LOCATION-SPECIFIC SPACE WEATHER HAZARDS TO ELECTRIC POWER GRIDS CALCULATED ON A GLOBAL SCALE

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EXECUTIVE SUMMARY

The largest documented geomagnetic storm due to a coronal mass ejection on the sun occurred in 1859. This storm caused telegraph operators communicating over 100-km-long wire lines to experience electric shocks, some nearly fatal. The historical record suggests that extreme space weather is likely to impact the Earth again in the future. However, modern electrotechnologies will be affected by space weather to a much larger degree than in the past. We are utilizing Maxwell's equations models of the Earth–ionosphere waveguide to calculate location-specific space weather hazards to electric power grids in order to prevent blackouts. Blue Waters permitted us, for the first time, to study electric field behavior near ocean–continent boundaries using realistic coastal geometries. Additionally, we developed stochastic models of electromagnetic wave propagation through uncertain and variable ionosphere regions. These algorithms are allowing us to determine the confidence level that a communication or similar system will work as expected during disturbed conditions.

RESEARCH CHALLENGE

The largest documented geomagnetic storm on Earth resulting from a coronal mass ejection (CME) on the sun occurred in 1859. That storm caused telegraph operators communicating over 100-km-long wire lines to experience electric shocks, some nearly fatal. Further, business transactions requiring telegraphic exchanges were completely shut down in the world's major capitals. A 2008 National Academies report indicates that extreme space weather events, "though rare, are likely to occur again sometime in the future." However, a reoccurrence of an 1859-magnitude space weather storm could disrupt today's society to a much greater degree than in 1859 due to the proliferation of vital but vulnerable electrotechnologies. Interruptions to radio communications, commercial airline flight plans, satellite operations, transportation, banking, financial systems, home and industrial computer electronics, and electric power grids are just some examples.

The focus of our research was to greatly enhance our understanding of the near-Earth electrodynamics associated with historically intense CMEs. The methodology of the proposed work was to advance and apply detailed, high-resolution Maxwell's equations models of the Earth-ionosphere waveguide developed by the PI over the past ~15 years [1]. These models are based on the robust finite-difference time-domain (FDTD) method [2]. They currently extend from -400 km below the Earth's surface to an altitude of +100 km. They uniquely account for the Earth's complete topography, oceans, lithosphere composition, geomagnetic field, and magnetized ionospheric plasma according to altitude, position, and time of day, all while solving the full-vector Maxwell's equations. As a result, these models created by the PI's group are the most advanced electrodynamics models of the Earth-ionosphere waveguide. They can model the entire world's response to a space weather event and provide location-specific information on possible hazards to societal infrastructure. Previous studies were limited to only the sinusoidal steady-state and involved simplifying geometries and physics (e.g., infinite line currents, layered lithosphere models, nonphysical constant magnetic fields assumed within each layer, only solutions to Poisson's equation, etc.)

METHODS & CODES

The first goal of our research was to help power grid stations better understand their individual risks to different space weather impact scenarios depending on their orientation and location. Of particular focus this past year was the electromagnetic field behavior in coastal regions in order to determine whether space weather poses unique hazards to power grids along coastlines.

For this work, we used the FDTD method to calculate electromagnetic fields at the surface of the Earth near ocean-continent boundaries. As a time-domain method, FDTD permits modeling of arbitrary source time-waveforms, variable current source orientations as shown in Fig. 1, and even the finite propagation velocity of the ionospheric currents. Further, as a grid-based method, FDTD permits modeling of complex geometries, such as sloping coastlines combined with finite depth oceans (rather than a coastline having a constant, infinitely-long slope as in the previous analytical studies).

The second goal of our research was to develop the first efficient, grid-based stochastic electrodynamics models of the Earth-ionosphere waveguide. Nearly all electrodynamics solvers assume average (mean) electrical properties of materials and solve for average (mean) electric and magnetic fields. However, assuming numerically only an average state of the ionosphere yields calculated output electromagnetic field waveforms that are not as rich and complex as measured electromagnetic fields. Further, there is great uncertainty in the content of the ionosphere at any given moment. The FDTD models we developed this past year solve for both the mean and variance of electromagnetic wave propagation through a varying/uncertain ionosphere.

