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

Allocation: NSF PRAC/2.30 Mnh
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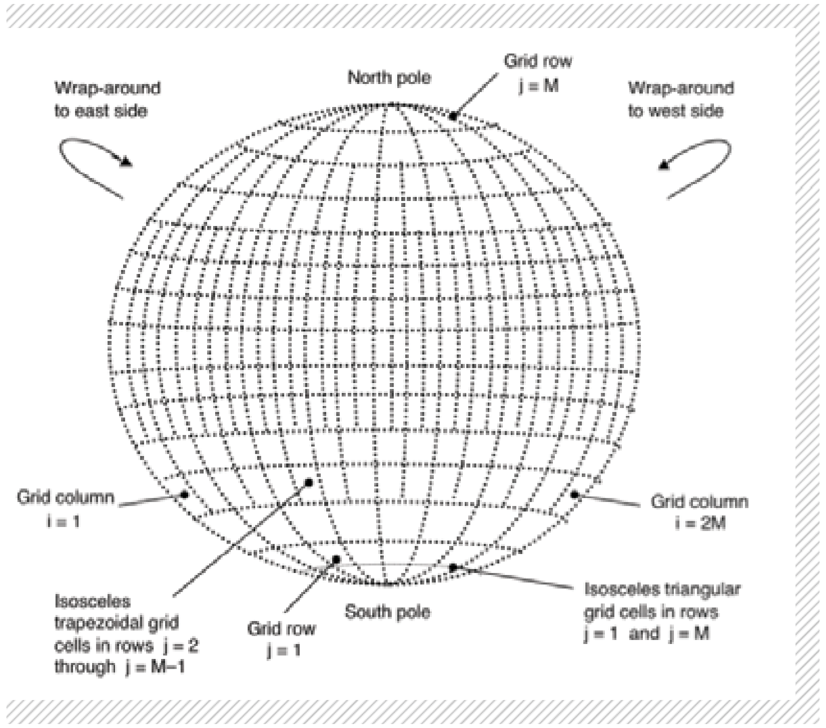
EXECUTIVE SUMMARY

The largest documented geomagnetic storm 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 electro-technologies will be affected by space weather to a much larger degree than in the past. We are using global 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 is permitting us to account, at high resolutions, for the Earth's topography, oceans, variable composition of the lithosphere, as well as the variable ionospheric composition, and source conditions according to time, altitude, and position around the globe. Previous analytical and computational approaches were localized in nature, assumed highly simplified geometries, and could not model arbitrary (realistic) source waveforms in time or space.

FIGURE 1: Layout of the 3D FDTD grid as seen from a constant radial coordinate.



INTRODUCTION

The historical record indicates the possibility of extremely intense space weather events directed toward the Earth from the sun. The largest documented geomagnetic storm occurred in 1859 [1] and caused telegraph operators communicating over 100-km-long wire lines to experience electric shocks, some nearly fatal [2]. Further, business transactions requiring telegraphic exchanges were completely shut down in the world's major capitals [2].

A 2008 National Academies report [3] indicates that extreme space weather events, "though rare, are likely to occur again some time in the future." However, a reoccurrence of an 1859-magnitude (coronal mass ejection-driven geomagnetic) storm could disrupt today's society to a much greater degree due to the proliferation of vital but vulnerable electro-technologies. Interruptions to radio communications, commercial airline flight plans, satellite operations, transportation, banking, financial systems, home and industrial computer electronics, and power grids are just some examples. The National Academies report estimates the overall economic cost of one such extreme event as ranging from millions to trillions of dollars, with a recovery time of four to 10 years [3].

