A 100-year Geoelectric Hazard Analysis for the U.S. High-Voltage Power Grid

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Abstract

A once-per-century geoelectric hazard map is created for the U.S. high-voltage power grid. A statistical extrapolation from 31 years of magnetic field measurements is made by identifying 84 geomagnetic storms with the Kp and Dst indices. Data from 24 geomagnetic observatories, 1,079 magnetotelluric survey sites, and 17,258 transmission lines are utilized to perform a geoelectric hazard analysis with the most comprehensive data publicly available. With these data, we estimate once-per-century geoelectric fields at the magnetotelluric survey sites and calculate the theoretical voltages within transmission lines in the U.S. power grid. Once-per-century geoelectric field strengths span more than 3 orders of magnitude from a minimum of 0.02 V/km at a site in Idaho to a maximum of 27.2 V/km at a site in Maine, with nearly 30% of the surveyed land area exceeding 1 V/km. We show the influence that geoelectric field polarization has on geoelectric hazards when viewed on a power transmission network. The calculated transmission line voltages can approach 1,000 V in some transmission lines. Four regions in the United States with particularly notable geoelectric hazards are identified and discussed: the East Coast, Pacific Northwest, Upper Midwest, and the Denver metropolitan area.

1. Introduction

Geoelectric fields in the solid Earth are induced by external geomagnetic field variations, often associated with geomagnetic storms, passing through a complex Earth filter that is determined by the conductivity structure of Earth’s interior. These induced geoelectric fields give rise to anomalous quasi-static voltages across transmission lines that lead to so-called geomagnetically induced currents (GICs) within power transmission networks, which can cause operational interference and damage to critical infrastructure (e.g., Molinski, 2002; Piccinelli & Krausmann, 2014). One of the strongest geomagnetic storms to impact modern power transmission networks occurred in March 1989 when GICs caused the collapse of the Hydro-Québec power grid in Canada (e.g., Bolduc, 2002).

Historically, large geomagnetic storms have led to radio communication blackouts, fires in telegraph networks, and signaling issues along railways (e.g., Knipp et al., 2016; Love & Coïsson, 2016; Times, 1921; Tsurutani et al., 2003). However, these large storms occurred prior to the recent rapid growth in electricity distribution that is an essential part of our modern, technology-dependent society. This leads to a large uncertainty about what impacts an extreme geomagnetic storm would have on modern power distribution systems. An extremely large coronal mass ejection in 2012 missed Earth by a mere 9 days but led to speculation over the impacts it would have on society if it had been directed toward the Earth (e.g., Baker et al., 2013; Ngwira et al., 2013).

In this paper, we bring together long records of geomagnetic field time series, modern magnetotelluric survey measurements, and the most recent publicly available maps of high-voltage power transmission lines for the United States to produce hazard maps for an extreme, once-in-one-hundred-year geomagnetic storm. We advance previous U.S. hazard maps that were created with synthetic magnetic variation data (Love et al., 2016) by considering long time series of magnetic observatory data. We further build on the recent advances in regional hazard maps (e.g., Love et al., 2017; Love, Lucas, Bedrosian, et al., 2018; Love, Lucas, Kelbert, et al., 2018) by expanding the physical measurements between geomagnetic observatories with estimates of ionospheric current distributions that are then used to model ground-level magnetic disturbance (Rigler et al., 2019). Combining all of these advances, we present a once-per-century geoelectric hazard map for the U.S. high-voltage power grid.
2. Data Sources

All of the localities of the data sets used in this analysis are shown in Figure 1 and will be described in more detail in the following paragraphs. For the magnetic field, we use definitive data from geomagnetic observatories that are absolutely calibrated and that have been processed to remove spikes and offsets. The data are historical 1-min averages reported at discrete intervals collected by the U.S. Geological Survey (USGS) (Love & Finn, 2011; USGS, 1985) and Natural Resources Canada (NRCan; Newitt & Coles, 2007), which are available through the INTERMAGNET collaboration (Love & Chulliat, 2013). We have chosen observatories with long histories of stable operations and data that are digitally available between 1985 and 2015. The 1-s data record from observatories is much shorter than the 1-min data record; therefore, we restrict ourselves to the more than 30 years of 1-min data available to make 100-year hazard estimates. Individual storms have been investigated to determine the difference between 1-s and 1-min sampling on the hazard in the Pacific Northwest, where Love, Lucas, Kelbert, et al. (2018) found an increased hazard of 30% when using 10-s sampling rates for those specific storms, which is far less than site-to-site differences that will be discussed later in the paper. Table 1 lists the 24 observatories used in this analysis along with the corresponding start and end dates for the data used, which are also shown as gold stars in Figure 1.

