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Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

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Key Points:

- We present a first analysis of the effects of space weather on insurance claims
- Geomagnetic variability couples into the low-voltage power network
- GIC effects lead to malfunctions in electrical and electronic devices

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Abstract Geomagnetically induced currents are known to induce disturbances in the electric power grid. Here we perform a statistical analysis of 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in North American commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment. We find that claim rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5% and by about 10% for the top third of most active days ranked by daily maximum variability of the geomagnetic field. When focusing on the claims explicitly attributed to electrical surges (amounting to more than half the total sample), we find that the dependence of claim rates on geomagnetic activity mirrors that of major disturbances in the U.S. high-voltage electric power grid. The claim statistics thus reveal that large-scale geomagnetic variability couples into the low-voltage power distribution network and that related power-quality variations can cause malfunctions and failures in electrical and electronic devices that, in turn, lead to an estimated 500 claims per average year within North America. We discuss the possible magnitude of the full economic impact associated with quality variations in electrical power associated with space weather.

1. Introduction

Large explosions that expel hot, magnetized gases on the Sun can, should they eventually envelop Earth, effect severe disturbances in the geomagnetic field. These, in turn, cause geomagnetically induced currents (GICs) to run through the surface layers of the Earth and through conducting infrastructures in and on these, including the electrical power grids. The storm-related GICs run on a background of daily variations associated with solar (X)(E)UV irradiation that itself is variable through its dependence on both quiescent and flaring processes.

The strongest GIC events are known to have impacted the power grid on occasion [see, e.g., *Kappenman et al.*, 1997; *Boteler et al.*, 1998; *Arslan Erinmez et al.*, 2002; *Kappenman*, 2005; *Wik et al.*, 2009]. Among the best known of such impacts is the 1989 Hydro-Québec blackout [e.g., *Bolduc*, 2002; *Béland and Small*, 2004]. Impacts are likely strongest at middle to high geomagnetic latitudes, but low-latitude regions also appear susceptible [*Gaunt*, 2013].

The potential for severe impacts on the high-voltage power grid and thereby on society that depends on it has been assessed in studies by government, academic, and insurance industry working groups [e.g., *Space Studies Board*, 2008; *FEMA and NOAA*, 2010; *Kappenman*, 2010; *Hapgood*, 2011; *JASON*, 2011]. How costly such potential major grid failures would be remains to be determined, but impacts of many billions of dollars have been suggested [e.g., *Space Studies Board*, 2008; *JASON*, 2011].

Noncatastrophic GIC effects on the high-voltage electrical grid percolate into financial consequences for the power market [*Forbes and St. Cyr*, 2004, 2008, 2010] leading to price variations on the bulk electrical power market on the order of a few percent [*Forbes and St. Cyr*, 2004].

Schrijver and Mitchell [2013] quantified the susceptibility of the U.S. high-voltage power grid to severe, yet not extreme, space storms, leading to power outages and power-quality variations related to voltage sags and frequency changes. They find, “with more than 3σ significance, that approximately 4% of the disturbances in the U.S. power grid reported to the U.S. Department of Energy are attributable to strong geomagnetic activity and its associated geomagnetically induced currents."

The effects of GICs on the high-voltage power grid can, in turn, affect the low-voltage distribution networks and, in principle, might impact electrical and electronic systems of users of those regional and local networks. A first indication that this does indeed happen was reported on in association with tests conducted by the Idaho National Laboratory (INL) and the Defense Threat Reduction Agency (DTRA). They reported [*Wise and Benjamin*, 2013] that "INL and DTRA used the lab's unique power grid and a pair of 138kV core form, 2 winding substation transformers, which had been in-service at INL since the 1950s, to perform the first full-scale testing to replicate conditions electric utilities could experience from geomagnetic disturbances." In these experiments, the researchers could study how the artificial GIC-like currents resulted in harmonics on the power lines that can affect the power transmission and distribution equipment. These "tests demonstrated that geomagnetic-induced harmonics are strong enough to penetrate many power line filters and cause temporary resets to computer power supplies and disruption to electronic equipment, such as uninterruptible power supplies."

In parallel to that experiment, we collected information on insurance claims submitted to Zurich North America (NA) for damage to, or outages of, electrical and electronic systems from all types of industries for a comparison with geomagnetic variability. Here we report on the results of a retrospective cohort exposure analysis of the impact of geomagnetic variability on the frequency of insurance claims. In this analysis, we contrast insurance claim frequencies on "high-exposure" dates (i.e., dates of high geomagnetic activity) with a control sample of "low-exposure" dates (i.e., dates with essentially quiescent space weather conditions), carefully matching each high-exposure date to a control sample nearby in time so that we may assume no systematic changes in conditions other than space weather occurred between the exposure dates and their controls (thus compensating for seasonal weather changes and other trends and cycles).

For comparison purposes, we repeat the analysis of the frequency of disturbances in the high-voltage electrical power grid as performed by *Schrijver and Mitchell* [2013] for the same date range and with matching criteria for threshold setting and for the selection of the control samples. In section 2 we describe the insurance claim data, the metric of geomagnetic variability used, and the grid-disturbance information. The procedure to test for any impacts of space weather on insurance claims and the high-voltage power grid is presented and applied in section 3. We summarize our conclusions in section 4 where we also discuss the challenges in translating the statistics on claims and disturbances into an economic impact.

2. Data

2.1. Insurance Claim Data

We compiled a list of all insurance claims filed by commercial organizations to Zurich NA relating to costs incurred for electrical and electronic systems for the 11 year interval from 1 January 2000 through 31 December 2010. Available for our study were the date of the event to which the claim referred, the state or province within which the event occurred, a brief description of the affected equipment, and a top-level assessment of the probable cause. Information that might lead to identification of the insured parties was not disclosed.

Zurich NA estimates that it has a market share of approximately 8% in North America for policies covering commercially used electrical and electronic equipment and contingency business interruptions related to their failure to function properly during the study period. Using that information as a multiplier suggests that overall some 12,800 claims are filed per average year related to electrical/electronic equipment problems in North American businesses. The data available for this study cannot reveal impacts on uninsured or self-insured organizations or impacts in events of which the costs fall below the policy deductable.

