Part I
Space Weather

1
An Introduction to Geomagnetically Induced Currents

Chigomezyo M. Ngwira[1,2,3] **and Antti A. Pulkkinen**[2]

ABSTRACT

Earth-directed space weather is a serious concern that is recognized as one of the top priority problems in today's society. Space weather-driven geomagnetically induced currents (GICs) can disrupt operation of extended electrically conducting technological systems. This threat to strategic technological assets, like power grids, oil and gas pipelines, and communication networks, has rekindled interest in extreme space weather. To improve national preparedness, it is critical that we understand the physical processes related to extreme events in order to address key national and international objectives. This paper serves to provide a basic introduction to space weather and GICs, and highlights some of the major science challenges the GIC community continues to face.

Key Points

- Geomagnetically induced currents (GICs) is a space weather-driven phenomena.
- It is a threat to strategic technological assets, such as power grids, oil and gas pipelines, and communication networks.
- This paper serves to provide basic introduction on space weather and GICs, and the major science challenges the GIC community continues to face.

1.1. INTRODUCTION

Space weather is a serious natural threat to national security, and is recognized as one of the top priority problems today. The term "space weather" generally refers to dynamic conditions on the Sun, in the solar wind, and in the near-Earth space environment that can influence the performance of man-made technology, and can also affect human health and activities. Space weather is a multi-faceted phenomenon, thus the scientific community is faced with a challenge to better understand this natural hazard in order to enhance preparedness.

Geomagnetically induced currents (GICs), a space weather-driven phenomena, have received increased international policy, science, industry, and public interest. GICs flowing on ground-based electrically conducting systems can disrupt operation of critical infrastructure such as power grids, pipelines, telecommunication cables, and railway systems (e.g., Barlow, 1849; Davidson, 1940; Boteler and Jansen van Beek, 1999; Molinski et al., 2000; Pirjola, 2000; Pulkkinen et al., 2001; Eroshenko et al., 2010, and references therein). The majority of community efforts focus on extreme forms of space weather which not only have severe impact on our technology and human space travel, but also challenge our understanding of the space weather phenomena.

Scientific investigations are critical for understanding the basic physics and predicting the potential impact of extreme space weather. Public opinions on the topic of extreme space weather include wide ranging views. This

[1] *Department of Physics, The Catholic University of America, Washington, DC, USA*

[2] *Goddard Space Flight Center, Space Weather Laboratory, National Aeronautics and Space Administration, Greenbelt, MD, USA*

[3] *Now at Atmospheric and Space Technology Research Associates, Louisville, CO, USA*

Geomagnetically Induced Currents from the Sun to the Power Grid, Geophysical Monograph 244, First Edition.
Edited by Jennifer L. Gannon, Andrei Swidinsky, and Zhonghua Xu.

chapter provides a high-level summary of space weather and GICs. While some of the topics touched on cover a broad range of space weather domains, the discussions are oriented/biased towards the geophysical facet of GICs. For more insight on specific GIC aspects, the reader is urged to consult other sections of this volume.

1.2. THE SPACE WEATHER CHAIN

The Sun is the primary source of all space weather in the heliosphere. Sudden, violent eruptions of solar material from the Sun's atmosphere (the corona) called coronal mass ejections (CMEs), mark the beginning of major space weather events that eventually produce geomagnetic storms (disturbances) in the Earth's upper atmosphere. The Sun's activity is closely governed by the solar activity cycle, which has an average length of about 11 years. The cycle is defined by the number of visible active sunspots on the solar surface.

During solar maximum period when solar activity is high, the Sun can launch multiple CMEs towards Earth per day. A CME can be perceived as a cloud of plasma with the solar magnetic field known as the interplanetary magnetic field (IMF) embedded within it. Upon arriving at Earth, CMEs interact with the magnetosphere, a low-density partially ionized region around the upper atmosphere dominated by Earth's magnetic field. This interaction then triggers geomagnetic disturbances (GMDs) that lead to violent global magnetic field variations.

Orientation of the IMF varies with time and is important for interaction between the solar wind and the magnetosphere. Historically, the most intense disturbances have been recorded when the IMF Bz component, which is parallel to the solar rotation axis is oppositely directed to the Earth's magnetic field, a condition often referred to as a southward or negative IMF. Under southward condition, the coupling between the solar wind and the magnetosphere is enhanced and the transfer of CME plasma, momentum, and energy into the near-Earth space environment is increased. This enhanced energy flow stimulates a chain of complex processes within the magnetosphere–ionosphere (M–I) coupled system that regulate phenomena such as storm enhanced density, ionospheric irregularities, substorms, GICs, and auroral displays at high-latitude locations. In addition to these effects, space weather can also compromise the integrity and performance of our technology (Lanzerotti, 2001). Figure 1.1 highlights some of the key technological assets affected by space weather. Per the purpose of this book, we now focus our discussions exclusively on GICs that occur at the end of the space weather chain.

1.3. GEOMAGNETICALLY INDUCED CURRENTS

Overall the GIC problem can be categorized by a two-step approach (Pirjola, 2000, 2002a). In step 1, the geophysical facet involving the estimation of the geoelectric field based on M-I currents and the ground conductivity is considered. Step 1 is fundamentally a science piece and the connection to space weather phenomenon. In step 2 ("engineering piece") the current flowing on the system is calculated based on the estimated geoelectric field and detailed information about the particular ground system (e.g., Lehtinen and Pirjola, 1985; Molinski et al., 2000; Pirjola, 2000). In other words, the magnitude of GICs flowing through a network is generally determined by a combination of the horizontal surface geoelectric field, the geology, and elements of a given network (e.g., Molinski et al., 2000; Pirjola, 2000). We now briefly examine each of these three components.

1.3.1. The Geoelectric Field

The ground geoelectric field is the actual link to space weather through M-I processes. The primary feature of geomagnetic storms that pertains to GICs is the variation of electric currents in the M-I mode. Intense time-varying magnetosphere and ionosphere currents lead to rapid fluctuation of the geomagnetic field on the ground. Faraday's law of induction is the basic principle related to the flow of GICs on ground networks: a changing magnetic field induces an electric field through geomagnetic induction in the earth. In turn this electric field is responsible for currents that flow on ground conductors, such as power grids, according to Ohm's law $\mathbf{J} = \sigma\,\mathbf{E}$, where $\mathbf{J}$ is the current density, σ is the conductivity, and $\mathbf{E}$ is the electric field. The key processes for the creation and flow of GICs are illustrated in Figure 1.2.

Mathematically, Faraday's law of induction can be expressed as:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}. \tag{1.1}$$

Hence, the observed induced surface geoelectric field depends only on geomagnetic field variations and electromagnetic induction in the earth determined by the local geology (e.g., Pirjola, 1982). It follows, therefore, that this induced geoelectric field is completely independent of any technological system but is determined by M-I currents that are a function of space weather conditions and the ground conductivity, as discussed before.

