interval when Cluster remained in the magnetotail (00:00 UT and 19:09 UT on 24 October 2002) is shaded in gray (left panel). Right panel shows the Cluster orbit for the same interval marked in pink.

Figure 2 illustrates another example of a Cluster magnetotail during a CIR-driven geomagnetic storm (Event 18, Table 1), focusing on the recovery phase interval (shaded gray area). Following the format of Fig. 1, the panels on the left present the time series for IMF  $B_z$  (top), solar wind speed ( $V_{sw}$ ), and dynamic pressure ( $P_{dyn}$ ), followed by the magnetotail  $B_x$ , the AE index, and the  $Dst$  and SYM- $H$  indices (bottom). In the last two panels, the recovery phase of the  $Dst$  and SYM- $H$  indices is clearly observed. The right panel displays the Cluster orbit, with the analyzed interval highlighted in pink.

From the top-left panel, as well as in the  $B_x$  and AE index plots (fourth and fifth panels, respectively), a prominent positive peak is observed across all three parameters, followed by a subsequent decrease. The IMF  $B_z$  exhibits oscillating patterns with several intervals of southward (negative) orientation. Furthermore, both the magnetotail and auroral regions show multiple substorm-like events, characterized by the typical signature of an AE index increase accompanied by a decrease in the magnetotail  $B_x$  magnitude (Gonzalez et al., 1994).



Cluster orbit 2005 242 (08/30) 11:00 UT to 2005 244 (09/01) 20:05 UT

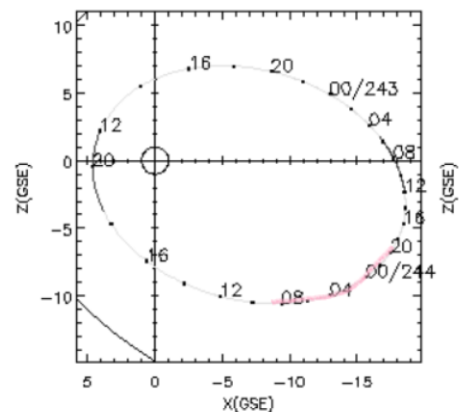


Figure 2. Time series of IMF  $B_z$  (left upper panel), solar wind speed ( $V_{sw}$ ), solar wind pressure ( $P_{dyn}$ ), magnetotail  $B_x$ , AE index,  $Dst$ , and  $SYM-H$  indices during the geomagnetic storm caused by a CIR between that occurred between 31 August and 01 September, 2005. The interval when Cluster remained in the magnetotail, from 19:00 UT, 31 August, to 08:40 UT, 01 September, 2005 is shaded in gray (left panel). The right panel shows the Cluster orbit. The time series interval is marked in pink.

### 3.1 Wavelet and Cross-Wavelet Analyses

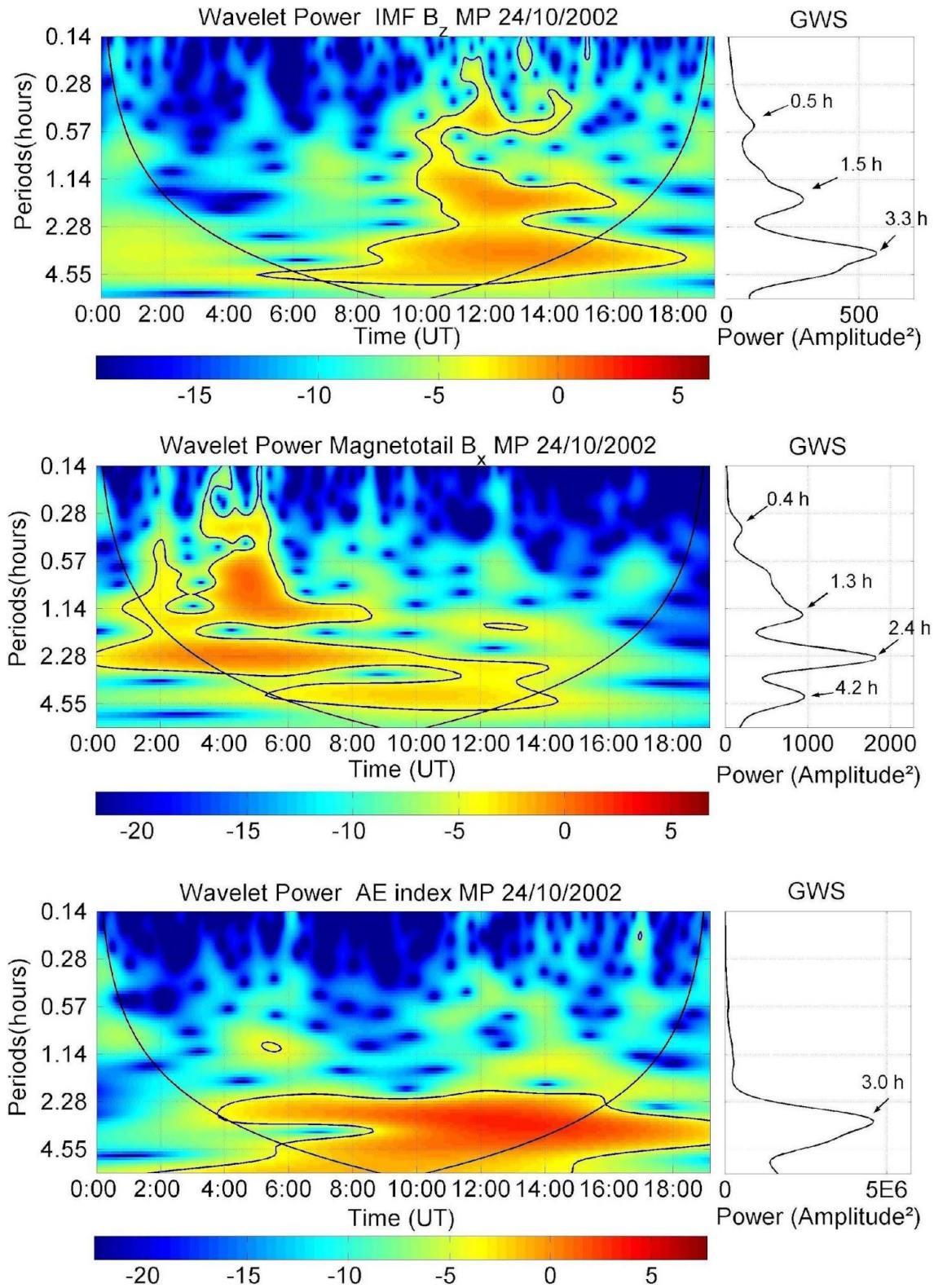
The Wavelet transform was applied to the IMF  $B_z$  component, to the magnetotail  $B_x$  component and to the AE index for intervals when the Cluster spacecraft was in the magnetotail during CIR-driven geomagnetic storms. The analysis is subdivided for intervals of main and recovery phases. The cross-wavelet between these variables was also computed for both geomagnetic storm phase intervals in order to investigate at which periods the correlation between them is higher.

### 3.2 Wavelet Analysis

#### 3.2.1 Main Phase

Figure 3 shows the wavelet spectrogram (map) applied to the IMF  $B_z$  component (top panel) and magnetotail  $B_x$  component (middle panel) and AE index (bottom panel) during a moderate geomagnetic storm main phase interval between 00:00 UT and 19:09 UT, 24 October 2002 (Event 06 from Table 1). In the upper panel, the left figure shows the wavelet spectrum of the IMF  $B_z$  and the right figure presents the global wavelet spectrum (GWS). In the GWS, three periods with higher energy can be identified. The first, around 0.5 h, can be characterized as having local distribution, since higher energy (integrated wavelet power) is observed in the wavelet spectrum only in a small interval between  $\sim 10:00$  UT and  $\sim 15:00$  UT. The second period is of 1.5 hours and also presents local distribution, located in a similar region of the first period (from  $\sim 10:00$  UT to  $\sim 16:00$  UT). The last observed period is around 3.3 hours, and in the wavelet spectrum it can be observed continuously for a long time interval, from around  $\sim 05:00$  UT to more than 16:00 UT, characterizing a quasi-continuous behavior. The quasi-continuous nature of the 3.3-hour period can indicate large-scale fluctuations in the solar wind's driving force. This is related to the characteristics of the high-speed stream (HSS) following the CIR, which can contain continuous fluctuations that drive the

361 magnetosphere over a long duration (Borovsky and Denton, 2006).



