Variability of relativistic electron flux ($E > 2$ MeV) during geo-magnetically quiet and disturbed days: a case study

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Abstract
We analyzed the relativistic electron fluxes ($E > 2$ MeV) during five different geomagnetic storms: moderate, intense, super-intense, ICME HILDCAA (High-Intensity Long Duration Continuous Aurora Activity), non-storm HILDCAA and a geomagnetically quiet period. We have opted for continuous wavelet (CWT) analysis techniques to comprehend the periodicity and dynamics of relativistic electron fluxes during storm conditions. The findings of CWT revealed the smooth and periodic trend of relativistic electrons during geo-magnetically quiet periods of 25 January 2007. In contrast, the dominant frequencies associated with the oscillations of relativistic electrons are observed during the recovery phase of the geomagnetic storms. A noteworthy finding of the study is the discrepancies in key periodicities at a lower scale connected with the sudden enhancement of the relativistic electron flux during HILDCAAs and other geomagnetic storms. While a key periodicity at a lower scale is observed at moderate, intense and super intense storms during the recovery phases of the storms, the HILDCAAs events exhibit high-frequency behaviour during both main and recovery phases. Our result substantiates that a geomagnetic storm is not the primary factor that pumps up the radiation belt. The geomagnetic storms can deplete, enhance or cause little effect on the outer radiation belt. To be precise, it exhibits event-specific behaviour. Additionally, we performed Multiresolution Analysis (MRA) to observe temporal distribution characteristics of relativistic electron flux using wavelet decomposition and reconstruction. MRA revealed the diurnal pattern of relativistic electrons flux for the quiet period of the magnetosphere, as depicted by the details and approximations coefficients. On the other hand, the relativistic electron enhancements during several geomagnetic storms are closely related to the presence of high-speed solar wind streams and southward IMF during the recovery phase of a geomagnetic storm.

Keywords Geomagnetic storms · Relativistic electron · HILDCAA · Multiresolution analysis · Wavelet transform

1 Introduction
The relativistic electron fluxes population in the Earth’s outer radiation belt is highly unsettled. Initially, the relativistic electrons were reported by Paulikas and Blake (1979), who then observed that upon impinging the magnetosphere, the electrons appeared to be associated with high-speed solar wind streamers (Hajra et al. 2013, 2015). The accepted standard theory for the source of the outer belt relativistic electrons is a three-step process: injection of sub-storm electrons ($\sim$10-100 keV) followed by a local acceleration of $\sim$100 keV electrons by whistler-mode chorus wave and then finally redistribution by radial diffusion (Meredith et al. 2003; Miyoshi et al. 2003; Thorne et al. 2013; Li et al. 2011). During storm conditions, the disparity of relativistic electron fluxes is supposed to be controlled by a delicate and complicated balance of acceleration and loss processes via different
physical processes. The delicate and comprehensive study of those physical processes has been another important area of study. The interplay between acceleration, loss and transport mechanism brings out the wide range of variability in radiation belts.

The scientific community has devoted a large amount of time and effort to understanding the physical processes that lead to the variability of outer radiation belt fluxes and their responses to geomagnetic storms. The perturbation of relativistic electron flux has been historically associated with geomagnetic storms, accepting that a decrease in the electron flux accompanies storms during the storm’s main phase, preceded by a recovery or increase during the recovery phase (Gonzalez et al. 1994; Reeves 1998). It has been well documented that the enhanced fluxes of relativistic electrons (<1 MeV) can be generated in the outer radiation belt (ORB) during storm conditions (Reeves 1998; Iles et al. 2002). During geomagnetic storms, the content of relativistic electrons in the ORB can fluctuate by magnitude on time scales from minutes to days (Turner et al. 2014). The storm’s main phase often produces large depletions of relativistic electrons.

O’Brien et al. (2001) carry on a statistical study of the responses in the outer belt using 0.3 to >2 MeV electron data. They conducted a cross-correlation analysis of solar wind and geomagnetic activity data that caused an enhancement of electrons for 33 storms at the geosynchronous orbit (GEO) and 29 storms that did not. They found that main phase intensity is not an absolute indicator of the electron response at GEO, storm duration, sustained and above-average solar wind speed, elevated Pc5 ultra low-frequency (ULF) wave power in the magnetosphere, and sustained, enhanced sub-storm activity during the recovery phase were the best indicator. Reeves et al. (2003) studied 276 geomagnetic storms (SYM-H ≥ −50 nT) and found that only 53% of the storms were associated with an enhancement event, 19% were associated with a net flux loss, and 28% showed no significant change at the geostationary orbit. Similar conclusions have been drawn in other studies (Moya et al. 2017; Turner et al. 2013; Zhao and Li 2013), confirming that storms are not always associated with enhancement or depletion in relativistic electron fluxes. Anderson et al. (2015) followed the study of Reeves et al. (2003); however, they examined small storms with Dst > −50 nT. They studied data of 342 small storms from 1989 to 2000, concluding that small storms can be equally as effective as large storms at enhancing and depleting fluxes with a slight difference that small storms are 10% less (more) likely to result in a flux enhancement (depletion) at GEO compared to large storms.