METHODS & RESULTS

Our goal is to greatly improve our ability to understand and predict space weather hazards in the near-Earth environment, especially on the operation of electric power grids. To achieve this goal, we are advancing and applying detailed, high-resolution Maxwell's equations models of the Earth-ionosphere waveguide developed by Professor Simpson over the past 15 years (e.g. [4, 5]). These models are based on the finite-difference time-domain (FDTD) method. FDTD allows for the modeling of realistic time-waveforms of disturbed ionospheric currents and resulting electromagnetic fields at the Earth's surface induced by space weather. FDTD is also a grid-based approach that permits modeling of intricate details on a global scale, such as the Earth's complete topography, oceans, variable composition of the lithosphere, as well as the variable ionospheric composition and disturbed ionospheric current systems according to altitude and position around the globe.

Using the global FDTD models, we are generating location-specific ground-level electromagnetic field data to help predict the induced voltages on electric power grids during space weather events. Fig. 1 illustrates a planar cut of the three-dimensional FDTD grid as seen from constant radial coordinate. The top half of Fig. 2 illustrates an example snapshot of the disturbed ionospheric electric fields during the October 2003 "Halloween" geomagnetic storm. These disturbed ionospheric fields are used as sources to the FDTD grid at ~100 km altitude, and then the ground-level electromagnetic fields are calculated. The ground-level electromagnetic fields corresponding to the time of the source currents in the top half of Fig. 2 are shown in the lower half of Fig. 2. Individual power grid operators may use the FDTD-computed results to design and implement effective mitigation strategies to protect the grid from voltages induced by geomagnetic storms.

WHY BLUE WATERS

FDTD can account for highly detailed three-dimensional geometries and material compositions. However, it is computationally expensive, especially when modeling the entire world. Blue Waters has helped us improve the parallelization of our global model, so that we can now model at resolutions on the order of 1 km x 1 km x 1 km and higher. Before the start of our Blue Waters project, our highest grid resolution was 40 km x 40 km x 5 km, so this is an **8,000 times improvement**. Achieving these high resolutions has been challenging because, as shown in Fig. 1, dividing the grid into equal sections for each processing core is challenging due to the merging of grid cells in the polar regions.

Furthermore, Blue Waters is allowing us to model **more realistic** ionospheric source time-waveforms and spatial distribution than previously possible. Hazards to electric power grids critically depend on the complex distribution of storm-driven ionospheric sources overhead, the grid's vicinity to ocean-continent boundaries, and the underlying rock structure. The FDTD-calculated results may be instrumental in helping protect individual power grids substations.

Blue Waters project **staff have been critical** to our success. They improved the efficiency of our model by 4% by helping us incorporate non-blocking message-passing interface (MPI) to send and receive commands into a section of our code. Also, the staff significantly aided our productivity by rapidly addressing issues and questions.