**Figure 3.** Wavelet transform analysis for the interval when Cluster remained in the magnetotail during the main phase of a geomagnetic storm caused by a CIR between 00:00 UT and 19:09 UT, 24 October, 2002 for the IMF  $B_z$  component (top panel) and magnetotail  $B_x$  geomagnetic field component (middle panel) and AE index (bottom

panel). Left panels show the wavelet power spectrum and right panels display the GWS.

In the middle panel of Fig. 3, the wavelet transform periodogram for the magnetotail  $B_x$  is shown. As for the IMF  $B_z$  wavelet spectrum, upper panel, the left figure shows the wavelet spectrum and the right panel shows the GWS. Four significant periods were identified in the GWS:  $\sim 0.4$  hour,  $\sim 1.3$  hour, 2.4 hours and 4.2 hours. From the wavelet spectrum one can see that local distribution is observed in the two first periods, which are found from about 03:00 UT to 05:20 UT and from about 01:00 to 08:30 UT, respectively. The other two periods show quasi-continuous distribution, where the period of 2.4 hours is the most energetic. The strong energy at these periods suggests that the magnetotail's internal dynamics, possibly related to current sheet flapping or other global oscillations, are being excited and maintained by the external solar wind driver (Runov et al, 2005). The wavelet analysis of the  $AE$  index (bottom panel) shows a single, significant quasi-continuous period around 3 hours. This timescale is consistent with the substorm cycle (Borovsky et al., 1993; Korth et al., 2011).

The coincidence of this dominant period with the quasi-continuous periodicities found in both the solar wind (IMF  $B_z$ ) and magnetotail ( $B_x$ ) provides evidence of a direct and efficient coupling mechanism between the external driver and the magnetospheric response. It indicates that fluctuations in the solar wind (IMF  $B_z$ ) are directly linked to magnetotail dynamics ( $B_x$ ) and subsequently drive auroral substorm activity ( $AE$ ).

We also applied the wavelet transform to the solar wind and magnetospheric data during the main phase intervals of the events from Table 1 when the Cluster spacecraft remained at least 10 hours in the magnetotail. A total of 6 events were analyzed (events: 6, 7, 9, 14, 26 and 30). The number of events analyzed for each variable varies due to gaps in the available data of IMF  $B_z$  and magnetotail  $B_x$  components. For the IMF  $B_z$  and magnetotail  $B_x$ , the WT was applied to data in 5 events: 6, 7, 9, 14 and 30 for IMF  $B_z$  and 6, 7, 9, 14 and 26 for magnetotail  $B_x$ . The statistical result of this analysis is shown in the subsection below along with the results of the recovery phase.

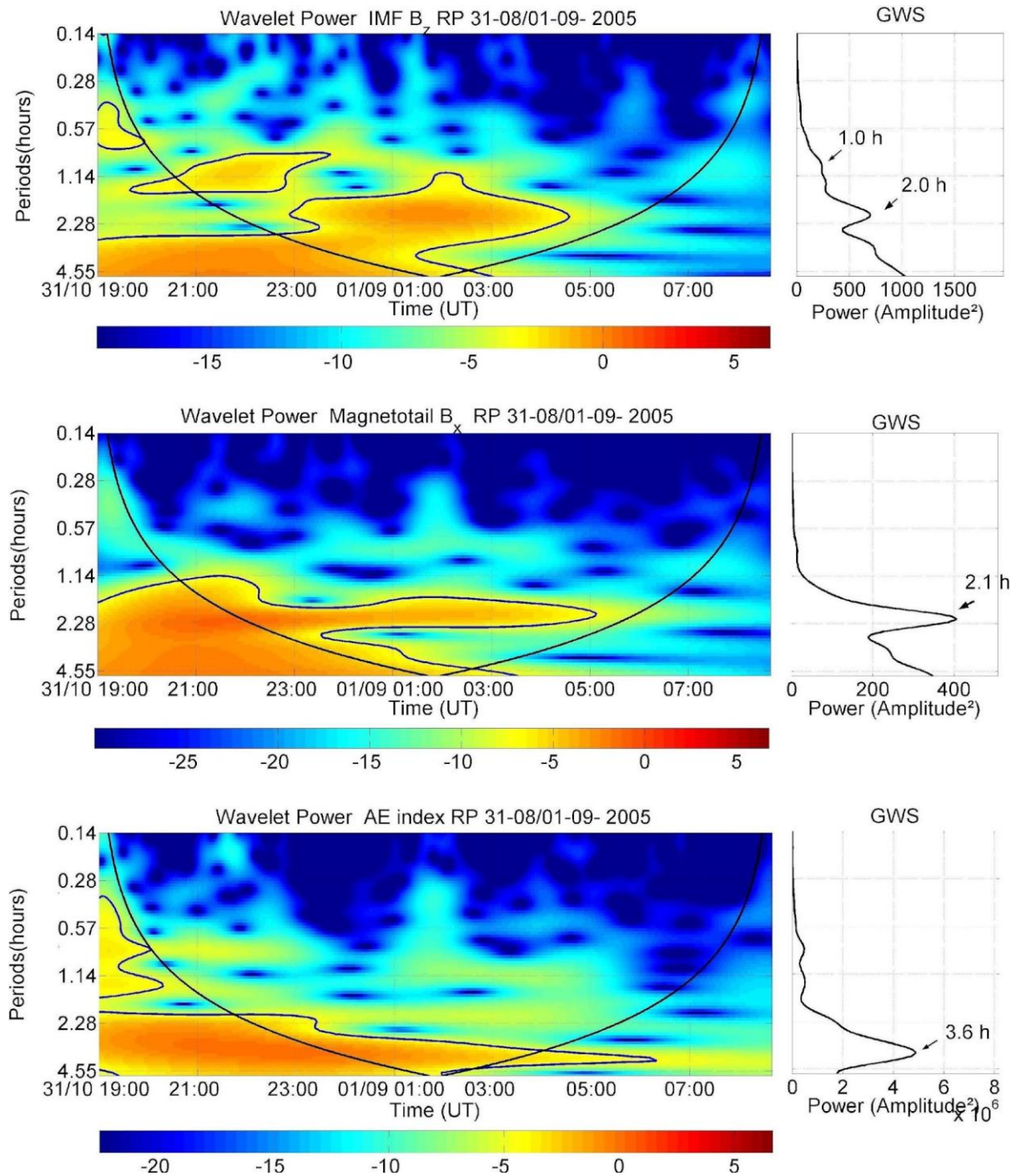
### 3.2.2 Recovery phase

As mentioned before, the WT was also applied to the CIR-driven geomagnetic

storm recovery phases during intervals when Cluster was in the magnetotail. Figure 4 shows one example, where the WT was performed for event 18 of Table 1, which occurred from 19:00 UT on 31 August to 08:40 UT on 1 September 2005 (intense storm).

Similarly as it was shown in Fig. 3, the upper panel shows WT for the IMF  $B_z$  component, the middle panel for the magnetotail  $B_x$  and the bottom panel shows the WT applied to the AE index. Again, the left panels correspond to the wavelet spectrum and the right panels to the global wavelet spectrum.

The GWS, shown in the top panel in Fig. 4, for IMF  $B_z$ , shows that two significant spectral peaks are observed, both with local distributions (left panel). The first period, near 1.0 h, is localized between 19:00 and 23:00 UT. The second one is observed at 2.0 hours, with higher energy (integrated wavelet power) concentrated between 23:00 UT on 31 August and ~04:20 UT on 1 September 2005.



