Location-Dependent Space Weather Hazards of Societal Significance within the Earth-Ionosphere Waveguide

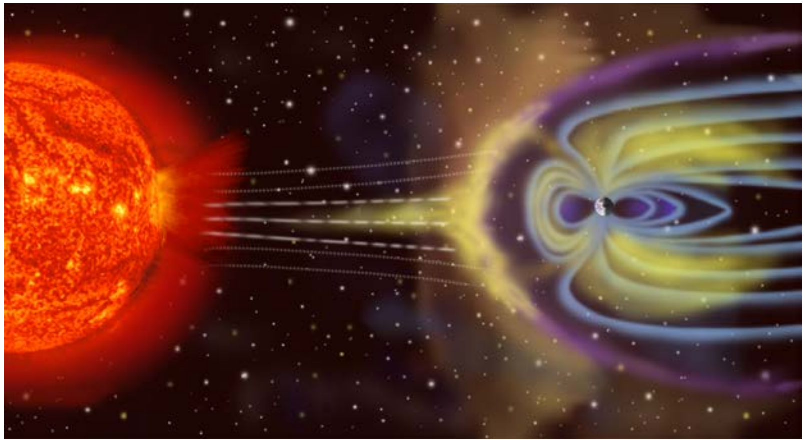
Jamesina Simpson, Associate Professor

Electrical and Computer Engineering Department, University of Utah, Salt Lake City, UT

URL: www.ece.utah.edu/~simpson

Historically Significant Coronal Mass Ejections (CMEs)

- Largest documented CME occurred in 1859:
  - Telegraph operators experienced nearly fatal electric shocks
  - Telegraphic business transactions were completely shut down in the world's major capitals.
- A (smaller) 1989 CME disrupted radio communications, satellite operations, transportation, banking, financial systems, and caused a nine-hour power failure of the HydroQuebec power grid. The overall economic cost was ~$13M.

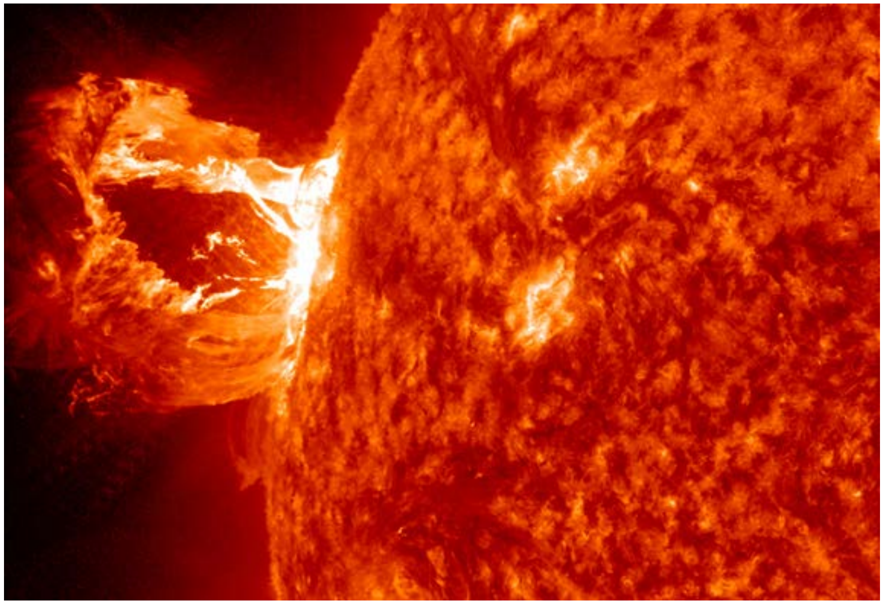


http://sec.gsfc.nasa.gov/popscise.jpg

Possibility of Future Extreme CME's

- A 2008 National Academy of Sciences (NAS) report estimates that the overall economic cost of one *extreme* CME event is in the trillions of dollars, with a recovery time of 4 – 10 years.