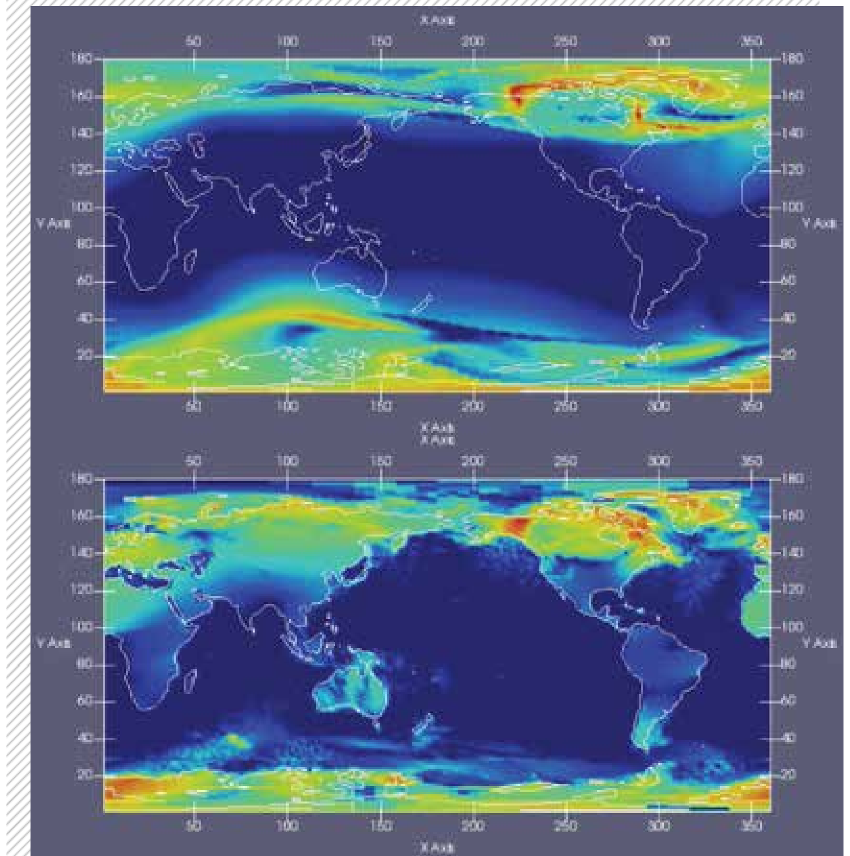


FIGURE 2: Snapshot of the electric field source amplitude versus position during the October 2003 Halloween geomagnetic storms as calculated by BATS-R-US model developed at the University of Michigan (top), and the resulting surface-level electric field values calculated by the global FDTD model (bottom).

NEXT GENERATION WORK

The next Track-1 system would allow us to extend our models higher into the ionosphere so that instead of projecting currents down to ~100 km in altitude, we could model the actual propagation and resulting physics of those currents. The FDTD models could be coupled to models of the magnetosphere to provide a more complete physics analysis of the effect of space weather on the earth.

PUBLICATIONS AND DATA SETS

Samimi, A., and J. J. Simpson, Parallelization of 3-D global FDTD Earth-ionosphere waveguide models at resolutions on the order of ~1 km and higher, *IEEE Antennas and Wireless Propagation Letters* (in press).

Samimi, A., M. Rodriguez, N. Dupree, R. Moore, and J. J. Simpson, The application of global 3-D FDTD Earth-ionosphere models to VLF propagation: Comparison with LWPC, *IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting*, Puerto Rico, June (2016).

PHYSICS-BASED STRONG GROUND MOTION SIMULATIONS

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EXECUTIVE SUMMARY

Earth scientists, engineers, and computer scientists working with the Southern California Earthquake Center (SCEC) use physics-based numerical simulations and high-performance computing (HPC) to improve the understanding of seismic hazards, and earthquake processes and their effects. This past year, SCEC teams used Blue Waters to perform deterministic earthquake ground motion simulations with frequencies up to 8 Hz, while introducing new physics required for more realistic ground motion simulations, including rough-fault geometrical complexity, frequency-dependent attenuation, material plasticity, small-scale material heterogeneities, and surface topography. Earthquake simulations using our improved numerical models were validated against records from past earthquakes. We also increased the computational performance of our research software through graphics processing unit (GPU) code and parallel I/O improvements, and through workflow optimizations.

INTRODUCTION

The SCEC performs fundamental research in earthquake system science and develops predictive models of earthquake processes. SCEC scientists develop and apply the best available geoscientific understanding of faulting and wave propagation processes, together with state-of-the-art computation techniques, to produce the next generation of physics-based seismic hazard models. SCEC's research program is a collaboration among several user communities with shared interests in reducing seismic risk and enhancing seismic resilience. SCEC's computational research activities help to educate a diverse STEM workforce from the undergraduate to the early-career levels, and cross-train scientists and engineers in challenging HPC environments.