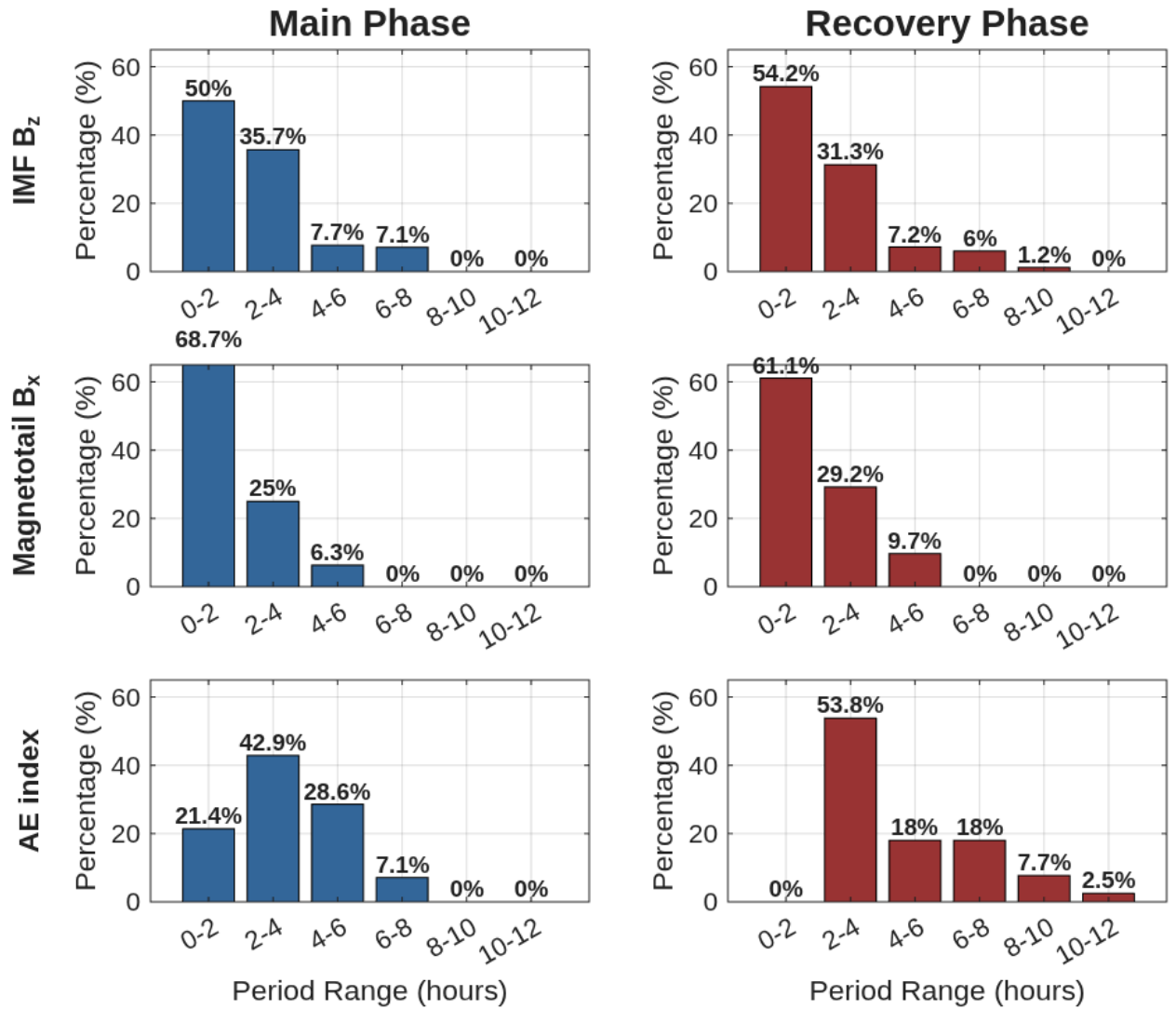
**Figure 4.** Wavelet transform analysis for the interval when Cluster remained in the magnetotail during the recovery phase of a geomagnetic storm caused by a CIR between 19:00 UT on 31 August and 08:40 UT on 1 September 2005 for IMF  $B_z$  component (top panel) and magnetotail  $B_x$  geomagnetic field component (middle panel) and AE index (bottom panel). Left panels show the wavelet power spectrum and right panels display the GWS.

For the magnetotail  $B_x$ , shown in the right middle panel, the GWS also shows only one significant period, very close to the periodicity observed for IMF  $B_z$ , 2.1 hours.

However, for the magnetotail  $B_x$  component, the energy distribution has a quasi-continuous variation (left middle panel), and is observed from the beginning of Cluster interval until about 05:00 UT of 1 September. In the  $AE$  index, (bottom panels), the wavelet analysis shows a period around 3.6 hours in the GWS, which also has a quasi-continuous distribution, from the beginning of the interval to the period at about 06:00 UT on 1 September 2002. Other short periods can be seen in the GWS, but in the wavelet distribution (left bottom panel), the higher energy is observed outside the cone of influence (COI), which delimits the region that is not affected by edge effects. Therefore they were discarded.

While the IMF  $B_z$  shows localized, high-energy periods at 1.0 and 2.0 hours, the magnetotail  $B_x$  and  $AE$  index display quasi-continuous dominant periods at 2.1 and 3.6 hours, respectively. This continuous nature suggests that even in the recovery phase, the magnetosphere is being driven by sustained solar wind fluctuations, a typical characteristic of HSS (Tsurutani and Gonzalez, 1987; Souza et al., 2018).

We followed the same criteria used to compute WT for both the main and recovery phases. For the Cluster magnetotail's periods this interval should be  $\geq 10$  hours. For the recovery phase, a much higher number of events followed this criterion (29 events). It is worth mentioning that for some cases only one or two variables meet the criterion due to the absence of available data. Figure 5 shows the histograms for period ranges, with bins of 2 hours, for the three variables for the main phase (left panels) and recovery phase (right panels). This figure shows that, except for the magnetotail  $B_x$ , longer periods begin to be observed in the recovery phases, right top and bottom panels. For the IMF  $B_z$  component histograms, main phase (left panels) and recovery phase (right panels), we can see the same dominant ranges of periods for both geomagnetic storm phases. Periods  $\leq 2$  hours represent 50.0 % of the main periods during the main phase, and 54.2 % of the periods during the recovery phase. The range between 2 and 4 hours corresponds to more than 35 % of the periods for the main phase, and 31.3 % for the recovery phase. These two ranges are also predominant for the magnetotail  $B_x$  periodicities. During HILDCAA events (Franco et al., 2019), the stronger magnetotail response to the IMF fluctuations are typically found in the substorm periodicity range (2 - 4 hours) (Borovsky et al., 1993; Franco et al., 2019).



**Figure 5.** Histograms with period ranges for the main phase (left panels) and recovery phase (right panels). From top to bottom the panels show: IMF  $B_z$ , magnetotail  $B_x$  and the AE index distributions.

For the magnetotail  $B_x$ , although the range between 2 and 4 hours corresponds to 25 % of the periods for the main phase, and 29.2 % for the recovery phase, periods  $\leq 2$  hours represent 68.7 % of the periods during the main phase and 61.1 % for the recovery phase. From our present results, it seems that during CIR-driven geomagnetic storms the magnetotail has a stronger response to lower periods than during HILDCAA events. This could occur because the prolonged duration and wave-driven nature of HILDCAAs favor longer characteristic periods, while the shorter, more intense driving of the CIR main phase emphasizes the shorter, internal magnetotail response periods. Further, these results show us that more than 80 % of the most energetic periods in the IMF  $B_z$  and magnetotail  $B_x$  during geomagnetic storms driven by CIRs are found for periods shorter than 4 hours, independently of the storm phase. Similar periods (1.8 hours to 3.1

hours) were found by Echer et al. (2017) in a study of the solar wind - magnetotail coupling during HSS and CIR intervals.

The *AE* index analysis revealed that periods between 2 and 4 hours are the most prominent during both the main (42.9 %) and recovery (53.7 %) phases of geomagnetic storms. However, there are notable differences between these phases. During the main phase, periods between 4 and 6 hours are the second range most often observed, followed by periods shorter than 2 hours. In contrast, during the recovery phase, no significant periods shorter than 2 hours were observed. Instead, the distribution of higher-energy periods seems to extend to longer durations, with the 4-6 hour and 6-8 hour ranges sharing the same percentage of periods. This difference may be attributed to the occurrence of HILDCAA events during the recovery phase (Kamide et al., 1998). These events are often associated with Alfvénic trains in the IMF, and typically have periods between 4 and 12 hours (Souza et al., 2016). While the increased number of analyzed recovery phase events could potentially influence the period distribution, we believe this is not the primary cause of the observed distribution. This is supported by the fact that the spread in periods was not observed for the magnetotail  $B_x$  component but it was noted only in the IMF  $B_z$  component distribution, which oscillations are usually due to Alfvén waves during CIR intervals. Furthermore, the absence of shorter periods during the recovery phase cannot be solely explained by the higher number of analyzed cases.