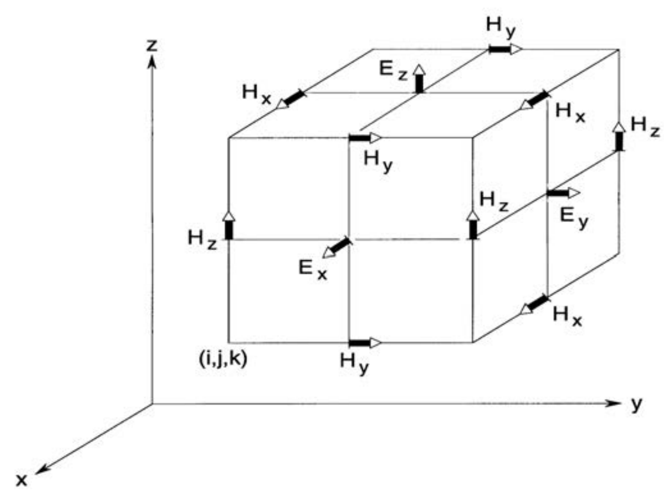
- The NAS report also states that although extreme events are rare, they are likely to occur again in the near future.



http://sec.gsfc.nasa.gov/popscise.jpg

Goal of Our Research

- Our goal is to significantly improve our understanding of space weather hazards to:
  - Electric power grids
  - Electromagnetic wave propagation up to ~20 kHz in the Earth-ionosphere waveguide
- The finite-difference time-domain (FDTD) method is used to solve Maxwell's equations within the global annular volume in unprecedented detail.



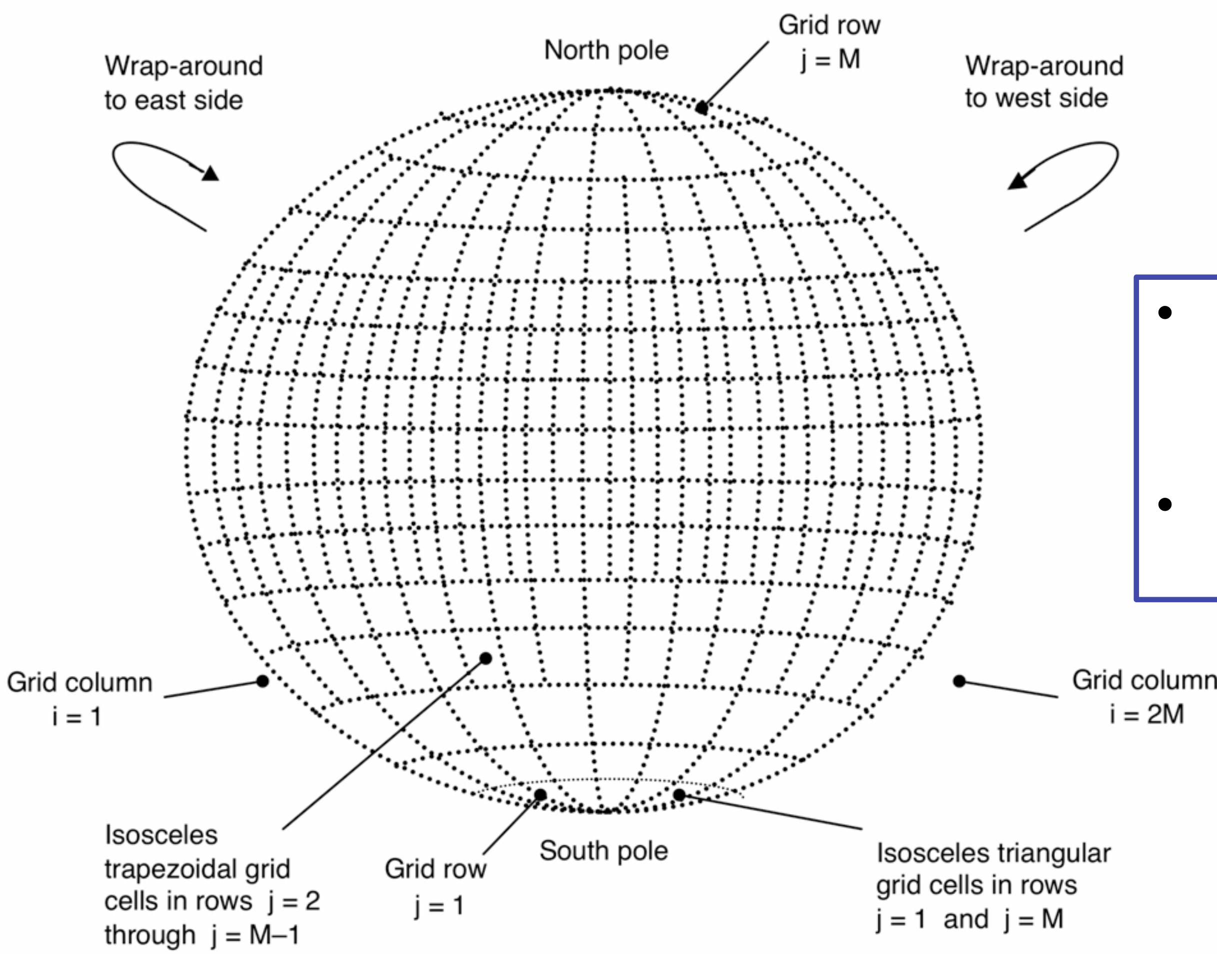
FDTD Applied to the Global Earth-Ionosphere Waveguide

