A framework for understanding and quantifying the loss and acceleration of relativistic electrons in the outer radiation belt during geomagnetic storms

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Running Title: Loss and acceleration phases of storms

Key points (140 characters including spaces)
1) The radiation belt responds to both CME and CIR driven geomagnetic storms in a consistent and repeatable way.
2) Two storm phases, dominated by loss and then acceleration, have strong albeit different correlations to solar wind and geomagnetic drivers.
3) These results provide an overarching framework which provides a coherent description of storm-time radiation belt dynamics.
Abstract

We present detailed analysis of the global relativistic electron dynamics as measured by total radiation belt content (RBC) during coronal mass ejection (CME) and co-rotating interaction region (CIR) driven geomagnetic storms. Recent work has demonstrated that the statistical response of relativistic electron in the outer radiation belt is consistent and repeatable during geomagnetic storms. In this manuscript we build on this work to show that radiation belt dynamics can be divided into two sequential phases which behave more predictably than the storm as a whole. In every storm, a phase dominated by loss is followed by a phase dominated by acceleration. Detailed analysis of the outer radiation belt dynamics during each phase demonstrates that they respond coherently to solar wind and magnetospheric driving. However, the response is different during each phase and is independent of the larger scale storm driver, either a CME or CIR. Our analysis shows that during the initial phase, radiation belt loss is organized by the location of the magnetopause and the strength of Dst and ULF wave power. During the second phase, radiation belt enhancements are extremely well-organized by the amplitude of ultra-low frequency waves, the auroral electroject index, and solar wind energy input. These results demonstrate that during geomagnetic storms the dynamics of the total radiation belt content are repeatable and well-characterized by solar wind and geomagnetic driving, albeit with a different dependence during each of the two phases of the storm.
1 Introduction

During intervals of enhanced solar wind driving, such as following the impact of interplanetary coronal mass ejections (CMEs) or co-rotating interaction regions (CIRs), the relativistic electron fluxes within the outer Van Allen radiation belt are extremely variable. These dynamic periods often lead to geomagnetic storms during which the flux of relativistic electrons can change by several orders of magnitude. Despite recent advances in understanding the nature of competing radiation belt acceleration and loss processes during geomagnetic storms (e.g., Kanekal et al., 2016; Li et al., 2014; Mann et al., 2016; Olifer et al., 2018; Reeves et al., 2013; Su et al., 2015; Tu et al., 2014), modeling and forecasting geomagnetic storms and the variation in relativistic electron flux in the outer Van Allen radiation belt has remained extremely challenging. This is in part because geomagnetic storms can produce a range of responses in the flux of outer radiation belt electrons including a net enhancement, a net depletion, or no net change (Anderson et al., 2015; Reeves et al., 2003). Moreover, although the solar wind drivers are well-defined from upstream spacecraft observations, previous analyses of the overall change in outer radiation belt flux resulting from geomagnetic storms have shown that the pre-storm and post-storm fluxes of relativistic electrons are highly uncorrelated and independent of storm strength (Anderson et al., 2015; Reeves et al., 2003).

Despite the inherent complexity in the dynamics of the outer radiation belt, recent studies have demonstrated that the dynamics of outer radiation belt can be quite well characterized when studied separately as a function of storm phase (e.g., Murphy et al., 2018), electron energy (e.g., Jaynes et al., 2015; Murphy et al., 2018; D. L. Turner et al., 2015), solar wind conditions (e.g., O’Brien et al., 2001), and solar wind driver (e.g., Bingham et al., 2018; Hietala et al., 2014; Kilpua et al., 2015; Miyoshi et al., 2013; Morley et al., 2010; Yuan & Zong, 2012) as discussed below.
In a statistical study of total radiation belt content (an estimate of the total number of electron in the outer radiation belt at a fixed first adiabatic invariant) derived from Van Allen Probes phase space density during 73 geomagnetic storms, Murphy et al. (2018) showed that the response of the seed (100s of keV), relativistic (~1 MeV), and ultra-relativistic (~2.5 MeV) electron radiation belt populations to the main phase and recovery phase of geomagnetic storms is well-ordered. During geomagnetic storms, the radiation belt seed population undergoes a strong and nearly immediate enhancement following the storm commencement which continues through the main phase (see also D. L. Turner et al., 2015). At higher energies, the relativistic and ultra-relativistic populations are characterized by a net loss of electrons during the main phase followed by a short period of net rapid acceleration during the storm recovery phase following the enhancement in the seed population (Murphy et al., 2018). In a study of an extended period of geomagnetic activity between August-September 2014, Jaynes et al. (2015) demonstrated that the behaviour of the radiation belt seed population was key to radiation belt enhancements in the relativistic and ultra-relativistic populations. Active geomagnetic conditions with sustained substorm activity lead to enhancements in low energy electrons and subsequently the relativistic and ultra-relativistic electron populations; whereas periods with limited substorm activity and lower energy electrons resulted in dearth of relativistic electrons in the outer radiation belt (Baker et al., 1998; Bingham et al., 2018; Jaynes et al., 2015). These results are qualitatively similar to those found by Murphy et al. (2018).

