Characterization of Transient Geomagnetic Fluctuations and Associated Rapid Ionospheric Currents

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Abstract

Disturbances in the magnetosphere-ionosphere system cause changes in the geomagnetic field that result in ground induced currents (GICs) that are potentially hazardous to electrical systems on Earth. Harmful GICs are driven by magnetic field fluctuations with timescales generally falling in the range of 1-10 minutes; much less attention has been placed on geomagnetic field fluctuations with short timescales (< 60 seconds) because they cause transient induced currents (TICs) that have not been considered to pose a legitimate threat to electrical systems since they are similar to electrical transients due to lightning. On the contrary, short-timescale magnetic field fluctuations have been found to be capable of coupling directly to power grids and electrical systems, inducing substantial voltages without first flowing in the ground. This ionospheric current coupling poses a potential threat to any of these systems, especially electronic equipment with low operating voltage or that does not have surge protection. Transmitting devices that are at risk by such currents are becoming increasingly more prevalent in society with the growth of the Internet of Things (IoT) network. Our characterization of transient magnetic field perturbations provides detail on short-timescale changes of the magnetosphere-ionosphere coupled system and supports the assessment of possible hazards to technological infrastructure on Earth. This research is enabled by modern magnetometers, both ground- and space-based, with high sampling rate capabilities that allow for the measurement of transient surface magnetic field fluctuations with short-timescales. We present the characteristics of transient magnetic field changes observed by the MACCS array in Arctic Canada by selecting events recorded on the ground and analyzing the behavior of the electromagnetic fluctuations within the ionosphere and magnetosphere during such events.

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Background and Motivation

Disturbances in the magnetosphere-ionosphere system cause changes in the geomagnetic field, resulting in ground induced currents (GIC) that are potentially hazardous to electrical systems on Earth.

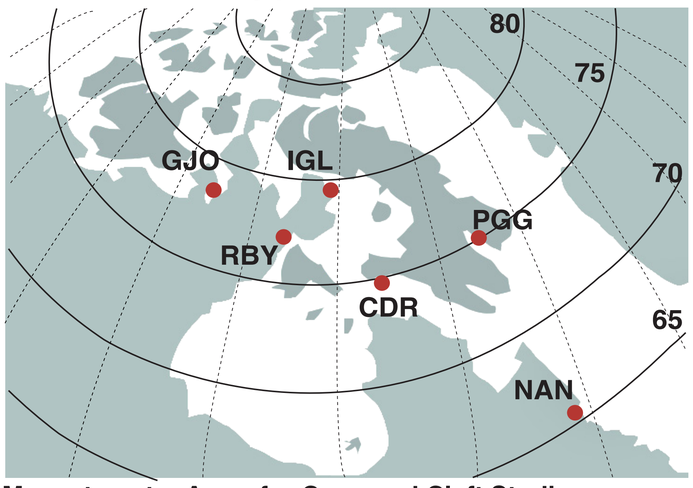
Harmful GICs are driven by magnetic field fluctuations with timescales generally falling in the range of 5-10 minutes; much less attention has been placed on geomagnetic field fluctuations with short timescales (< 5 minutes) because they cause **transient induced currents (TIC)** that have not been considered to pose a legitimate threat to electrical systems.

On the contrary, modeling results from Simpson [2011] concluded that transient coronal mass ejection-induced ionospheric currents of order 1 s may be capable of inducing high voltages (> 10 kV) on long parallel overhead power transmission lines.

It is possible that the transient ionospheric currents are capable of coupling directly to power grids and electrical systems without first flowing through the Earth's surface (i.e. the ground conductivity may have no effect on the strength or path of the induced current).

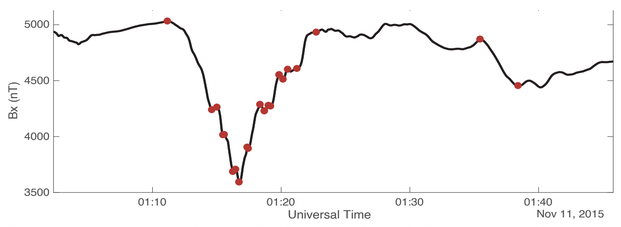
This characterization provides insight into the physical processes that generate TICs and enables the assessment of potential hazards to electrical systems.

Methodology



Magnetometer Array for Cusp and Cleft Studies (MACCS) Map

Because of the relationship described by Faraday's law, measurements of the surface magnetic field are used as a proxy to observe the ionospheric currents which generate the magnetic field perturbations. TICs are characterized here by identifying short timescale (< 5 minute) surface magnetic field changes that induce transient currents in electrical systems on Earth.