To calculate the geoelectric field, a simple but illustrative 1-dimensional (1-D) model that assumes a plane wave propagating vertically downwards and a uniform

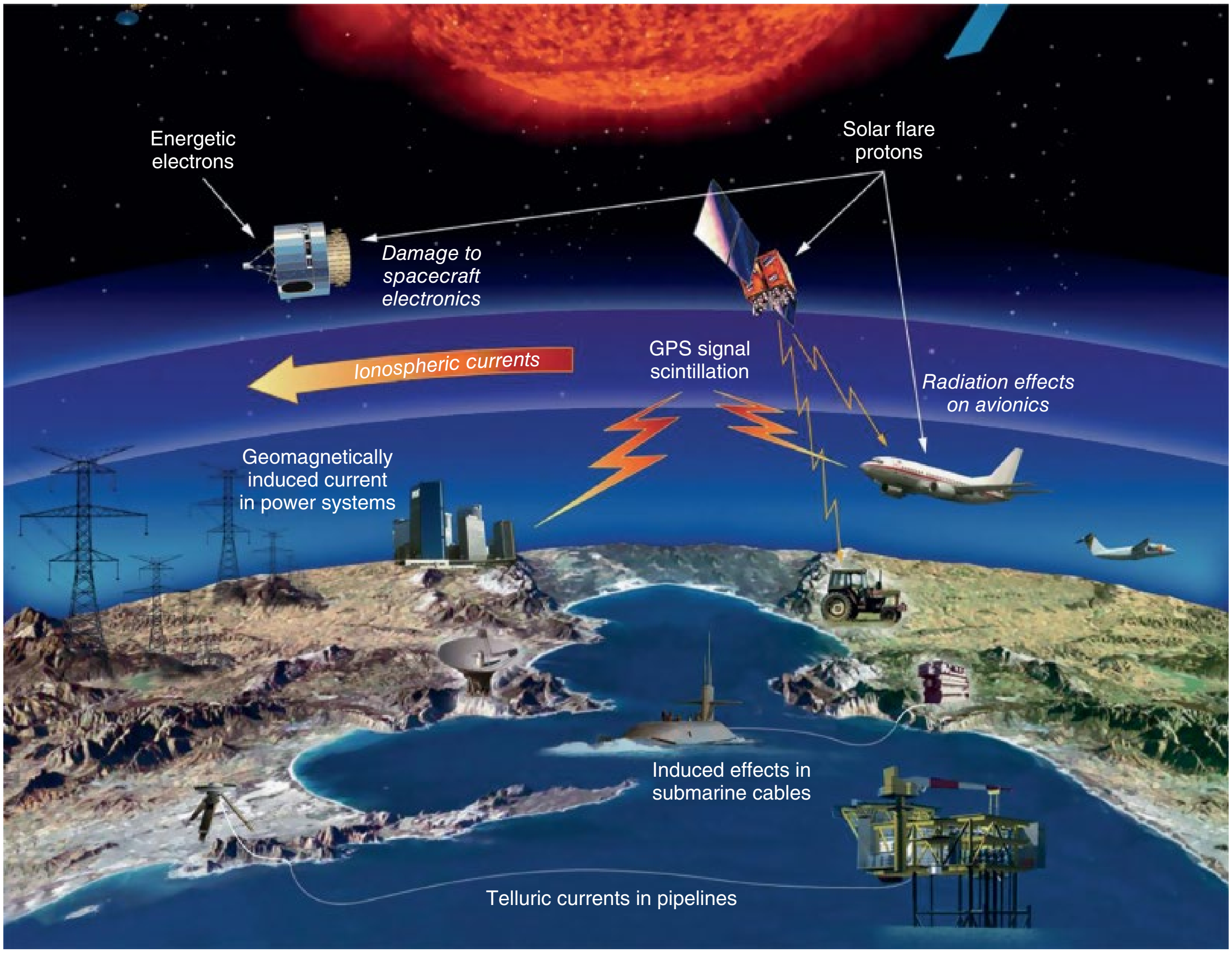

Figure 1.1 Technological infrastructure affected by space weather events at the Earth. Source: Courtesy of NASA: https://www.nasa.gov/mission_pages/rbsp/science/rbsp-spaceweather.html. (*See electronic version for color representation of this figure*.)

half-space earth with conductivity σ is traditionally used (Cagniard, 1953; Pirjola, 1982). The fields are all presumed to be horizontally uniform to simplify the modeling. Adopting a single frequency ω, then the geoelectric field E_x and E_y components can be deduced in terms of the perpendicular geomagnetic field component B_y and B_x as:

$$E_{x,y}(\omega) = \pm\sqrt{\frac{\omega}{\mu_0\sigma}}e^{\frac{i\pi}{4}}B_{y,x} \tag{1.2}$$

where μ_0 is permeability of free space, whereas the layer of air between the ground and the ionosphere is taken to have zero conductivity to limit significant attenuation of external electromagnetic fields. Since Equation (1.2) outlines the basis for deriving the Earth's conductivity using geoelectric and geomagnetic field measurements recorded at the surface, it is considered as the "basic equation of magnetotellurics."

1.3.2. Ground Conductivity

The Earth's geology is another key ingredient in the geomagnetic induction process. Penetration of the geomagnetic field into the Earth's crust is determined by the ground conductivity and frequency of the geomagnetic field variations. That is to say, the rate of attenuation of the induced electric field is dependent on the vertical distribution of the resistivity of the ground, and the period considered. Upper layers generate stronger influences at short periods, and deeper layers are more bearing at long periods, as depicted in Figure 1.3. It should be noted that the geomagnetic induction process is not fully discussed in the present paper. Here, we mostly emphasize the different conductivity models used for GIC applications. However, Part 2 of this volume is dedicated to discussions on geomagnetic induction.