The 11 year period under study has the same duration as that characteristic of the solar magnetic activity cycle. Figure 1 shows that the start of this period coincides with the maximum in the annual sunspot number for 2000, followed by a decline into an extended minimum period in 2008 and 2009, ending with the rise of sunspot number into the start of the next cycle.

The full sample of claims, regardless of attribution, for which an electrical or electronic system was involved includes 11,242 entries. We refer to this complete set as set *A*.

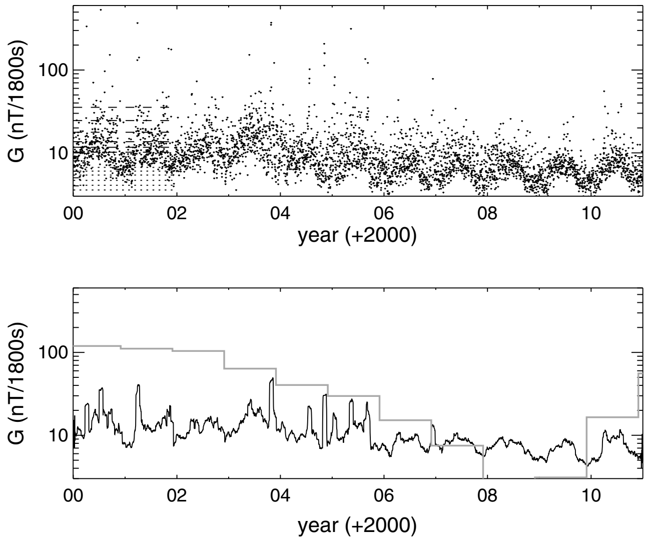

Figure 1. (top) Daily values $G \equiv \max(|dB/dt|)$ based on 30 min intervals (dots; nT/1800s) characterizing geomagnetic variability for the contiguous United States versus time (in years since 2000). The 27 day running mean is shown by the solid line in the bottom panel. The levels for the 98, 95, 90, 82, 75, and 67 percentiles of the entire sample are shown by dashed lines (sorting downward from the top value of G) and dotted lines (sorting upward from the minimum value of the daily geomagnetic variability as expressed by $G \equiv \max(|dB/dt|)$). (bottom) The grey histogram shows the annual mean sunspot number.

Claims that were attributed to causes that were in all likelihood not associated with space weather phenomena were deleted from set *A* to form set *B* (with 8151 entries remaining after review of the Accident Narrative description of each line item). Such omitted claims included attributions to water leaks and flooding, stolen or lost equipment, vandalism or other intentional damage, vehicle damage or vehicular accidents, animal intrusions (raccoons, squirrels, birds, etc.), obvious mechanical damage, and obvious weather damage (ice storm damage, hurricane/windstorm damage, etc.). The probable causes for the events making up set *B* were limited to the following categories (sorted by the occurrence frequency, given in percent): Misc: Electrical surge (59%); Apparatus, Miscellaneous Electrical - Breaking (30%); Apparatus, Miscellaneous Electrical - Arcing (4.1%); Electronics - Breaking (1.6%); Apparatus, Miscellaneous Electrical - Overheating (1.4%); Transformers - Arcing (0.9%); Electronics - Arcing (0.6%); Transformers - Breaking (0.5%); Generators - Breaking (0.4%); Apparatus, Electronics - Overheating (0.3%); Generators - Arcing (0.2%); Generators - Overheating (0.2%); and Transformers - Overheating (0.1%).

Figure 2 shows the number of claims received as a function of the mean geomagnetic latitude for the state within which the claim was recorded. Based on this histogram, we divided the claims into categories of comparable size for high and low geomagnetic latitudes along a separation at 49.°5 north geomagnetic latitude to enable testing for a dependence on proximity to the auroral zones. We note that we do not have access to information about the latitudinal distribution of insured assets, only on the claims received. Hence, we can only assess any dependence of insurance claims on latitude in a relative sense, comparing excess relative claim frequencies for claims above and below the median geomagnetic latitudes, as discussed in section 3.

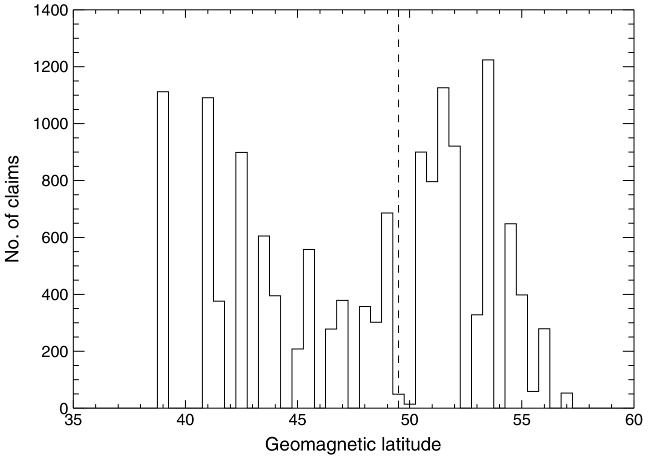

Figure 2. Number of insurance claims sorted by geomagnetic latitude (using the central geographical location of the state) in 0.5° bins. The dashed line at 49.5° is near the median geomagnetic latitude of the sample (at 49.3°), separating what this paper refers to as high latitude from low-latitude states.

2.2. Geomagnetic Data

Geomagnetically induced currents are driven by changes in the geomagnetic field. These changes are caused by the interaction of the variable, magnetized solar wind with the geomagnetic field and by the insolation of Earth's atmosphere that varies globally with solar activity and locally owing to the Earth's daily rotation and annual revolution in its orbit around the Sun. A variety of geomagnetic activity indices is available to characterize geomagnetic field

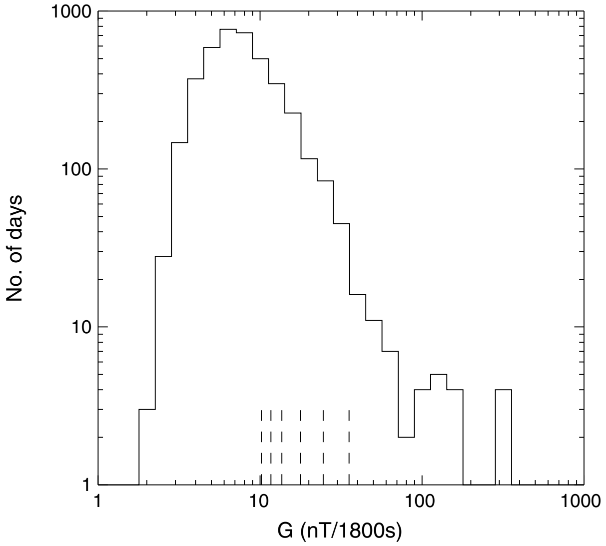

Figure 3. Histogram of the number of days between 1 January 2000 and 31 December 2010 with values of $G \equiv \max(|\mathrm{d}B/\mathrm{d}t|)$ in logarithmically spaced intervals as shown on the horizontal axis. The 98, 95, 90, 82, 75, and 67 percentiles (ranking G from low to high) are shown by dashed lines.