Several studies have also demonstrated the radiation belt depletions and enhancements are associated with specific large-scale solar wind features and characteristic IMF or solar wind drivers. With regard to radiation belt loss, Morley et al. (2010) showed that stream interfaces (SIs) were generally associated with electron loss or radiation belt dropouts. These authors contributed the observed losses to outward radial diffusion and magnetopause shadowing (e.g., Loto’aniu et al., 2010; Shprits et al., 2006; D. L. Turner, Shprits, et al., 2012) and chorus-driven microbursts (e.g., O’Brien et al., 2004). Though these
authors did not specifically study storm-time radiation belt dynamics, Morley et al. (2010) did demonstrate that outer radiation belt electrons respond consistently to SIs. Kilpua et al. (2015) characterized the response of energetic electrons at geosynchronous orbit to large scale solar wind drivers, including CMEs and CIRs and their substructure (see Kilpua et al. (2015) for details). These authors found that radiation belt electron loss at high L tended to dominate during SIs, similar to Morley et al. (2010), as well as during the ejecta and sheath portions of a CME (see also Hietala et al., 2014). In a study of storm-time EMIC waves, Halford et al. (2010) found that the occurrence of EMIC waves peaked during the main phase of storms. These authors postulated that pitch angle scattering by EMIC waves could be an important radiation belt loss process during the main phase of storms (e.g., Meredith et al., 2003; Ukhorskiy et al., 2010). Recent modelling work supports this (e.g., Shprits et al., 2013a). For an excellent overview of radiation belt losses and dropouts we direct the reader to Turner et al. (2012 b).

Regarding radiation belt enhancements specifically, O’Brien et al. (2001) concluded that storm-time enhancement of the outer radiation belt at geosynchronous orbit requires a period of sustained high-speed solar wind and enhanced ULF wave power in the inner-magnetosphere (see also Mathie & Mann, 2000, 2001). In a statistical study of CME and CIR driven storms and total radiation belt content derived from SAMPEX observations, Yuan and Zong (2012) demonstrated that over the entire outer radiation belt CME driven storms are more effective then CIR driven storms in accelerating radiation belt electrons. These authors also demonstrated that CME driven storms are more effective at driving enhancement at lower L-shells, whereas at geosynchronous orbit CIRs are more effective at driving enhancements (see also Miyoshi & Kataoka, 2005). Miyoshi and Kataoka (2005) attributed the radial differences in storm time electron enhancements observed in CME and CIR driven storms to solar cycle phase. During solar maximum, when the occurrence of CMEs peaks, the outer radiation belt moves inward to lower L-shells, and during the declining phase, when the occurrence of CIRs peaks, the outer
radiation belt moves outward. Hence these authors concluded that enhancements in radiation belt electrons are more likely to be observed closer to the Earth when driven by CMEs and further from the Earth when driven by CIRs, a simple function of the location of the outer radiation belt. Finally, in a statistical study of storm-time radiation belt electron dynamics observed by the Van Allen Probes, Bingham et al. (2018) also found that CME driven storms, on average, showed greater radiation belt electron enhancements compared to CIR driven storms, consistent with Yuan and Zong (2012). These authors concluded that this difference was likely due to an earlier and deeper penetration of radiation belt seed electrons driven by enhanced convection and substorm activity during observed during CME driven storms (Baker et al., 1998; Jaynes et al., 2015).

In this study we build on the extensive body of work studying the dynamics of the outer radiation belt to help further understand the physical processes which control both loss and acceleration of relativistic electrons during geomagnetic storms. We investigate storm-time radiation belt dynamics driven by CMEs and CIRs utilizing data from SAMPEX and the derived radiation belt content index (RBC; Baker et al., 2004). Our analysis and framework combines aspects of both autoregressive and multiple regression techniques used to describe and forecast time-varying processes (e.g., Borovsky, 2014; Shumway & Stoffer, 2006) to quantify the processes controlling relativistic electron loss and acceleration through geomagnetic storms. The details of this analysis, including the calculation of the radiation belt content index, the storm database used, and the storm-time dynamics of the outer radiation belt are presented in Section 2. Section 3 provides a detailed discussion of the results presented in Section 2 and the investigations main conclusions. In short, by separating each storm into two independent phases, an initial phase dominated by losses and a second dominated by enhancements, and quantifying the physical processes controlling radiation belt dynamics (based on the work described above), we are able to demonstrate that the entire outer radiation belt responds consistently to solar wind and geomagnetic driving during geomagnetic storms. Significantly, we demonstrate that a large component of relativistic
electron loss in the outer radiation belt during storms is consistent with the Dst effect and ULF wave enhanced magnetopause shadowing. Storm-time enhancements of relativistic electron fluxes in the outer radiation during storms have a strong contribution from solar wind energy input, substorms, and likely energization via Ultra Low Frequency (ULF) and Very Low Frequency (VLF) waves.

2 Data and Analysis

2.1 The Radiation Belt Content Index

The Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) is a low-Earth orbiting satellite designed to study cosmic rays, solar energetic particles, and magnetospheric electron precipitation at relativistic energies (see the review by Baker & Blake, 2012 and reference therein). Despite being designed to study electron precipitation, SAMPEX can also be used to study the dynamics of outer radiation belt electrons during geomagnetic storms, due to a coherence in outer radiation belt electrons which exists as a function of altitude (when compared between two sets of observations) (Chen et al., 2016; Kanekal et al., 2001) or of electron pitch angle (when observed in-situ with single point observations) (Murphy et al., 2018). Hence, though low Earth orbiting satellites observe the tail of the equatorial pitch angle distribution they can still be used to study storm-time radiation belt electron dynamics (Chen et al., 2016; Kanekal et al., 2001). As a radiation belt monitor, SAMPEX also has the capability to investigate outer radiation belt dynamics over an entire solar cycle (e.g., Baker & Blake, 2012).

In this study we use the Proton/Electron Telescope (Baker & Blake, 2012) onboard SAMPEX to derive a radiation belt content (RBC) index (Baker et al., 2004) and statistically characterise the temporal response of storm-time relativistic electron dynamics during previously identified geomagnetic storms which are described in detail below. The RBC index provides a means to reduce the dimensionality of the SAMPEX PET instrument data by removing relativistic electron dynamics as a function of L while still being able to characterize the temporal dynamics of the overall system including periods dominated by
electron loss or acceleration (e.g., Murphy et al., 2018). In this study the RBC is calculated by integrating the daily averaged 1.5-6 MeV electron flux between MacIwain's L=2 and L=8 (as provided by CDAWeb) stepped every 6 hours. This integration provides an estimate of the total number of electrons in the energy range 1.5-6 MeV between fixed inner and outer L-shell boundaries with a 6 hour cadence (c.f., Baker et al., 2004; Yuan & Zong, 2012). Details of the calculation of the RBC can be found in Baker et al. (2004) and in supplementary material.