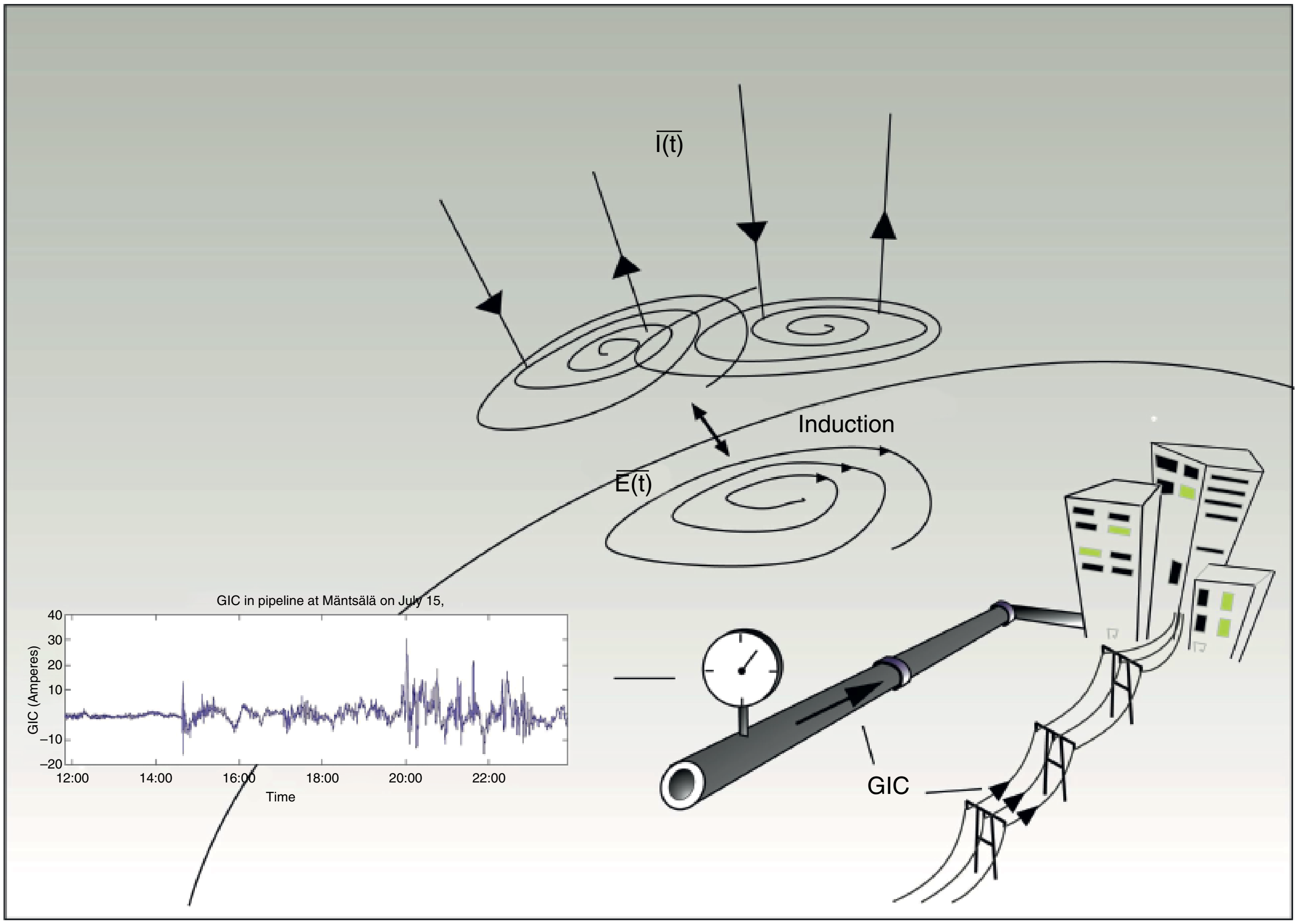

Figure 1.2 The basic principle for the generation of GICs: variations of the ionospheric currents ($I(t)$) generate an electric field ($E(t)$) through geomagnetic induction in the earth. This electric field then drives GICs on ground conductors. Also shown are actual GIC recordings from the Finnish natural gas pipeline. Image credit Wikipedia. (*See electronic version for color representation of this figure.*)

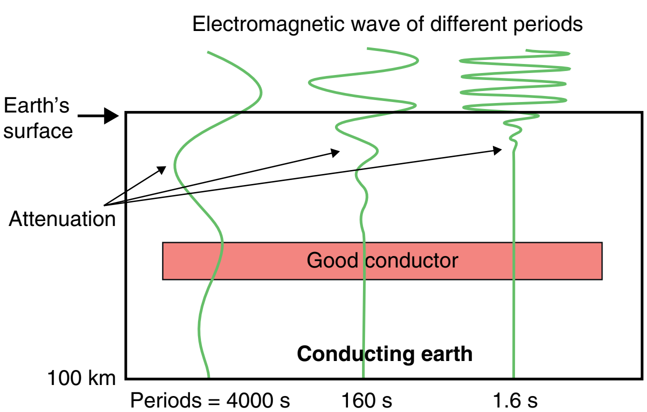

Figure 1.3 Depiction of electromagnetic signal penetration at different periods. Long-period signals penetrate deeper into the underground than short periods. Source: Adopted with modification: http://userpage.fu-berlin.de/mtag/MT-principles.html.

The "plane wave" approach described above is a firmly-established and simplest procedure for calculating GICs (see e.g., Pirjola, 2002a; Viljanen et al., 2006; Ngwira et al., 2008; Liu et al., 2009; da Silva Barbosa et al., 2015; Pulkkinen et al., 2015). This approach has also been applied to extreme events with much success (Wik et al., 2009; Pulkkinen et al., 2012; Ngwira et al., 2013, 2015). Historically, the most widely used ground structure has been the 1-D layered conductivity (where σ is depth dependent) applied to specific or given location (e.g., Boteler and Pirjola, 1998; Viljanen et al., 2006; Pulkkinen et al., 2007; Ngwira et al., 2008; Fernberg, 2012; Zhang et al., 2012). In the United Kingdom, however, past studies have calculated GICs flowing on the high-voltage transmission system using the "thin-sheet" approximation (Beamish et al., 2002; McKay, 2003; Thomson et al., 2005; Beggan, 2015). The thin-sheet approach uses a spatially varying conductance on a 2-D surface covering the region of interest, combined with a 1-D layered conductivity of upper lithosphere conductance (McKay, 2003). Thus, a thin-sheet model incorporates the effect of lateral conductivity variations on redistribution of regional currents induced elsewhere (e.g., oceans or shelf seas).

Several recent studies emphasize the use of 3-D conductivity that more accurately represent the true 3-D earth response (e.g., Love, 2012; Bonner IV and Schultz, 2017; Kelbert et al., 2017, and references therein). Unfortunately, these 3-D conductivity models are not readily available in many areas, thus their application is quite limited. In the United States, data from magnetotelluric (MT) campaigns such as EarthScope USArray MT program (http://ds.iris.edu/spud/emtf) are improving the conductivity models (e.g., Schultz, 2009). So far, nearly 60% of the continental United States has already been covered [Adam Schultz, personal communication]. In Figure 1.4 is a map showing the locations and current status of the NSF-funded EarthScope USArray MT project.

With the development of 3-D ground models, one challenge is to pinpoint exactly when and where the 1-D case fails and the 3-D case becomes necessary for GIC purposes. This is partly due to the data limitation mentioned before but with more 3-D models becoming available, the picture is beginning to change. Take for instance the recent Mid-Atlantic region case study by Love et al. (2018). They estimate that geoelectric fields calculated from 3-D conductivity models could be a few orders of magnitude larger than the fields estimated from 1-D models. If indeed the 1-D models under-estimate the induced fields (the order of magnitude might vary), then this could raise significant concern for power system operators in affected regions. However, the actual impact of such fields on any system is a matter requiring more detailed analysis that consider all sides of the problem, including the coupling of space weather processes to the grid.

1.3.3. Engineering Considerations

Generally, information about the geoelectric field produced on the ground during GMD events is acquired as described above. Once this information is obtained, determining the level of GICs flowing through a given node for any ground system is relatively straightforward. The GIC can be calculated by considering the geoelectric field to be uniform in the near vicinity of the network using the expression

$$GIC(t) = aE_x(t) + bE_y(t) \tag{1.3}$$

where a and b are the network coefficients specific to each network node depending only on the resistance and geometrical composition of a system (Viljanen and Pirjola, 1994). This is a purely engineering task that requires a full description of the system under consideration, which is beyond the scope of this paper. Nevertheless, readers can turn to Lehtinen and Pirjola (1985) or Viljanen and Pirjola (1994), and more recently Boteler (2014), for more information concerning this procedure. In addition, Part 3 of this volume contains several discussions on GICs and the power system.

1.4. EXTREME EVENTS

While mild and moderate space weather is fairly "common," relatively speaking, it is often the extreme events that gather the most attention because they are "infrequent" but pose the highest risk. A truly extreme and rare space weather event could have produced large GICs that can seriously disrupt technology. Policy makers, the general public, industry, and the science community are all interested to know "how bad can space weather really get?" Recent policy action at the White House level in terms of development of the National Space Weather Strategy and National Space Weather Action Plan (SWAP) has sparked renewed interest on this topic (National Science and Technology Council, 2015a,b). It is worth noting at this point that goal 1 of the SWAP calls for extracting information about extreme 1-in-100 year geoelectric fields and theoretical maximums. While GICs are not the only space weather hazard highlighted in these policies, the phenomenon does play an important role in them. In this section, a general view of GICs, extreme events, and impact are covered.