variability [e.g., *Jursa*, 1985]. These indices are sensitive to different aspects of the variable geomagnetic-ionospheric current systems as they may differentially filter or weight storm-time variations (*Dst*), disturbance-daily variations (Ds), or solar quiet daily variations (known as the *Sq* field), and may weight differentially by (geomagnetic) latitude. Here we are interested not in any particular driver of changes in the geomagnetic field but rather need a metric of the rate of change in the strength of the surface magnetic field as that is the primary driver of geomagnetically induced currents.

To quantify the variability in the geomagnetic field, we use the same metric as *Schrijver and Mitchell* [2013] based on the minute-by-minute geomagnetic field measurements from the Boulder (BOU) and Fredericksburg (FRD) stations (available via http://ottawa.intermagnet.org): we use these measurements to compute the daily maximum value, G, of $|\mathrm{d}B/\mathrm{d}t|$ over 30 min intervals, using the mean value for the two stations. We selected this metric recognizing a need to use a more regional metric than the often-used global metrics but also recognizing that the available geomagnetic and insurance claim data have poor geographical resolution so that a focus on a metric responsive to relatively low-order geomagnetic variability was appropriate.

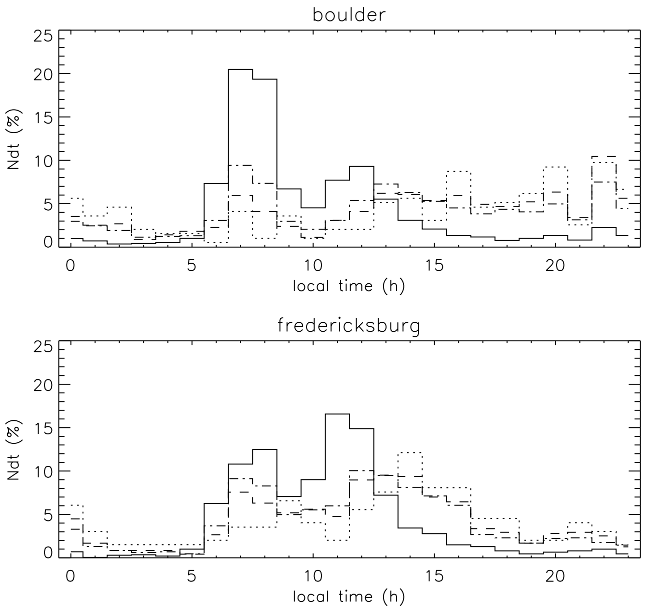

Figure 4. Normalized histograms of the local times for which the values of $G \equiv \max(|\mathrm{d}B/\mathrm{d}t|)$ reach their daily maximum: (top) Boulder and (bottom) Fredericksburg. The solid histogram shows the distribution for daily peaks for all dates with G values in the lower half of the distribution, i.e., for generally quiescent conditions. The dotted, dashed, and dash-dotted histograms show the distributions for dates with high G values, for thresholds set at the 95, 82, and 67 percentiles of the set of values for G, respectively.

We chose a time base short enough to be sensitive to rapid changes in the geomagnetic field but long enough that it is also sensitive to sustained changes over the course of over some tens of minutes. For the purpose of this study, we chose to use a single metric of geomagnetic variability, but with the conclusion of our pilot study revealing a dependence of damage to electrical and electronic equipment on space weather conditions, a multiparameter follow up study is clearly warranted, ideally also with more information on insurance claims, than could be achieved with what we have access to for this exploratory study.

The BOU and FRD stations are located along the central latitudinal axis of the U.S. The averaging of their measurements somewhat emphasizes the eastern U.S. as do the grid and population that uses that. Because the insurance claims use dates based on local time we compute the daily G