- The beauty of RBC index used in this investigation is that it reduces the dimensionality of the SAMPEX 1.5-6 MeV electron flux which in turn allows the dynamics of the outer radiation belt of the course of many storms to be analysed in detail (e.g., Baker et al., 2004; Forsyth et al., 2016; Murphy et al., 2018; Yuan & Zong, 2012). Though the RBC index is ideal for statistically characterizing storm-time radiation belt dynamics it is not without its limitations, as Baker et al. (2004) noted, physical processes in the outer radiation belt are both physically complex and can be spatially varied which will effect any estimation of RBC. For example, two physical processes which affect the RBC derived here are the motion of the electron mirror point and adiabatic effects, both of which can act to artificially reduce the RBC index, especially during geomagnetic storms. These processes are discussed below.

During geomagnetic storms, the electron mirror point for certain pitch angles can move above low-altitude satellites such as SAMPEX, such that the satellite observes an apparent decrease in electron flux (Selesnick, 2006; Tu & Li, 2011), thus affecting any calculation of the RBC. However, in the presence of moderate pitch angle scattering, such as that observed during storms (Li et al., 2007), the loss cone rapidly refills limiting the effects of changing mirror points at low altitudes (Selesnick, 2006; Selesnick & Kanekal, 2009). Further, Chen et al. (2016) have shown a high coherence exists between equatorial and low-altitude observations of the outer radiation belt and have demonstrated the robustness of low altitude observations in predicting equatorial radiation belt dynamics. Therefore, the effects of mirror point motion on the estimation of the RBC index will be limited.
As noted above and in supplementary material, the RBC index is derived from electron flux as a function of L and thus is also susceptible to adiabatic changes during geomagnetic storms including the Dst effect. In this study, adiabatic changes in electron flux are partially mitigated by integrating over an extended range in L-shell such that any adiabatic changes in electron flux resulting from either the Dst effect or compressions of the magnetospheric magnetic field are still captured within the RBC index. Kim et al. (2010) demonstrated that during storms the change in L of equatorial electrons due to the Dst effect in the heart of the radiation belt (L ~3.5–4.5) is less 1 R_E. By integrating over fixed L=[2,8] the core of the radiation belt flux at 3–5 R_E (e.g., Yuan & Zong, 2012) is always included in the RBC derivation, even during such adiabatic changes. In addition, Morley et al. (2010) noted that the dynamics of electron flux during SIs as a function of L and L* are qualitatively similar, thus, for the purpose of characterizing large scale electron dynamics the RBC index derived here is still able to characterize both electron loss and acceleration, without being significantly contaminated by those adiabatic and transient changes. Thus, while we could not completely exclude adiabatic effects in this study, through the choice of L domain we are able to mitigate them. Finally, it is important to note that while adiabatic effects exist, understanding how the absolute flux of relativistic electrons vary during storms throughout the magnetosphere, regardless of adiabatic or non-adiabatic changes, is of importance for satellite operations and for mitigating the effects of space weather on satellite infrastructure (e.g., Horne et al., 2013; Schrijver et al., 2015).

In this study we balance the limitations discussed above with the benefit of this robust index which provides a global proxy for radiation belt dynamics and can be studied statistically over an extended period to study the physical processes driving radiation belt loss and enhancements.

### 2.2 Storm Database

In this study we use previously identified storms compiled from Denton and Borovksy (2006), Kataoka and Miyoshi et al., (2006) and Hutchinson et al. (2011) to study dynamics of the outer radiation belt as
characterized by the RBC index during CME and CIR driven storms. The Denton and Borovsky (2006)
database contains 124 CIR driven storms between 1993-2005 that are selected based on prevailing solar
wind conditions. Kataoka and Miyoshi (2006) identified isolated storms by a decrease in Dst below -100
nT and further characterized the predominant solar wind driver as either a CME or CIR related. This list
comprises 55 storms, 49 CME driven storms and 6 CIRs. The Hutchinson et al. (2011) storm list contains
143 storms, 104 CME driven storms and 39 CIR driven storms. Hutchinson et al. (2011) used the
characteristic response of Sym-H to characterize geomagnetic storms; events were selected if they
exhibited an initial phase (or sudden commencement), main phase and recovery phase. The prevailing
solar wind conditions were then used to further subdivide these events into CME and CIR driven storms.
In each of these three storm lists, no geomagnetic storm is identified based on the dynamics of the
outer radiation belt and thus there is no assumed a priori response of the outer radiation belt.

In our study we consider only storms where SAMPEX, OMNI, and ground-based magnetometer data are
all available. Both OMNI and ground-based magnetometer data are used to analyse changes in RBC and
thus are required for subsequent analysis. We also remove duplicate and overlapping storms, as defined
by the storm start and end times (below). This leaves a total of 64 storms, 29 CME driven storms and 35
CIR driven storms.