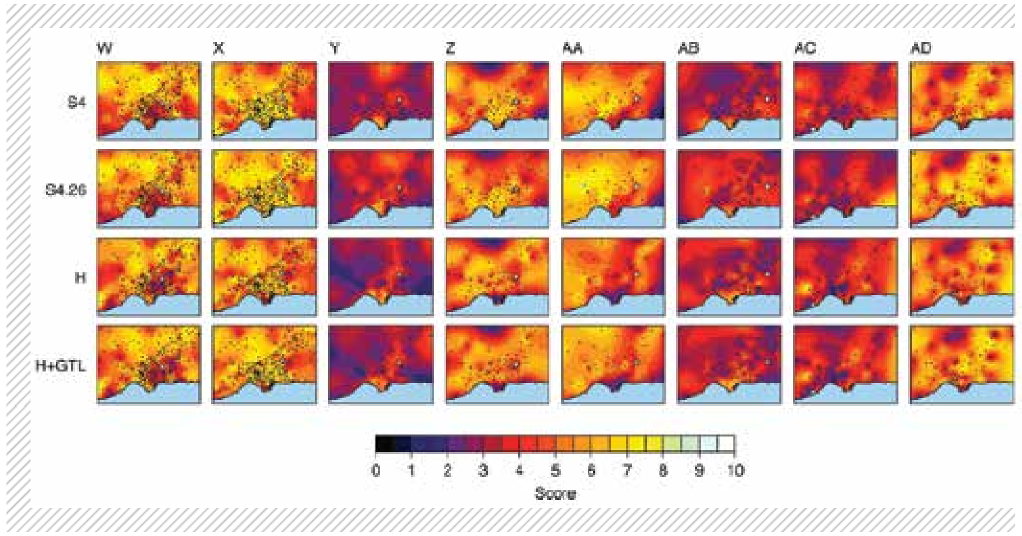

FIGURE 1: Goodness-of-fit (GOF) maps for all events with 53 or more stations used for validation. Contours indicate the score obtained by averaging the GOF values for all three components of motion (EW, NS and UD). Dots correspond to the location of stations and stars indicate the epicenters for each event. Event labels at the top of each set of four maps correspond to the results obtained using alternate velocity models (CVM-S4, CVM-S4.26, CVM-H and CVM-H+GTL), as indicated with labels on the left margin.

METHODS & RESULTS

SCEC researchers used Blue Waters to perform simulations of earthquake faulting and wave propagation at frequencies of interest to civil engineers. A significant focus of our Blue Waters computational research this year involved validating simulations against data, with much of this effort led by engineering seismologists and engineers, who recognize the potential of SCEC's efforts in physics-based ground-motion prediction.

SCEC approaches seismic hazard analysis as an earthquake system science problem that requires integration of several interrelated computational models, including accurate 3D earth structural models, friction-based fault rupture models, and anelastic wave propagation (AWP) models. SCEC's approach iteratively improves these models, re-validates them against observed ground motions, and then re-combines the models, producing an improvement in broad-impact seismic hazard computational methods.

A team led by Ricardo Taborda at University of Memphis used Blue Waters to evaluate four existing southern California velocity models by assessing how well each predicted ground motion in the greater Los Angeles region when used as inputs to deterministic wave propagation simulations. These evaluations were performed by running multiple earthquake simulations and then using quantitative comparisons between simulated motions and a collection event data. The team used Blue Waters to simulate earthquakes within a domain with a surface area of 180 km x 135 km. Each earthquake was modeled as a point source with rupture parameters scaled according to magnitude. Hercules—finite-element software developed by SCEC-affiliated scientists—was used to simulate the ground motions for each earthquake and velocity model combination. Hercules has shown to be a reliable tool for 3D earthquake ground motion simulation [1,2]. The group simulated 30 moderate-magnitude earthquakes (3.5 to 5.5) and compared synthetics with data recorded by seismic networks on over 800 stations. Each of the 120 simulations (30 earthquakes, four velocity models) was run with a maximum frequency of 1 Hz and a minimum shear wave velocity of 200 m/s. The comparisons between data and synthetics were ranked quantitatively using standard seismological goodness-of-fit (GOF) criteria. The regional distribution of the GOF results for all events and models were analyzed and ranked according to the performance of each velocity model (Fig.1). The group identified one of the southern