1.4.1. General View of GIC Studies

Space weather is a global phenomenon, however, most notable effects tend to occur locally, that is, isolated area, as is the case for GICs. For this reason, many GIC studies focus on specific regions or networks. Nevertheless, there are several examples of studies that have a wider scope and provide a global snapshot of events (e.g., Pulkkinen et al., 2012; Ngwira et al., 2013, 2015; Fiori et al., 2014; Kataoka and Ngwira, 2016; Carter et al., 2016; Moldwin and Tsu, 2017; de Villiers et al., 2017; Barbosa et al., 2017; Oliveira et al., 2018, and references therein).

The largest number of GIC studies have come from high-latitude regions because of the proximity to the auroral zone (Pirjola, 1982; Lehtinen and Pirjola, 1985; Viljanen and Pirjola, 1994; Boteler et al., 1998; Boteler, 2001; Pulkkinen et al., 2001; Pirjola, 2002b,c; Pulkkinen et al., 2003; Trichtchenko and Boteler, 2004; Thomson et al., 2005; Viljanen et al., 2006; Wintoft, 2005; Wik et al., 2009; Myllys et al., 2014; Beggan, 2015; Ngwira et al., 2018a, and references therein). The most interesting

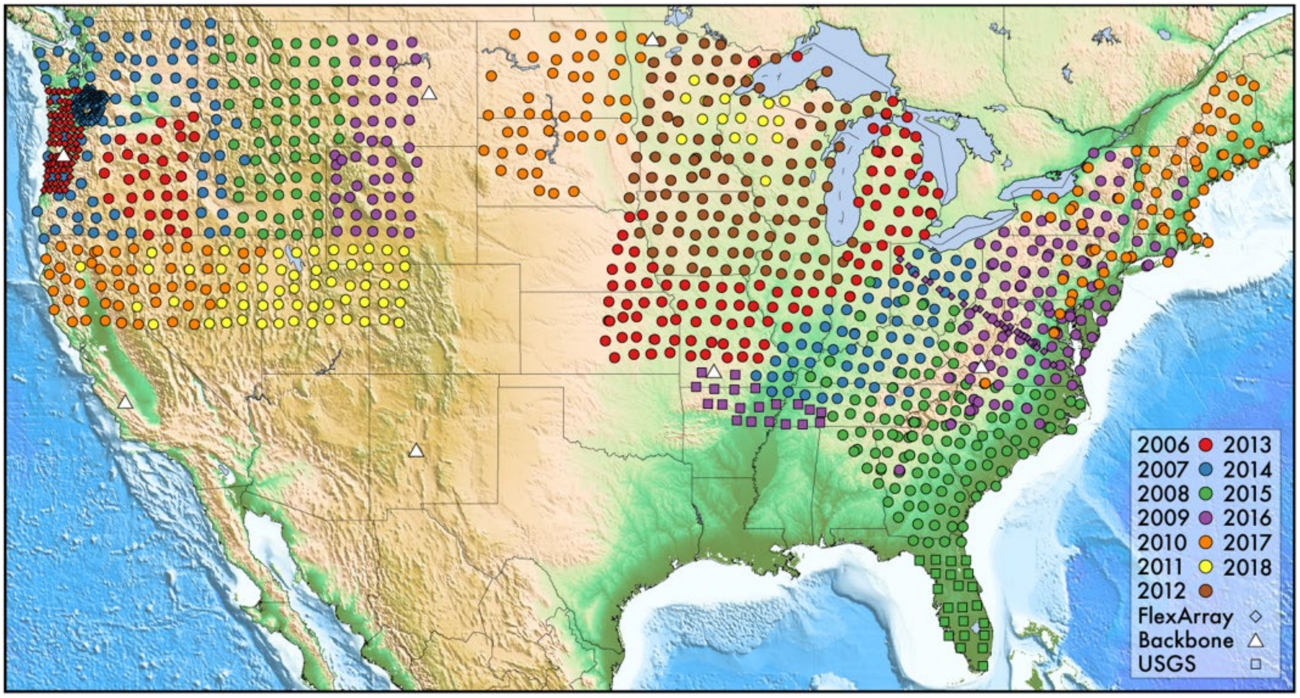

Figure 1.4 EarthScope USArray MT status map across the lower-48 U.S. The stations are spaced in an approximate 70 km grid. http://www.usarray.org/researchers/obs/magnetotelluric. (*See electronic version for color representation of this figure*.)

feature about the auroral zone is associated with auroral electrojet current flowing in the ionosphere. During storms, this current system can be strongly intensified mostly by magnetospheric substorms, thereby causing large GICs on the ground.

For many years, it was believed that GICs were a high-latitude phenomena, thus mid-low latitudes were generally not regarded to be susceptible to adverse impact by GICs. But this picture changed after evidence in South Africa revealed that GICs may have contributed significantly to the failure of several transformers (see reports by Koen, 2002; Gaunt and Coetzee, 2007). Since then, the GIC community has experienced a major growth in the number of studies focusing on mid-latitude locations such as, Australia, China, France, Greece, Hungary, Ireland, Japan, New Zealand, South Africa, Spain, and the United States (Kappenman, 2006; Bernhardi et al., 2008; Ngwira et al., 2008, 2009; Watari et al., 2009; Turnbull et al., 2009; Liu et al., 2009; Ngwira et al., 2011; Love, 2012; Torta et al., 2012; Zois, 2013; Marshall et al., 2013; Lotz and Cilliers, 2014; Fujii et al., 2015; Blake et al., 2016; Matandirotya et al., 2016; Lotz and Danskin, 2017; Kelly et al., 2017; Love et al., 2018, and references therein).

In general, low-latitude geomagnetic variations tend to be relatively smaller than those experienced at mid- and high-latitudes, thus the region has largely been overlooked and is the least studied area in terms of GICs. One of the earliest studies on low-latitude networks was conducted in Brazil by Trivedi et al. (2007). However, on examining the March 1989 and October 2003 extreme geomagnetic storms, Pulkkinen et al. (2012) first showed that induced surface geoelectric fields can be strongly amplified at the magnetic equator, thus could pose a higher threat to power systems at low-latitudes than at mid-latitudes. Then, Ngwira et al. (2013) extended study of extreme storms not only confirmed the findings by Pulkkinen et al. (2012), but also associated the effect to amplification of equatorial electrojet (EEJ) current by high-latitude penetration electric fields. Penetration electric fields are attributed to sudden changes in the strength of field-aligned currents, which are required for shielding the inner magnetosphere and the low-mid-latitude ionosphere from the dawn–dusk magnetospheric convection electric field (Fejer et al., 2007; Maruyama and Nakamura, 2007). After the extended study of extreme storms, Carter et al. (2015) investigated the potential effects of interplanetary shocks on the equatorial region and further demonstrated that their magnetic signature was amplified by the EEJ. Partly due to the investigation by Pulkkinen et al. (2012), we have witnessed an increased interest in GICs at low-latitudes during the last 5 years (e.g., Liu et al., 2014; da Silva Barbosa et al., 2015; Barbosa et al., 2015; Adebesin et al., 2016; Moldwin and Tsu, 2017; Oliveira et al., 2018, and references therein).

1.4.2. Extreme GICs

In the past three decades, the space weather field has observed significant progress that has strengthened insight on the central processes driving GICs. However, rare but extremely intense geomagnetic storms continue to challenge our understanding of space weather (Kataoka and Ngwira, 2016; Pulkkinen et al., 2017; Ngwira and Pulkkinen, 2018; Tsurutani et al., 2018; Ngwira et al., 2018b). As noted in our introduction, scientific investigations are critical for raising awareness and predicting the impact of extreme space weather.