In 2006 the National Science Foundation (NSF) EarthScope program commenced a magnetotelluric survey covering the United States on a grid with a quasi-regular 70-km station spacing (Schultz et al., 2006–2018). This program came to an end in 2018 with roughly the upper two thirds of the contiguous United States completed. For each location in the survey, a fluxgate magnetometer and a pair of electric dipoles are deployed to measure all three components of the magnetic field and two horizontal components of the electric field. The concurrent measurements of the geomagnetic field and geoelectric field can then be used to calculate a magnetotelluric impedance tensor as a function of frequency, $Z(\omega)$ (e.g., Egbert, 2007). Measurements at each survey site are typically conducted over several weeks to obtain sufficient data to estimate magnetotelluric impedance tensors at periods in excess of 10,000 s. Impedance tensors derived from the survey sites cover the range of periods from roughly 10 to 20,000 s with an estimated error that is generally smaller than 5% except at the longest periods (Schultz, 2010). The USGS performed a magnetotelluric survey in 2015 across the Florida Peninsula to supplement the NSF EarthScope program (Bedrosian et al., 2015). All of the data from these surveys have been publicly released through an online database (Kelbert et al., 2011). Each survey site has an associated quality rating (1–5) with it, and we have chosen to use all sites with a quality
Table 1

The 24 Geomagnetic Observatories Used in This Analysis and Their Respective Starting and Ending Dates

| Observatories (IAGA codes) | Latitude | Longitude | Distance to closest observatory (km) | Start date | End date |
|----------------------------|----------|-----------|--------------------------------------|------------|----------|
| USGS BOU                   | 40.14    | −105.24   | 1,013.14                            | 1985-01-01 | 2015-12-31 |
| BRW                        | 71.32    | −156.62   | 305.09                              | 1985-01-01 | 2015-12-31 |
| BSL                        | 30.35    | −89.64    | 1,082.83                            | 1986-04-18 | 2015-12-31 |
| CMO                        | 64.87    | −147.86   | 610.72                              | 1985-01-01 | 2015-12-31 |
| DED                        | 70.36    | −148.79   | 305.09                              | 2011-01-01 | 2015-12-31 |
| DLR                        | 29.30    | −100.80   | 1,001.28                            | 1985-01-01 | 2007-12-31 |
| FRD                        | 38.20    | −77.37    | 814.46                              | 1985-01-01 | 2015-12-31 |
| FRN                        | 37.09    | −119.72   | 986.57                              | 1985-01-01 | 2015-12-31 |
| GUA                        | 13.59    | 144.87    | 6,090.22                            | 1985-01-01 | 2015-12-31 |
| HON                        | 21.32    | −158.00   | 3,789.59                            | 1985-01-01 | 2015-12-31 |
| NEW                        | 48.26    | −117.12   | 465.67                              | 1985-01-01 | 2015-12-31 |
| SHU                        | 55.35    | −160.46   | 1,263.69                            | 2005-01-01 | 2015-12-31 |
| SIT                        | 57.06    | −135.33   | 1,097.21                            | 1985-01-01 | 2015-12-31 |
| SJG                        | 18.11    | −66.15    | 2,485.69                            | 1985-01-01 | 2015-12-31 |
| TUC                        | 32.17    | −110.73   | 986.57                              | 1985-01-01 | 2015-12-31 |
| NRCan BLC                  | 64.32    | −96.01    | 626.41                              | 1985-01-01 | 2015-12-31 |
| NRCan CBB                  | 69.12    | −105.03   | 663.86                              | 1985-01-01 | 2015-12-31 |
| NRCan FCC                  | 58.76    | −94.09    | 626.41                              | 1985-01-01 | 2015-12-31 |
| NRCan MEA                  | 54.62    | −113.35   | 752.87                              | 1985-01-01 | 2015-12-31 |
| NRCan OTT                  | 45.40    | −75.55    | 814.46                              | 1985-01-01 | 2015-12-31 |
| NRCan RES                  | 82.61    | −94.89    | 1,519.10                            | 1985-01-01 | 2015-12-31 |
| NRCan STJ                  | 47.59    | −52.68    | 1,761.25                            | 1985-01-01 | 2015-12-31 |
| NRCan VIC                  | 48.52    | −123.42   | 465.67                              | 1985-01-01 | 2015-12-31 |
| NRCan YKC                  | 62.48    | −114.48   | 852.96                              | 1985-01-01 | 2015-12-31 |

This leaves a total of 1,079 magnetotelluric survey sites that are used in this analysis (91.5% of the total sites), which are shown as blue circles in Figure 1.