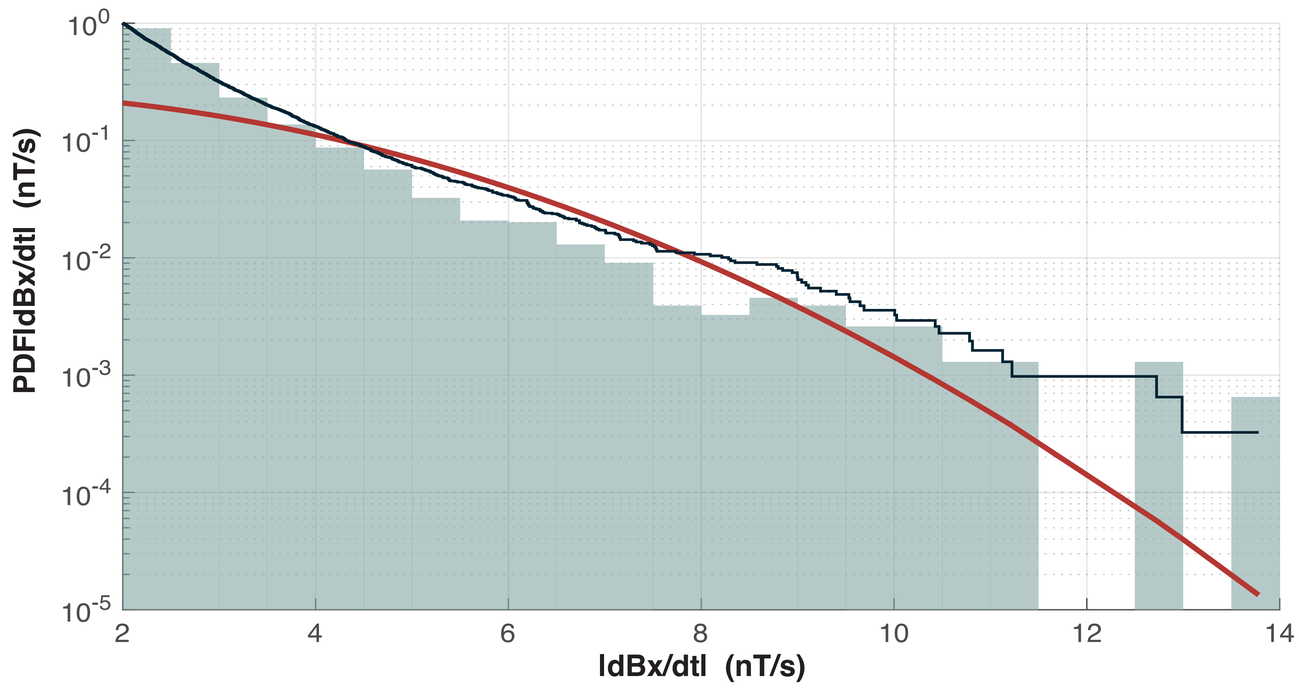


Example of multiple TIC events at Repulse Bay (RBY)

The magnetic field disturbances identified all occurred throughout 2015 at one (or more) of six MACCS stations. These events were identified via a semi-automated algorithm developed by the author at the University of Michigan. The algorithm uses a series of filters to identify events in which the magnetic field is changing by more than 2 nT/s in less than five minutes. The locations of the stations are shown above. Six of the nine MACCS stations were used for this statistical study due to data availability for the year of 2015, these stations are shown as red dots on the map above.