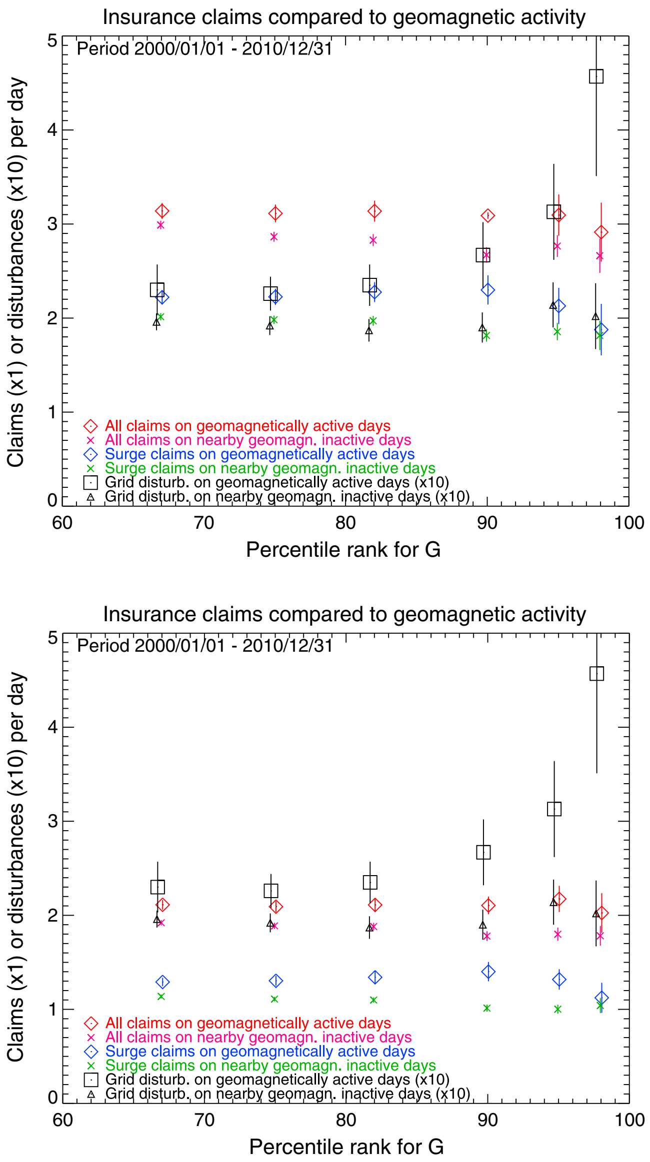

Figure 5. (top) Claims per day for the full sample of insurance claims (set *A*) and (bottom) for the sample from which claims likely unrelated to any space weather influence have been removed (set *B*). Each panel shows mean incident claim frequencies $n_i \pm \sigma_c$ (diamonds) for the most geomagnetically active dates, specifically for the 98, 95, 90, 82, 75, and 67 percentiles of the distribution of daily values of $G \equiv \max(|\mathrm{d}B/\mathrm{d}t|)$ sorted from low to high (shown with slight horizontal offsets to avoid overlap in the symbols and bars showing the standard deviations for the mean values). The asterisks show the associated claim frequencies $n_c \pm \sigma_c$, for the control samples. The panels also show the frequencies of reported high-voltage power grid disturbances (diamonds and triangles for geomagnetically active dates and for control dates, respectively), multiplied by 10 for easier comparison, using the same exposure-control sampling and applied to the same date range as that used for the insurance claims.

values based on date boundaries of U.S. central time. Figure 3 shows the distribution of values of *G*, while also showing the levels of the percentiles for the rank-sorted value of *G* used as threshold values for a series of subsamples in the following sections.

Figure 4 shows the local times at which the maximum variations in the geomagnetic field occur during 30 min intervals. The most pronounced peak in the distribution for geomagnetically quiet days (solid histogram) occurs around 7–8 o'clock local time, i.e., a few hours after sunrise, and a second peak occurs around local noon. The histograms for the subsets of geomagnetically active days for which *G* values exceed thresholds set at 67, 82, and 95 percentiles of the sample are much broader, even more so for the Boulder station than for the Fredericksburg station. From the perspective of the present study, it is important to note that the majority of the peak times for our metric of geomagnetic variability occurs within the economically most active window from 7 to 18 hours local time; for example, at the 82 percentile of geomagnetic variability in *G*, 54% and 77% of the peak variability occur in that time span for Boulder and Fredericksburg, respectively.

From a general physics perspective, we note that periods of markedly enhanced geomagnetic activity ride on top of a daily background variation of the ionospheric current systems (largely associated with the "solar quiet" modulations, referred to as the *Sq* field) that is induced to a large extent by solar irradiation of the atmosphere of the rotating Earth, including the variable coronal components associated with active-region gradual evolution and impulsive solar flaring. We do not attempt to separate the impacts of these drivers in this study, both because we do not have information on the local times for which the problems occurred that lead to the insurance claims and because the power grid is sensitive to the total variability in the geomagnetic field regardless of cause.

The daily *G* values are shown versus time in Figure 1, along with a 27 day running mean and (as a grey histogram) the yearly sunspot number. As expected, the *G* value shows strong upward excursions particularly

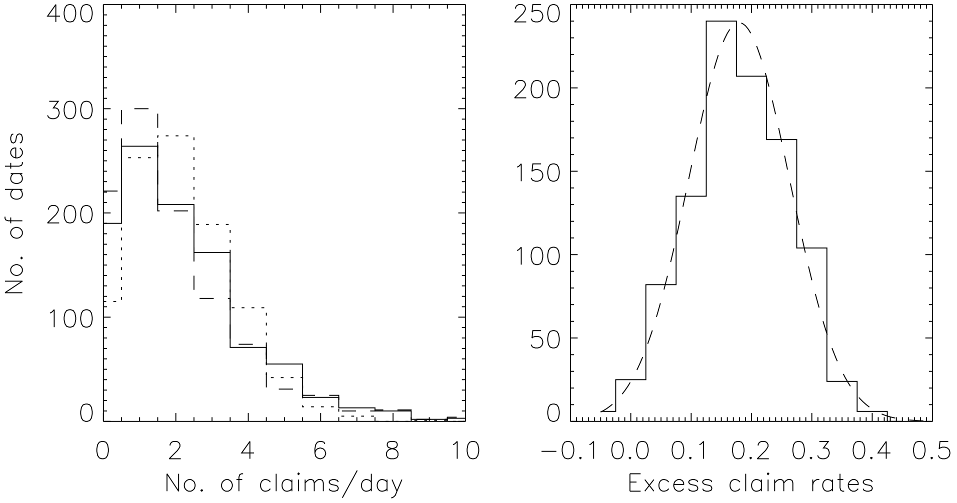

Figure 6. (left) Distribution of the number of claims per geomagnetically active day for set *B* for the top 25% of *G* values (solid) compared to that for the distribution of control dates (divided by 3 to yield the same total number of dates; dashed). For comparison, the expected histogram for a random Poisson distribution with the same mean as that for the geomagnetically active days is also shown (dotted). (right) Distribution (solid) of excess daily claim frequencies during geomagnetically active days (defined as in Figure 6 (left)) over those on control dates determined by repeated random sampling from the observations (known as the bootstrap method), compared to a Gaussian distribution (dashed) with the same mean and standard deviation.

during the sunspot maximum. Note the annual modulation in *G* with generally lower values in the northern hemispheric winter months than in the summer months.

2.3. Power Grid Disturbances

In parallel to the analysis of the insurance claim statistics, we also analyze the frequencies of disturbances in the U.S. high-voltage power grid. *Schrijver and Mitchell* [2013] compiled a list of “system disturbances” published by the North American Electric Reliability Corporation (NERC: available since 1992) and by the Office of Electricity Delivery and Energy Reliability of the Department of Energy (DOE; available since 2000). This information is compiled by NERC for a region with over 300 million electric power customers throughout the USA and in Ontario and New Brunswick in Canada, connected by more than 340,000 km of high-voltage transmission lines delivering power generated in some 18,000 power plants within the U.S. [*JASON*, 2011]. The reported disturbances include, among others, “electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of the bulk electric systems, and fuel problems.” We use the complete set of disturbances reported from 1 January 2000 through 31 December 2010 regardless of attributed cause. We refer to *Schrijver and Mitchell* [2013] for more details.