For each of the 64 storms we identify two distinct times; the start of the storm and the end of the storm
determined by enhanced solar wind driving and storm-time Dst in a similar manner to Murphy et al.
(2018). Briefly, the start of each geomagnetic storm $t_0$ is identified by enhanced solar wind driving as the
initial peak in solar wind dynamic pressure or solar wind velocity above nominally quiet time values of
500 km/s and 6 nPa (e.g., Hutchinson et al., 2011; Kataoka & Miyoshi, 2006). Similarly, the end of each
storm is determined by either the recovery of Dst to nominally quiet values or the end of enhanced solar
wind driving. The recovery of Dst is defined when Dst rises above -10 nT. If this threshold is never
reached then the recovery is defined as the final peak in Dst after which Dst is no longer increasing.
(recovering), i.e. Dst reaches a steady state where it is no longer increasing, characterizing a quiet or near stable ring current following a recovery period. The end of enhanced solar driving is defined by the period when solar wind velocity or dynamic pressure drops below 450 km/s and 4 nPa for a period longer than 24 hours. The end of the storm is then defined as latest of these times, $t_1$. The solar wind and dynamic pressure thresholds to define the start and end of each storm have been identified by the superposed epoch studies of Kataoka and Miyoshi (2006), and Hutchinson et al. (2011). It is important to note that both the start and end times of the storms are defined independent of electron and RBC dynamics. Figure 1 shows an example CME storm which occurred on 11 February 2000, and the identification of the start of the storm and end of the storm, $t_0$ and $t_1$ respectively. See figure caption for details. By identifying the start and the end of a storm we investigate radiation belt electron dynamics, specifically net losses and net enhancements, throughout each event with respect to potential drivers as described in the next section.

### 2.3 Storm-time Dynamics of the Radiation Belt Content Index

Figure 2 shows the variation RBC content during each CME (top) and CIR (bottom) driven geomagnetic storms. In order to plot the storms on a similar time axis we have defined a common time during each storm as the time of minimum Dst $t_{\text{Dst}}$. In the plots, $t_{\text{Dst}}$ is set to zero. We then defined two intervals, the storm main phase, $t_0-t_{\text{Dst}}$, and the storm recovery phase, $t_{\text{Dst}}-t_1$. Since the storms can be of varying length and the duration of the main and recovery phases of each storm can be different, we have normalized the duration of each main phase to 24 hours (-24 – 0 h) and each recovery phase to 120 hours (0 – 120 h) such that each storm is on a similar time axis as was done in Hutchinson et al. (2011) (see also, Halford et al., 2010; Yokoyama & Kamide, 1997). In Figure 2, each individual storm is plotted as a horizontal line at a constant y-value and the color denotes the variation in the RBC throughout the storm, normalized to 1 to aid inter-comparison between storms. Finally, for each storm we mark the time of minimum RBC by a red circle.
Evident in Figure 2 is that the time of minimum RBC (red circles) can be observed during either of the storm main or recovery phases and is not clearly or systematically related to the time of minimum Dst. For CMEs the mean difference between the time minimum RBC compared to minimum Dst (in normalized time) is -0.27 hours with a standard deviation of 8.08 hours while CIRs have a mean and standard deviation of -1.75 and 10.32 hours, respectively. The minimum in RBC during geomagnetic storms naturally separates storms into two phases: one characterized by a net loss of radiation belt electrons where loss processes dominate over acceleration processes, and a second characterized by a net enhancement in radiation electrons where acceleration processes dominate over loss processes. The spread in the difference between the time of minimum Dst and minimum RBC, for both CME and CIR driven storms, demonstrates that though the time of minimum Dst may be a good way to separate the main and recovery phase for some aspects of storm analysis, such as ring current strength, however it does not provide a clear separation of storm-time radiation belt electron dynamics which is the focus of this investigation and in generally most radiation belt studies.

In this study we wish to investigate the processes driving periods of net electron loss and enhancement during storms as measured by RBC. For this reason, we use the time of minimum RBC $t_{RBC}$ during each storm to define two intervals, an initial interval from the start of the storm to the time of minimum RBC, $t_0-t_{RBC}$, characterizing a period of net loss and a second interval from the time of minimum RBC to the end of the storm, $t_{RBC}-t_1$, characterizing a net enhancement in radiation belt electrons. In this way we can statistically investigate the physical processes during both radiation belt loss and acceleration during geomagnetic storms without the inherent pitfalls of a superposed epoch analysis; namely smearing or averaging or temporal dynamics within a time-series where the epoch time is not best suited to the dynamics of dataset (c.f., Figure 2).

In the remainder of this section we focus on analysis of the relative changes in RBC during $t_0-t_{RBC}$ and $t_{RBC}-t_1$ to compare net loss and net enhancements of radiation belt electrons during geomagnetic storms.
to solar-wind and geomagnetic activity. Between \( t_0 \) to \( t_{RBC} \) we define the fractional change in RBC as

\[
\Delta_{RBC} = \frac{RBC(t_{RBC})}{RBC(t_0)},
\]

since the amount of the radiation belt that is available to be lost during any particular storm is dependent on the initial content in the pre-storm outer radiation belt. During the second phase of the storm, \( t_{RBC} \) to \( t_1 \), we define the absolute change in RBC as

\[
|\Delta_{RBC}| = RBC(t_1) - RBC(t_{RBC}),
\]

which provides a measure of the total enhancement in the outer radiation belt during this second phase of a storm, since the total enhancement may not be dependent upon the content of the radiation belts at the start of the acceleration phase. Finally, the fractional loss and absolute change in RBC during the two phases \( t_0 \) to \( t_{RBC} \) and \( t_{RBC} \) to \( t_1 \) allow for a direct comparison between changes in RBC during each storm studied.