Moya et al. (2017) performed a statistical study of 78 storms to administer the effect of geomagnetic storms on relativistic electrons fluxes in the outer radiation belt. They found that the probability of enhancement, depletion and no change in flux values depends strongly on the L-shell and energy content of the fluxes. They noted that enhancement events were more common for ∼2 MeV electrons at L∼5, with the number of events decreasing with increasing energy at any given L shell. Turner et al. (2019) statistically studied 110 storms with energy ranging from 30 keV to 6.3 MeV as a function of L-shell, energy and epoch time. Their study supports the energy and L-shell dependency; the relativistic electrons show main phase dropouts with instantaneous and unpredictable replenishment levels during the recovery phase alone for relativistic electron enhancements.

Many more recent studies have focused on the radiation belt activity during non-storm time periods (e.g., Su et al. 2014, 2016) and storm events (e.g., Reeves et al. 2003; Moya et al. 2017; Murphy et al. 2017; Turner et al. 2019; Murphy et al. 2020) undervaluing the need of reporting on electron dynamics during quiet geomagnetic times (Anderson et al. 2015) and HILDCAAs. The present work is thus intended to comprehend the periodic nature and dependency of relativistic electron fluxes E > 2 MeV with six different geomagnetic disturbances: moderate storm, intense storm, super-intense storm, HILDCAAs (High-Intensity Long Duration Continuous Aurora Activity), non-storm HILDCAAs and one geomagnetically quiet period using MRA and wavelet analysis. Extracting hidden signals that may persist, which could be handy for future studies, is another goal of this case study.

This manuscript is organized as follows: event data and methodologies opted are discussed in Sect. 2. Wavelet and MRA analysis of those selected events and their discussions are presented in Sect. 3. Section 4 discusses the possible mechanisms and conclusions based on our findings and compares past results.

2 Dataset and methodologies

The studied events were randomly selected and were during the solar cycle 23. The datasets of solar wind parameters and geomagnetic activity indices have been extracted from OMNI (Operating Mission as Nodes on the Internet) webpage and downloaded from the official website of NASA Goddard Space Flight Center (NASA-GSFC) Coordinated Data Analysis Web (CDAWeb, https://omniweb.gsfc.nasa.gov). The integrated fluxes of electrons with energies E > 2 MeV at the geosynchronous orbit (L = 6.6) are collected from the GOES-8 (GOES: Geostationary Operational Environment Satellites) and GOES-10 (https://ngdc.noaa.gov/stp/satellite/goes/dataaccess.html). This database provides 1-min temporal resolution data obtained from the sets of ACE, Wind, and IMP-8 satellites Goddard Space Flight Center provided. The list of events with their respective occurrence date and types of storm conditions is given in Table 1.
As mentioned, the events were randomly selected and did not follow any specific peculiarity except the SYM-H value. The events were singly classified according to their SYM-H values by visual inspection of the data as defined by Perreault and Akasofu (1978) and references therein. The SYM-H index is calculated from the perturbation in the horizontal component (H) of the geomagnetic field, affected by the changes in the ring current (Iyemori 1990). We expect to identify and extract singularities from these particular events, which would contribute to the space weather scientific community.

Particularly, HILDCAAs are geomagnetic activity associated with the periodic southward interplanetary magnetic field (IMF) components of Alfvén waves, which satisfy the conditions: (a) The AE index peaks to 1,000 nT at least once during the event, (ii) AE does not drop below 200 nT for more than 2 hr at a time, (iii) the conditions last for minimum two days, and (iv) they occur outside the main phases of geomagnetic storms (Tsurutani and Gonzalez 1987).

### 2.1 Wavelet transform

Wavelet transform is an effective mathematical tool for the analysis of transient signals. A continuous wavelet transform (CWT) maps a one-dimensional signal to a two-dimensional timescale that produces a time-frequency decomposition of the signal, separating individual signal components constructively, unlike the short-time Fourier transforms (STFT). The square modulus of the wavelet coefficient, analogous to the Fourier analysis, lays out the energy distribution in the timescale plane (Adhikari et al. 2018). In our study, using the CWT scalogram, the vertical axis provides periodicity information at different scales as a function of time in the horizontal axis. It helps to comprehend the behaviour and distribution of the energy at different scales (Adhikari et al. 2017b). The wavelet transform, particularly continuous wavelet transforms, helps to understand the behaviour of the energy at different scales and MRA to observe temporal distribution characteristics of relativistic electron flux using wavelet decomposition and reconstruction. A detailed explanation of the theory associated can be found in various research papers (e.g. Adhikari and Chapagain 2015; Adhikari et al. 2017a, 2018; Usoro 2015). The details of CWT can be obtained from Torrence and Compo (1998), Mendes et al. (2005), Domingues et al. (2005), and Khanal et al. (2019). We believe, to our knowledge, this unique and effective mathematical tool has not been approached to analyze the storm conditions and related signal diagnostics.