- Our models have been developed over the past 15+ years.
- Example applications include:
  - Schumann resonances
  - Geolocation
  - Remote sensing of ionospheric disturbances
  - Hypothesized earthquake precursors
  - Remote-sensing of subsurface structures (within the lithosphere or oceans)

Some Key Advantages of Using FDTD

- Includes 3-D spatial variations of the ionosphere, topography, oceans, geomagnetic field…
- Permits modeling of the realistic spatial and time variation of disturbed ionospheric currents
- Calculates all important ionospheric effects on signals, including absorption, refraction, phase and group delay, frequency shift, polarization, and Faraday rotation.

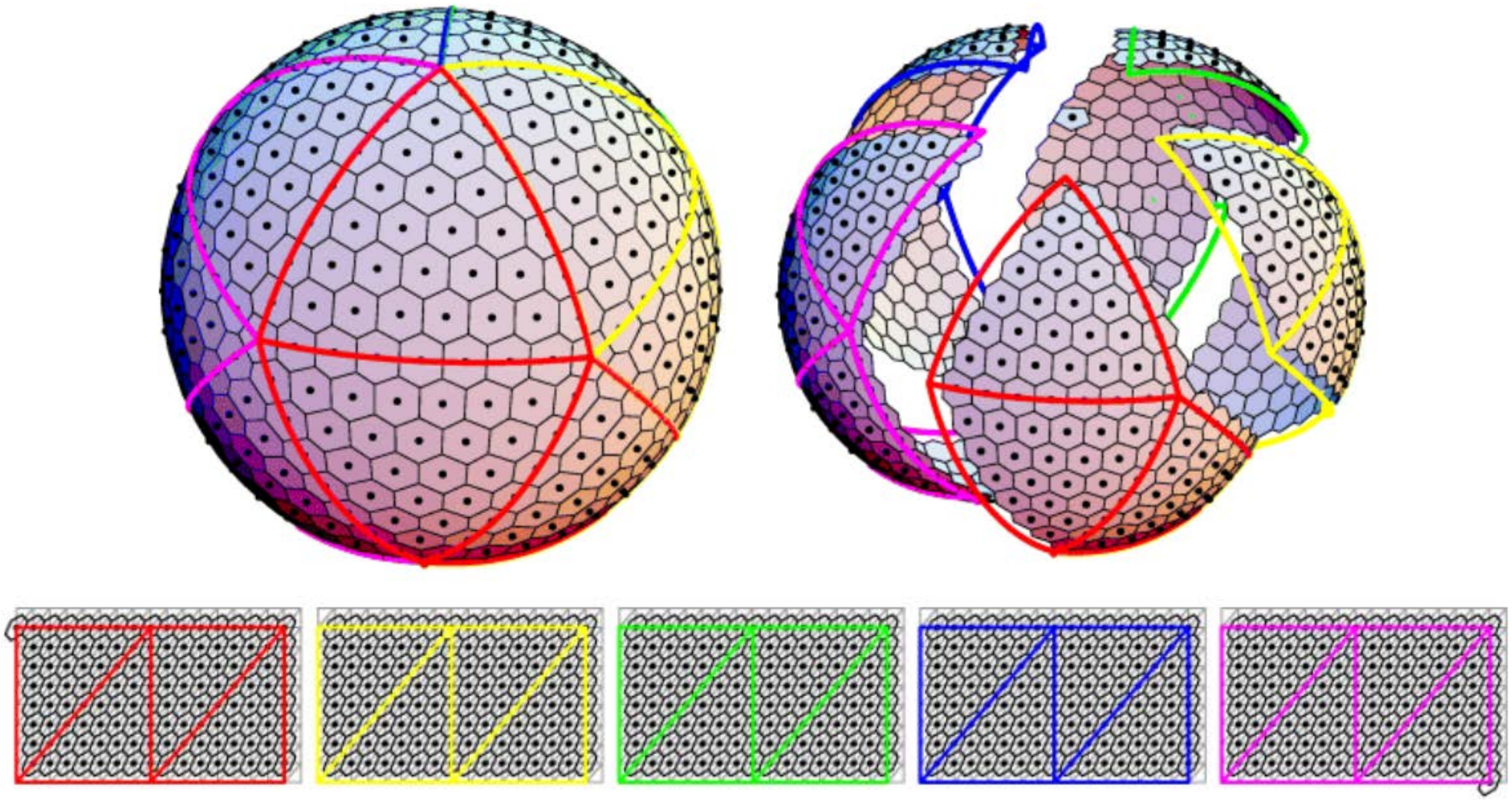
Generation #1: A 3-D Latitude-Longitude Global Model