Figure 3 shows a log-log comparison of the fractional loss in RBC between \( t_0 \) to \( t_{RBC} \) and the absolute change in RBC \( t_{RBC} \) to \( t_1 \) for CME (blue) and CIR (red) driven storms. Evident in Figure 3 is that there is no direct relationship between the loss and acceleration phase of each individual storm. Storms with a significant amount of loss in the initial phase \( t_0 \) to \( t_{RBC} \) are not necessarily associated with large enhancements during the second phase \( t_{RBC} \) to \( t_1 \). There is also no clear separation between loss and enhancements observed during CME and CIR driven storms. Quantitatively, we can compare the distributions of \( \Delta_{RBC} \) and \(|\Delta_{RBC}|\) for CME and CIR driven storms using the two-sided Kolmogorov-Smirnov statistic (KS statistic). The KS statistic can be used to determine if two data sets come from distinctly different distributions (Press, 1992). By comparing the cumulative distribution of two data sets the KS statistic defines the maximum distance \( D \) between the cumulative distributions. If \( D \) is greater than a critical value (e.g., O’Connor & Kleyner, 2012) or the significance level is large (Press, 1992) then it is likely that the two data sets are drawn from two distinct distributions. If \( D \) is smaller than a critical value or the significance level is small then we cannot reject the null hypothesis that the two data sets come from a common distribution of values. Table 1 shows the value of \( D \) when comparing the distributions of \( \Delta_{RBC} \) and \(|\Delta_{RBC}|\) for CME and CIR driven storms. In both cases the value of \( D \) is smaller than the critical
value of $D$ at a 95% confidence level and the significance level is greater than 0.05. Together this means that we cannot reject the null hypothesis and suggests that it is likely that changes in RBC as measured by $\Delta_{RBC}$ and $|\Delta_{RBC}|$ for CME and CIR driven storms are drawn from similar distributions. This is a critical finding as it suggests that the radiation belt responds in the same way during periods of net loss and enhancement, and independent of the large-scale storm driver and solar wind structure characterised as either a CIR or a CME. For the remainder of this section we consider changes in RBC driven by CME and CIR driven storms to be part of a similar distribution and compare these changes to known drivers of radiation belt electron loss, acceleration and transport.

| Storm Phase | Derived value of $D$ | Critical value of $D$ at 95% confidence | Derived significance level | Are the variations in RBC during CME and CIR driven storms from two distinct distributions? |
|-------------|---------------------|----------------------------------------|---------------------------|----------------------------------------------------------------------------------|
| $t_0-t_{RBC}$, $\Delta_{RBC}$ | 0.29 | 0.34 | 0.11 | No |
| $t_{RBC}-t_1$, $|\Delta_{RBC}|$ | 0.19 | 0.34 | 0.56 | No |

Utilizing the RBC index, we can analyze the $\Delta_{RBC}$ and $|\Delta_{RBC}|$ shown in Figure 3 to investigate the role of solar wind and magnetospheric activity and specific physical processes in driving periods of net loss and net enhancements, during CME geomagnetic storms. During net losses ($t_0-t_{RBC}$) we compare $\Delta_{RBC}$ to minimum magnetopause distance as a proxy for loss due to magnetopause shadowing (West et al., 1972) and minimum Sym-H as an estimate of ring current strength and outward adiabatic transfer leading to enhanced loss through the magnetopause. In both these cases radiation belt electron loss
may result from the intersection of the last closed drift shell with the magnetopause boundary (e.g.,
Olifer et al., 2018). We also compare $\Delta R_{BC}$ with the duration of the loss period, the total geomagnetic
index $K_p$, and total ULF wave power (as a proxy for ULF wave radial diffusion) during the loss period. For
example, increased geomagnetic and ULF wave activity might be expected to lead to increased loss via
enhance precipitation during the initial period of a storm (e.g., O’Brien et al., 2004) or outward radial
diffusion following an initial period of magnetopause shadowing (e.g., Shprits et al., 2006).

During net enhancements in RBC ($t_{RBC} - t_1$) we compare $|\Delta R_{BC}|$ to total solar wind velocity and total solar
wind energy input estimated by the sum of solar wind coupling function ($\epsilon$ parameter) (Perreault &
Akasofu, 1978) over the acceleration phase, the duration of the acceleration phase, substorm activity
and strength as estimated from the total auroral electrojet index $AE$ (which additionally may also be
considered to be a proxy for VLF waves, e.g., Meredith et al. (2001)) and the total ULF wave power. We
hypothesize that increases in these parameters during the enhancement phase of storms—can be
expected to lead to increased acceleration and transport of relativistic electrons within the outer
radiation belt.

Changes in the RBC during both periods of net loss, and enhancements are compared to the total ULF
wave power during as a proxy for the strength of radial diffusion. During periods of net loss and net
enhancements we expect ULF wave power to be a proxy electron loss through outward radial diffusion
(e.g., Shprits et al., 2006; D. L. Turner, Shprits, et al., 2012), and enhanced acceleration via either inward
radial diffusion (e.g., Ma et al., 2018) or coherent ULF wave-particle interactions (e.g., Ian R. Mann et al.,
2013). Further we assume that periods of net loss occur during a time interval when a negative gradient
in electron phase space density existed in order to facilitate outward radial diffusion and periods of net
enhancements ($t_{abc} - t_2$) occur during an interval when a positive gradient in electron phase space density
existed to facilitate inward radial diffusion (e.g., Mann et al., 2016 supplementary material). The total
ULF wave power is estimated from a database of hourly power spectra calculated from the east-west magnetic field component observed by ground-based magnetometers (Kyle R. Murphy et al., 2011; Pahud et al., 2009; Rae et al., 2012). Each hourly power spectrum is summed between 0.83-15.83 mHz providing an estimate of ULF wave power. These hourly estimates are then summed over the duration of the loss or acceleration phase to provide estimates of the total ULF wave power during each phase. The east-west magnetic field component is used as it is expected to map to an azimuthal electric field which can drive strong radial diffusion in the outer radiation belt (Ozeke et al., 2013). For the purpose of this study we use data from two ground-based magnetometer stations, Gillam (GILL) and Pinawa (PINA), both stations in the Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) (Mann et al., 2008) magnetometer network and for simplicity we consider only a single station during each storm phase.