Thousands of high-voltage transmission lines in the United States create a backbone for electricity transmission. Here, we restrict our study to calculating voltages set up within transmission lines by induced geoelectric fields. These voltages are generated by direct coupling of transmission lines to ground at substations; together with network topology and grid operating state, these voltages can be used to estimate the magnitude (in Amperes) of the GICs. The dynamic network topology, however, together with limited and often unavailable information on substation grounding resistances, renders the calculation of GICs at a national scale challenging at present. The locations of the high-voltage transmission lines are obtained from the open-access Department of Homeland Security website and contain the latitude and longitude for numerous points along each transmission line, here defined as the complex path between line junctions (substations). We consider all transmission lines that are identified as having a 100 kV or higher transmission voltage, a total of 17,258, which are shown as orange lines on Figure 1. We have chosen 100 kV as a threshold because voltages higher than this are primarily used for long-distance electricity transmission across the United States.

3. Spatial Interpolation of Geomagnetic Fields

The 24 geomagnetic observatories listed in Table 1 are spread across the North American continent, often with many thousands of kilometers separating the sites. We interpolate the geomagnetic field between measurements made at observatories to limit the impact of these large separation distances. To generate a consistent representation of magnetic field disturbance at locations between the sparse distribution of observatories, we fit an ionospheric equivalent current system, specifically, a spherical elementary current system...
Figure 2. The measured magnetic field disturbance (black) at the Boulder geomagnetic observatory (BOU) during the March 1989 geomagnetic storm and the leave-one-out SECS estimated magnetic field at BOU (blue) and the difference of the two signals (red). The time is in UTC and the X/Y labels are the North/East directions in geographic coordinates. The SECS estimates show good agreement at the beginning of the time series, but obvious regional enhancements occurred during the early hours of 14 March as shown by the misfits during the main phase of the storm. There is a data gap at the geomagnetic observatory toward the end of 14 March, highlighted in gray, while generating a prediction with a SECS still predicts some large-scale features during that time period.

(SECS; Amm, 1997; Amm & Viljanen, 1999), to the magnetic field observations at each instant in time. The SECS method provides the physical constraint that the magnetic field is divergence free across the entire Earth (Amm, 1997; Amm & Viljanen, 1999). The generated SECS at each instant in time is then used to estimate the ground-level magnetic disturbance at any location between the observatories (e.g., McLay & Beggan, 2010; Rigler et al., 2019; Weygand et al., 2011).

To give an indication of what this method produces and the benefits and limitations of using it, we have performed a leave-one-out analysis with the Boulder magnetic observatory (BOU) during the March 1989 geomagnetic storm. Figure 2 shows the measured magnetic field (black) at the Boulder geomagnetic observatory (Love et al., 2015) and the leave-one-out prediction of the magnetic field with SECS (blue). On 13 March, with storm sudden commencement occurring at 01:28 (Allen et al., 1989), the SECS field shows a generally good prediction of the measured magnetic field. Over this period of time, the geomagnetic field is likely of sufficiently large scale to be accurately predicted by the SECS fits to the observatories (even without BOU; Marsal et al., 2017). In contrast, near the beginning of 14 March, during the main phase of the storm, an obvious misfit between the predicted and measured fields indicates a regional disturbance that is not well predicted by the SECS without BOU. This regional difference could be due to a lack of magnetic field measurements to constrain the auroral oval that has dipped to midlatitudes during this large disturbance. The SECS method is not causing the misfit, but, rather, observatory measurements within the highly disturbed region are lacking to constrain the estimation. Finally, toward the end of 14 March, when the storm had quieted down, the observatory data have a gap that is highlighted in gray, while the SECS method is still able to make a prediction of the large-scale features during this time.