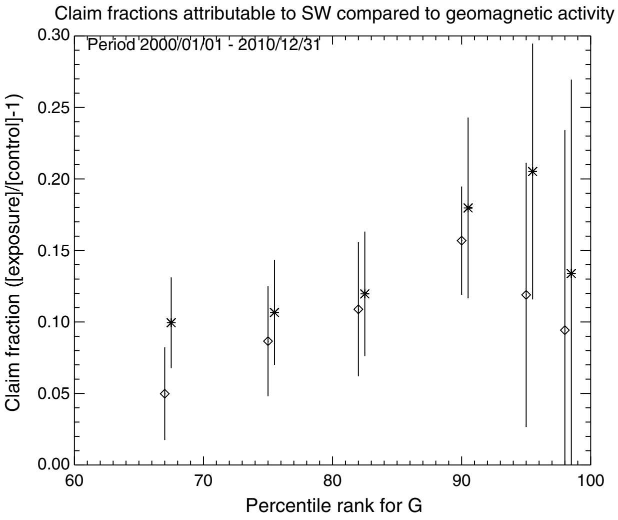

Figure 7. Relative excess claim frequencies statistically associated with geomagnetic activity (difference between claim frequencies on geomagnetically active dates and the frequencies on control dates as shown in Figure 5, i.e., $(n_i - n_c)/n_c$) for the full sample (*A*; diamonds) and for the sample (*B*; asterisks) from which claims were removed attributable to apparently nonspace weather-related causes.

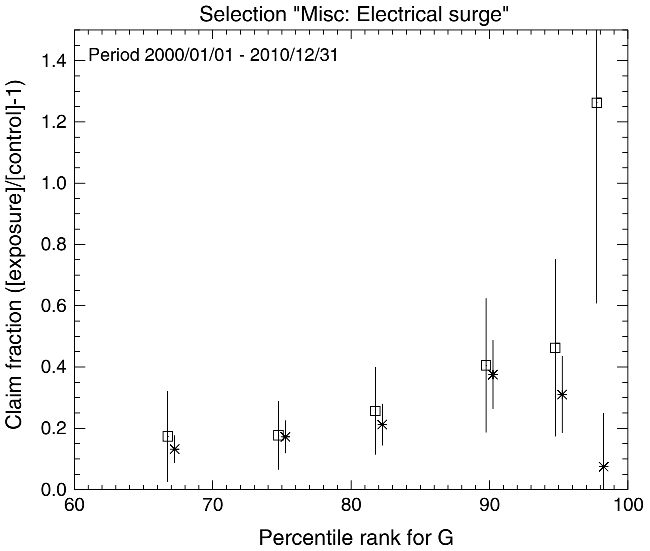

Figure 8. Same as Figure 7 but for sample *B* limited to those claims attributed to "Misc.: Electrical surge" (asterisks) (for 57% of the cases in that sample), compared to the fraction of high-voltage power grid disturbances statistically associated with geomagnetic activity (squares).

3. Testing for the Impact of Space Weather

In order to quantify effects of geomagnetic variability on the frequency of insurance claims filed for electrical and electronic equipment, we need to carefully control for a multitude of variables that include trends in solar activity, the structure and operation of the power grid (including, for example, scheduled maintenance and inspection), various societal and technological factors changing over the years, as well as the costs and procedures related to the insurance industry, and, of course, weather and seasonal trends related to the insolation angle and the varying tilt of the Earth's magnetic field relative to the incoming solar wind throughout the year.

There are many parameters that may influence the ionospheric current systems, the quality and continuity of electrical power, and the malfunctioning of equipment running on electrical power. We may not presume that we could identify and obtain all such parameters or that all power grid segments and all equipment would respond similarly to changes in these parameters. We therefore do not attempt a multiparameter correlation study but instead apply a retrospective cohort exposure study with tightly matched controls very similar to that applied by *Schrijver and Mitchell* [2013].

This type of exposure study is based on pairing dates of exposure, i.e., of elevated geomagnetic activity, with control dates of low geomagnetic activity shortly before or after each of the dates of exposure, selected from within a fairly narrow window in time during which we expect no substantial systematic variation in ionospheric conditions, weather, the operations of the grid, or the equipment powered by the grid. Our results are based on a comparison of claim counts on exposure dates relative to claim counts on matching sets of nearby control dates. This minimizes the impacts of trends (including "confounders") in any of the potential factors that affect the claim statistics or geomagnetic variability, including the daily variations in quiet-Sun irradiance and the seasonal variations as Earth orbits the Sun, the solar cycle, and the structure and operation of the electrical power network. This is a standard method as used in, e.g., epidemiology. We refer to *Wacholder et al.* [1992, and references therein] for a discussion on this method particularly regarding ensuring of time comparability of the "exposed" and control samples, to *Schulz and Grimes* [2002] for a discussion on the comparison of cohort studies as applied here versus case-control studies, and to *Grimes and Schulz* [2005] for a discussion of selection biases in samples and their controls (specifically their example on pp. 1429–1430).

Table 1. Probability (p) Values Based on a Kolmogorov-Smirnov Test That the Observed Sets of Claim Numbers on Geomagnetically Active Dates and on Control Dates Are Drawn From the Same Parent Distribution, for Date Sets With the Geomagnetic Activity Metric G Exceeding the Percentile Threshold in the Distribution of Values

	All Claims		Attributed to Electrical Surges	
Percentile	Set *A*	Set *B*	Set *A*	Set *B*
67	2×10^{-10}	2×10^{-19}	1×10^{-27}	0
75	3×10^{-7}	4×10^{-14}	8×10^{-20}	4×10^{-35}
82	0.0004	2×10^{-7}	1×10^{-13}	6×10^{-24}
90	0.010	0.0002	1×10^{-7}	8×10^{-13}
95	0.05	0.013	0.0001	2×10^{-7}
98	0.33	0.06	0.003	0.0001

We define a series of values of geomagnetic variability in order to form sets of dates including different ranges of exposure, i.e., of