Figure 4 shows the log-log comparison of the fractional change in RBC $\Delta_{RBC}$ between $t_0$-$t_{RBC}$ for each storm as a function of (a) Sym-H, (b) minimum magnetopause distance, (c) loss phase duration, (d) total ULF wave power, and (e) total Kp for all storms. In the bottom left of each panel the correlation between the fractional loss and driver is shown for the entire distribution and the dashed line shows the linear fit to each distribution. Evident in Figure 4 (a-e) is that as solar wind and geomagnetic activity increase there is more loss in the radiation belt.

Since we expect that loss processes act in unison during periods of net radiation belt loss, a multiple regression or correlation analysis can help to assess which processes are most important to net radiation belt loss during geomagnetic storms. For each combination of loss processes shown in Figure 4 (a-e), a total of 26, we perform a multiple linear regression fit with $\Delta_{RBC}$ in log space and determine the resulting correlation of the fit with $\Delta_{RBC}$. For example, considering minimum Sym-H and ULF wave power, we fit $\Delta_{RBC}$ to a function of the form...
We then identify the fit where the correlation fit is maximized, and the coefficients of the fit make physical sense. Figure 4 (f) shows this multiple regression analysis with the variables Sym-H, duration, minimum magnetopause distance and total Kp, with $\Delta_{RBC}$. These four processes variables give the highest correlation in the multiple regression analysis and where the coefficients of the fit make physical sense. This is evidenced by the clear linear relationship.

Figure 5 shows a similar analysis as in Figure 4 but for the acceleration phase of each storm. The absolute change in RBC $|\Delta_{RBC}|$ is plotted against: (a) solar wind energy input, (b) total solar wind velocity, (c) acceleration phase duration, (d) total ULF wave power from GILL, and (e) total AE, during the acceleration phase in the same format as Figure 4. Similar to the loss phase, increased solar wind and geomagnetic activity during the acceleration phase leads to a larger enhancement in RBC during storms following periods of net loss. This is most clearly evident in Figure 5 (d) where increased ULF wave power leads to a higher RBC.

We also perform the same multiple regression analysis for every combination of variables in Figure 5 (a-e) with net radiation belt enhancements $|\Delta_{RBC}|$. This is shown in Figure 5(f). The correlation peaks, while maintaining coefficients which make physical sense, when using solar wind energy input and AE with a value of 0.56. When considering multiple variables, the correlation is lower than when considering ULF wave power alone.

It is important to note that when investigating net losses and enhancements in the RBC in Figures 4 and 5 that we use two magnetometer stations to estimate the strength of radial diffusion. During periods of net RBC losses, we use the low latitude Pinawa magnetometer station ($L \sim 4.06$) located near the center of the radiation belt to assess the connection between RBC and the ULF waves which might deplete the

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\log_{10}(\Delta_{RBC}) = a_0 \times \log_{10}(\text{Sym} - H_{\text{min}}) + a_1 \times \log_{10}\left(\sum \text{ULF}_{\text{PSD}}\right)
$$
belts during outward radial diffusion along a negative phase space density gradient (D. L. Turner, Shprits, et al., 2012). Since the radiation belt flux peaks in this region, for ULF waves to contribute significantly to losses seen in RBC arising from outward radial diffusion following an initial period of magnetopause shadowing requires ULF power to be significant there. During periods of net RBC enhancements, we use the higher latitude Gillam magnetometer station (L~6.15) near the outer edge of the outer radiation belt. As the radiation belt recovers due to the inward transport of available source electrons arising for instance from substorm injections (Baker et al., 1998; Boyd et al., 2016; Forsyth et al., 2016; Jaynes et al., 2015; Murphy et al., 2018), inward transport down a positive radial phase space gradient can have an impact on RBC by electron transport reaching somewhat higher L regions (Mann et al., 2016; Mann & Ozeke, 2016). To impact RBC the newly supplied radiation belt electrons of course do not need to reach all the way the heart of the belt at L~4, and will be expected to be seen in the RBC as soon as they are transported to the outer edge of the belt so long as their energy is high enough to add to the RBC count at those L-shells. Despite the use of different stations in the analysis reported here for the loss and acceleration phases, the results shown in Figure 4 and 5 are largely independent of the magnetometer station used in the analysis, this is likely as ULF wave power is generally correlated as function of L (Mathie & Mann, 2001); regardless of the similarities in the analysis we have chosen to use two separate stations as the separation in L between the stations is important for properly characterizing the physical processes, namely radial diffusion, in driving radiation belt dynamics during different stages of a geomagnetic storm.

Finally, due to limited in-situ coverage of the magnetosphere during the SAMPEX era it is impossible to construct a continuous and global database of direct measurements of the processes controlling radiation belt dynamics, for example VLF and EMIC wave power. For this reason, in the analysis presented above we have chosen to use proxies, including AE, as estimates for these processes as these proxies provide a continuous data set with which to complete the statistical analysis.
In the next section we discuss the implications of the analysis shown in this section in relation to storm-time radiation belt loss and acceleration.

3 Discussion and Conclusions

Understanding the dominant processes driving electron loss and acceleration during geomagnetic storms is critical for space weather and radiation belt forecasting. In this manuscript we have used data from the SAMPEX PET instrument to investigate the dynamics of the outer radiation belt during 29 CME driven storms and 35 CIR driven storms. In order to reduce the dimensionality of the data from SAMPEX we and study the temporal dynamics of outer radiation belt electrons in a large number of events we derive a radiation belt content (RBC) index from observations of electron flux between 1.5-6 MeV. The RBC index provides an estimate of the total number of electrons in the outer radiation belt and is ideal for statistical studies as it reduces the dimensionality of the data set by removing the radial or L-shell dependence (Baker et al., 2004; Forsyth et al., 2016; Murphy et al., 2018).