- Extends radially inward and outward from the Earth's surface.
- Includes the continents, oceans, and ionosphere.

Source: Simpson & Taflove, *IEEE Trans. Ant. Prop.*, pp. 443-451, 2004.

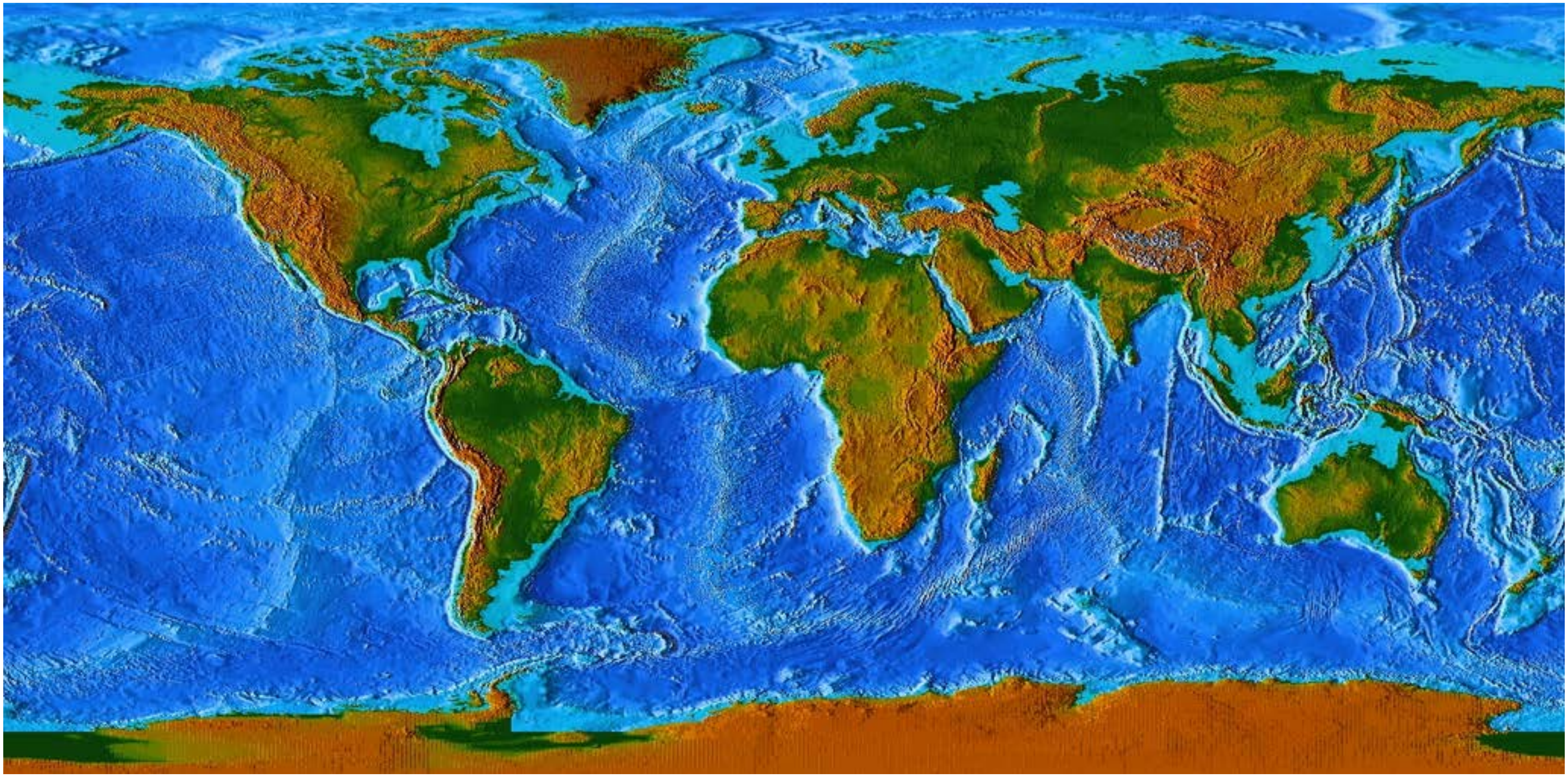
Generation #2: An Efficient Geodesic Global Model