Figure 6 represents the energy distribution across the main identified periods for each variable and period range during the main and recovery phases. Considering all ranges, the continuous behavior dominates the IMF  $B_z$  energy distribution during the main phase with 35.7 % of the cases, which is also observed for individual ranges, except for the range  $\leq 2$  hours, at which local distribution dominates. During the recovery phase, the local and intermittent distributions are the most common observed energy distribution types, while the continuous distributions represent only 3.6 % of the most energetic periods identified. Further, note that during the main phase, the local characteristic dominates the range with the larger occurrence of energetic periods ( $\leq 2$  h), while during the recovery phase, the intermittent behavior is dominant for this period range. This distinction in energy distribution characteristics is significant, as the main phase of geomagnetic storms is frequently characterized by enhanced substorm activity and the most intense occurrence of magnetotail dipolarizations (Lee & Min, 2002).

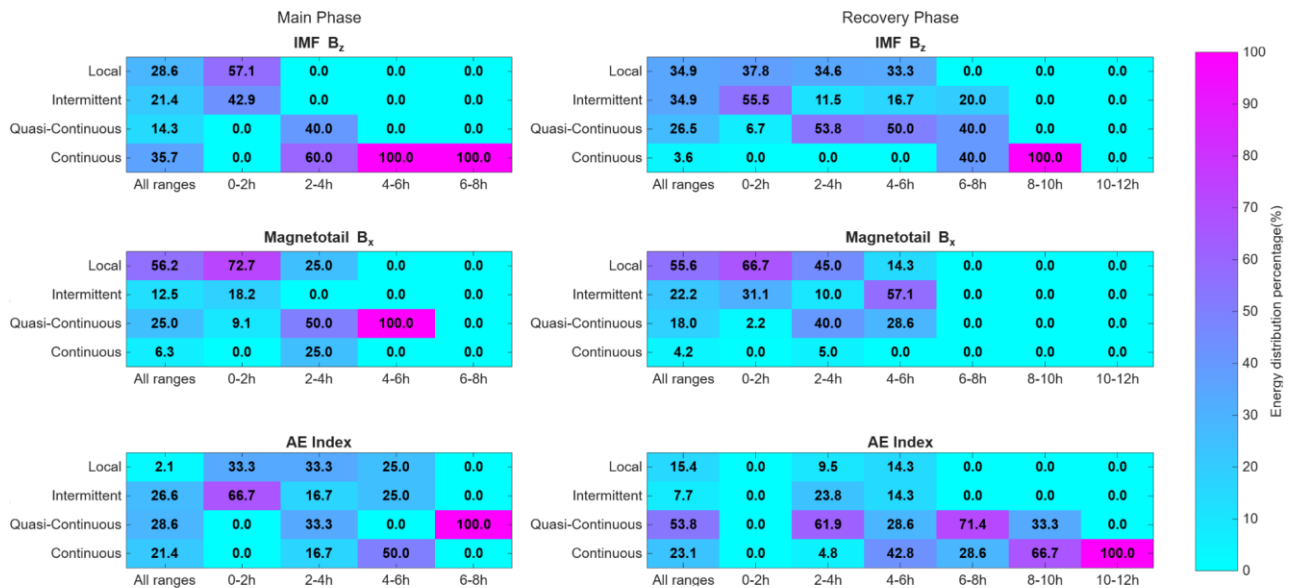


Figure 6- Color maps of energy distribution classification percentage. Maps for IMF  $B_z$  (upper panels), magnetotail  $B_x$  (middle panels), and the AE index (bottom panels) display the percentage distribution across period ranges (x-axis) and energy distribution classification (y-axis). Results are separated by storm phase: main phase (left column) and recovery phase (right column).

Near Earth, these events can be associated with localized fast plasma jets during intense substorms, which may justify the local distribution observed in the most energetic periods during the main phase (Nakamura et al., 2002, 2017). The quasi-continuous behavior observed in the recovery phase was also seen in the IMF  $B_z$  component during HILDCAA events. For shorter periods ( $\leq 2$  hours), an intermittent distribution was observed, which might be related to the events that occur during geomagnetic storm recovery phases (A. M. Souza, 2015; A. Souza et al., 2016).

For the magnetotail  $B_x$  component, the local type distribution of the periodicities was the most often observed for both main and recovery phases considering all ranges. The same characteristic is observed for the range with the higher occurrence of the main periods ( $\leq 2$  h) with 72.7 % for the main phase, which could also be related to localized fast plasma jets in the magnetotail (Nakamura et al., 2017). The same predominant distribution was also observed for the recovery phases (66.7 %). This result differs from those found in a previous magnetotail study during HILDCAAs (Franco et al., 2019), that showed that more than 50 % of the magnetotail  $B_x$  periods presented quasi-continuous and intermittent distributions, which is a characteristic of substorms. In the AE index, quasi-continuous and intermittent distributions dominate for all ranges in the main phase. Intermittent behavior was also observed for periods  $\leq 2$  hours. In the

recovery phases, the quasi-continuous characteristic is more frequent for all ranges, which is also seen for the main range, between 2 and 4 hours. Again, these results differ from that observed from HILDCAAs (Souza et al., 2016), which presented intermittent energy distribution as the most observed type of periodicity in the wavelet spectrum. As it was perceived during supersubstorms studied by (Hajra et al., 2023), during geomagnetic storms, in short periods, the local and intermittent behavior is dominating while for longer periods, quasi-continuous and continuous distributions are more often observed.

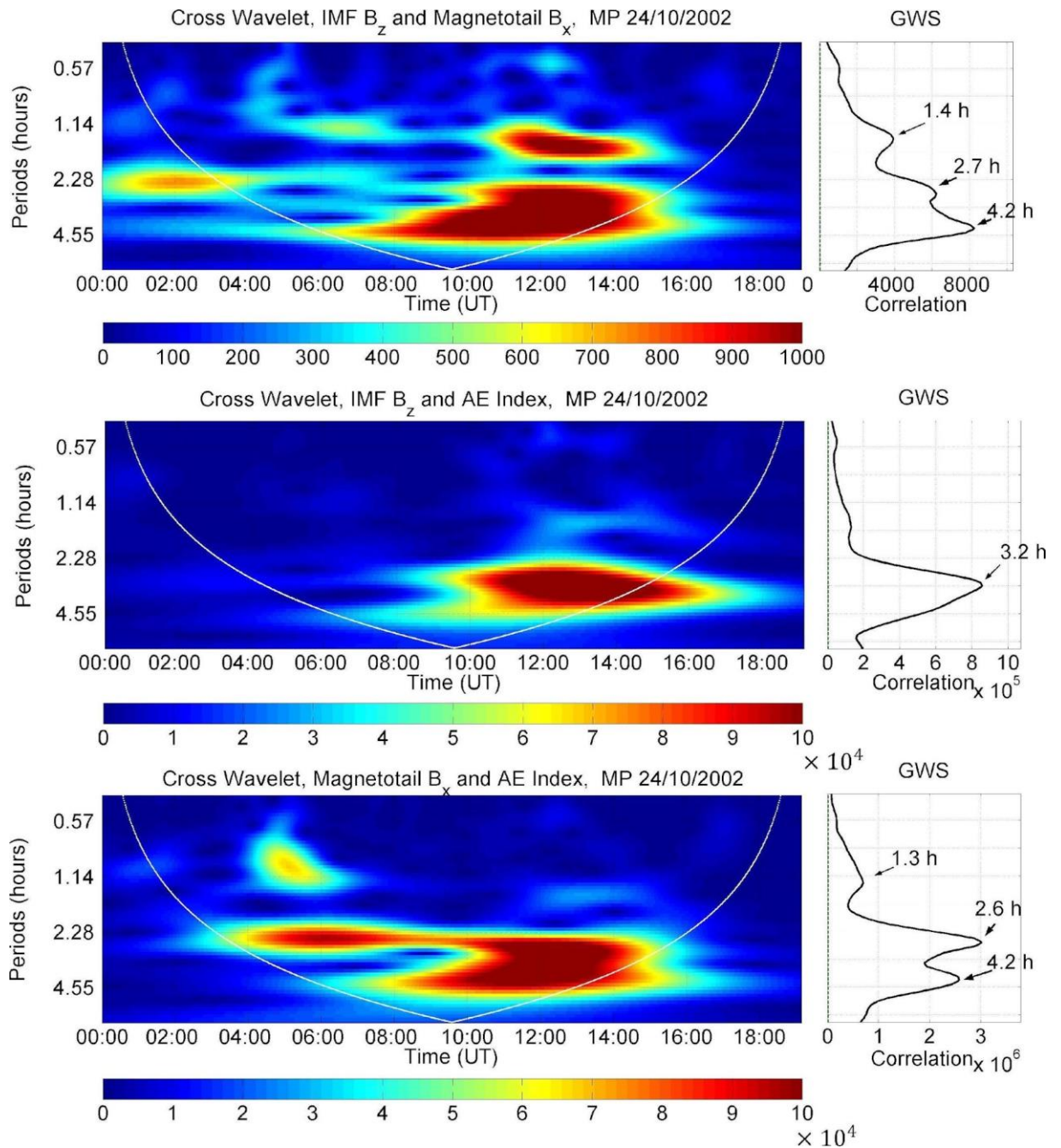
### 3.3 Cross-Wavelet Analysis

With the aim to identify the periodicities at which there is higher correlation between the solar wind and the magnetotail (IMF  $B_z \times$  magnetotail  $B_x$ ), between solar wind and the auroral region (IMF  $B_z \times$  AE index) and between the magnetotail and the auroral region (magnetotail  $B_x \times$  AE index) during the main and recovery phases of these events, the cross-wavelet transform was employed. This study allows us to identify the main periods at which the energy transfer of the solar wind to the magnetotail, as well as the energy transfer from magnetotail-stored energy to the auroral region, occurs during geomagnetic storms caused by CIRs.