The time series in Figure 2 shows the usefulness of the SECS method in that it can predict the large-scale features of the magnetic field with a physically consistent set of basis functions. However, at the same time, it shows the limitations of this method by failing to capture the localized features that need a more dense set of measurements from geomagnetic observatories. Regardless, as we are far from the ideal of having a
4. Geoelectric Fields During a Geomagnetic Storm

During a geomagnetic storm, the geomagnetic field disturbance induces a geoelectric field within the Earth. The local geoelectric field can be related to the geomagnetic disturbance through a complex-valued Earth impedance tensor, which is dependent on the local geologic structure of the region. Here, we expand upon the 3-D geoelectric field calculations that were used in Lucas et al. (2018) for the mid-Atlantic region by using a spatially variable magnetic field and applying it across the entire United States. To summarize the entire process for a single storm, we first detrend the magnetic field observatory data and use the magnetic field disturbance from all observatories with data during the given time period to generate a SECS that was described in section 3. The SECS is then used to predict the magnetic field at each of the 1,079 magnetotelluric sites. The magnetic field time series at each site, $B_{site}(t)$, is then convolved with the 3-D site magnetotelluric impedance, $Z_{site}$, to calculate a geoelectric field time series at each site, $E_{site}(t)$ (Love et al., 2017; Love, Lucas, Kelbert, et al., 2018; Lucas et al., 2018),

$$E_{site}(t) = Z_{site} * B_{site}(t).$$

The impedance tensor at magnetotelluric site COP24 is of high quality (with a site quality rating of 5 out of 5; Kelbert, 2019) and situated close to the Boulder geomagnetic observatory, which we leverage to conduct the same leave-one-out analysis for the March 1989 storm as we did for the geomagnetic disturbances. The time-varying geoelectric field at the site, $E_{COP24}(t)$, estimated from geomagnetic excitations determined with and without observatory BOU, is shown in Figure 3 and highlights that high-frequency differences in geoelectric-field estimates can be of the same order of magnitude as the signal itself even though their maximum amplitudes over the duration of the March 1989 geomagnetic storm are similar.
Figure 4. A leave-one-out analysis for the SECS method centered around four individual observatories indicated with a gold star. (a) Newport (NEW), (b) Boulder (BOU), (c) Ottawa (OTT), and (d) Fredericksburg (FRD) showing the ratio of maximum geoelectric fields (leave-one-out divided by the estimate with all data) for every magnetotelluric site. Using all observatories, the maximum-predicted geoelectric field spans 3 orders of magnitude from a minimum of 0.02 V/km to a maximum of 22.4 V/km. The ratio of estimated geoelectric fields with a leave-one-out analysis to the estimate with all observatories shows that leaving an observatory out of the analysis can lead to ratios in the predicted maximums that are generally less than a factor of 2, far lower than the 3 orders of magnitude that is seen in regions across the United States. The differences are unsurprisingly centered around the observatory that was left out of the analysis and fall off with distance from the observatory that was left out, indicating the largest errors are centered around the missing data.

We have shown time series of geomagnetic and geoelectric fields at an individual site and the detailed differences that arise in the time series when comparing actual data to the leave-one-out analysis. We now apply those same techniques to all of the 1079 magnetotelluric stations across the United States to produce a unique time series at each site for both the SECS method and the SECS method without a specific magnetic observatory, producing 2,158 separate time series for each leave-one-out analysis. For each time series, we then select the maximum magnitude of the geoelectric field during the storm for further analysis. Figure 4 shows the ratios of maximum geoelectric fields with the leave-one-out analysis (the SECS estimates without the observatory divided by the SECS estimate with all observatories) for each magnetotelluric site and for the following four observatories: (a) Newport (NEW), (b) Boulder (BOU), (c) Ottawa (OTT), and (d) Fredericksburg (FRD).

The maximum ratios arising from the leave-one-out analysis are close to a factor of 2, which are, unsurprisingly, centered around the observatory that was left out of the analysis. For the 1989 storm, the maximum predicted geoelectric field at all of the magnetotelluric sites, using all observatories in the SECS method, is 22.4 V/km at a site in Maine (MEE62), while the minimum predicted geoelectric field is 0.02 V/km at a site in Idaho (IDK15).

These four observatories were chosen for a leave-one-out analysis because they span the boundary of the EarthScope magnetotelluric survey in the United States. Leaving an observatory out of the analysis creates large interpolation distances between the remaining observatories. These may seem like large errors, with
ratios of up to a factor of 2, but these ratios are much smaller than the 3 orders of magnitude span in geoelectric amplitudes that arises from site-to-site variability. This means that the errors introduced from the SECS method are far less severe than using the incorrect impedance, which could introduce orders of magnitude errors into the calculations (e.g., Bedrosian & Love, 2015; Love et al., 2016, 2017; Love, Lucas, Bedrosian, et al., 2018; Love, Lucas, Kelbert, et al., 2018).