Unfolding of grid cells for parallel-processing on a supercomputer.

Sources: [1] Simpson & Taflove, *IEEE Trans. Ant. Prop.*, pp. 1734-1741, June 2006.
[2] D. A. Randall et. al., *Comput. Science and Eng.*, pp. 32 – 41, Sept./Oct. 2002.

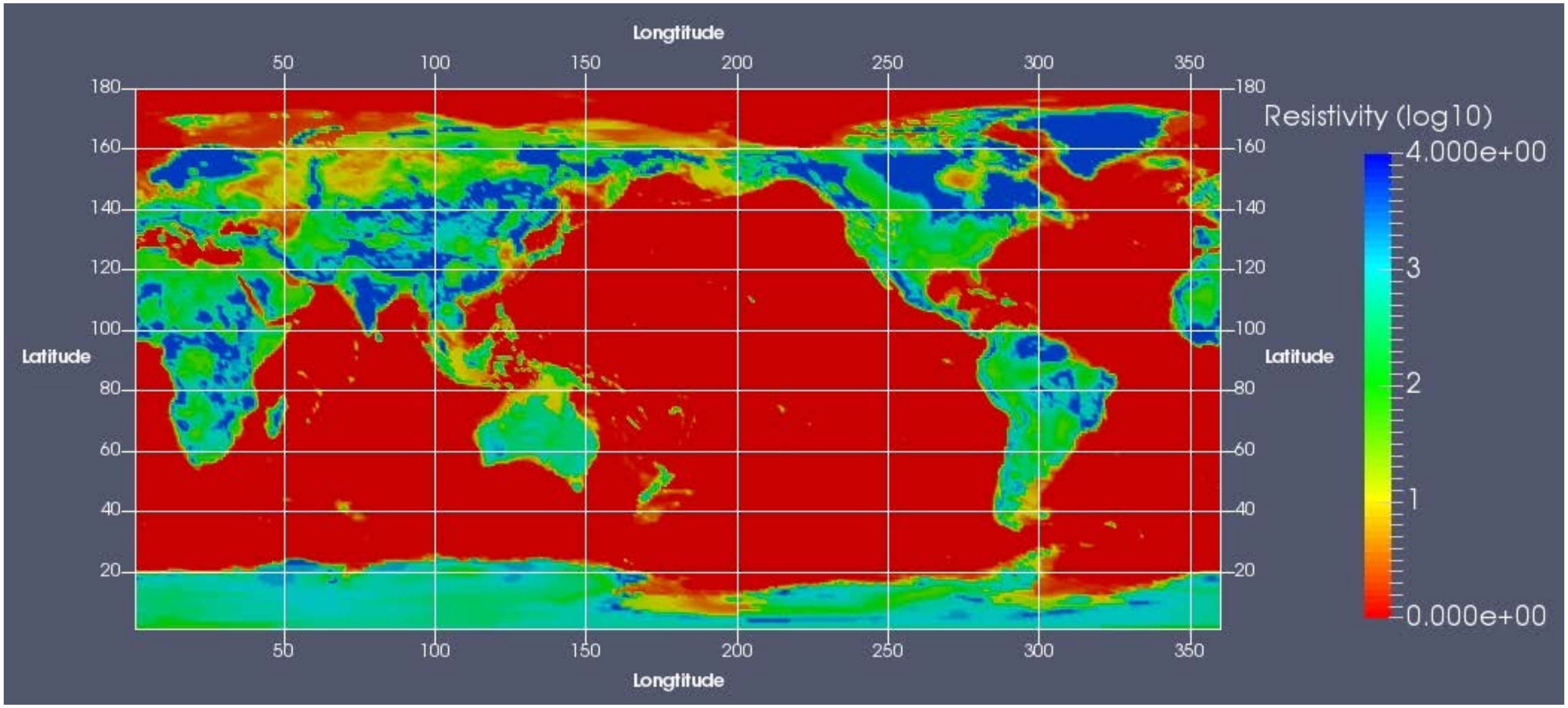