The space weather community is well aware that during extreme geomagnetic storms, intense high-latitude currents can expand into the mid-latitudes (e.g., Kappenman, 2005; Ngwira et al., 2013, 2014). However, understanding how deep into the lower latitudes the high-latitude ionospheric currents can extend is still a challenge. Figure 1.5 shows global maximum geomagnetic field *dB/dt* distribution computed from ground magnetometer recordings. The distribution in this figure comprises of data from 12 from historical extreme geomagnetic storms that occurred between the years 1989 and 2005 (see report by Ngwira et al., 2013). Firstly, the figure clearly illustrates the impact of extreme storms on geomagnetic field perturbations at the geomagnetic equator, as seen by the amplified response near zero geomagnetic latitude. Secondly, the dark gray dashed lines mark the geomagnetic latitude boundary (GLB) location, a dynamic transition zone between high- and mid-latitudes, while the thick solid curve is the sixth order polynomial fit.

The GLB is crucial because it identifies the latitude band where *dB/dt* (or the geoelectric field) experience roughly an

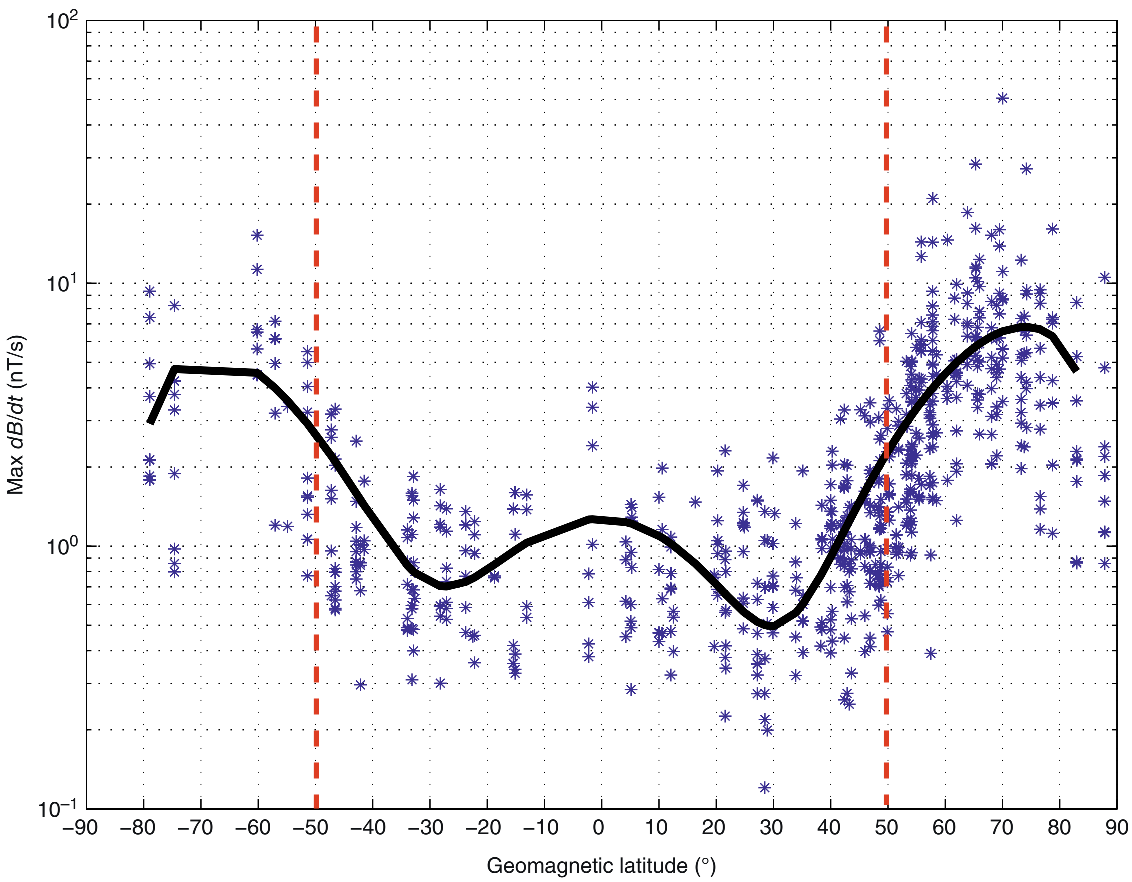

Figure 1.5 Geomagnetic latitude distributions comprising 12 extreme events that occurred between 1989 and 2005. Plot shows the maximum time derivative of the horizontal magnetic field, *dB/dt*, at specific ground sites represented by the "*" symbol. Source: Image credit *Ngwira et al.* (2013). Reproduced with permission of John Wiley and Sons. (*See electronic version for color representation of this figure.*)

order of magnitude drop/jump, and hence helps to define locations most exposed to the GIC hazard. Some investigators have determined the GLB location to be around 50–55°. geomagnetic latitude (e.g., Thomson et al., 2011; Pulkkinen et al., 2012; Ngwira et al., 2013). However, Ngwira et al. (2014) suggest that under extremely strong space weather conditions ("Carrington-type" event), the GLB location can be substantially displaced deeper (~40° geomagnetic latitude) into the lower latitudes. Such a location is much lower than previously determined for observed extreme geomagnetic storms, including the March 1989 and the October 2003 Halloween storm.

1.4.3. Impact

Reducing the Nation's vulnerability to space weather is identified as a national priority, and GICs are also identified as the top threat (National Science and Technology Council, 2015b). The telegraph system was the first technology to report disruption (1847) by space weather-driven GICs (Barlow, 1849). But perhaps in todays society, the power grid is the most critical infrastructure affected by GICs due to the wide-spread demand for electrical power. The first reported disruption on power grids was in 1940 (Davidson, 1940; McNish, 1940).

However, the most widely known impact of space weather on any system is the collapse of the Hydro-Quebec power network grid in Canada during the 13 March 1989 superstorm. Intense GICs produced during the superstorm triggered a complete blackout of the entire Hydro-Quebec network in a relatively short time interval (Boteler, 2001; Bolduc, 2002, and references therein). It is believed that after a large substorm, system stability was lost thereby cutting off main load points from a major generation source (see Bolduc, 2002, for a more detailed discussion). During the same March 1989 event, a generator step-up power transformer was damaged in New Jersey, USA.

Other, more recent but perhaps not well-known GIC impacts on power grids include, failure of a high-voltage power transmission system in Sweden (e.g., Pulkkinen et al., 2005; Wik et al., 2009), and possible transformer damages in South Africa (Gaunt and Coetzee, 2007). These two event are both associated with the "Halloween storm" of October 2003. GICs affect a wide range of technologies, as noted above. An extensive record of GIC impact on different systems within the last 80 years was recently compiled by Ngwira and Pulkkinen (2018).

1.5. CONCLUDING REMARKS

Space weather is an interesting but complex phenomenon. One of the top priorities of the science community today is extending our current understanding of the space weather phenomena. Extreme events in particular not only challenge our understanding of the physics of this phenomena, but can also cause deleterious effects. With several on-going national and international efforts, our awareness of the problem is growing, thus could help to resolve outstanding challenges. More detailed discussion on specific areas of the GIC problem are provided in different chapters of this volume.

ACKNOWLEDGMENTS

We thank Peter Schuck at NASA Goddard Space flight Center and the two anonymous reviewers for assisting this effort. The discussion presented in this chapter relies on the data collected at magnetic observatories. The authors thank the national institutes that support their operation and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org). Research effort at The Catholic University of America (CUA) was supported via NASA Grants NNG11PL10A 670.135 and NNG11PL10A 670.157 to CUA/IACS.