5. Transmission Line Voltages Induced During a Geomagnetic Storm

The geospatial distribution of the geoelectric vectors can be combined with the geometry of the transmission grid to calculate transmission line voltages, $V_{\text{line}}$, for every transmission line following a Delaunay integration method (e.g., Bonner & Schultz, 2017; Lucas et al., 2018) that accounts for the polarization of the electric field along the transmission line. The Delaunay method computes the electric field at the numerous points specified along the transmission line, $E_{\text{line}}$, by taking into account weights based on the distance from the point to three surrounding site electric fields, $E_{\text{sites}}$, and then integrates the electric field along the geometry of the transmission line, $G$,

$$V_{\text{line}}(t) = \int_G E_{\text{line}} \cdot dl.$$

The voltages can be used as the input to power grid models that calculate GICs, which account for all of the connections and resistances within the power transmission network (e.g., Boteler & Pirjola, 1998, 2017; Boteler et al., 1998; Horton et al., 2012; Overbye et al., 2013; Sun & Balch, 2019; Viljanen & Pirjola, 1994). The transmission line voltage is highly dependent on the length of the transmission lines due to the integration of the electric field along the entire complex path of the line between two junctions. This can potentially obscure the hazard that results from the geoelectric fields. To better illustrate the hazard of interest, we divide these voltages by the length of the transmission line to obtain an average electric field for every transmission line, $E_{\text{line}}$,

$$E_{\text{line}}(t) = \frac{V_{\text{line}}(t)}{L_{\text{line}}},$$

where the length of the line, $L_{\text{line}}$, is equal to the integral of the transmission line path, $L_{\text{line}} = \int G dl$.

The Delaunay spatial integration is repeated at each instant in time during a storm to produce a time series of the line-averaged electric field, $E_{\text{line}}(t)$, for every transmission line. The results from a single snapshot of the historic March 1989 geomagnetic storm time series are shown in Figure 5. The magnetic field at each magnetotelluric site seen in Figure 5a shows large-scale features between the magnetic observatories, while the geoelectric field in Figure 5b shows considerable small-scale structure and has large variability in the vector directions that are introduced by the convolution of the magnetic field with the local site impedance. Figure 5c takes the spatial distribution of the geoelectric fields into account and shows the voltage in the transmission lines, which is proportional to the length of the transmission line. Thus, long transmission lines are highlighted in the figure even where small geoelectric fields are present (e.g., western Montana). Finally, Figure 5d accounts for the varying lengths of transmission lines by incorporating the lengths of the lines to show the line-averaged electric field, $\bar{E}$, for each transmission line. Here, we use this information as a basis for statistical hazard analysis.

6. Geomagnetic Storm Statistics

Thus far, we have only been discussing results from a single geomagnetic storm, the March 1989 event. However, regulators and insurance entities are often interested in a once-per-century event or some more extreme case than that for which we currently have data (e.g., Federal Energy Regulatory Commission, 2013; National Science and Technology Council, 2015). Therefore, we apply statistical techniques to calculate a statistically probable outcome from the 31 years worth of historical data that we have.

First, we identify geomagnetic storms, times of heightened geomagnetic activity, in the data sets. To classify a time period as being a geomagnetic storm, we utilize the Kyoto Dst index (Sugiura & Kamei, 1991) and the Kp index (Bartels, 1949). In this work, we use both indices to identify storms because a large storm on one index could be relatively weak on the other index. For example, a large auroral enhancement could be
Figure 5. The (a) geomagnetic field, (b) geoelectric field, (c) geoelectrically induced voltage, and (d) average line electric field at 01:00 UTC on 14 March 1989. The geomagnetic field in (a) shows large-scale structures across the United States (with observatory measurements in green), while the geoelectric field (b) shows more spatial granularity with the vectors pointing in many different directions. The geoelectrically induced voltage in (c) integrates the spatial distribution of geoelectric fields with the transmission line paths between junctions in the power grid, while (d) shows the line-averaged electric field that takes into account the length of transmission lines.

registered at high latitudes, which would lead to a high Kp value, while the low-latitude Dst index could remain relatively low for that same storm.

