

The Solar Cycle, Geology, and Geoelectric Hazards for Power Grids

The Sun's variability is notably seen in the waxing and waning of the number and size of sunspots over the approximately 11-year period of a solar cycle. Sunspots are concentrations of tangled magnetic-field lines. With their occasional and abrupt rearrangement, concentrations of superheated and electrically conducting plasma (electrons, protons, and ions) can be ejected from the Sun. If one of these "coronal-mass ejections" happens to be directed toward the Earth, it can cause a "magnetic storm"—a global disturbance of the geomagnetic field that can last a day or two.

During a storm, electromagnetic disturbance descends from the near-Earth space environment to the Earth's surface, and into its interior. The strength of the electromagnetic fields in the Earth, and the depth of their penetration, depend on the rate at which the field varies in time and the electrical conductivity of the underlying geologic structures. For example, 10-second-period field variation can penetrate a kilometer or so into wet sedimentary rock (a relatively good conductor), but 100 kilometers or so into dry metamorphic or igneous rock (which are usually electrically resistive). Longer-period variation can penetrate even deeper hundreds of kilometers or more. Geoelectric fields generated at Earth's surface are generally of low amplitude over sedimentary basins and of high amplitude over metamorphic provinces. For some storms, more than 10 volts per kilometer (V/km) can be induced over electrically resistive parts of the Earth ([Love and others, 2022](#page-3-0)).

Consider a power-transmission line that happens to be deployed across a metamorphic province. Storm-induced electric currents will meet resistance in flowing through the poorly conducting rock, and this is where the power grid offers an alternative path—one of less resistance. For a power line of

100 km in length, the integration of 10 V/km adds up to 1,000 V. Such voltages can drive currents through grounding points at high-voltage transformer substations and into the power grid. They are not the tightly managed alternating currents that power grids are designed to carry. Magnetic-storm-induced currents can interfere with grid operation and even damage or destroy transformers.

This long chain of physical effects, stretching from the Sun to the Earth to the power grid, can be especially consequential for the most intense magnetic storms that are produced by the strongest coronal-mass ejections. A very intense magnetic superstorm could, potentially, result in prolonged and widespread blackouts, possibly spanning international boundaries. Such an event is more probable around the time of sunspot "solar maximum," when spots are relatively numerous.

History of Sunspots and Storms

For hundreds of years, astronomers have observed and counted sunspots. Since the middle of the 19th century, geophysicists have regularly measured geomagnetic disturbance at ground-based stations. The combination of these two types of data provides a long history of solar-terrestrial activity. [Figure 1](#page-1-0) shows time series representing sunspot number (*R*) from 1843 to 2024 ([Clette and Lefèvre, 2016](#page-3-1); [WDC-SILSO, 2024\)](#page-3-2) and geomagnetic disturbance (*aa*) from 1868 to 2024 [\(Lockwood and](#page-3-3) [others, 2018](#page-3-3); [Mayaud and others, 2023](#page-3-4)). The semiregular solar cycle is clearly seen in the sunspot data. Intense magnetic storms tend to occur when sunspot numbers are high, and they are rare when sunspot numbers are low.

Photograph by Tebnad, Dreamstime.com.

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The magnetic storm of March 1989 happened during the ascending phase of the solar cycle, just before sunspot maximum in November 1989. This storm damaged satellites and disrupted geophysical surveys and radio communication. Geomagnetically induced currents led to the complete collapse of the Hydro-Québec electric power grid in Canada ([Allen and others, 1989](#page-3-5); [Bolduc,](#page-3-6) [2002\)](#page-3-6), caused substantial interference in U.S. power grids ([North](#page-3-7) [American Electric Reliability Corporation, 1990\)](#page-3-7), and damaged a high-voltage transformer at a nuclear power plant in New Jersey ([Rossi, 1990](#page-3-8); [Barnes and others, 1991\)](#page-3-9).

Looking further back in time, the great magnetic storm of May 1921 occurred during the declining phase of the solar cycle, following sunspot maximum in August 1917. This storm, one of the most intense ever recorded, caused worldwide disruption of telegraph and telephone systems—which, in those days, relied on long-grounded networks of wires (like power grids of today). In New York State and City, the storm caused fires in telegraph stations used by railroad companies (for example, [Hapgood,](#page-3-10) [2019](#page-3-10); [Love and others, 2019\)](#page-3-11).