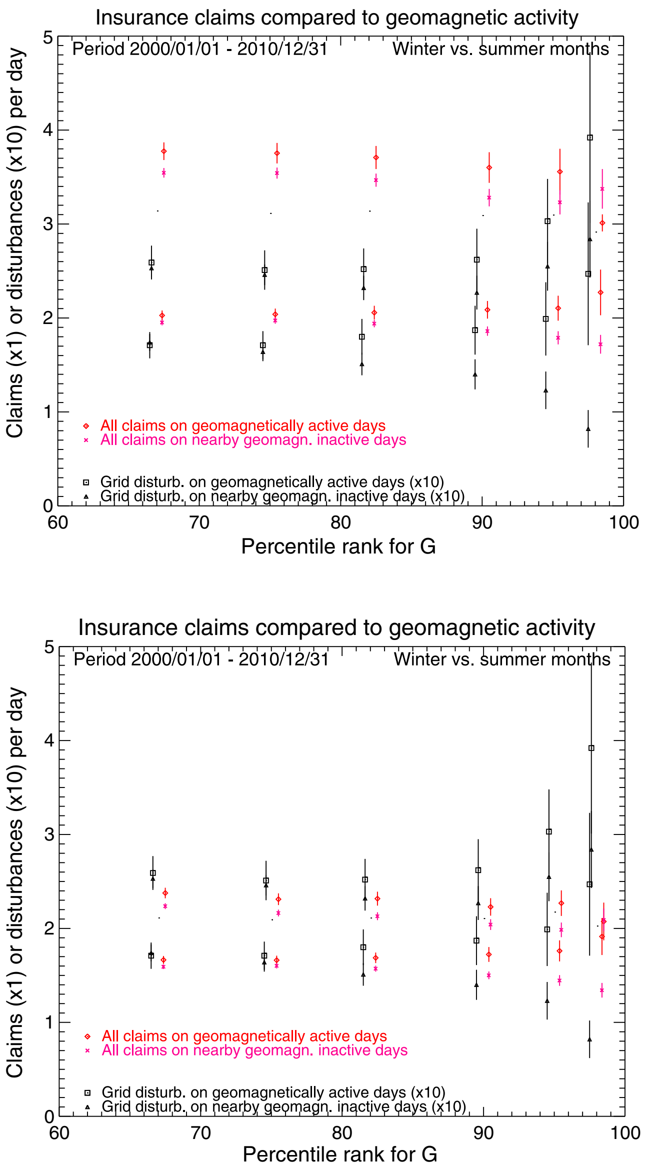

Figure 9. As Figure 5 but separating the winter half year (October through March) from the summer half year (April through September), for (top) the full sample of insurance claims (set *A*) and (bottom) the sample from which claims likely unrelated to any space weather influence have been removed (set *B*). Values for the summer months are shown offset slightly toward the left of the percentiles tested (98, 95, 90, 82, 75, and 67), while values for the winter months are offset to the right. Values for the winter season are systematically higher than those for summer months.

geomagnetic variability, so that each high-exposure date is matched by representative low-exposure dates as controls. We create exposure sets by selecting a series of threshold levels corresponding to percentages of all dates with the most intense geomagnetic activity as measured by the metric *G*. Specifically, we determined the values of *G* for which geomagnetic activity, sorted from least active upward, includes 67%, 75%, 82%, 90%, 95%, and 98% of all dates in our study period. For each threshold value we selected the dates with *G* exceeding that threshold (with possible further selection criteria as described below). For each percentile set, we compute the mean daily rate of incident claims, n_i, as well as the standard deviation on the mean, σ_i, as determined from the events in the day-by-day claims list.

In order to form tightly matched control samples for low "exposure," we then select three dates within a 27 day period centered on each of the selected high-activity days. The 27 day period, also known as the Bartels period, is that characteristic of a full rotation of the solar large-scale field as viewed from the orbiting Earth; *G* values within that period sample geomagnetic variability as induced during one full solar rotation. This window for control sample selection is tighter than that used by *Schrijver and Mitchell* [2013] who used 100 day windows centered on dates with reported grid disturbances. For the present study we selected a narrower window to put even stronger limits on the potential effects of any possible long-term trends in factors that might influence claim statistics or geomagnetic variability. We note that there is no substantive change in our main conclusions for control windows at least up to 100 days in duration.

The three dates selected from within this 27 day interval are those with the lowest value of *G* smoothed with a 3 day running mean. We determine the mean claim rate, n_c, for this control set and the associated standard deviation in the mean, σ_c.

Figure 5 shows the resulting daily frequency of claims and the standard deviations in the mean, $n_i \pm \sigma_i$, for the selected percentiles, both for the full sample *A* (top) and for sample *B* (bottom) from which claims were omitted that were attributed to causes not likely associated directly or indirectly with geomagnetic activity. For all percentile sets, we see that the claim frequencies n_i on geomagnetically active days exceed the frequencies n_c for the control dates.

The frequency distributions of insurance claims are not Poisson distributions, as can be seen in the example in Figure 6 (left): compared to a Poisson distribution of the same mean, the claims distributions on geomagnetically active dates, $N_{\mathrm{B,a,75}}$, and for control days, $N_{\mathrm{B,c,75}}$, are skewed to have a peak frequency at lower numbers and a raised tail at higher numbers; a Kolmogorov-Smirnov (KS) test suggests that the probability that $N_{\mathrm{B,c,75}}$ is consistent with a Poisson distribution with the same mean is 0.01 for this example. The elevated tail of the distribution relative to a Poisson distribution suggests some correlation between claim events, which is of interest from an actuarial perspective as it suggests a nonlinear response of the power system to space weather that we cannot investigate further here owing to the signal-to-noise ratio of the results given our sample.