Sifting through the data, we select the minimum Dst and classify the preceding and following 1.5 days from this time as a geomagnetic storm. This procedure is iterated to identify the next minimum Dst that is not already classified as a storm until all of the Dst values smaller than $-140 \text{ nT}$ have been selected. The same procedure is repeated with the Kp index to also mark all time periods plus or minus 1.5 days when Kp is

Figure 6. The (a) Kp index and (b) Dst index from 1985 to 2015 with 84 geomagnetic storms identified in orange. The red lines show the cutoff for storm identification, with (a) Kp great than or equal to 8 or (b) Dst less than $-140 \text{ nT}$.
greater than or equal to 8. The full storm criteria is, therefore, whenever Dst < −140 nT or Kp ≥ 8. This process identifies 92 disturbance periods that satisfy the aforementioned criteria between the years 1985 and 2015. If a strong disturbance lasts longer than 1.5 days, this procedure would classify these events as two separate storms. To account for this, if any storm times overlap, we combine the two storms together into one disturbance period, which can be longer than the 3-day period identified before. Merging the long-lasting storms reduces the total number of storms to 84 during the 31-year period of 1985–2015. Figure 6 shows the Kp index (a) and the Dst index (b) over these 31 years and highlights the storm times identified through this process in orange. Of the 84 identified storms, 44 satisfy both the Kp and Dst criteria, 5 satisfy only the Kp criteria, and 35 satisfy only the Dst criteria.

These 84 storms are the basis for our extrapolation to the strength of a more extreme, say, once-in-one-hundred year, geomagnetic storm. For each storm, the maximum absolute value of the magnetic field, $B_{\text{site}}(t)$, electric field, $E_{\text{site}}(t)$, and voltage, $V_{\text{line}}(t)$, are used to calculate exceedance probabilities. For this analysis, we make the physical assumption that the maximum storm-time values result from numerous multiplicative processes in the driving solar wind parameters. This assumption leads us to fit a lognormal statistical distribution to the list of peak storm-time values from all sites and transmission lines, which follows from previous hazard analyses (Love et al., 2017; Love, Lucas, Bedrosian, et al., 2018; Love, Lucas, Kelbert, et al., 2018). For fitting the distributions, we use modified forms of maximum likelihood estimators that have been designed to test whether the tails of empirical distributions are fit by a power law or, in this case, a lognormal distribution (e.g., Alstott et al., 2014; Clauset et al., 2009).

Maximum values of the geoelectric field during the 84 geomagnetic storms are shown as a complementary cumulative distribution function for three magnetotelluric stations in Figure 7 with two different magnetic field inputs, a SECS prediction with all of the data (black) and a leave-one-out SECS prediction without the BOU observatory data (blue). The solid lines are lognormal fits to the data, and the circles on the x axis indicate the once-per-century estimate. Magnetotelluric sites COP24 and COP25 are located near the BOU observatory and separated by less than 70 km but have nearly 2 orders of magnitude difference in their predicted once-per-century geoelectric fields, which is most heavily influenced by the local electrical impedance of the sites. The factor of 2 errors that arise from the leave-one-out analysis are far lower than the errors that can be introduced through the use of an incorrect local impedance. The maximum once-per-century geoelectric field is at a site in Maine (MEE62) that is far removed from the BOU observatory, where the leave-one-out analysis has a negligible effect on the predictions at this site. This analysis gives us confidence in making once-per-century estimates where magnetotelluric surveys have been completed and in regions with stable long-term measurements of the magnetic field.

### 7. Extreme Geomagnetic Storm Hazard Maps

We define an extreme geomagnetic storm as an event that is expected to occur on average once per century. Here, we do not simulate or model an individual extreme event, but rather, we statistically extrapolate data to an extreme event based on long time series of historical events using the methods described earlier. For this analysis, we follow the same bootstrap with replacement (Efron & Tibshirani, 1994) procedure outlined in Love et al. (2017). The extreme values we present are the median values from a 100-sample bootstrap analysis. The bootstrap samples also provide a 95% confidence interval for each magnetotelluric survey site centered around the median, $m$, with an average confidence interval over all survey sites of [0.74 m, $m$, 1.37 m]. The confidence interval for the magnetotelluric sites is again less than a factor of 2, which is much smaller than the site-to-site variability in extreme values.
Figure 8. The once-per-century extreme geomagnetic storm event predictions of the geoelectric field at magnetotelluric sites in the United States. Regions of both high and low hazard are present throughout the country, which shows the geoelectric complexity of the United States.

Figure 8 shows the estimated once-per-century values of the geoelectric field at the 1,079 magnetotelluric sites spread across the United States. Regional investigations close to geomagnetic observatories have previously shown the large influence that geology plays in determining geoelectric hazards in small regions (e.g., Love et al., 2017; Love, Lucas, Bedrosian, et al., 2018; Love, Lucas, Kelbert, et al., 2018). We now expand that view to the entire United States and can see how variable the geoelectric hazards are across the nation.