In September 1859, an astronomer named Richard Carrington was looking at sunspots through a telescope when he saw a very bright solar flare. Seventeen hours later, one of history's greatest magnetic storms transpired. The storm was so intense it overwhelmed magnetometer systems used at most observatories at the time. The Carrington storm disrupted telegraph systems and caused fires at numerous telegraph stations around the world.

With the rise of the global economy and humanity's ever-increasing reliance on electricity-based technology, a recurrence of a storm like that of March 1989 could carry a worldwide economic impact of \$2.4 trillion to \$3.4 trillion, equivalent to a global loss in gross productivity of 3.9 to 5.6 percent ([Schulte](#page-3-12) [in den Bäumen and others, 2014](#page-3-12)). The future occurrence of a Carrington-class magnetic storm might carry an economic cost for the United States alone of \$0.6 trillion to \$2.6 trillion (for example, [National Research Council, 2008](#page-3-13); [Lloyd's of London, 2013\)](#page-3-14).

Geoelectric Hazard Maps

As part of an interagency Federal Government project to improve national preparedness for space-weather hazards, U.S. Geological Survey (USGS) Geomagnetism Program scientists have performed research on magnetic-storm-induced geoelectric fields. This work relies on two important and very different datasets: (1) multidecadal records of magnetic storms acquired at ground-based monitoring stations operated by the USGS (for example, [Love and](#page-3-15) [Finn, 2011](#page-3-15); [Love and Lewis, 2021](#page-3-16)) and Natural Resources Canada (for example, [Newitt and Coles, 2007\)](#page-3-17), and (2) measurements of the electromagnetic properties of the Earth acquired through nationalscale surveys supported by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the USGS (for example, [Schultz, 2010](#page-3-18); [Kelbert and others, 2018\)](#page-3-19).

The combination of these datasets permits retrospective mapping of time-dependent geoelectric fields across the contiguous United States (CONUS). The USGS and the

Figure 1. *A*, Variation in sunspot number (*R*), 1843–2024; *B*, variation in geomagnetic disturbance (*αα*), in nanoteslas, 1868–2024. Note the 11-year modulation in both time series and their correlation. The 1921 and 1989 magnetic storms are labeled.

National Oceanic and Atmospheric Administration (NOAA) also collaborate on the presentation of real-time geoelectric field maps.

[Figure 2](#page-2-0) shows a map of the amplitudes of geoelectric fields induced across CONUS during the March 1989 magnetic storm. The same figure also shows a map of the locations of reported instances of power-grid interference during that storm ([Love and](#page-3-0) [others, 2022\)](#page-3-0). Notably, geoelectric amplitudes were high in the Upper Midwest and in the Eastern United States. These are regions of electrically resistive metamorphic and igneous rock ([Kelbert](#page-3-20) [and others, 2019\)](#page-3-20). Conversely, geoelectric amplitudes were low over more electrically conductive sedimentary basins, such as in Michigan and Illinois. During the March 1989 storm, operational

interference for U.S. power grids was greatest where geoelectric amplitudes were high, occurring in power grids serving many of the largest cities in the United States: Boston, Massachusetts; New York City, New York; Philadelphia, Pennsylvania; Baltimore, Maryland; and Washington, District of Columbia—a combined megalopolis of more than 50 million people.

Retrospective mapping of storm-time geoelectric fields, such as for the March 1989 storm, shows where utility companies might concentrate their efforts to improve the resilience of the Nation's electric-power grids to the deleterious impacts of magnetic storms. It also shows where utility companies could be especially vigilant in operating power transmission systems during a magnetic storm to help ensure operational continuity.

B. **Locations of March 1989 power-grid interference**

Figure 2. *A*, Map of geoelectric field amplitudes realized during the March 1989 magnetic storm. *B*, Map of the locations of power-grid interference realized during the March 1989 magnetic storm.

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Northern lights over Iceland. Photograph by Simone Renoldi, Dreamstime.com.

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