Topography and Oceans Modeled



Source: *mapsnet.org and ngdc.noaa.gov/mgg/topo*

Example 3-D Global Lithosphere Data

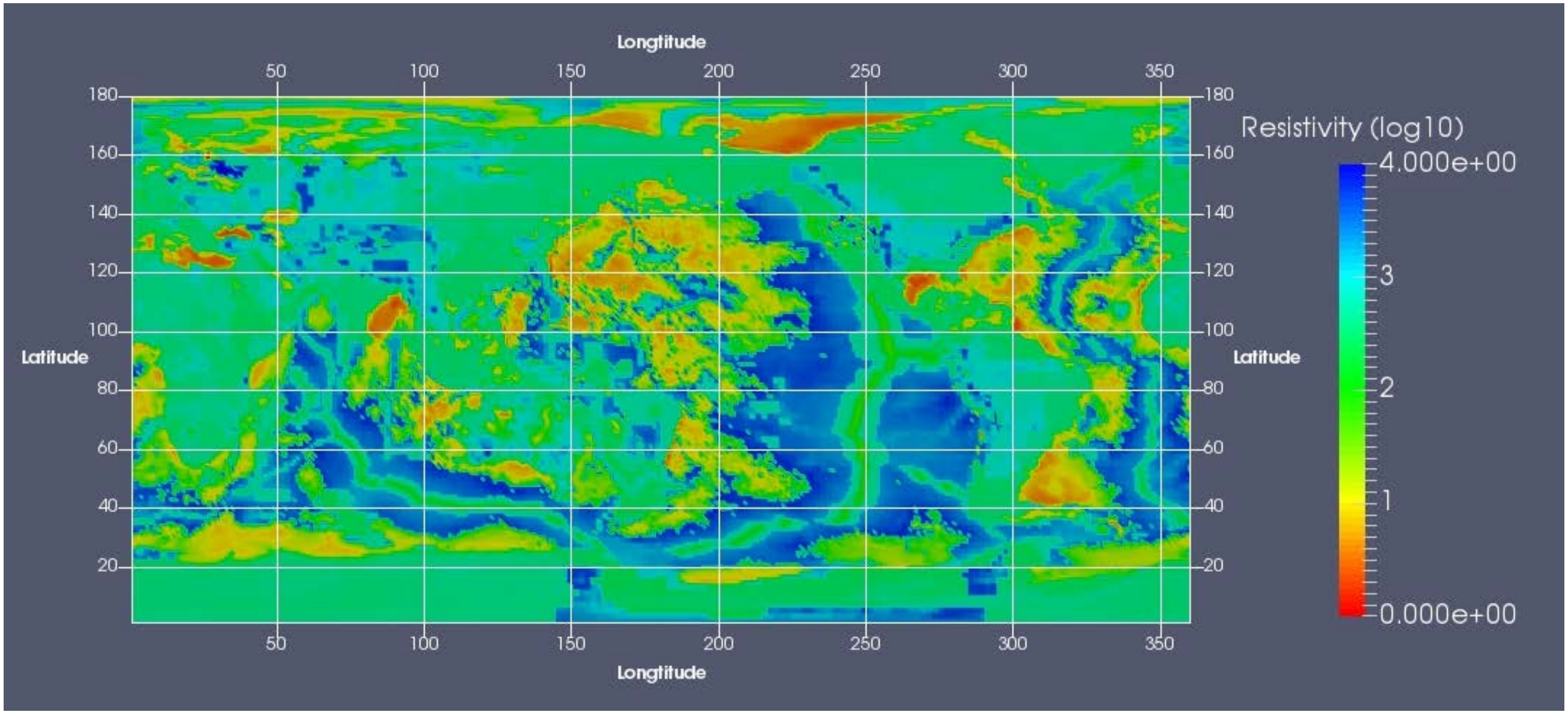
0 – 5 km Depth



Source: Alekseev *et al., Earth, Planets, Space*, 7:108 (2015)