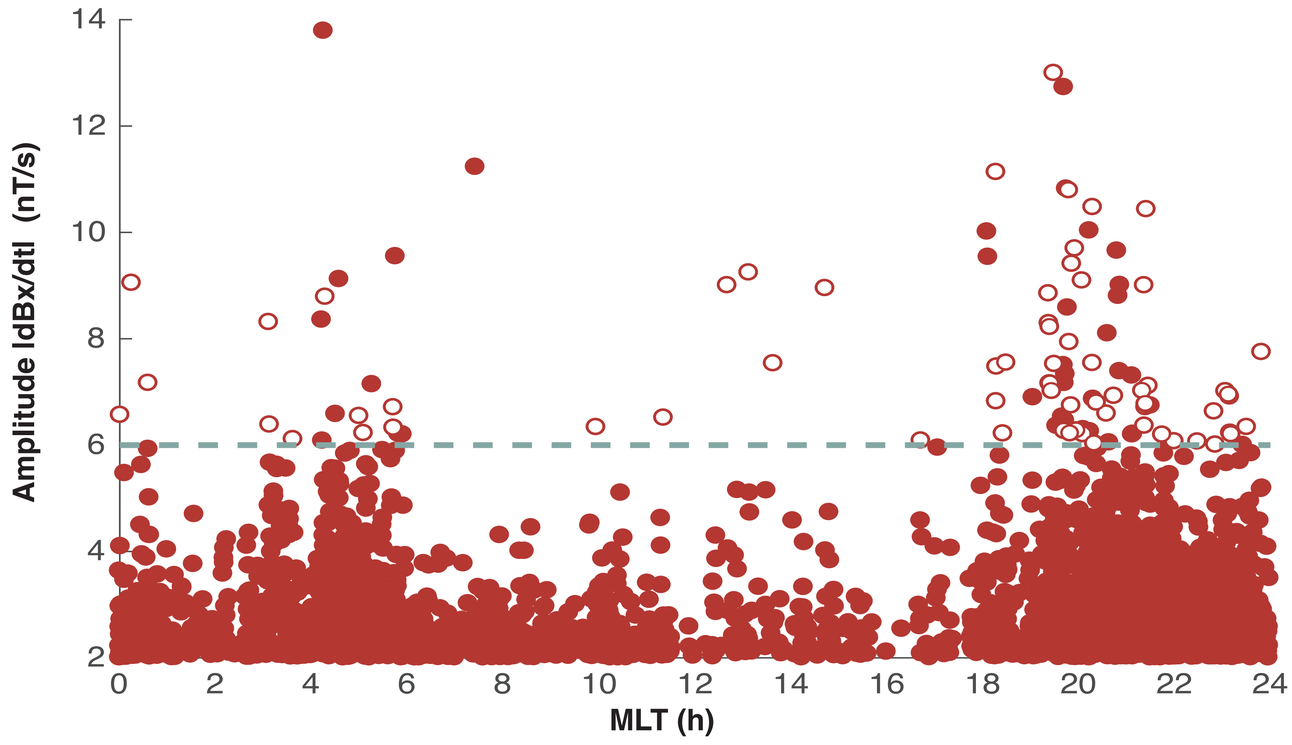
After identifying the events, the TIC characteristics were statistically analyzed to determine their frequency of occurrence, temporal dependence and proximity in time from geomagnetic storms and substorms. The event delay from substorm onset was determined with the substorm event list for the year of 2015 from SuperMAG. The provisional Dst index for 2015 from the WDC Kyoto was used for storm phase determination.

Probability Distribution of Short-timescale Geomagnetic Field Perturbations



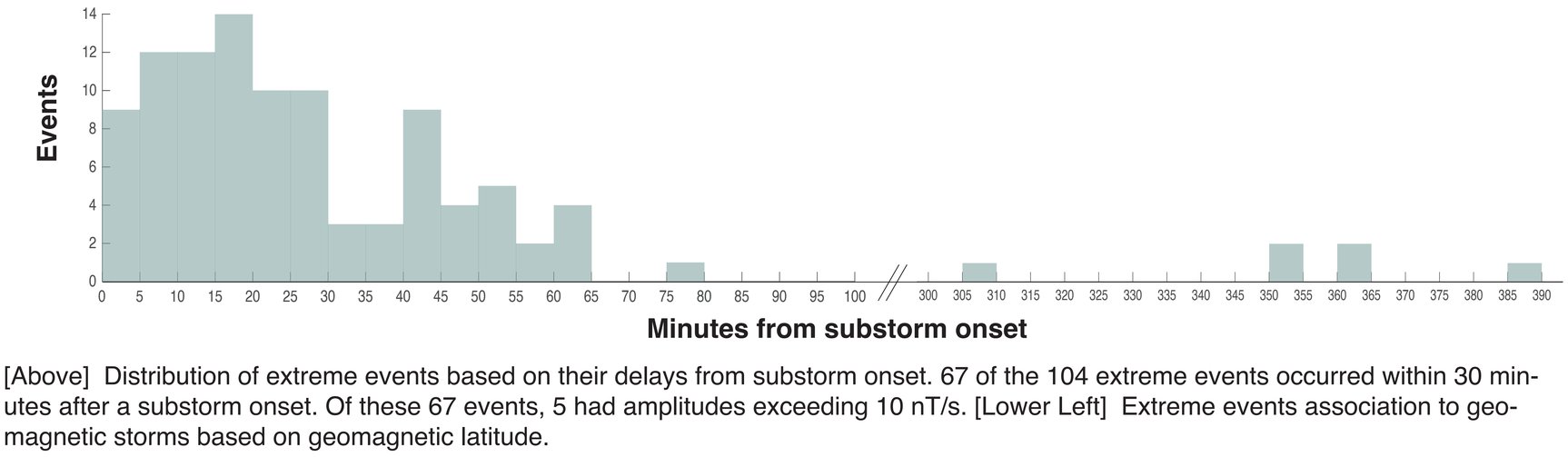
[Left] Probability distribution of short-timescale X-component geomagnetic field changes, IdBx/dtI, that may cause sufficient TICs. These events all lasted < 5 minutes with derivative amplitude IdBx/dtI > 2 nT/s. The distribution is fitted with a half-normal distribution (red) and the exceedance probability is shown black. The events considered to be "extreme" are those that exceed 6 nT/s. There are 3078 total events with 104 extreme events. The extreme events occurred on 30 days throughout 2015. All extreme events lasted less than 146.5 seconds.