#### 3.3.1 Main Phase

The cross-wavelet results applied for the interval of the magnetotail Cluster crossing during the main phase of the event 6 (24 October 2002) of CIR-driven geomagnetic storm presented in Table 1 are shown in Fig. 7. For this same event the wavelet transform was applied (presented in Fig. 3). The cross wavelet spectrum is presented in the left panels: IMF  $B_z$  component and magnetotail  $B_x$  (upper panel), IMF  $B_z$  component and AE index (middle panel) and magnetotail  $B_x$  and AE index (bottom panel). The GWS is shown in the right panel of the respective figure. Then the XWT between IMF  $B_z$  and magnetotail  $B_x$  (top panel) and between magnetotail  $B_x$  and AE index (bottom panel) shows three similar main periods of correlation around: 1.30 h, 2.60 h and 4.20 h. The local distribution dominates these periods, except for the period near 2.60 h of the bottom panel (magnetotail  $B_x \times$  AE index), where quasi-continuous behavior is observed. In the middle panel (IMF  $B_z \times$  AE index) only one significant period is seen, which shows local distribution and a period of 3.21 h. Note that in the cross-wavelet

spectrum, the region with higher correlation occurs between 08:00 UT and 15:00 UT for the top and bottom panels, which is also observed in the middle panel, but with a shift in time (10:00 UT and 16:30 UT). These similar dominant periods (1.30 h, 2.60 h and 4.20 h) of correlation between solar wind-magnetosphere-auroral region oscillations can indicate resonant modes of the coupling of the solar-wind-magnetosphere-ionosphere system, and represent the time scales at which the energy transfer is most efficient. This supports the idea of a linked chain of events: solar wind fluctuations drive magnetotail oscillations, which in turn drive substorms and auroral activity at the same time scales.



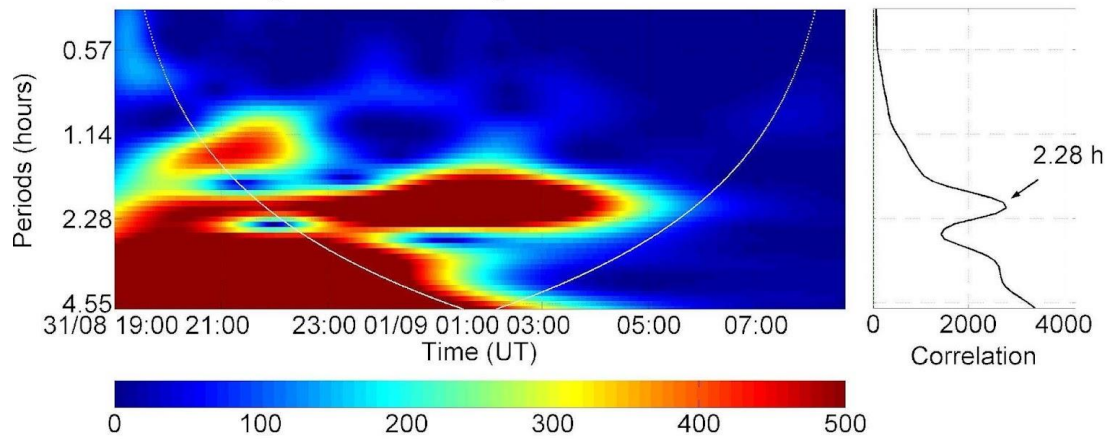
**Figure 7.** Cross-wavelet between IMF  $B_z$  component and magnetotail  $B_x$  (left upper panel), IMF  $B_z$  component and AE index (left middle panel) and between magnetotail  $B_x$  and AE index (left bottom panel) for the interval when Cluster remained in the magnetotail during the main phase of a geomagnetic storm caused by a CIR that occurred between 00:00 UT and 19:09 UT on 24 October 2002. The right panels show the GWS.

Following the WT analysis approach, we initially planned to apply the cross-wavelet transform to the 6 events with data intervals of at least 10 hours. However, as not all analyzed variables met the duration criterion within these events, the number of events suitable for cross-wavelet analysis varied depending on the availability of IMF  $B_z$  and magnetotail  $B_x$  data. The XWT was applied between IMF  $B_z$  and magnetotail  $B_x$  in only 4 events (6, 7, 9 and 14 from Table 1). For IMF  $B_z$  and the AE index, it was applied in 5 events (6, 7, 9, 14 and 30 from Table 1), and for magnetotail  $B_x$  and the AE index, it was applied in 5 events (6, 7, 9, 14 and 26 from Table 1). The results of this analysis are presented in the following subsection, combined with the recovery phase analysis results.

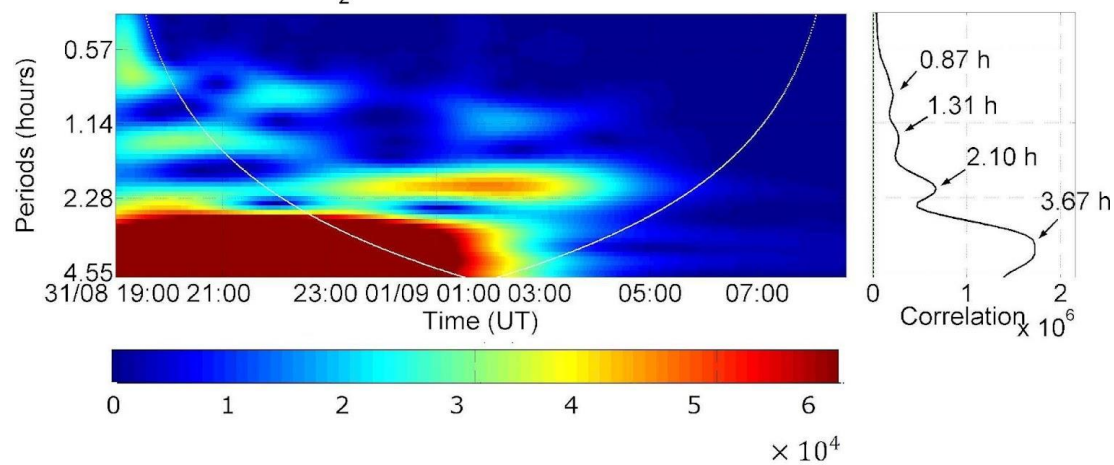
### 3.3.2 Recovery Phase

Figure 8 shows the cross-wavelet transform applied to the event 18 (31 August to 1st September 2005) from Table 1, the same event shown in Fig. 4. The left panels show the cross wavelet spectrum between the IMF  $B_z$  component and magnetotail  $B_x$  (upper panel), IMF  $B_z$  component and AE index (middle panel) and between magnetotail  $B_x$  and AE index (bottom panel). The right panel shows the GWS, where we can note that the period near 2.28 hours is present in the three cases. These intervals show quasi-continuous behavior for the top and bottom panels, and local correlation distributions for the middle panel (IMF  $B_z \times$  AE index). Further, periods with higher correlation are observed near 0.80 h and  $\sim 3.5$  h in the GWS of the middle (IMF  $B_z \times$  AE index) and bottom (magnetotail  $B_x \times$  AE index) panels. For both cases, the periodicity around 0.80 h shows local distribution, while the 3.5 h shows a quasi-continuous distribution. In the middle panel, (IMF  $B_z \times$  AE index), an intermittent higher correlation distribution is found for the period of 1.31 h.