REFERENCES

Adebesin, B. O., A. Pulkkinen, and C. M. Ngwira (2016), The interplanetary and magnetospheric causes of extreme db/dt at equatorial locations, *Geophysical Research Letters*, *43*, 11501–11509, doi:10.1002/2016GL071526.

Barbosa, C., L. Alves, R. Caraballo, G. A. Hartmann, A. R. R. Papa, and R. J. Pirjola (2015), Analysis of geomagnetically induced currents at a low-latitude region over the solar cycles 23 and 24: Comparison between measurements and calculations, *Journal of Space Weather and Space Climate*, *55*, A35, doi:10.1051/swsc/2015036.

Barbosa, C. S., R. Caraballo, L. R. Alves, G. A. Hartmann, C. D. Beggan, A. Viljanen, C. M. Ngwira, A. R. R. Papa, and R. J. Pirjola (2017), The Tsallis statistical distribution applied to geomagnetically induced currents, *Space Weather*, *15*, 9, 1094–1101, doi:10.1002/2017SW001631.

Barlow, W. H. (1849), On the spontaneous electrical currents observed in the wires of the electric telegraph, *Philosophical Transactions of the Royal Society of London*, *139*, 61–72.

Beamish, D., T. G. D. Clark, E. Clarke, and A. W. P. Thomson (2002), Geomagnetically induced currents in the UK: Geomagnetic variations and surface electric fields, *Journal of Atmospheric and Solar Terrestrial Physics*, *64*, 1779–1792.

Beggan, C. D. (2015), Sensitivity of geomagnetically induced currents to varying auroral electrojet and conductivity models, *Earth, Planets, and Space*, *67*, 24, doi:10.1186/s40623-014-0168-9.

Bernhardi, E., P. J. Cilliers, and C. T. Gaunt (2008), Improvement in the modeling of geomagnetically induced currents in South Africa, *South African Journal of Science*, *104*, 265–272.

Blake, S. P., P. T. Gallagher, J. McCauley, A. G. Jones, C. Hogg, J. Campanya, C. Beggan, A. W. P. Thomson, G. S. Kelly, and

D. Bell (2016), Geomagnetically induced currents in the Irish power network during geomagnetic storms, *Space Weather*, *14*, 1136–1154, doi:10.1002/2016SW001534.

Bolduc, L. (2002), GIC observations and studies in the Hydro-Québec power system, *Journal of Atmospheric and Solar Terrestrial Physics*, *64*(16), 1793–1802.

Bonner IV, L. R., and A. Schultz (2017), Rapid prediction of electric fields associated with geomagnetically induced currents in the presence of three-dimensional ground structure: Projection of remote magnetic observatory data through magnetotelluric impedance tensors, *Space Weather*, *15*, doi:10.1002/2016SW001535.

Boteler, D. H. (2001), Space weather effects on power systems, In *Space Weather*, Edited by D. Song, H.J. Singer, and G.L. Siscoe, *AGU Geophysical Monograph 125*, AGU, Washington, DC, pp. 347–352.

Boteler, D. H. (2014), Methodology for simulation of geomagnetically induced currents in power systems, *Space Weather and Space Climate*, *4*, A21, doi:10.1051/swsc/2014018.

Boteler, D. H., and G. Jansen van Beek (1999), August 4, 1972 revisited: A new look at the geomagnetic disturbance that caused the L4 cable system outage, *Geophysical Research Letters*, *26*(5), 577–580.

Boteler, D. H., and R. J. Pirjola (1998), Modeling geomagnetically induced currents produced by realistic and uniform electric fields, *IEEE Transactions on Power Delivery*, *13*(4), 13031308.

Boteler, D. H., R. J. Pirjola, and H. Nevanlinna (1998), The effects of geomagnetic disturbances on electrical systems at the Earth's surface, *Advances in Space Research*, *22*(1), 17–27.

Cagniard, L. (1953), Basic theory of the magneto-telluric methods of geophysical prospecting, *Geophysics*, *18*(3), 605.

Carter, B. A., E. Yizengaw, R. Pradipta, A. J. Halford, and K. Zhang (2015), Interplanetary shocks and the resulting geomagnetically induced currents at the equator, *Geophysical Research Letters*, *42*, doi:10.1002/2015GL065060.

Carter, B. A., E. Yizengaw, R. Pradipta, J. M. Weygand, M. Piersanti, A. Pulkkinen, M. B. Moldwin, R. Norman, and K. Zhang (2016), Geomagnetically induced currents around the world during the 17 March 2015 storm, *Journal of Geophysical Research*, *121*, 10496–10507, doi:10.1002/2016JA023344.

da Silva Barbosa, C., G. A. Hartmann, and K. J. Pinheiro (2015), Numerical modeling of geomagnetically induced currents in a brazilian transmission line, *Advances in Space Research*, *55*, 1168–1179, doi:10.1016/j.asr.2014.11.008.

Davidson, W. F. (1940), The magnetic storm of March 24, 1940–Effects in the power system, *Edison Electric Institute Bulletin*, *8*, 365–366.

de Villiers, J. S., M. Kosch, Y. Yamazaki, and S. Lotz (2017), Influences of various magnetospheric and ionospheric current systems on geomagnetically induced currents around the world, *Space Weather*, *17*, 403–417, doi:10.1002/2016SW001566.

Eroshenko, E. A., A. V. Belov, D. Boteler, S. P. Gaidash, S. L. Lobkov, R. Pirjola, and L. Trichtchenko (2010), Effects of strong geomagnetic storms on Northern railways in Russia, *Advances in Space Research*, *46*, 1102–1110, doi:10.1016/j.asr.2010.05.017.

Fejer, B. G., J. W. Jensen, T. Kikuchi, M. A. Abdu, and J. L. Chau (2007), Equatorial ionospheric electric fields during the November 2004 magnetic storm, *Journal of Geophysical Research*, *112*, A10304, doi:10.1029/2007JA012376.

Fernberg, P. (2012), One-dimensional Earth resistivity models for selected areas of continental United States and Alaska. EPRI Technical Update 1026430, Palo Alto, CA.

Fiori, R. A. D., D. H. Boteler, and D. M. Gillies (2014), Assessment of GIC risk due to geomagnetic sudden commencements and identification of the current systems responsible, *Space Weather*, *12*, 76–91, doi:10.1002/2013SW000967.

Fujii, I., T. Ookawa, S. Nagamachi, and T. Owada (2015), The characteristics of geoelectric fields at Kakioka, Kanoya, and Memambetsu inferred from voltage measurements during 2000 to 2011, *Earth, Planets, and Space*, *67*, 62, doi:10.1186/s40623-015-0241-z.

Gaunt, C. T., and G. Coetzee (2007), Transformer failure in regions incorrectly considered to have low gic-risks, *IEEE Power Tech.*, Conference *Paper 445*, Lausanne, July, pp. 807–812.

Kappenman, J. G. (2005), An overview of the impulsive geomagnetic field disturbance and the power grid impacts associated with the violent Sun-Earth connection events of 29-30 October 2003 and a comparative evaluation with other contemporary storms, *Space Weather*, *3*, S08C01, doi:10.1029/2004SW000128.

Kappenman, J. G. (2006), Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921, *Advances in Space Research*, *38*, 188–199, doi:10.1016/j.asr.2005.08.055.

Kataoka, R., and C. Ngwira (2016), Extreme geomagnetically induced currents, *Progress in Earth and Planetary Science*, *3*, 23, doi:10.1186/s40645-016-0101-x.