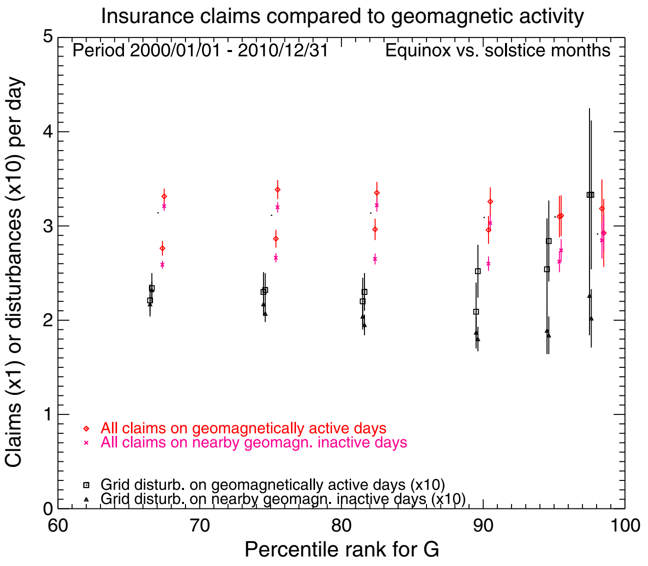

Figure 10. As Figure 9 but separating the months around the equinoxes (February–April and August–October) from the complementing months around the solstices, for the full sample of insurance claims (set *A*). Values for the equinox periods are shown offset slightly toward the left of the percentiles tested (98, 95, 90, 82, 75, and 67), while values for the solstice months are offset to the right. Mean claim frequencies for the solstice periods are systematically higher than those for equinox periods, but the frequencies for high-*G* days in excess of the control sample frequencies are slightly larger around the equinoxes than around the solstices.

For the case shown in Figure 6 for the 25% most geomagnetically active dates in set *B*, a KS test shows that the probability that $N_{\mathrm{B,a,75}}$ and $N_{\mathrm{B,c,75}}$ are drawn from the same parent distribution is of order 10^{-14}, i.e., extremely unlikely.

The numbers that we are ultimately interested in are the excess frequencies of claims on geomagnetically active dates over those on the control dates and their uncertainty. For the above data set, we find and excess daily claims rate of $(n_{\mathrm{B,i}} - n_{\mathrm{B,c}}) \pm \sigma_{\mathrm{B}} = 0.20 \pm 0.08$. The uncertainty σ_{B} is in this case determined by repeated random sampling of the claim sample for exposure and control dates and subsequently determining the standard deviation in a large sample of resulting excess frequencies (using the so-called bootstrap method). The distribution of excess frequencies (shown in Figure 6 (right)) is essentially Gaussian, so that the metric of the standard deviation gives a useful value to specify the uncertainty. We note that the value of σ_{B} is comparable to the value $\sigma_{a,c} = (\sigma_{\mathrm{a}}^2 + \sigma_{\mathrm{b}}^2)^{1/2}$ derived by combining the standard deviations for the numbers of claims per day for geomagnetically active dates and the control dates, which in this case equals $\sigma_{a,c} = 0.07$. Thus, despite the skewness of the claim count distributions relative to a Poisson distribution as shown in the example in Figure 6 (left), the effect of that on the uncertainty in the excess claim rate is relatively small. For this reason, we show the standard deviations on the mean frequencies in Figures 5–11 as a useful visual indicator of the significance of the differences in mean frequencies.

Figure 7 shows the relative excess claim frequencies, i.e., the relative differences $r_e = (n_i - n_c)/n_c$ between the claim frequencies on geomagnetically active dates and those on the control dates, thus quantifying the claim fraction statistically associated with elevated geomagnetic activity. The uncertainties shown are computed as $\sigma_e = (\sigma_i^2/n_i^2 + \sigma_c^2/n_c^2)^{1/2}\, r_e$, i.e., using the approximation of normally distributed uncertainties, warranted by the arguments above. We note that the relative rate of claims statistically associated with space weather is slightly higher for sample *B* than for the full set *A* consistent with the hypothesis that the claims omitted from sample *A* to form sample *B* were indeed preferentially unaffected by geomagnetic activity. Most importantly, we note that the rate of claims statistically associated with geomagnetic activity increases with the magnitude of that activity.

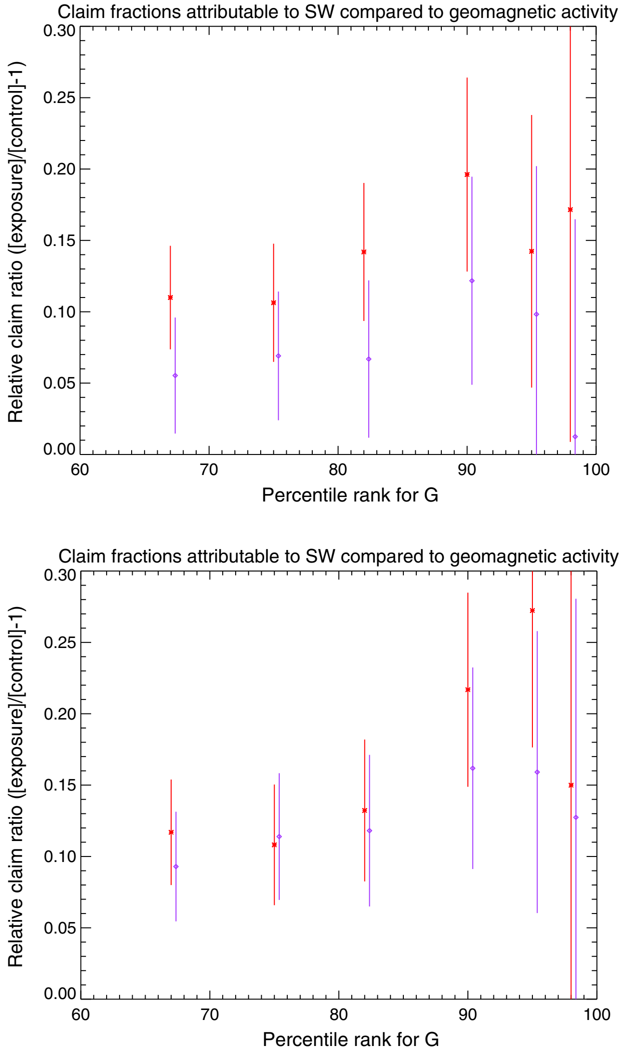

Figure 11. Relative excess claim frequencies $(n_i - n_c)/n_i$ on geomagnetically active dates relative to those on control dates for geomagnetic latitudes below 49.5°N (asterisks, red) compared to those for higher latitudes (diamonds, purple; offset slightly to the right) for the percentiles tested (98, 95, 90, 82, 75, and 67). (top) The results for the full sample (*A*) and (bottom) for sample *B* from which apparently nonspace weather-related events were removed (see section 2.1).