One of the downsides of continuous wavelet analysis is the high correlation coefficient between scales, which results in a lot of duplicate data (Daubechies 1998). So, a filtering process adapted from the Meyer wavelet decomposition and reconstruction was employed in this work. This procedure allows a decomposition of the signal into bands with periods in multiples of $2^n$ of the data cadence (1 min), with $n = 1, 2, 3, \ldots$. Each decomposed band is called a “detail” and represented by $D_n$, where $n$ represents the decomposition level. More details about this technique can be found in Meyer and Roques (1993) and Kumar and Foufoula-Georgiou (1997).

We pick to describe the MRA via the concept of a filter. A set of finite impulse response (FIR) filters is characterized along with $L$ coefficients. We have two filters - high pass filter and low pass filter, where both filters are switched on and off at half the sampling frequency. MRA can be characterized by utilizing these filters and implementing them repetitively. The input time series are then treated with filters to get low and high pass components, $x_1(n)$ and $x_2(n)$, respectively (White 2001).

\[
x_1(n) = \sum_{k=0}^{L-1} a_k x(n-k)
\]

\[
x_2(n) = \sum_{k=0}^{L-1} d_k x(n-k)
\]

Here, $a_k$ represents the coefficient of the low-pass, and $d_k$ represents the coefficient of high-pass filters. Furthermore, the two pairs of filter coefficients are associated through:

\[
d_k = (-1)^k a_{L-k}
\]

The computational advantages are gained in MRA over CWT as it uses a representation that applies a minimum number of possible coefficients.

### 3 Results and discussion

The relativistic electron population in the outer radiation belt is extremely volatile during periods of enhanced geomagnetic activity. Electron fluxes are commonly seen to be depleted during the storm main phase, fluxes can recover to pre-storm levels in the recovery phase and stay depleted.

| Events | Year/Month/day | Event type |
|--------|----------------|------------|
| Event 1 | 2007/01/25 | Quiet period |
| Event 2 | 2008/09/04 | Moderate |
| Event 3 | 2006/12/15 | Intense |
| Event 4 | 2001/03/31 | Super intense |
| Event 5 | 2005/05/15-18 | HILDCAAs |
| Event 6 | 2003/04/20-23 | Non-storm HILDCAAs |
or buildup to exceed pre-storm levels (Reeves et al. 2003; Meredith et al. 2011). The flux dropout can combine adiabatic and non-adiabatic effects and losses through magnetopause and atmospheric precipitation (Millan and Thorne 2007). In this work, we have selected six different events depicted in Table 1. The selection of storm types was based on the SYM-H value following the explanation by Perreault and Akasofu (1978), Gonzalez et al. (1994), and Wanliss and Showalter (2006).

3.1 Event 1: the quietest day (25 January 2007)

Figure 1 depicts the quietest day, 25 January 2007. On the sixth panel, the value of SYM-H falls to a minimum of $-30$ nT at $\sim20:00$ UT and at the same time IMF-Bz $\sim -4$. The fluctuation of IMF-Bz is mostly southward for almost the entire day with small variations, which may be due to the presence of Alfvén waves (Adhikari and Chapagain 2015). The first panel at the top of Fig. 1 represents the fluctuation of solar wind pressure ($\sim2$ nPa at $\sim2.5$ nPa). The second panel shows the fluctuation of the solar wind speed ($V_{sw}$) ($\sim750$ km/s at 00:00 UT and gradually decreases to its lowest value of $\sim600$ km/s towards the end of the day). The fluctuation of solar plasma density ($N_{sw}$) is represented by a fourth panel (value lies between $\sim2$ to $\sim3$ n/cc). As the solar wind pressure is not so high enough to compress the magnetosphere, the high-speed solar wind will bring the energetic solar wind plasma into the magnetosphere. Since the IMF-Bz component is mostly southward throughout the day with little fluctuation, allowing the energetic particles to inject into the magnetosphere. Thus, the relativistic electron fluxes ($E > 2$ MeV) seem to be populated in the radiation belt showing a maximum value of $\sim3500$ ccm$^{-2}$ s$^{-1}$ sr$^{-1}$, hereafter we call the flux unit ‘FU’ for convenience, with slight fluctuation recording its lowest value of $\sim2700$ FU at 22:00 UT (shown in the fifth panel of Fig. 1). As high-speed solar wind streams come in contact with the magnetosphere, the electrons gain their acceleration (Baker et al. 1993; Paulikas and Blake 1979). The bottom panel indicates the fluctuation of the AE index, reaching a maximum of $\sim800$ nT, corresponding to the minimum value of SYM-H.

3.2 Event 2: moderate storm (4 September 2008)

Figure 2 shows the time-series profile of different interplanetary structures during a moderate storm on 4 September 2008. The sequence of panels is the same for all events hereafter, as explained in the previous event. The SYM-H value drops to $\sim-70$ nT, indicating the storm is a moderate storm as defined by (Perreault and Akasofu 1978; Wanliss and Showalter 2006). The fluctuation of IMF-Bz (in the third panel) is directed southward during the storm’s main phase, allowing the charged particles to enter easily into the magnetosphere (Lemaire 2012).