Kelbert, A., C. C. Balch, A. Pulkkinen, G. D. Egbert, J. J. Love, E. J. Rigler, and I. Fujii (2017), Methodology for time-domain estimation of storm time geoelectric fields using the 3-D magnetotelluric response tensors, *Space Weather*, *15*, 874–894, doi:10.1002/2017SW001594.

Kelly, G. S., A. Viljanen, C. D. Beggan, and A. W. P. Thomson (2017), Understanding GIC in the UK and French high-voltage transmission systems during severe magnetic storms, *Space Weather*, *15*, 99–114, doi:10.1002/2016SW001469.

Koen, J. (2002), Geomagnetically induced currents in the Southern African electricity transmission network, Ph.D. thesis, University of Cape Town, March.

Lanzerotti, L. J. (2001), Space weather effects on technologies, In *Space Weather*, Edited by D. Song, H.J. Singer, and G.L. Siscoe, *AGU Geophysical Monograph 125*, AGU, Washington, DC, pp. 11–22.

Lehtinen, M., and R. Pirjola (1985), Currents produced in earthed conductor networks by geomagnetically-induced electric field, *Annales Geophysicae*, *3*(4), 479–484.

Liu, C.-M., L.-G. Liu, R. Pirjola, and Z.-Z. Wang (2009), Calculation of geomagnetically induced currents in mid- to low-latitude power grids based on the plane wave method: A preliminary case study, *Space Weather*, *7*, S04005, doi:10.1029/2008SW000439.

Liu, C., Y. Li, and R. Pirjola (2014), Observations and modeling of GIC in the Chinese large-scale high-voltage power networks, *Journal of Space Weather and Space Climate*, *4*, A03, doi:10.1051/swsc/2013057.

Lotz, S. I., and P. J. Cilliers (2014), A solar wind-based model of geomagnetic field fluctuations at a mid-latitude station, *Advances in Space Research*, *55*, 220–230, doi:10.1016/j.asr.2014.09.014.

Lotz, S. I., and D. W. Danskin (2017), Extreme value analysis of induced geoelectric field in South Africa, *Space Weather*, *15*, doi:10.1002/2017SW001662.

Love, J. J. (2012), Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms, *Geophysical Research Letters*, *39*, L10301, doi:10.1130/G32655.1.

Love, J. J., G. M. Lucus, A. Kelbert, and P. A. Bedrosian (2018), Geoelectric hazard maps for the mid-atlantic United States: 100 Year extreme values and the 1989 magnetic storm, *Geophysical Research Letters*, *45*, 5–14, doi:10.1002/2017GL076042.

Marshall, R. A., H. Gorniak, T. V. D. Walt, C. L. Waters, M. D. Sciffer, M. Miller, M. Dalzell, T. Daly, G. Pouferis, G. Hesse, and P. Wilkinson (2013), Observations of geomagnetically induced currents in the Australian power network, *Space Weather*, *11*, 1–11.

Maruyama, T., and M. Nakamura (2007), Conditions for intense ionospheric storms expanding to lower midlatitudes, *Journal of Geophysical Research*, *112*, A05310, doi:10.1029/2006JA012226.

Matandirotya, E., P. J. Cilliers, R. R. Van Zyl, D. T. Oyedokun, and J. de Villiers (2016), Differential magnetometer method applied to measurement of geomagnetically induced currents in Southern African power networks, *Space Weather*, *14*, 221–232, doi:10.1002/2015SW001289.

McKay, A. J. (2003), Geoelectric fields and geomagnetically induced currents in the United Kingdom, Ph.D. thesis, University of Edinburgh, UK.

McNish, A. G. (1940), The magnetic storm of March 24, 1940, *Terrestrial Magnetism and Atmospheric Electricity*, *45*(3), 359–364.

Moldwin, M. B., and J. S. Tsu (2017), Stormtime equatorial electrojet ground-induced currents: Increasing power grid space weather impacts at equatorial latitudes, In *Ionospheric Space Weather: Longitude and Hemispheric Dependences and Lower Atmosphere Forcing*, Edited by T. Fuller-Rowell et al., *AGU Geophysical Monograph*, *220*, pp. 33–40, doi:10.1002/978111892916.ch3.

Molinski, T. S., W. E. Feero, and B. L. Damsky (2000), Shielding grids from solar storms, *IEEE Spectrum*, *37*, 55, doi:10.1109/6.880955.

Myllys, M., A. Viljanen, ø. A. Rui, and T. M. Ohnstad (2014), Geomagnetically induced currents in Norway: the northernmost high-voltage power grid in the world, *Journal of Space Weather and Space Climate*, *4*, A10, doi:10.1051/swsc/2014007.

National Science and Technology Council (2015a), National Space Weather Strategy, Executive Office of the President (EOP), USA. Available at https://www.whitehouse.gov/sites/default/files/microsites/ostp/final_nationalspace- weather-strategy_20151028.pdf.

National Science and Technology Council (2015b), National Space Weather Action Plan, Executive Office of the President (EOP), USA. Available at https://www.whitehouse.gov/sites/default/files/microsites/ostp/final_nationalspace- weatheractionplan_20151028.pdf.

Ngwira, C. M., and A. Pulkkinen (2018), An overview of science challenges pertaining to our understanding of extreme geomagnetically induced currents, In *Extreme Events in Geospace: Origins, Predictability and Consequences*, Edited by N. Buzulukova et al., Elsevier, pp. 187–208.

Ngwira, C. M., A. Pulkkinen, L. A. McKinnell, and P. J. Cilliers (2008), Improved modeling of geomagnetically induced currents in the South African power network, *Space Weather*, *6*, S11004, doi:10.1029/2008SW000408.

Ngwira, C. M., L. A. McKinnell, P. J. Cilliers, A. Viljanen, and R. Pirjola (2009), Limitations of the modelling of geomagnetically induced currents in the South African power network, *Space Weather*, *7*, S10002, doi:10.1029/2009SW000478.

Ngwira, C. M., L.-A. McKinnell, and P. J. Cilliers (2011), Geomagnetic activity indicators for geomagnetically induced current studies in South Africa, *Advances in Space Research*, *48*, 529–534.

Ngwira, C. M., A. Pulkkinen, F. D. Wilder, and G. Crowley (2013), Extended study of extreme geoelectric field event scenarios for geomagnetically induced current applications, *Space Weather*, *11*, 121–131, doi:10.1002/swe.20021.

Ngwira, C. M., A. Pulkkinen, M. M. Kuznetsova, and A. Glocer (2014), Modeling extreme "Carrington–type" space weather events using three-dimensional MHD code simulations, *Journal of Geophysical Research*, *119*, 4456–4474, doi:10.1002/2013JA019661.

Ngwira, C. M., A. Pulkkinen, E. Bernabeu, J. Eichner, A. Viljanen, and G. Crowley (2015), Characteristics of extreme geoelectric fields and their possible causes: Localized peak enhancements, *Geophysical Research Letters*, *42*, doi:10.1002/2015GL065061.

Ngwira, C. M., D. Sibeck, M. V. D. Silveria, M. Georgiou, J. M. Weygand, Y. Nishimura, and D. Hampton (2018a), A study of intense local dB/dt variations during two geomagnetic storms, *Space Weather 16*, 676–693, doi:10.1029/2018SW001911.

Ngwira, C. M., A. Pulkkinen, M. M. Kuznetsova, and A. Glocer (2018b), Reply to comments by Tsurutani et al. on "Modeling extreme 'Carrington–type' space weather events using three-dimensional MHD code simulations", *Journal of Geophysical Research*, *123*, doi:10.1002/2017JA024928.