The largest estimated once-per-century geoelectric field is 27.2 V/km at a site located in Maine (MEE62), while the lowest estimated once-per-century geoelectric field is 0.02 V/km at a site located in Idaho (IDK15). That is more than 3 orders of magnitude variation in geoelectric field that spans the entire country. Across the upper two thirds of the United States that has been surveyed, estimated geoelectric fields for a once-per-century geomagnetic storm are predicted to exceed 1 V/km at 322 of the 1079 magnetotelluric sites, nearly 30% of the surveyed land area in the United States.

The once-per-century transmission line voltage (a) and transmission line electric field (b) are shown on the U.S. high-voltage power transmission network in Figure 9. It is worth noting that this is not a simple reprojection of the maximum geoelectric fields seen in Figure 8 but, rather, time series and extrapolations are independently calculated for all 17,258 transmission lines. These once-per-century transmission line hazards are for the current transmission line geometries. If the transmission line paths are changed or new transmission lines are added to the network, the hazard map would need to be updated accordingly.

In the eastern United States, there is a particularly high hazard region just east of the Appalachian Mountains that trends northeast-southwest and extends from Maine to Georgia (Kelbert et al., 2019). This area of high hazard between the Atlantic Coastal Plain and the Appalachian Mountains is associated with an anomalous coast-parallel resistor within the upper mantle (Murphy & Egbert, 2017) and is in stark contrast to areas of relatively low hazard on either side of it. This region highlights the important role that the solid Earth plays in generating geoelectric hazards and has been discussed in a previous article that describes the polarizations of the geoelectric field vectors of the region (Love, Lucas, Bedrosian, et al., 2018).

In Figure 9, we show how the polarization and amplitude of geoelectric fields conspire with the transmission line network geometry to produce a representation of the geoelectric hazard for power system and network operators.

In the northwest United States, several geoelectric hazard analyses have been conducted with the nearby Victoria (VIC) and Newport (NEW) geomagnetic observatories (e.g., Gannon et al., 2017; Love, Lucas, Kelbert, et al., 2018), but separate extrapolation techniques have been applied to analyze a potential extreme event. Gannon et al. (2017) scaled the 1989 Ottawa magnetic observatory time series, whereas Love, Lucas,
Figure 9. The once-per-century extreme geomagnetic storm event predictions of the (a) transmission line voltage and (b) average transmission line electric field, $\bar{E}$. This analysis shows how the polarization direction and amplitude of the geoelectric field impact the transmission lines in the United States. Particularly high hazard regions are seen up and down the Eastern Seaboard and in the Upper Midwest, consistent with Bedrosian and Love (2015) and Love, Lucas, Bedrosian, et al. (2018). A hotspot can be seen around the Denver metropolitan of Colorado, which should be interpreted with caution, and is analyzed further in Figure 10 and the associated discussion.

Kelbert, et al. (2018) generated a long time series and used a statistical extrapolation method equivalent to that employed in this paper. The northwest region does not produce the large amplitudes seen in the eastern United States, but the region reveals how polarization of the electric fields produce more pronounced geoelectric hazards along the east-west transmission lines. Detailed three-dimensional magnetotelluric inversions of the Pacific Northwest region have imaged considerable spatial variability in the Earth’s conductivity structure, which is heavily influenced by conductive partial melt beneath the Cascades volcanic arc and the adjacent resistive Siletz terrane (e.g., Bedrosian & Feucht, 2014; Meqbel et al., 2014). The directionality of these geoelectric hazards is only observed because we are utilizing the full 3-D magnetotelluric tensors.

The next region of interest that we draw attention to is in the Upper Midwest, primarily located in the states near the United States-Canada border (the Dakotas, Minnesota, and Wisconsin). This region is located at a high geomagnetic latitude and is also underlain by crystalline rocks of the Superior Craton, part of the ancient core of North America. These rocks are highly resistive (Bedrosian, 2016; Yang et al., 2015), creating a large region of high geoelectric hazard. Most of the transmission lines in the region located in northwestern Minnesota have an average once-per-century transmission line electric field in excess of 5 V/km. This region is additionally full of long transmission lines that connect geographically sparse population centers that could conspire to create an area particularly susceptible to GICs within the power grid.
Figure 10. The maximum (a) transmission line voltage and (b) average transmission line electric field, $\bar{E}$, during the March 1989 geomagnetic storm with all survey sites centered on Denver, Colorado. Panels (c) and (d) are the same as (a) and (b) but leave out survey site COP24 from the hazard analysis. Colored circles indicate the maximum electric field at each survey site during the 1989 storm. Leaving survey site COP24 out of the analysis shows a reduction in the hazard around the Denver metropolitan area.