The seventh panel shows the fluctuation of the AE index with a value of $\sim1600$ nT corresponding to the lowest value of IMF-Bz, indicating the normal auroral activities. The first panel at the top of Fig. 2 shows the solar wind pressure around $\sim9$ nPa at the early phase of the storm at 01:00 UT and gradually decreases to attain the lowest value of $\sim1$ nPa at the end of the day. The fluctuation of solar wind velocity at the second panel shows the gradual increment of its magnitude, about 480 km/s at 00:00 UT and crossing 600 km/s at 14:00 UT. The flux of relativistic electrons is almost constant with a value of $\sim100$ FU until 16:00 UT and then accelerates to the maximum value of $\sim2900$ FU at 24:00 UT. Thus, it is inferred that high solar wind speed indicates one-on-one relation between them. Therefore, we might expect enhancement events initiated by geospace disturbances combined with large and long-lasting values of solar wind speed with persistently southward z component (Bz) of the IMF (Interplanetary Magnetic Field). This is consistent with Reeves et al. (2011); relativistic electron enhancements are correlated (however, not linearly) with the presence of high-speed solar wind streams and southward IMF during the recovery phase of a geomagnetic storm.
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3.3 Event 3: the intense geomagnetic storm (15 December 2006)

Figure 3 shows the time-series profile of solar wind parameters, the interplanetary magnetic field $Bz$ component, flux of relativistic electrons ($E > 2$ MeV) geomagnetic indices SYM-H, and AE during an event on 15 December 2006. In the fifth panel of Fig. 3, SYM-H reached a minimum of about $-220$ nT at 01:00 UT and remained under $-100$ nT until 12:00 UT, indicating the storm condition as an intense geomagnetic storm, categorized by (Perreault and Akasofu 1978; Wanliss and Showalter 2006). In the last (seventh) panel, the fluctuation of the AE index is shown, reaching its value of around $1200$ nT, corresponding to which the IMF $Bz$ (shown in the third panel) shows $-18$ nT, continuing to recover towards the northward direction. In the fifth panel, we have the fluctuation of relativistic electron flux, which is almost constant during the storm time, attaining the value of about $1100$ FU until 12:00 UT and abruptly accelerating to a maximum of $46000$ FU at 14:00 UT for almost an hour and stepping towards normal. A high solar wind velocity of $850$ km/s can be observed around $01:00$ UT. An earlier study by Kilpua et al. (2015) suggested that a high solar wind velocity would result in more energetic particle buildup after a storm activity (recover phase). However, in our case, the relativistic electrons were depleted. Moreover, as the velocity decreased to $600$ km/s during the recovery phase, the flux increased for a few hours. This result agrees with Reeves et al. (2003). They analyzed the data set that compared 15 years of solar wind data of MeV electrons flux, resulting in the high solar wind speeds, not as the primary factor for enhancement of relativistic electrons; instead, increment in southward IMF value is the essential condition to cause acceleration of MeV electrons in the outer radiation belt. In addition, Borovsky and Denton (2005) found a considerable spatial overlap of the super-dense ion plasma sheet...
with plasmaspheric drainage plumes for high-speed stream-driven storms. This would lead to the growth of electromagnetic ion-cyclotron waves that can cause relativistic electron precipitation loss. Since the super dense plasma sheet is associated with high Nsw, large Nsw would enhance such loss. This seems to be the case for this event as well.

3.4 Event 4: the super intense storm (31 March 2001)

In Fig. 4, the sixth panel indicate the gradual decay of SYM-H value up to $-410$ nT at around 08:00 UT, inferring the geomagnetic storm as super-intense (Perreault and Akasofu 1978; Wanliss and Showalter 2006). The rapid fluctuation of solar wind parameters started with the compression of bow shock at around 01:00 UT. The main event occurred at around 08:00 UT and lasted for several hours. The third panel shows the variation of the IMF-Bz component, having a strongly negative value of $-50$ nT from 06:00 UT to 08:00 UT, corresponding to the SYM-H value of $-410$ nT, indicating that the magnetopause was briefly pushed inward of the geostationary orbit. IMF Bz shows fluctuation between $-50$ nT and $+50$ nT, allowing the charged particles to penetrate repeatedly into the magnetosphere causing high auroral activity ($AE \sim 2400$ nT, shown in the seventh panel). During the initial phase of the main storm, the solar wind velocity shows an abrupt increment up to $\sim 850$ km/s, which then maintains to $\sim 700$ km/s during the storm’s main phase. At the same time, the solar wind pressure (first panel) elevates to a maximum value of $\sim 60$ nPa at the initial phase of the storm and then decreases to $\sim 20$ nPa at 06:00 UT and then remains around the same value throughout the day. The fluctuation of Nsw with maximum peak value $\sim 60$ n/cc at 05:00 UT, as shown in the fourth panel of Fig. 4, followed by the decreases in its value and thereafter, the low fluctuation was observed. The flux of relativistic electrons shows a maximum value of $\sim 740$ FU at 00:00 UT and decreases to $\sim 160$ FU after 01:00 UT. The possible mechanism for this scenario is that for the high-speed stream (HSS) driven storms, there is a considerable spatial overlap of super dense ion plasma sheets with plasmaspheric drainage plumes (Borovsky and Denton 2005). This would lead to the growth of electromagnetic ion-cyclotron waves that can cause relativistic electron precipitation loss. As the super dense plasma sheet is associated with high Nsw, large Nsw would enhance such loss (Li et al. 2011). This implies that Nsw plays a crucial role in relativistic electron loss. However, the strong effect of solar wind density on relativistic electrons is relatively unexpected because the former is not a primary factor in generating geomagnetic disturbance (Wanliss and Showalter 2006). Nevertheless, the possible effects of solar wind density on relativistic electrons may be the compression of the dayside magnetosphere by the high-density solar wind and the effect of solar wind density on “shielding” the inner magnetosphere. Although the electron loss mechanism due to the compression of the dayside magnetosphere by the high-density solar wind seems reasonable, the electron fluxes did not correlate well with the solar wind pressure, suggesting that the compression of the magnetosphere is probably not the main factor affecting the loss of relativistic electrons (Lyatsky and Khazanov 2008).