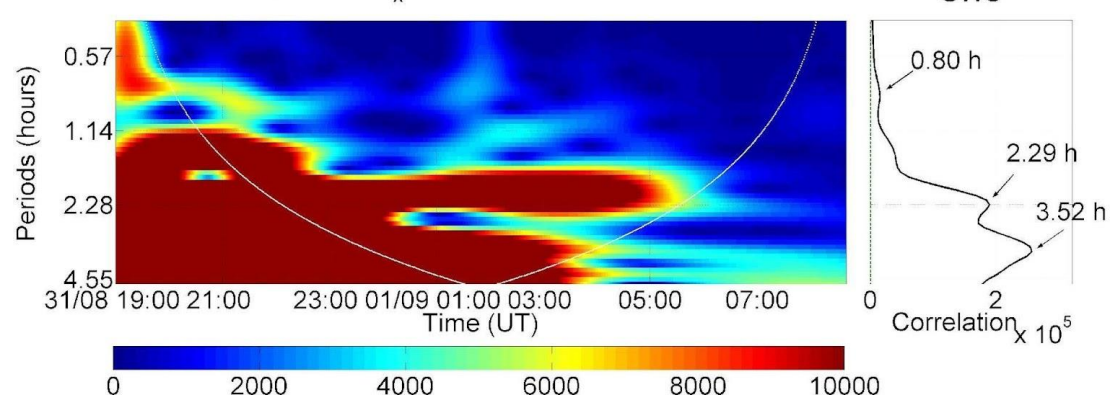
Cross Wavelet, IMF  $B_z$  and Magnetotail  $B_x$ , RP, August 31- September 01, 2005 GWS



Cross Wavelet, IMF  $B_z$  and AE index, RP, 31/08/2005 - 01/09/2005



Cross Wavelet, Magnetotail  $B_x$  and AE index, RP, 31/08/2005 - 01/09/2005



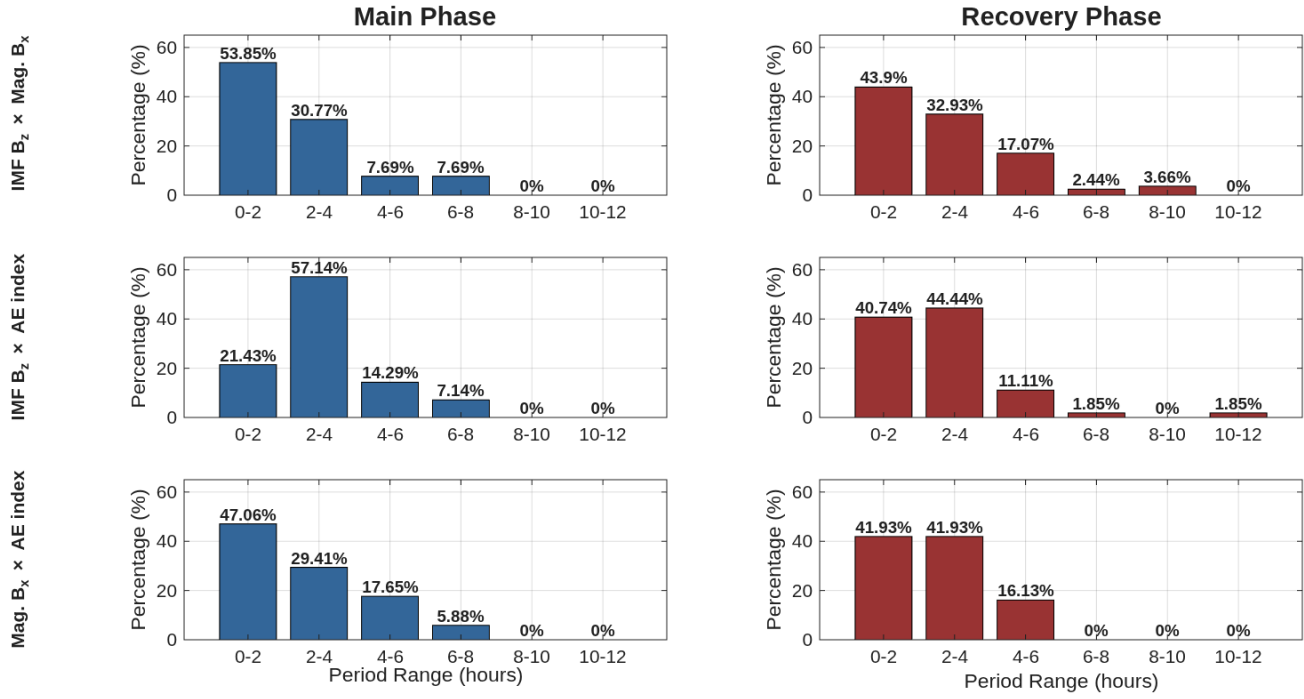
**Figure 8.** Cross-wavelet between IMF  $B_z$  component and magnetotail  $B_x$  (left upper panel), IMF  $B_z$  component and AE index (left middle panel) and between magnetotail  $B_x$  and AE index (left bottom panel) for the interval when Cluster remained in the magnetotail during the recovery phase of the geomagnetic storm caused by a CIR between 19:00 UT on 31 August and 08:40 UT on 1 September 2005. The right panels show the GWS.

In Figure 9, histograms with the range of periods with higher correlation obtained from the XWT are presented for the main and recovery phases. As it was seen in the wavelet analysis, in the main phase the periodicities are restricted for periods shorter than 8 hours, while during the recovery phase, except for the magnetotail  $B_x \times AE$  index analysis, longer periods are observed. Despite that, even for the recovery phases, more than 95 % of the periods are lower than 8 hours. Similar periods that were found for the IMF  $B_z$  WT analysis were obtained in the correlation between the IMF  $B_z$  and magnetotail  $B_x$  (upper panel). Most of the higher correlation intervals,  $\sim 54$  % for the main phase and  $\sim 44$  % (recovery phase), occurred for shorter periods ( $\leq 2$  hours). Further, the second range (2-4 hours) also represents about 30 % of the periods with higher correlation for main ( $\sim 31$  %) and recovery ( $\sim 33$  %) phases. These results are in agreement with those results that were found in the XWT analysis performed by (Franco et al., 2019) for HILDCAAs events.

A significant difference can be observed between the main and the recovery phases in the periods of correlation between the IMF  $B_z$  and the  $AE$  index. Although the dominant range is the same (2 – 4 hours) in both phases, during the recovery phase, periods  $\leq 2$  hours represent more than 40 % of periods while in the main phase they represent only 21.4 %. Furthermore, considering ranges with longer periods, the main phase has more than 21 % of the periods of correlation between 4 and 8 hours, while less than 15 % of the periods of correlation during the recovery phase are found for periods  $> 4$  hours. This change reflects a transition from external, sustained driving to the magnetosphere's internal process of unloading stored energy through a series of more frequent, cyclic substorms. Further, the dominance of periods  $\leq 4$  hours in the recovery phase coincide with cyclic substorm periods (Korth et al., 2011). The periodicity with higher correlation observed in the range between 10 and 12 hours may be related to Alfvén waves present in the IMF  $B_z$  during periods of HILDCAAs in the magnetotail (Smith et al., 1995; Souza et al., 2016).

In the analysis of the periods at which the energy stored in the magnetotail is transferred to the auroral region (XWT between magnetotail  $B_x \times AE$  index), the histogram with the periods of correlation distribution is presented in the lower panels of Fig. 9. In the main phase (left panel), the percentage of periods of correlation per range decreased as the periods increased. About 47 % of the periods with higher correlation are  $\leq 2$  hours. The range between 2-4 hours corresponds to almost 30% of the periods,

followed by 17.65 % (4-6 hours) and 5.88 % in the range between 6 and 8 hours. In the recovery phase (right panel) the range 0-2 hours and the range 2-4 hours showed the same percentage of periods (41.93 %). The others ~ 16 % intervals are found in the range between 4-6 hours, indicating that all the periods with higher correlation are shorter than 6 hours. As the periods with higher energy from the previous analysis, the periodicities with higher correlation values occur for substorms.



**Figure 9.** Histograms for period ranges with significant correlation (cross wavelet power) for the main phase (left panels) and recovery phase (right panels). From top to bottom the panels show: IMF  $B_z \times$  magnetotail  $B_x$ , IMF  $B_z \times$  magnetotail  $B_x$  and magnetotail  $B_x \times$  AE index distributions.