The final region of interest is the Wyoming and Colorado high hazard region. There are several survey sites in Wyoming that have large geoelectric hazards (>1 V/km), seen in Figure 8, arising from the highly resistive Wyoming Craton. However, when the geoelectric fields are coupled with the transmission lines, these high hazard areas are not as apparent due to the sparsity of transmission lines through Wyoming. On the other hand, in the Denver metropolitan area, only a few large geoelectric field amplitude survey sites surround it, but due to the density of high-voltage transmission lines, the hazard near Denver shows itself very clearly in Figure 9.

Here, we conduct a leave-one-out analysis with survey site COP24 to show the influence that survey site placement has on the subsequent hazard analysis. Figure 10 shows the maximum transmission line voltage and average transmission line electric field surrounding Denver, Colorado, during the March 1989 storm with all survey sites (a and b) and the same analysis while leaving survey site COP24 out of the analysis (c and d). Geoelectric hazard for the city of Denver is considerably reduced when COP24 is left out of the analysis.

This analysis highlights the limited spatial resolution of the sparse EarthScope station spacing in areas of geologic complexity. The Denver metropolitan area is situated over the conductive Denver Basin just east of the resistive Rocky Mountains (Feucht et al., 2017). While the majority of transmission lines in the region lie within the Denver Basin, the nearest MT station, COP24, sits atop the Rocky Mountains. Due to its proximity, the large peak electric field at this resistive site (Figure 8) has the highest weight during the Delaunay
spatial integration and thus strongly influences the resulting hazard in the Denver area (Figure 10). Generally speaking, transmission lines that are located within a conductive (resistive) region but whose nearest MT site falls in an adjacent resistive (conducting) region will tend to over (under) estimate the true hazard. Such situations are likely to arise where abrupt conductivity contrasts are located near major population centers and should be the focus of more detailed magnetotelluric surveys, which can map out in greater detail high and low hazards within the region.

8. Conclusion

In this work, we have presented a new once-per-century extreme event hazard analysis for geoelectric fields at magnetotelluric survey sites and voltages in transmission lines across the United States. The analysis was done in an empirical fashion, using historical data from long-standing geomagnetic observatories and magnetotelluric data from a large-scale field campaign that has spanned the past 15 years. The combination of these high-quality data sets has elucidated several distinct high-hazard regions: just east of the Appalachian Mountains, in the Upper Midwest, and within the Pacific Northwest. These regions highlight that although the magnetic field variations drive induction in the solid Earth, it is just as important to characterize the solid Earth appropriately in order to calculate geoelectric fields for hazard analysis.

The North American Electric Reliability Corporation (NERC) has historically utilized roughly drawn physiographic one-dimensional conductivity regions (Fernberg, 2012) combined with magnetic latitude scaling factors to create standards that power companies must meet for once-per-century geoelectric hazards (North American Electric Reliability Corporation, 2013, 2016). There are often significant discrepancies between the estimated geoelectric fields using magnetotelluric surveys and the identified physiographic regions (e.g., Cuttler et al., 2018). The magnetotelluric survey data used in this analysis could be further utilized to inform future geomagnetic hazard standards. Presently, it is difficult for researchers to access data on connections and resistances of transmission lines within the U.S. power transmission network due to the sensitive nature of the information. This knowledge is critical, however, to make realistic estimates of GICs within the power grid. This is an obvious next step for geomagnetic hazard research within the United States.

Another future avenue of research could be to utilize conductivity models created through magnetotel-
laric data inversion. The inverse models combine data from the surveys along with physical constraints to solve for subsurface conductivity structures that could enhance the empirical data by adding additional forward-modeled impedance information between the survey sites. Generally, these models are run for local regions (e.g., Bedrosian, 2016; Meqbel et al., 2014; Murphy & Egbert, 2017), but recent progress extends and combines these regional models to cover the entire United States (Kelbert et al., 2019), which could prove useful for future geomagnetic hazard work.

The U.S. hazard map shown in Figure 9 shows considerable granularity in the predicted voltages and line-averaged electric field, $E$, and highlights the importance of using magnetotelluric surveys to inform hazard analyses. Our analysis identifies regions of both higher and lower hazard than the 100-year values using the NERC benchmark storm and calculated using the physiographic 1-D regions. It also motivates higher density MT surveys in regions where major conductivity contrasts, as indicated by abrupt changes in extreme electric field amplitude (Figure 8), lie close to major population centers. This work can be used to inform future standards for geomagnetic hazard analysis and can be utilized by utility companies to identify the portions of their grid most susceptible to geomagnetic hazards.

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