Another possible cause for the strong effect of solar wind density on relativistic electrons may be based on the correlation observed between solar wind density and plasma density in the plasma sheet (Borovsky et al. 1998), which effectively controls “shielding” the inner magnetosphere from penetrating the large-scale electric fields (Lyatsky et al. 2006). If that is the case, enhanced solar wind density may significantly reduce the penetration of large-scale electric fields into the inner magnetosphere. This results in increasing the size of the plasmasphere due to filling it with new ionospheric plasma with a timescale from a few hours to a few days (Lawrence et al. 1999), which affects the generation of ion-cyclotron and whistler waves, responsible for losses of energetic electrons (Meredith et al. 2003).
3.5 Event 5: an ICME preceding HILDCAA (May 15-18, 2005)

Figure 5 shows HILDCAA preceded by ICME on 15-18 May 2005. The interplanetary cause of this storm was the shock driven by an ICME containing a magnetic cloud structure (Hajra et al. 2013; Ojeda et al. 2013) characterized by large southward IMF-Bz with a peak of $-20$ nT. The main storm phase starts at $\sim 8$ hrs. During the storm onset time, the ICMEs are faster enough (solar wind speed $V_{sw} > 800$ km/s) to form a forward shock (Kennel et al. 1985). These interplanetary structures contain relatively high density ($N_{sw} \sim 30$ n/cc) and solar dynamic pressure ($P_{sw} \sim 45$ nPa) compared to the normal solar wind. The interaction of these structures with the front of the magnetosphere causes compression of the magnetosphere and can cause magnetopause shadowing losses (Nishida and Akasofu 1979; Hi-
etala et al. 2014). The plot depicts this as the relativistic flux is very low and constant for almost a day. The corresponding SYM-H value is $-300$ nT with AE $\sim 1000$ nT. The High-Intensity, Long-Duration, Continuous AE Activity, or HILDCAA event starts with the recovery phase after mid-day of 15 May, for which the AE value is $\sim 1000$ nT (Tsurutani and Gonzalez 1987). These intense AE intervals inject anisotropy 10-100 keV electrons into the magnetosphere, which becomes the source for acceleration to MeV electrons. During HILDCAA, the IMF Bz is directed southwards ($B_z \sim -20$ nT and remains modest for the rest of the day), solar wind speed gradually decreases, and so does the pressure and density. After nearly 1.5-day of HILDCAA, the flux of relativistic electrons starts to accelerate ($\sim 10 \times 10^4$ FU). This intensification of flux was maintained for the whole HILDCAA event. This is in agreement with the study of Guarnieri et al. (2006), who noted that the HILDCAA might accelerate the flux of relativistic electrons.

3.6 Event 6: non-storm HILDCAA (April 20-23, 2003)

Figure 6 represents the signatures of the Non-storm HILDCAA event of 20-23 April 2003, which is not preceded by the geomagnetic storm. The HILDCAA event started at the
mid-day of 20 April 2003 to the beginning of 23 April 2003. The IMF Bz fluctuations were around zero with amplitudes around ±8 nT. The solar wind speed Vsw remains fairly constant with an average value of ~560 km/s. The SYM-H value drops to ~−40 nT at 25 hrs and exhibits one decrease (~−60 nT at 80 hrs). The corresponding AE value was ~1100 nT, indicating the HILDCAA event. The fluctuations of solar dynamic pressure and solar density were fairly similar and low. During the event, the flux of the relativistic electron has an average value of ~0.5 × 10^4 FU until ~62 hrs and then increases abruptly with ~1.8 × 10^4 FU for nearly 16 hrs and again decreases to normal value. However, this event is characterized by high auroral activity via particle injection but does not indicate the acceleration or loss of energetic particles.