Figure 10 shows the results with the classification of the type of correlation distribution. Considering all periods, the local distribution is dominant in three investigated cases: IMF  $B_z \times$  magnetotail  $B_x$ , IMF  $B_z \times$  AE index and magnetotail  $B_x \times$  AE index (also intermittent) during the main phase. For the recovery phase, only the analysis between IMF  $B_z$  and magnetotail  $B_x$  data did not show the predominance of local distribution, with the intermittent behavior as the most commonly observed, probably related to substorm events.



Figure 10 – Color maps correlation distribution classification percentage obtained from the XWT analysis. Maps for IMF  $B_z \times$  magnetotail  $B_x$  (upper panels), IMF  $B_z \times$  AE index (middle panels), and magnetotail  $B_x \times$  AE index (bottom panels) display the percentage distribution across period ranges (x-axis) and correlation distribution classification (y-axis). Results are separated by storm phase: main phase (left column) and recovery phase (right column).

### 3.4 Power Law analysis

In order to determine the spectral index for the solar wind, magnetospheric and auroral data during the geomagnetic storms main and recovery phases, we applied the Fourier analysis to the IMF  $B_z$ , magnetotail  $B_x$  and AE index data. The datasets were separated in two categories: main and recovery phases.

#### 3.4.1 Main Phase

Results from the main phase are summarized in Table 2, and the spectral indices for event 7 are shown in Fig. 11a). According to Table 2, considering all analyzed events, it is possible to observe that mean values of the spectral indices were  $(-1.62 \pm 0.04)$  for the IMF  $B_z$ ,  $(-1.70 \pm 0.22)$  for the magnetotail  $B_x$  and  $(-1.92 \pm 0.38)$  for the AE index. Recently, Rakhmanovaa et al. (2020) studied the dependence of the spectral indices over plasma turbulence and showed that both the solar wind parameters and bow shock geometry have a great influence on the variation on the spectral index values. This fact shows that these values are sensible to this kind of parameters and the geometry from the space environment. These dependencies from the space geometry for the spectral indices are due to the formation of several kinds of phenomena, such as Alfvén waves, and also the coherent structures inside the plasma turbulence. This dependence of the spectral indices over the space environment was also demonstrated in Neptune day side magnetosheath fluctuations during Voyager-2 flyby (Echer et al., 2023) and during solar-wind high-speed streams (HSSs) at high heliolatitudes during the last two solar-cycle minima (SCM) (Echer et al., 2022).

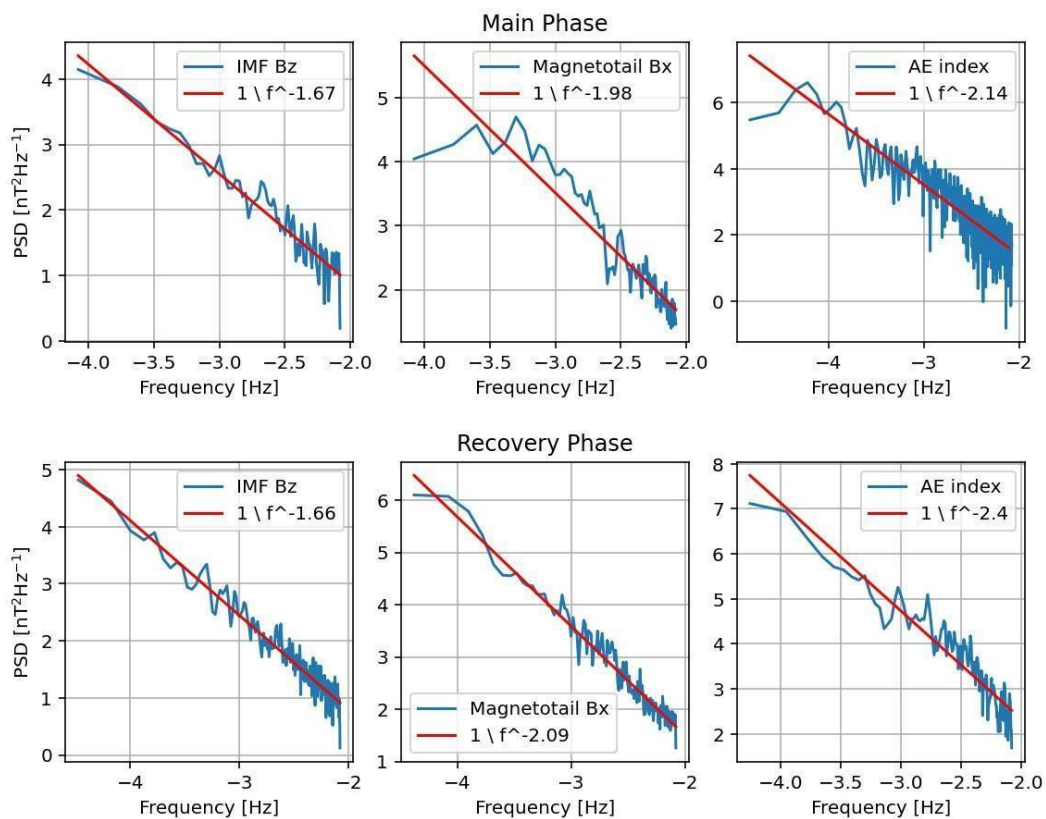
**Table 2.** Spectral indices (IMF  $B_z$ , magnetotail  $B_x$  and AE index) obtained for Main Phase.

| Spectral index (Main Phase)                                       |           |                   |          |
|-------------------------------------------------------------------|-----------|-------------------|----------|
| Events                                                            | IMF $B_z$ | magnetotail $B_x$ | AE index |
| 6                                                                 | -         | -                 | -1.65    |
| 7                                                                 | -1.67     | -1.98             | -2.14    |
| 9                                                                 | -1.63     | -1.67             | -2.24    |
| 21                                                                | -         | -                 | -1.29    |
| 26                                                                | -1.56     | -1.45             | -2.20    |
| 30                                                                | -1.63     | -                 | -2.05    |
| Mean $\pm$ std $-1.62 \pm 0.04$ $-1.70 \pm 0.22$ $-1.92 \pm 0.38$ |           |                   |          |

Bolzan (2005) showed that the coherent structures present in solar wind time series increase (in absolute value) the spectral indices. The idea is that, into the turbulence flow, these organized structures are responsible to lead the energy from large to small scales in the fast and energetic way like a cascade as proposed by (Kolmogorov, 1941). According to Müller & Biskamp (2000), MHD turbulence is driven by the Alfvén wave effect, which couples small-scale velocity and magnetic fluctuations. This results in an energy spectrum consistent with a  $\propto^{-5/3}$  law (the K41 law), which also aligns with

observations of solar wind turbulence. Thus, our results from spectral indices mean values found for the *AE* index are consistent with previous works, where the difference found between  $-1.67 = -5/3$  and value  $= -1.92$  are due to the intermittency phenomena present in the MHD turbulence.

An interesting aspect observed in this study is the difference found between spectral index mean values obtained for the *AE* index time series and the solar wind-magnetotail time series (IMF  $B_z$  and magnetotail  $B_x$ ). Three important points are noted: first, the mean values for the IMF  $B_z$  and magnetotail  $B_x$  series matches the K41 law which corresponds to  $-\frac{5}{3}$ ; second, despite the standard deviation, there is a notable difference between these spectral indices for these both kinds of time series; third, the mean values for the *AE* index are in agreement with results from (Tsurutani et al., 1990). Tsurutani et al. (1990) suggested that high amplitude fluctuations in the southward IMF component will generate flux variations in the magnetotail and may be related to the increase of the ionospheric conductivity, which can be associated with the higher spectral index values found for *AE* index.



**Figure 11.** Spectral indices for IMF  $B_z$ , magnetotail  $B_x$  and AE index for a) Main Phase (event 7) and b) Recovery Phase (event 1).

In a previous work, similar results were obtained for the study of the Earth's magnetotail variability during supersubstorms (Hajra et al., 2023). In that study it was found that the IMF  $B_z$  exhibits the lowest spectral index (compared to the magnetotail  $B_x$  and SML auroral indices), thus, corroborating our results. It is important to mention that the solar wind turbulence is significantly amplified after crossing the bow shock, and plasma flows are generated in the magnetosheath region. In the nightside, eddy vortices are generated due to those large-scale magnetospheric flows, which can drive the magnetotail turbulence (Antonova & Stepanova, 2021).