Transient IdBx/dtI events as a function of Magnetic Local Time



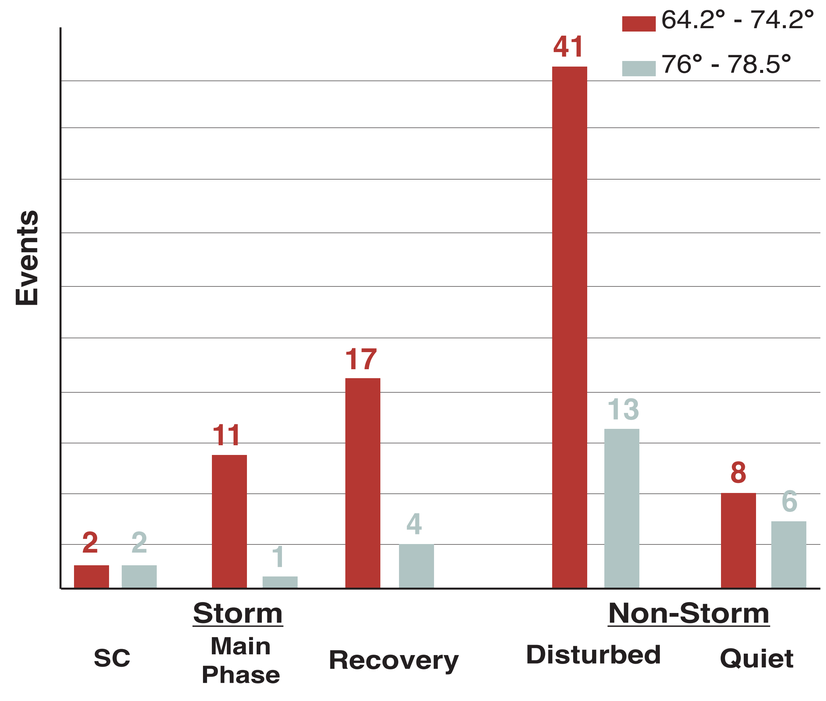
[Left] Scatter plot of short-timescale x-component derivative amplitudes as a function of magnetic local time. The hollow red dots are extreme events which occurred within 30 minutes of a substorm onset. The results of this plot show that at these six stations, large amplitude transient IdBx/dtI events occurred far more frequently during nighttime hours than daytime hours. These results indicate that the largest and most potentially hazardous TICs are most likely to occur during nighttime, ± 4 hours from local magnetic midnight. The dotted line signifies the extreme event threshold.

Time delays from substorm onset until extreme TIC occurrence



[Above] Distribution of extreme events based on their delays from substorm onset. 67 of the 104 extreme events occurred within 30 minutes after a substorm onset. Of these 67 events, 5 had amplitudes exceeding 10 nT/s. [Lower Left] Extreme events association to geomagnetic storms based on geomagnetic latitude.

Storm association of extreme events



Conclusions

- **A total of 3078 TIC events in the x-component were identified for the year of 2015 at six MACCS stations**
- **104 of the events are extreme (> 6 nT/s), occurring on 30 days throughout the year**
- **64.4% of the extreme events occurred within 30 minutes of a substorm onset**
- **35.6% of the extreme events are associated with geomagnetic storms**
- **28.8% of the extreme events are not associated with storms or substorms**
- **The events at lower latitudes are more strongly associated with storms than events at higher latitudes**