### 3.7 CWT analysis of the events: scalogram

The use of the wavelet power spectrum (WPS) technique is adopted to substantiate the obtained results and close inspection of the existing trends of relativistic electrons in six time-series events. This technique provides an unbiased and true periodicity estimation as the original signal gets decomposed to several components using continuous wavelet transform (CWT) (Torrence and Compo 1998; Markovic and Koch 2005; Santos and de Morais 2013). Figure 7 is the scalogram or squared modulus of the wavelet coefficients of CWT, suggesting the energy distribution over time series. The Y-axis represents the scale or the period in minutes (0.0625, 0.125, 0.5, 1, 2, 4, ……) that depicts the oscillations of the signal within the individual wavelet concerning the time series in hours plotted on the X-axis (Khanal et al. 2019). Also, Scale = 1/Frequency, such that the lower the scale value, the higher the frequency and vice versa. A cone of influence, the thin black line curve, divides the time-frequency system into two parts that show the validity of data within the curve; however, it limits the usability outside the curve. Moreover, the appearance of colour index intensity circumvents with black contour indicates the concentration of power with a 95% confidence level or a 5% level of significance (Markovic and Koch 2005; Manyilizu et al. 2014; Yan et al. 2017). The colour index represents the intensity of relativistic electrons.

Figure 7(a) - 7(f) show the results of CWT of relativistic electrons during the time interval of geomagnetic storms. The colour index represents the intensity of the power spectrum. Figure 7(a) depicts relativistic electrons’ smooth and periodic trend during geomagnetically quiet periods of 25 January 2007. In this figure, no intense colour distribution is seen. The period provides oscillations within the wavelet. It indicates the uniform and periodic flow of the relativistic electrons during the quiet condition of the magnetosphere. In Fig. 7(b) (Moderate storm, 4 September 2008), the dominant frequencies are observed around 950–1000 minutes, corresponding to key periodicities of 16–32 minutes. It may be noted that the sudden enhancement in the relativistic electrons during the recovery phase of the geomagnetic storms is captured by the wavelet transform, as seen by the high-power regions in the wavelet spectrum. From Fig. 7(c), short discontinuous signals are observed at lower period regions in case of an intense geomagnetic event. Yet, the oscillation of signals is more continuous and broader at higher periods (minutes). WPS confirms and reveals an appropriate perturbed state at various periods in correspondence to the temporal variability in relativistic electrons. Furthermore, the wavelet spectrum depicts the integrated maximum power accumulation in the regions of 800-950 minutes with key periodicities of 128-256 minutes and 256-512 minutes due to enhanced oscillatory activity of relativistic electrons.

Figure 7(d) depicts the power (as an absolute value squared) generated using the wavelet transform for relativistic electrons during the time interval of a super intense storm. The gradual increment in the intensity, as seen from the distribution of colour index at time intervals 1300-1500 minutes, from low period to higher period in minutes, confirms the occurrence of the main event with an accumulated power, which depicts the flow of relativistic electrons in the magnetosphere-ionosphere system (MIS). Also, the dominant frequencies are observed at a lower scale, suggesting that the relativistic electrons exhibit high-frequency behaviour during a super intense geomagnetic storm. Thus, the power spectrum helps identify the relativistic electrons’ impacts during the main event. The increment of power, unbiased and consistent, in WPS, hints at the most turbulent times that might represent the significant impact on space weather.

Now, the impact of relativistic electrons injection in the magnetosphere is investigated through two different HILDCAA events. In the case of ICME-HILDCAA (shown in Fig. 7(e)), the broader distribution of colour is observed in three regions, first at 3000-3500 minutes, second at 4300-4500 minutes and third at 4800-5100 minutes. All three correspond to the periodicities of 12-128 minutes. In addition, a long-term intensification is observed around 3300-4700 minutes with a key periodicity of 256-512 minutes. It is interesting to see that the SYM/H value for the midday hours of 15 May in Fig. 5 suggests the main event of ICME-HILDCAA; however, no significant effect of relativistic electrons is observed. This is in agreement with the findings of Hajra et al. (2015). The effects at 3300-4700 minutes are due to the perturbation of relativistic electrons during the recovery phase. Unlike other events, a large accumulation of power is observed during the recovery phase of ICME-HILDCAA.

Similarly, in Fig. 7(f), the CWT spectra of relativistic electrons during Non-storm HILDCAA (20-23 April 2003)
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3.8 Multiresolution analysis (MRA)

Figure 8 portrays the wavelet decomposition and reconstruction of relativistic electrons for different geomagnetic events. The horizontal axis represents the time in minutes, and the vertical axis represents the range of wavelet coefficients. The panels on the right side are the “details”, identified by D1 to D10. The panels on the left side are the “approximations”, which can be viewed as a cumulative sum of details (Kumar and Foufoula-Georgiou 1997; Guarnieri et al. 2018). The residual of the decomposition process can show the presence of a 95% level of significance indicated by the dark contour during 4000-4500 minutes interval showing oscillations within multiple scale bands, 32-64 minutes, 64-128 minutes. Besides, we also witnessed a long-term intensification in the relativistic electron flux at a higher time scale of 512-1024 minutes, which accounts for the slowly varying oscillations.