Our analysis of the RBC index during CIR and CME driven geomagnetic storms highlights five key aspects of outer radiation belt electron dynamics.

1) First, the minimum in Dst does not coincide with the minimum of RBC. There can be 30-120 minute offset between the two parameters.

2) Second, CME and CIR driven storms both show a period of net loss followed by a net enhancement of radiation belt electrons during geomagnetic storms. Analysis of changes in RBC demonstrates that intervals of net radiation belt loss and enhancements during different storms are drawn from the same distribution such that these dynamics independent of the large-scale storm driver, i.e. of either CME or CIR.

3) The net loss of electrons during geomagnetic storms is most strongly related to the minimum in Sym-H during the loss period, minimum magnetopause location, and duration of the loss period.
4) The net enhancement of electrons during geomagnetic storms is most strongly related to the total ULF wave power during the enhancement period.

5) Net enhancements and net losses of radiation belt electrons during geomagnetic storms can be considered to act effectively independently as they have sufficiently different dependencies on physical drivers of electron loss and acceleration. We discuss these points below.

Figure 2 shows the storm-time variation in the RBC index relative to the time of minimum Dst (t=0) for both CME (top) and CIR (bottom) driven storms, separating each storm into a main and recovery phase. The red dots in both panels of Figure 2 mark the time of minimum RBC during each storm. Evident in Figure 2 is that the time of minimum Dst during each storm does not clearly order storm-time electron dynamics. For instance, the time of minimum RBC during any given storm naturally divides a storm into two periods; an initial period which is dominated by electron loss and a second period dominated by electron enhancements which is particularly useful when studying the large-scale drivers of radiation belt acceleration or loss, whatever those processes may be. As shown in Figure 2 this time can occur during either the storm main phase (pre minimum Dst) or the storm recovery phase (post minimum Dst), such that neither phase consistently characterizes changes in storm-time electron dynamics (e.g., Borovsky & Shprits, 2017). This is not surprising; while the Dst index may be an indicator of the strength of any particular geomagnetic storm and terrestrial ring current and provides insight into adiabatic changes in electron flux (e.g., H. Kim & Chan, 1997), it is also a measure of both the magnetopause currents (e.g., O'Brien & McPherron, 2000), and cross-tail current systems (N. E. Turner et al., 2000). If we wish to understand and statistically characterize storm-time radiation belt electron dynamics, it is more meaningful to use the time of minimum RBC as opposed to the time of minimum Dst. By separating storms into periods of net radiation belt electron loss and enhancements these periods can be separately investigated without conflating together intervals of electron loss and enhancement allowing for a more physically meaningful analysis of storm-time radiation belt dynamics.
Figure 3 shows an example of the analysis described above and compares net losses and net enhancements during CME and CIR driven storms as defined by the start of the storm to the time of minimum RBC and the time of minimum RBC to the end of the storm, respectively. Evident in Figure 3 is that both CME and CIR driven storms can experience large variations in electron loss and acceleration during any particular storm (see Figure 3). There is also no clear separation between the distribution of losses and enhancements for CME and CIR driven storms as measured by the Kolmgorov-Smirnov statistic. This suggests that the changes in RBC are part of a single distribution as opposed to two different distributions dependent on storm driver. This statistical analysis suggests that the strength of the physical processes determine the behaviour of the outer radiation belt, not the exact nature of the solar wind driver that generates those physical processes. In other words, the magnetosphere does not register whether the solar wind driver is a CIR or a CME, rather it responds to the efficiency of the Dungey cycle, or the strength of the waves generated (e.g., Mathie & Mann, 2000; O’Brien et al., 2003, 2004; Shprits et al., 2013a; D. L. Turner, Morley, et al., 2012; Ukhorskiy et al., 2010).

Figure 4 presents a log-log plot of the fractional change in RBC during the interval of net electron loss of each of the geomagnetic storms as a function of four geomagnetic variables indicative of storm strength and electron loss processes (as discussed in detail in the previous section). As Sym-H increases there is more radiation belt electron loss; there is also more loss during storms where the magnetopause is closer to the Earth and with increased -ULF wave power; conversely there is little relation between the duration of the loss phase and the overall amount of radiation belt electron loss. This suggests that the loss occurs rapidly, or at least is not developed more slowly and cumulatively in response to a continuing and more gradual but ongoing action of a less efficient loss processes. However, we do not expect individual loss mechanisms to act independently. Rather loss processes are likely to act in unison to drive the overall net loss in electron RBC during the loss phase. Figure 4 (f) shows support for this hypothesis in the form of the multiple regression analysis of the fractional loss as
a function of Sym-H, minimum magnetopause distance, duration of the loss phase period, and total Kp during the loss period. Using a combination of these three parameters provides the highest correlation between the fractional loss and geomagnetic variables—which may be related to storm-time radiation belt loss.

In the context of previous work, the results shown in Figure 4 can be used to make an inference regarding the physical processes and sequence of events driving net radiation belt electron during the early stages of a geomagnetic storm. As a CME or CIR impacts the magnetosphere the magnetopause moves inward due to enhanced southward IMF and plasma pressure (e.g., Shue et al., 1998; Sibeck, 1990). The inward motion of the magnetopause results in magnetopause shadowing (West et al., 1972); storms where the magnetopause pushes closer to the Earth resulting in the largest loss. Strong geomagnetic activity coupled with magnetopause shadowing further aids in the loss of radiation belt electrons. Magnetopause shadowing creates a negative gradient in the electron phase space density allowing for additional loss driven by enhanced ULF wave power and outward radial diffusion (Loto’aniu et al., 2010; Mann et al., 2016; Shprits et al., 2006; D. L. Turner, Shprits, et al., 2012). Enhancements in the ring current push radiation belt electrons closer to the magnetopause aiding in the loss of electrons through the magnetopause (e.g., Ukhorskiy et al., 2006) and finally the duration of the loss period tends to an overall increase in the amount of radiation belt loss.