Oliveira, D. M., D. Arel, J. Raeder, E. Zesta, C. M. Ngwira, B. A. Carter, E. Yizengaw, A. J. Halford, B. T. Tsurutani, and J. W. Gjerloev (2018), Geomagnetically induced currents caused by interplanetary shocks with different impact angles and speeds, *Space Weather*, *16*, 636–647 doi:10.1029/2018SW001880.

Pirjola, R. (1982), Electromagnetic induction in the Earth by a plane wave or by fields of line currents harmonic in time and space, *Geophysica*, *18*(1–2), 1–161.

Pirjola, R. (2000), Geomagnetically induced currents during magnetic storms, *IEEE Transactions on Plasma Science*, *28*(6), 1867–1873.

Pirjola, R. (2002a), Review on the calculation of the surface electric and magnetic fields and geomagnetically induced currents in ground based technological systems, *Surveys in Geophysics*, *23*, 71–90.

Pirjola, R. (2002b), Space weather effects on technological systems on the ground, *Asia-Pacific Conference on Environmental Electromagnetics*, CEEM'2000 (IEEE Cat. No.00EX402), Shanghai, China, 7 May 2002, IEEE. doi:10.1109/CEEM.2000.853936

Pirjola, R. (2002c), Fundamentals about the flow of geomagnetically induced currents in a power system applicable to estimating space weather risks and designing remedies, *Journal of Atmospheric and Solar Terrestrial Physics*, *64*, 1967–1972.

Pulkkinen, A., A. Viljanen, K. Pajunpaa, and R. Pirjola (2001), Recordings and occurrence of geomagnetically induced currents in the Finnish natural gas pipeline network, *Journal of Applied Geophysics*, *48*, 219–231.

Pulkkinen, A., A. Thomson, E. Clarke, and A. McKay (2003), April 2000 geomagnetic storm: Ionospheric drivers of large geomagnetically induced currents, *Annales Geophysicae*, *21*, 709–717.

Pulkkinen, A., S. Lindahl, A. Viljanen, and R. Pirjola (2005), Geomagnetic storm of 29-31 October: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, *Space Weather*, *3*, S08C03, doi:10.1029/2004SW000123.

Pulkkinen, A., R. Pirjola, and A. Viljanen (2007), Determination of the ground conductivity and system parameters for optimal modeling of geomagnetically induced current flow in technological systems, *Earth Planets and Space*, *59*, 999–1006.

Pulkkinen, A., E. Bernabeu, J. Eichner, C. Beggan, and A. W. P. Thomson (2012), Generation of 100-year geomagnetically induced current scenarios, *Space Weather*, *10*, S04003, doi:10.1029/2011SW000750.

Pulkkinen, A., E. Bernabeu, J. Eichner, A. Viljanen, and C. M. Ngwira (2015), Regional-scale high-latitude extreme geoelectric fields pertaining to geomagnetically induced currents, *Earth, Planets, and Space*, *67*, 93, doi:10. 1186/s40623-015-0255-6.

Pulkkinen, A., E. Bernabeu, A. Thomson, A. Viljanen, R. Pirjola, D. Boteler, J. Eichner, P. J. Cilliers, D. Welling, N. P. Savani, R. S. Weigel, J. J. Love, C. Balch, C. M. Ngwira, G. Crowley, A. Schultz, R. Kataoka, B. Anderson, D. Fugate, J. J. Simpson, and M. MacAlester (2017), Geomagnetically induced currents: Science, engineering and applications readiness, *Space Weather*, *15*, 28–856, doi:10.1002/2016SW001501.

Schultz, A. (2009), EMScope: A continental scale magnetotelluric observatory and data discovery resource, *Data Science Journal*, *8*, PIGY6–IGY20.

Thomson, A. W. P., E. Clarke, A. McKay, and S. J. Reay (2005), Surface electric fields and geomagnetically induced currents in Scottish Power grid during 30 October 2003 geomagnetic storm, *Space Weather*, *3*, S11002, doi:10.1029/2005SW00156.

Thomson, A. W. P., E. B. Dawson, and S. J. Reay (2011), Quantifying extreme behavior in geomagnetic activity, *Space Weather*, *9*, S10001, doi:10.1029/2011SW000696.

Torta, J. M., L. Serrano, J. R. Regué, A. M. Sánchez, and E. Roldán (2012), Geomagnetically induced currents in a power grid of northeastern Spain, *Space Weather*, *10*, S06002, doi:10.1029/2012SW000793.

Trichtchenko, L., and D. H. Boteler (2004), Modeling geomagnetically induced currents using geomagnetic indices and data, *IEEE Transactions on Plasma Science*, *32*(4), 1459–1469.

Trivedi, N. B., I. Vitorello, W. Kabata, S. L. G. Dutra, A. L. Padilha, M. S. Bologna, M. B. de Pádua, A. P. Soares, G. S. Luz, F. de A. Pinto, R. Pirjola, and A. Viljanen (2007), Geomagnetic conjugate observations of large-scale traveling ionospheric disturbances using GPS networks in Japan and Australia, *Space Weather*, *5*, S04004, doi:10.1029/2006SW000282.

Tsurutani, B. T., G. S. Lakhina, E. Echer, R. Hajra, C. Nayak, A. Mannucci, and X. Meng (2018), Comment on "Modeling extreme 'Carrington-type' space weather events using three-dimensional global MHD simulations by C. M. Ngwira, A. Pulkkinen, M. M. Kuznetsova, and A. Glocer", *Journal of Geophysical Research*, *123*, doi:10.1002/2017JA024779.

Turnbull, K. L., J. A. Wild, F. Honary, A. W. P. Thomson, and A. J. McKay (2009), Characteristics of variations in the ground magnetic field during substorms at mid latitudes, *Annales Geophysicae*, *27*, 3421–3428.

Viljanen, A., and R. Pirjola (1994), Geomagnetically induced currents in the Finnish high-voltage power system, *Surveys in Geophysics*, *15*, 383–408.

Viljanen, A., A. Pulkkinen, R. Pirjola, K. Pajunpää, P. Posio, and A. Koistinen (2006), Recordings of geomagnetically induced currents and a nowcasting service of the Finnish natural gas pipeline, *Space Weather*, *4*, S10004, doi:10.1029/2006SW000234.

Watari, S., M. Kunitake, K. Kitamura, T. Hori, T. Kikuchi, K. Shiokawa, N. Nishitani, R. Kataoka, Y. Kamide, T. Aso, Y. Watanabe, and Y. Tsuneta (2009), Measurements of geomagnetically induced current (GIC) in a power grid in Hokkaido, Japan, *Space Weather*, *7, S03002*, S03002, doi:10.1029/2008SW000417.

Wik, M., R. Pirjola, H. Lundstedt, A. Viljanen, P. Wintoft, and A. Pulkkinen (2009), Space Weather events in July 1982 and October 2003 and the effects of geomagnetically induced currents on Swedish technical systems, *Annales of Geophysicae*, *27*, 1775–1787.

Wintoft, P. (2005), Study of solar wind coupling to the time difference horizontal geomagnetic field, *Annales Geophysicae*, *23*, 1949–1957.

Zhang, J. J., C. Wang, and B. B. Tang (2012), Modeling geomagnetically induced electric field and currents by combining a global MHD model with a local one-dimensional method, *Space Weather*, *10*, S05005, doi:10.1029/2012SW000772.

Zois, I. P. (2013), Solar activity and transformer failures in the Greek national electric grid, *Journal of Space Weather and Space Climate*, *3*, A32, doi:10. 1051/swsc/2013055.