Using wavelet analysis, we show that the oscillation and accumulation of power for relativistic electrons dominated the low-frequency region (i.e., in the higher period (minutes)). We identified the discrete and continuous oscillations during various events (ICME-HILDCAA, Super Intense storm, Moderate storm, Non-storm HILDCAA, and Geomagnetically Quiet period) with peaks consistent in time and period resembling the injection of relativistic electrons in the magnetosphere.
Fig. 8 Wavelet Decomposition of Relativistic Electrons for geomagnetic events, viz. (a) 24-25 January 2007 (Quiet), (b) 3-4 September 2008 (Moderate) (c) 14-15 December 2006 (Intense) (d) 30-31 March 2001 (Super Intense) (e) 15-18 May 2005 (ICME- HIDLCAA) and (f) 20-23 April 2003 (Non-Storm HIDLCAA). The upper panel shows the original signal; D1 means the first decomposition signals and D10 means the tenth decomposition signals, respectively; similarly, A1 – A10 means the first to tenth low-frequency reconstruction signals.

be regarded as the higher approximation levels, such as A8, A9, and A10, as depicted in Fig. 8. At these levels, the average value of the data series is found. The high frequency is gradually reduced among these decompositions, leaving the lower one to quantitatively depict the trend in relativistic electrons. As a result, the high-frequency coefficient is
primarily composed of disturbance noises and random fluctuations of abnormal mutations, which reflect the abrupt changes and disturbances of the provided signal. On the other hand, the low-frequency coefficient is primarily composed of deterministic components, which correspond to the variation features of the relativistic electrons.

In Fig. 8, low-frequency reconstruction signals (left panel) provide good frequency and poor time resolution, whereas good time and poor frequency resolution can be witnessed from the details (right panel). We choose the A10 level to terminate the decomposition since details of higher orders are so smoothed that they are not useful for analyz-
ing the features we are looking into the signal. Previous work (Guarnieri et al. 2006) observed that the levels A0, A1, A2, and A3 incorporate the majority of the high frequencies, which reduces correlation and does not considerably improve signal characterization because of the presence of noisy, turbulent activity. So, an approximation level has to be chosen to avoid these high frequencies and, at the same time, represent the particularities of the signal. Consequently, we chose the levels A7–A10 and found that the number of the relativistic electrons follows a diurnal pattern, without much variation in its number, for the quiet period of the magnetosphere, as depicted by the details and approxi-
mations coefficients of Fig. 8 (a). For the moderate event of 4 September 2008, the relativistic electron number was of the order $1 \times 10^2$ till 16:00 UT, then the sudden variation in Re number is clearly identified in all levels of waveform decomposition, as indicated by Fig. 8 (b). Similarly, for the intense event of 15 December 2006, the variation features of Relativistic Electron (Re) flux in better time and frequency resolution in the order of $\sim 5 \times 10^5$ at its maximum and $10^3$ at its minimum is characterized in the wavelet decomposing signals and the low-frequency reconstructed time series (see Fig. 8 (c)). Similar behaviour is also present for the super intense geomagnetic events of 31 March 2001, clearly evident from Fig. 8 (d). It is thus inferred that the relativistic electron enhancements are closely related to the presence of high-speed solar wind streams and southward IMF during the recovery phase of a geomagnetic storm.

Moreover, the results in 8 (e) and 8 (f) presented the relativistic electron enhancements via wavelet decomposing signals and the low-frequency reconstructed time series. For the ICME preceded HILDCAA event of 15-18 May 2005, the abrupt changes or disturbances in relativistic electron number started nearly 1.5-day of HILDCAA, as depicted by the high-frequency coefficients in all decomposition levels. One can notice that the reconstructed low-frequency coefficients in all levels were relatively stable, providing information on particularities present in the original signal. This is in agreement with the study of Guarnieri et al. (2006), who noted that the HILDCAA might accelerate the flux of relativistic electrons. Similarly, for the HILDCAA event of 20-23 April 2003, which was not preceded by the geomagnetic storm, three minor enhancements of relativistic electron flux occurred before an abrupt increase of nearly 16 hrs, as shown by the Fig. 8 (f). The occurrence of these pre-enhancements and the sudden rise in relativistic electron flux are reflected via high-frequency coefficients in wavelet decomposing signal levels. Although this event is characterized by high auroral activity via particle injection, it does not indicate the acceleration or loss of energetic particles. Thus, the hidden information in the relativistic electron time-series changes was unveiled as a result of wavelet analysis, which reflects the variation trend of the original signals over different timescales. The findings revealed that the cycles during the six different events were identical. During a particular geomagnetic event, the analysis of relativistic electrons should focus on not just the main phase of the storms but also different storm phases, as depicted in all the decomposition levels.