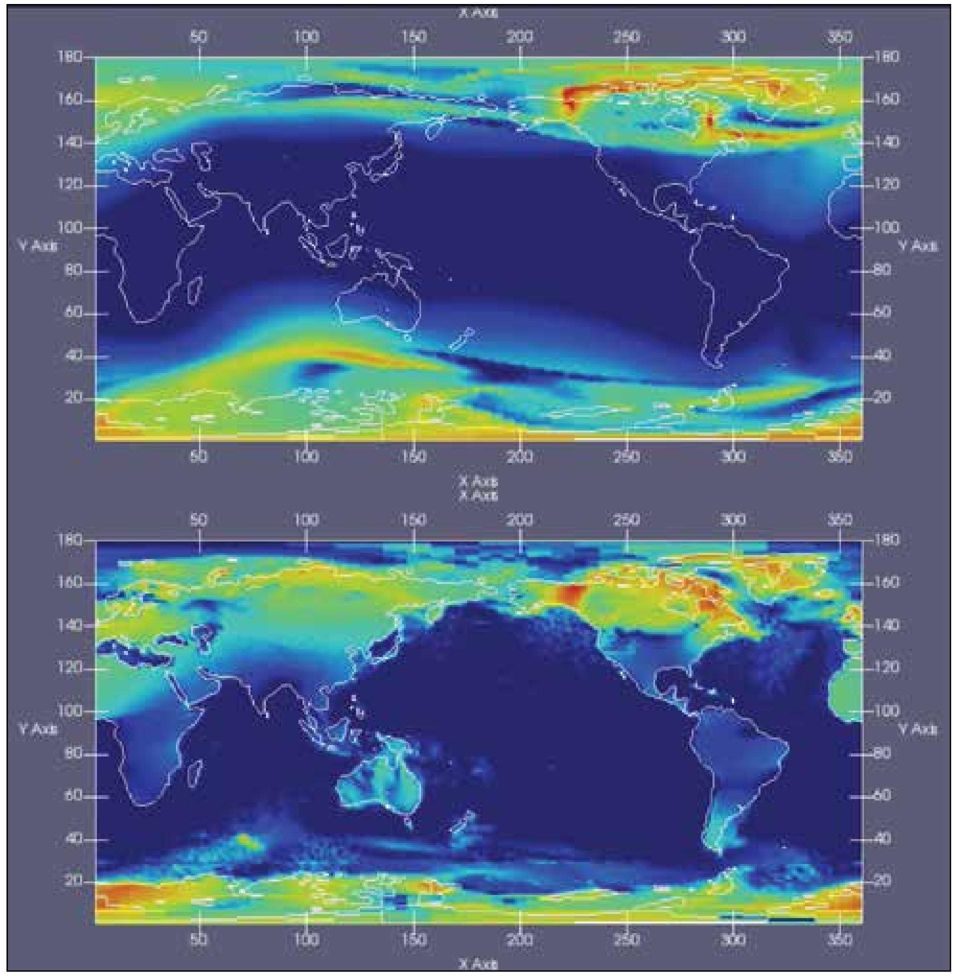

Figure 1: Snapshot of the electric field source amplitude versus position during the October 2003 Halloween geomagnetic storms as calculated by BATS-R-US model developed at the University of Michigan (top image) and the resulting surface-level electric field values calculated by the global FDTD model (bottom image).

RESULTS & IMPACT

In 2015, Prof. Simpson was among 20 researchers who participated in the NASA Living with a Star Working Group Institute on Geomagnetically Induced Currents. The issue of ocean-continent boundaries and whether they pose significant risks to power grids was among the list of topics that were considered important and unresolved. Blue Waters allowed us to take a closer look at this issue this past year using an established numerical technique (FDTD) that offers more flexibility than previously possible using analytical approaches, and provides more rigorous (full-vector Maxwell's equations) solutions. In order for space weather to pose a unique risk to electric power grids at ocean-continent boundaries, high electric fields must extend at least 100 km inland from the coast. Counter to the conclusions of previously published work, we were able to determine that space weather does not induce intense electric fields over a sufficiently large area to pose a risk to power grids [3].

WHY BLUE WATERS

We were able to use Blue Waters to develop higher grid resolutions than previously possible by over an order of magnitude (~1 x 1 x 1 km vs. ~40 x 40 x 5 km). This has opened up a wide variety of new applications because we can model higher frequencies of electromagnetic waves and also model smaller geometries. For example, we are now working with the Defense Advanced Research Projects Agency to examine the use of our models for developing a new electromagnetic system for geolocation. We are also now working with the Office of Naval Research to detect objects submerged in the ocean. Other possibilities due to the higher grid resolutions achieved include communications during space weather events, new remote sensing applications, and studying very low-frequency signals detected by spacecraft around the times of earthquakes.

PUBLICATIONS AND DATA SETS

S. Pokhrel, B. Nguyen, J. J. Simpson, FDTD applied to GICs at ocean-continent boundaries, *AGU Fall Meeting*, San Francisco, Calif., December 12–16, 2016.