Example 3-D Global Lithosphere Data

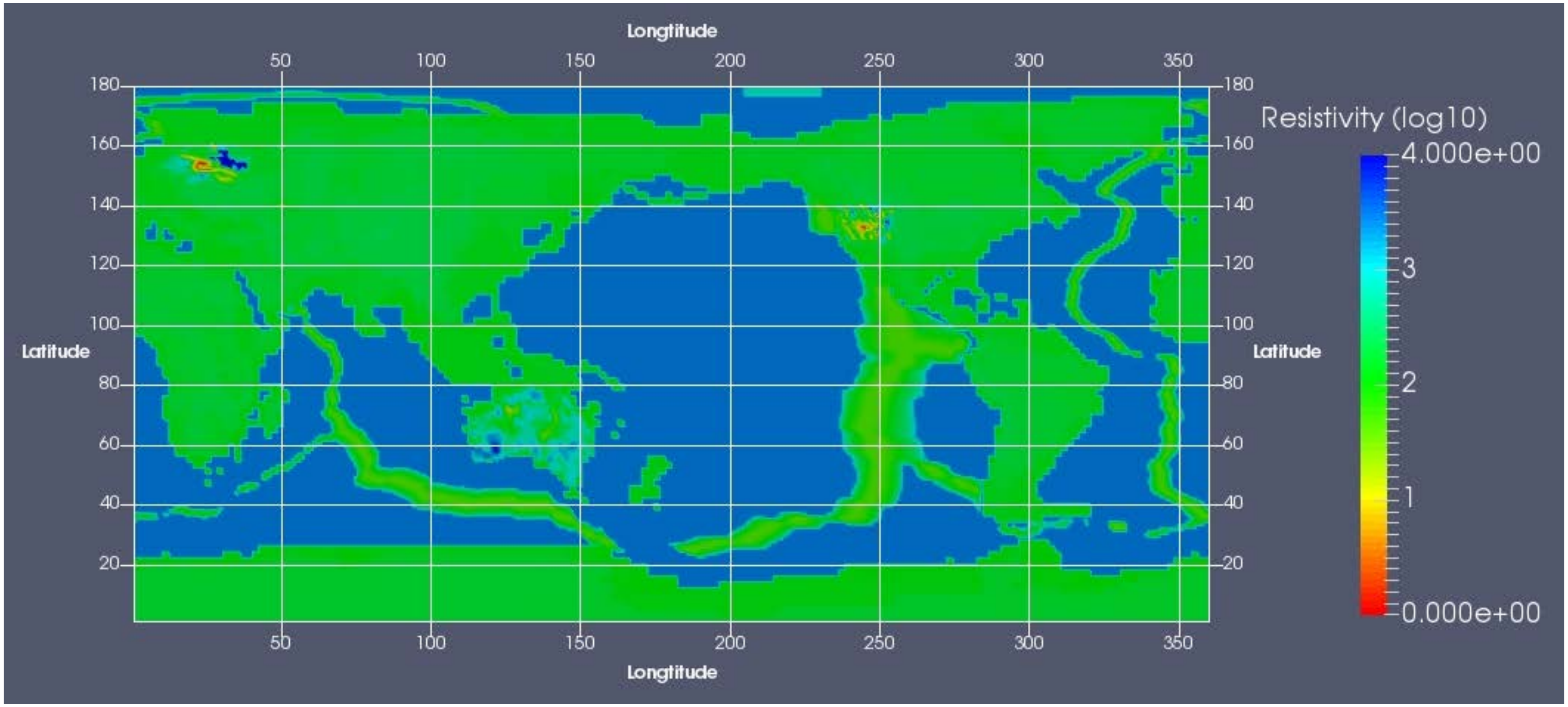
5 – 20 km Depth



Source: Alekseev *et al., Earth, Planets, Space*, 7:108 (2015)