Through this study, the overall behaviour of relativistic electrons is identified with the help of multiresolution analysis. The decomposition levels have proved sufficient to isolate the variation characteristics of the relativistic electron in response to geomagnetic events of varying intensity and interplanetary causes.

| Events              | Date                  | Relativistic electron ratios (Post-storm/Pre-storm) |
|---------------------|-----------------------|-----------------------------------------------------|
| Quiet               | 24-25 January 2007    | 0.6856                                              |
| Moderate            | 3-4 September 2008    | 3.8628                                              |
| Intense             | 14-15 December 2006   | 1.6744                                              |
| Super intense       | 30-31 March 2001      | 4.7852                                              |
| ICME-HILDCAA        | 15-18 May 2005        | 1.6798                                              |
| Non-storm HILDCAA   | 20-23 April 2003      | 1.7056                                              |

### 3.9 Geosynchronous flux statistics:

Table 2 lists the enhancement or depletion of relativistic electrons during the time of different events discussed in this study. We define the ‘pre-storm flux’ as the maximum flux in the 1–2 days prior to the storm (not including the day of the storm). We define the ‘post-storm flux’ as the maximum flux in the 1–3 days after the storm (including the day of the storm). We then calculate the ratio of the pre-storm to post-storm fluxes, as suggested by Anderson et al. (2015). Events of 3-4 September 2008 (Moderate storm) and 30-31 March 2001 (Super intense storm) with the ratio of 3.86 and 4.78, respectively, indicate the enhancement of relativistic electrons during these event intervals; however, depletion of relativistic electrons is seen on other events.

### 4 Conclusion

In this paper, we have analyzed various solar wind parameters and geomagnetic indices with relativistic electron flux ($E > 2$ MeV) datasets for the six geomagnetic events selected (Table 1). To study the response of relativistic electron flux distribution and energy profile, CWT analysis was adopted. The study concluded the following points:

- In each of the events, except super-intense, the relativistic electron flux seems to increase whenever the solar wind exceeds 600 km/s. This is consistent with previous results, which show a large average solar wind speed ($V_{sw} > 500$ km/s) is characteristic of enhancement events (Paulikas and Blake 1979; Reeves et al. 2011).
- The solar wind dynamic pressure and IMF-Bz play an indispensable role in causing the relativistic flux dropouts as the magnetopause is compressed closer to Earth or located very far. In fact, the depletion events are accompanied by weak and short-lived southward Bz components. The impingement of high-speed solar wind, suppressing the dayside magnetoosphere and enhancing the drift shell splitting of charged particles, impacts the possible loss
mechanisms of the magnetospheric relativistic electron, as in the case of super intense storms (super sub-storms).

- This study suggests that the oscillation and the concentration of power of relativistic electrons showed significant peaks across lower scales (e.g., 1, 2 and 4 minutes) in all six events; however, these responses are typical characteristics in the WPS analysis. Our result substantiates that geomagnetic storms are not the primary factors that pump up the radiation belt. The geomagnetic storms can deplete, enhance or cause little effect on the outer radiation belt. To be precise, it exhibits event-specific behaviour. MRA gives an accurate background for comprehending such behaviour of relativistic electrons at all approximation levels. The geomagnetic storms and substorms play a vital role in radiation belt seed population dynamics (Tang et al. 2017). These seed populations then accelerated to higher energies via local acceleration or radial diffusion of ULF waves. The relativistic electron flux ratio (values displayed in Table 2, which are not correlated) also supports our assertion, as moderate storm (3.8628) has the largest ratio than intense storm (1.6744) and HILDCAAs events (1.6798 for ICME and 1.7056 for non-storm). This assertion seems natural as fewer events have the capability of creating electrons that penetrate deep into the inner boundary of the outer radiation belt, and even fewer events can accelerate electrons to relativistic and ultra-relativistic energies (Reeves and Daglis 2016).

The study’s findings demonstrate that the suggested methods, CWT and MRA, are simple, effective, and robust methods for detecting the most energetic periods and understanding the overall feature of relativistic electrons for each storm event. To obtain these periods is important to identify the frequencies on which the relativistic electrons showed significant peaks. This frequency information is crucial to understand the coupling of energy between solar wind-magnetosphere and energetic particles’ acceleration, loss and transport mechanism during a geomagnetic event. Using these tools, the hidden information in the relativistic electron time-series changes was unveiled, which reflects the variation trend of the relativistic electron flux over different phases of the geomagnetic storms.

In summary, with the aid of strong statistical techniques, this article revealed that the count of relativistic electron flux (E > 2 MeV) decreases as the intensity of geomagnetic storms increases, from quiet to super severe storms (Table 1). Additionally, in the case of an intense geomagnetic storm, a high increase in flux count (even larger than in a typical quiet state) is recorded throughout the post-storm period, indicating the presence of an unperturbed ionosphere a precursor to any future space weather effects. This work would benefit from a more exhaustive analysis of the period during which those major oscillations occurred in the power spectrum of CWT in order to extract new information. Additionally, similar techniques can be used to investigate a large number of events over extended time periods in order to gain a detailed understanding of geospace magnetic storms and the Van Allen radiation belts.

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Declarations

Ethical disclosures Disclosure of potential conflicts of interest research involving human participants and/or animals informed consent.

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