About 59% of the claims in sample *B* attribute the case of the problem to "Misc.: Electrical surge", so that we can be certain that some variation in the quality or continuity of electrical power was involved. Figure 8 shows the relative excess claim rate $(n_i - n_c)/n_c$ as function of threshold for geomagnetic activity. We compare these results with the same metric, based on identical selection procedures, for the frequency of disturbances in the high-voltage power grid (squares). We note that these two metrics, one for interference with commercial electrical/electronic equipment and one for high-voltage power, agree within the uncertainties, with the possible exception of the infrequent highest geomagnetic activity (98 percentile) although there the statistical uncertainties on the mean frequencies are so large that the difference is less than 2 standard deviations in the mean values.

To quantify the significance of the excess claim frequencies on geomagnetically active days, we perform a nonparametric Kolmogorov-Smirnov (KS) test of the null hypothesis that the claim events on active and on control days could be drawn from the same parent sample. The resulting *p* values from the KS test, summarized in Table 1, show that it is extremely unlikely that our conclusion that geomagnetic activity has an impact on insurance claims could be based on chance, except for the highest percentiles in which the small sample sizes result in larger uncertainties. We note that the *p* values tend to decrease when we eliminate claims most likely unaffected by space weather (contrasting set *A* with *B*) and when we limit either set to events attributed to electrical surges: biasing the sample tested toward issues more likely associated with power grid variability increases the significance of our findings that there is an impact of space weather.

Figure 9 shows insurance claims differentiated by season: the frequencies of both insurance claims and power grid disturbances are higher in the winter months than in the summer months, but the excess claim frequencies statistically associated with geomagnetic activity follow similar trends as for the full date range. The same is true when looking at the subset of events attributed to surges in the low-voltage power distribution grid.

Figure 10 shows a similar diagram to that of Figure 9 (top), now differentiating between the equinox periods and the solstice periods. Note that although the claim frequencies for the solstice periods are higher than those for the equinox periods, that difference is mainly a consequence of background (control) frequencies:

the fractional excess frequencies on geomagnetically active days relative to the control dates are larger around the equinoxes than around the solstices.

Figure 11 shows the comparison of claim ratios of geomagnetically active dates relative to control dates for states with high versus low geomagnetic latitude, revealing no significant contrast (based on uncertainties computed as described above for Figure 7).

4. Discussion and Conclusions

We perform a statistical study of North American insurance claims for malfunctions of electronic and electrical equipment and for business interruptions related to such malfunctions. We find that there is a significant increase in claim frequencies in association with elevated variability in the geomagnetic field, comparable in magnitude to the increase in occurrence frequencies of space weather-related disturbances in the high-voltage power grid. In summary,

1. The fraction of insurance claims statistically associated with geomagnetic variability tends to increase with increasing activity from about 5 to 10% of claims for the top third of most active days to approximately 20% for the most active few percent of days.
2. The overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is $\approx$ 4%. With a market share of about 8% for Zurich NA in this area, we estimate that some 500 claims per year are involved overall in North America.
3. Disturbances in the high-voltage power grid statistically associated with geomagnetic activity show a comparable frequency dependence on geomagnetic activity as do insurance claims.
4. We find no significant dependence of the claim frequencies statistically associated with geomagnetic activity on geomagnetic latitude.

For our study, we use a quantity that measures the rate of change of the geomagnetic field regardless of what drives that. Having established an impact of space weather on users of the electric power grid, a next step would be to see if it can be established what the relative importance of various drivers is (including variability in the ring current, electrojet, substorm dynamics and solar insolation of the rotating Earth), but that requires information on the times and locations of the impacts that is not available to us.

The claim data available to us do not allow a direct estimate of the financial impacts on industry of the malfunctioning equipment and the business interruptions attributable to such malfunctions: we do not have access to the specific policy conditions from which each individual claim originated, so we have no information on deductable amounts, whether (contingency) business interruptions were claimed or covered or were excluded from the policy, whether current value or replacement costs were covered, etc. Moreover, the full impact on society goes well beyond insured assets and business interruptions, of course, as business interruptions percolate through the complex of economic networks well outside of direct effects on the party submitting a claim. A sound assessment of the economic impact of space weather through the electrical power systems is a major challenge, but we can make a rough order-of-magnitude estimate based on existing other studies as follows.

The majority (59% in sample *B*) of the insurance claims studied here are explicitly attributed to “Misc.: electrical surge,” which are predominantly associated with quality or continuity of electrical power in the low-voltage distribution networks to which the electrical and electronic components are coupled. Many of the other stated causes (see section 2.1) may well be related to that, too, but we cannot be certain given the brevity of the attributions and the way in which these particular data are collected and recorded. Knowing that in most cases the damage on which the insurance claims are based is attributable to perturbations in the low-voltage distribution systems, however, suggests that we can look to a study that attempted to quantify the economic impact of such perturbations on society.

That study, performed for the Consortium for Electric Infrastructure to Support a Digital Society [*Lineweber and McNulty*, 2001], focused on the three sectors in the U.S. economy that are particularly influenced by electric power disturbances: the digital economy (including telecommunications), the continuous process manufacturing (including metals, chemicals, and paper), and the fabrication and essential services sector (which includes transportation and water and gas utilities). These three sectors contribute approximately 40% of the U.S. gross domestic product.

Lineweber and McNulty [2001] obtained information from a sampling of 985 out of a total of about 2 million businesses in these three sectors. The surveys assessed impact by “direct costing” by combining statistics on grid disturbances and estimates of costs of outage scenarios via questionnaires completed by business officials. Information was gathered on grid disturbances of any type or duration, thus resulting in a rather complete assessment of the economic impact. The resulting numbers were corrected for any later actions to make up for lost productivity (actions with their own types of benefits or costs).

For a typical year (excluding, for example, years with scheduled rolling blackouts due to chronic shortages in electric power supply), the total annual loss to outages in the sectors studied is estimated to be $46 billion and to power-quality phenomena almost $7 billion. Extrapolating from there to the impact on all businesses in the U.S. from all electric power disturbances results in impacts ranging from $119 billion/yr to $188 billion/yr (for about year 2000 economic conditions).

Combining the findings of that impact quantification of all problems associated with electrical power with our present study on insurance claims suggests that, for an average year, the economic impact of power-quality variations related to elevated geomagnetic activity may be a few percent of the total impact or several billion dollars annually. That very rough estimate obviously needs a rigorous follow up assessment, but its magnitude suggests that such a detailed, multidisciplinary study is well worth doing.

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