A similar analysis can be performed to determine how the outer radiation belt responds to multiple solar wind and geomagnetic drivers during the net enhancements in radiation belt electrons during geomagnetic storms (Figure 5). This analysis shows that net enhancements of RBC during the acceleration phase correlate remarkably well with total ULF wave power (Mathie & Mann, 2000). Both $\varepsilon$ and AE (Figure 5, panels a and e), proxies for solar wind energy input, and substorm and VLF wave activity, are also well correlated with increases in RBC. Solar wind velocity and the acceleration phase duration are both poorly correlated with net changes in RBC during the acceleration phase. Surprisingly
there is also a stronger relationship between intervals of radiation belt electron enhancements and ULF wave power than any combination of variables in a multiple regression analysis.

Overall the results shown in Figures 5 suggest that ULF waves (e.g., Brautigam & Albert, 2000; I.R. Mann et al., 2012; Mathie & Mann, 2000; O’Brien et al., 2003; Ozeke et al., 2013), substorm and VLF wave activity (as measured by AE) (e.g., Meredith et al., 2001, 2002), and solar wind driving (e.g., Baker et al., 1990; Lyatsky & Khazanov, 2008; Rigler, 2004; Rigler et al., 2007) play pivotal roles in the storm-time enhancement of radiation belt electron, consistent with previous work. As described in Jaynes et al. (2015) it is likely that substorms provide an enhanced source of lower energy electrons (Baker et al., 1998 e.g., Boyd et al., 2016), coupled with strong VLF wave activity also driven by substorm activity (e.g., Li et al., 2014; Meredith et al., 2002), and intense ULF wave power (e.g., Mathie & Mann, 2000; O’Brien et al., 2003) and a positive phase space density gradient developing in the response to substorm activity and recovery of the belt (e.g., Murphy et al., 2018) this leads to the efficient acceleration of electrons during geomagnetic storms and the net enhancement of RBC observed here.

Finally, our analysis of the net radiation belt loss and enhancements during geomagnetic storms demonstrate that that no single variable describes both strong loss and strong acceleration during the overall duration of a storm. As a result, no single variable can be successfully used to parameterise the overall response of the outer radiation belt during geomagnetic storms. This provides a powerful explanation for the previously reported lack of correlation between pre-storm and post-storm fluxes in the outer radiation belt (e.g., Anderson et al., 2015; Reeves et al., 2003). If the loss and acceleration phases have sufficiently different driver dependencies, then attempts to correlate pre-and post-storm fluxes naturally generate such a conclusion. Thus, these two phases can be considered to act effectively independently. It is the superposition of the different solar wind and geomagnetic activity dependencies of these two phases which together explain the overall response of the RBC during geomagnetic storms.
The results presented here provide a clear support for a framework that can explain both losses and enhancements during geomagnetic storms and could lead to significant improvement in radiation belt forecasting. For example, future work utilising the Van Allen Probes could incorporate both EMIC and VLF wave power into this framework and use electron PSD as opposed to flux to investigate changes the dynamics of the outer radiation belt. Recent work has demonstrated that EMIC wave occurrence peaks during the start of a storm (Halford et al., 2010) and may be important in radiation belt loss (e.g., Shprits et al., 2013b). Direct observations of wave power will also likely be better than inferring wave activity from proxies such as the AE index (Watt et al., 2017). With regard to modelling and forecasting the radiation belt during geomagnetic storms, using the framework presented here and separating periods of net loss and enhancement may provide more meaning full results and forecasts. For example, separating periods of net loss from net enhancement can reduce errors propagated through models. This in turn will provide more meaningful comparisons to data and potentially more accurate forecasts.

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Figure 1: An example of a CME storm on 11 February 2000 and the identification of the start, minimum \( t_0 \), \( t_{\text{DST}} \), and end of the storm, \( t_f \), respectively. (a) 1.5-6 MeV from SAMPEX, (b) 1.5-6 MEV RBC, (c) solar wind velocity, (d) solar wind dynamic pressure, (e) solar wind Bz and (f) Dst.
Figure 2: Variation in the normalized RBC during each of the CME (top) and CIR (bottom) driven storms. In each panel individual storms are plotted along the y-axis along a normalized time axis. The zero time, t=0, of each storm is the time of minimum Dst. The red dots show the time of minimum RBC during each storm.
Figure 3: Comparison of the fractional change in RBC during net radiation belt losses and the absolute change in RBC during net enhancements. The distribution is divided into CME (blue) and CIR (red) driven storms for comparison.
Figure 4: Log-log plot of the fractional change in RBC during storm-time radiation belt losses during CME (blue) and CIR (red) storm as a function of: (a) minimum SYM-H during the loss phase, (b) minimum magnetopause location during the loss phase, (c) loss phase duration, (d) total ULF wave power during the loss phase, and (e) total Kp. Panel (f) shows the multiple regression of minimum SYM-H (a), minimum magnetopause distance (b), loss phase duration (c), and total Kp (c) as a function of fractional change in RBC. The correlation coefficient is shown in the bottom left corner of each panel. The dashed lines show the linear regression of each distribution.
Figure 5: Log-log plot of the absolute change in RBC during storm-time net RBC enhancements during CME (blue) and CIR (red) geomagnetic storms as a function of the following parameters linked to electron acceleration: (a) solar wind coupling function, (b) solar wind velocity, (c) acceleration phase duration, (d) total ULF wave power during the acceleration phase, and (e) total AE. Panel (f) shows the result from a multiple regression solar wind energy input (a) and AE (b) with the absolute change in RBC during the acceleration phase. The correlation coefficient is shown in the bottom left of each panel. The dashed lines show the linear regression of each panel.
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