**Table 3.** Spectral indices (IMF  $B_z$ , magnetotail  $B_x$  and AE index) obtained for Recovery Phase.

| Events         | Spectral index   | (Recovery Phase)  |                  |
|----------------|------------------|-------------------|------------------|
|                | IMF $B_z$        | magnetotail $B_x$ | AE index         |
| 1              | -1.66            | -2.09             | -2.4             |
| 2              | -                | -                 | -2.37            |
| 3              | -                | -                 | -2.36            |
| 4              | -                | -                 | -2.31            |
| 5              | -                | -                 | -2.60            |
| 6              | -                | -                 | -1.85            |
| 9              | -                | -                 | -2.28            |
| 11             | -1.53            | -2.20             | -2.38            |
| 12             | -1.41            | -1.79             | -2.20            |
| 13             | -1.74            | -2.13             | -2.08            |
| 15             | -1.56            | -1.69             | -2.51            |
| 18             | -1.57            | -3.47             | -2.32            |
| 20             | -1.56            | -1.81             | -2.12            |
| 21_2           | -1.83            | -                 | -                |
| 22_1           | -1.74            | -                 | -                |
| 22_2           | -1.74            | -1.45             | -                |
| 23_1           | -1.74            | -                 | -1.97            |
| 23_2           | -1.65            | -1.83             | -                |
| 24_1           | -                | -1.46             | -2.27            |
| 24_2           | -1.40            | -1.61             | -2.42            |
| 25             | -1.31            | -1.98             | -2.30            |
| 26             | -                | -                 | -2.13            |
| 27             | -                | -1.82             | -1.97            |
| 29             | -                | -                 | -2.32            |
| 31             | -                | -                 | -2.32            |
| 32             | -                | -                 | -2.38            |
| 35             | -                | -                 | -2.29            |
| 36             | -                | -                 | -2.33            |
| 38_1           | -                | -                 | -2.01            |
| 38_2           | -                | -                 | -1.82            |
| 39             | -                | -                 | -1.92            |
| Mean $\pm$ std | $-1.60 \pm 0.15$ | $-1.95 \pm 0.51$  | $-2.23 \pm 0.20$ |

### 3.4.2 Recovery Phase

Similarly to the analyses conducted for the main phase intervals, we performed the Fourier Transform in all data in order to obtain the spectral indices during the recovery phase. An example is shown in Fig. 11b, which displays the spectral indices obtained for the parameters analyzed during Event 1. Table 3 shows the results where the mean values found for IMF  $B_z$ , magnetotail  $B_x$  and  $AE$  index were  $-1.60 \pm 0.15$ ,  $-1.95 \pm 0.51$  and  $-2.23 \pm 0.20$ , respectively. For the IMF  $B_z$  index, the spectral index is lower in the recovery phase than during the main phase, while for the magnetotail and auroral data, higher mean absolute values are found, where they were  $-1.95 \pm 0.51$  and  $-2.23 \pm 0.20$ , respectively. A sharp break is observed in the magnetotail  $B_x$  and  $AE$  index PSDs during the main phase, which is not seen during the recovery phase (Fig. 11). We may conjecture that during the recovery phase the geomagnetic field promotes a fast transfer of the energy from the large to small scales in order to leave the magnetosphere to return to almost steady state.

We also have separated the spectral indices from  $AE$  indices time series and magnetic ones (IMF  $B_z$  and  $B_x$ ) where the results were, respectively,  $-2.23 \pm 0.2$  and  $-1.72 \pm 0.38$ . Note, again, the magnetic time series, IMF  $B_z$  and  $B_x$ , following the  $K41$  law, corroborating results from (Müller & Biskamp, 2000). Furthermore, these results, similar to those observed in the main phase, suggest a characteristic of  $AE$  index time series: a distinct behavior compared to magnetic time series, as previously discussed in (Hajra et al., 2023). Also, despite the large standard deviation, it is possible to recognize that the mean values of the spectral indices for the recovery phases are greater if compared with those noted during the main phase. We can associate this result with the presence of the strong turbulence present during the recovery phase. It is just in this phase that the turbulent phenomena need to act in order to promote the transferring of energy from large to small scales like a Kolmogorov cascade.

## 4 Conclusions

In this work, the magnetotail response to geomagnetic storms driven by CIRs was investigated using wavelet and power spectrum analyses. By examining a

comprehensive dataset of 40 CIR-driven storms over a 15-year period (2001–2016), this study provides a significantly broader statistical basis than previously reported in the literature. The wavelet analyses applied to the IMF  $B_z$  and the magnetotail  $B_x$  time series showed that during CIR-driven geomagnetic storms the magnetotail responds stronger to lower periods than for HILDCAA events. Furthermore, we extended this analysis by distinguishing the magnetotail response between the main and recovery phases, allowing for quantitative comparison of turbulence levels.

The results demonstrate that more than 80% of the most energetic periods in the IMF  $B_z$  and magnetotail  $B_x$  in the magnetotail during geomagnetic storms driven by CIRs were found at  $\leq 4$  hours, independently of the storm phase. For the  $AE$  index, periodicities between 2 and 4 hours dominate during both phases. A notable difference is that, during the main phase, the second range with higher number of periodicities was found in the interval between 4 and 6 hours, followed by periods  $\leq 2$  hours, while for the recovery phase, no energetic period was observed below 2 hours. Further, besides the dominant range, the number of periods of higher energy seems to be spread in longer periods, with the 4-6 hours and 6-8 hours ranges showing the same percentage of periods. The explanation of this difference may happen because during the recovery phase of geomagnetic storms, HILDCAA events often occur (Kamide et al., 1998 Tsurutani and Gonzalez 1987). It is well known that the main periodicities of the  $AE$  index during HILDCAAs are generally found between 4 and 12 h and that they are associated with Alfvénic trains in the IMF (Souza et al., 2016).

The XWT analyses performed to the magnetotail  $B_x \times AE$  index and IMF  $B_z \times AE$  index data indicated that the percentage of periods of correlation per range decreased as the periods increased. About 47 % of the periods of higher correlation are found at  $\leq 2$  hours for the main phase. For the recovery phase we obtained almost the same results. This analysis shows that the energy transfer from the solar wind, IMF  $B_z$ , to the magnetotail  $B_x$ , and finally to the auroral region,  $AE$ , occurs mainly at oscillations with periods  $\leq 4$  hours. Similar values were also found during HILDCAAs by (Franco et al., 2019). The HSS is associated with the generation of CIRs, and the periods found here correspond to cyclic substorm periods caused by Alfvén waves in the IMF during the HSS (Lee et al., 2006; Echer et al., 2017).

Results from spectral indices obtained for the IMF  $B_z$  during both the main and recovery phases showed agreement to K41  $(-5/3)$  law. Besides, we observed a

difference between the spectral index mean values obtained for  $AE$  indices time series and IMF  $B_z$  and magnetotail  $B_x$  for the main phase. These results show that the mean values for the interplanetary and magnetospheric time series are close to K41 law which corresponds to  $\square^{-5/3}$  while  $AE$  spectral index values are close to  $-1.93$ . For the recovery phase, higher values of spectral indices were found for the magnetotail  $B_x$  ( $-1.92$ ) and  $AE$  index  $-2.23$ , corroborating results from Tsurutani et al. (1990). Two results can be summarized:

1) The IMF  $B_z$  and magnetotail  $B_x$  magnetic time series following the K41 ( $-5/3$ ) law during the main phase, corroborating results from Müller & Biskamp (2000);

2) The mean values of the spectral indices for the recovery phase is greater, in the magnetotail and auroral region, if compared with the main phase. We can associate this result with the presence of the strong turbulence present in these regions during the recovery phase.

Several studies were performed about the effect of geomagnetic activity in the Earth's magnetotail and they allowed us to have a general idea of the energy transfer from solar wind to the magnetotail during different kind of events (Nakamura & Kokubun, 2000; Nakamura et al., 2002; Franco et al., 2019; Hajra et al., 2023). Here we conducted a study on geomagnetic storms caused by CIRs in the Earth's magnetotail. The findings of this study support the conclusion that the magnetosphere responds to CIR-driven solar wind forcing mainly at the 2-4 hour timescales characteristic of substorms. It would be interesting to perform this kind of investigation about solar wind magnetosphere coupling on the magnetotail of other planets (Souza Echer et al., 2021).

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## Author contribution

E.E. provided the original idea for this study. A.M.S.F., R.R., and M.J.A.B. performed the data analysis. All authors contributed to the writing and revision of the manuscript.

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