Example 3-D Global Lithosphere Data

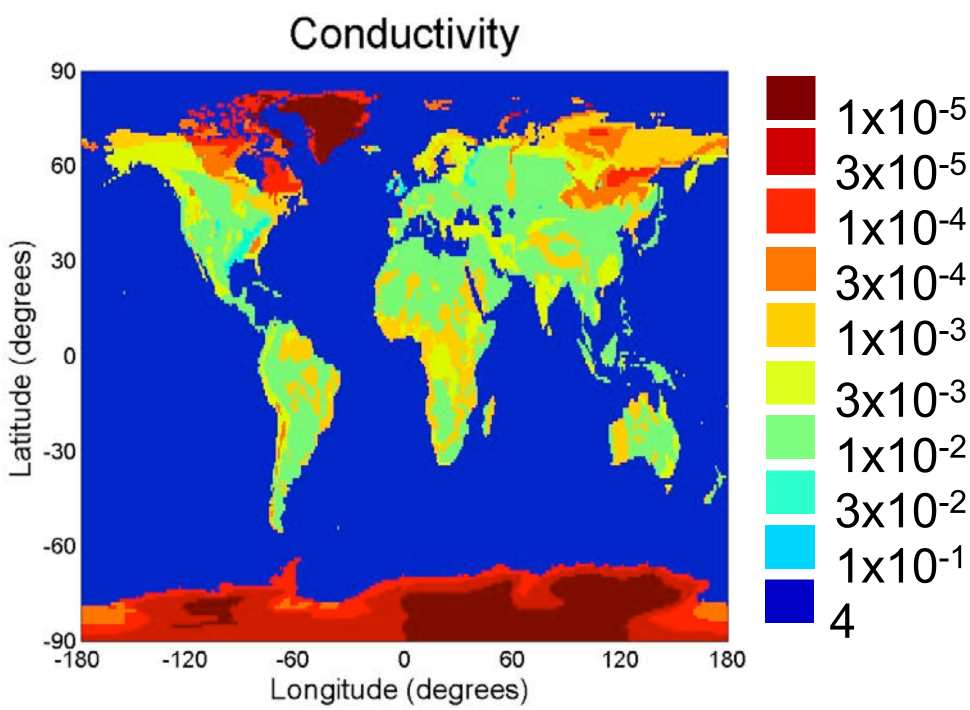
20 – 45 km Depth

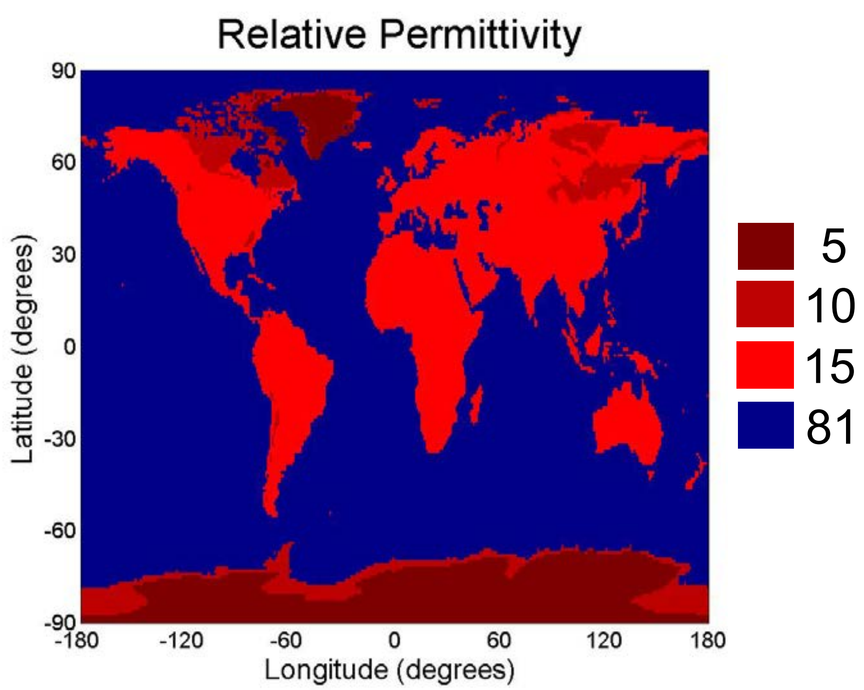


Source: Alekseev *et al., Earth, Planets, Space*, 7:108 (2015)

Alternative: Surface Impedance Boundary Condition (SIBC)

- Calculates the fields outside a lossy dielectric or conducting structure without having to model its interior.
- Significantly reduces the computational requirements.
- Employ at the Earth's surface to account for oceans and continents.



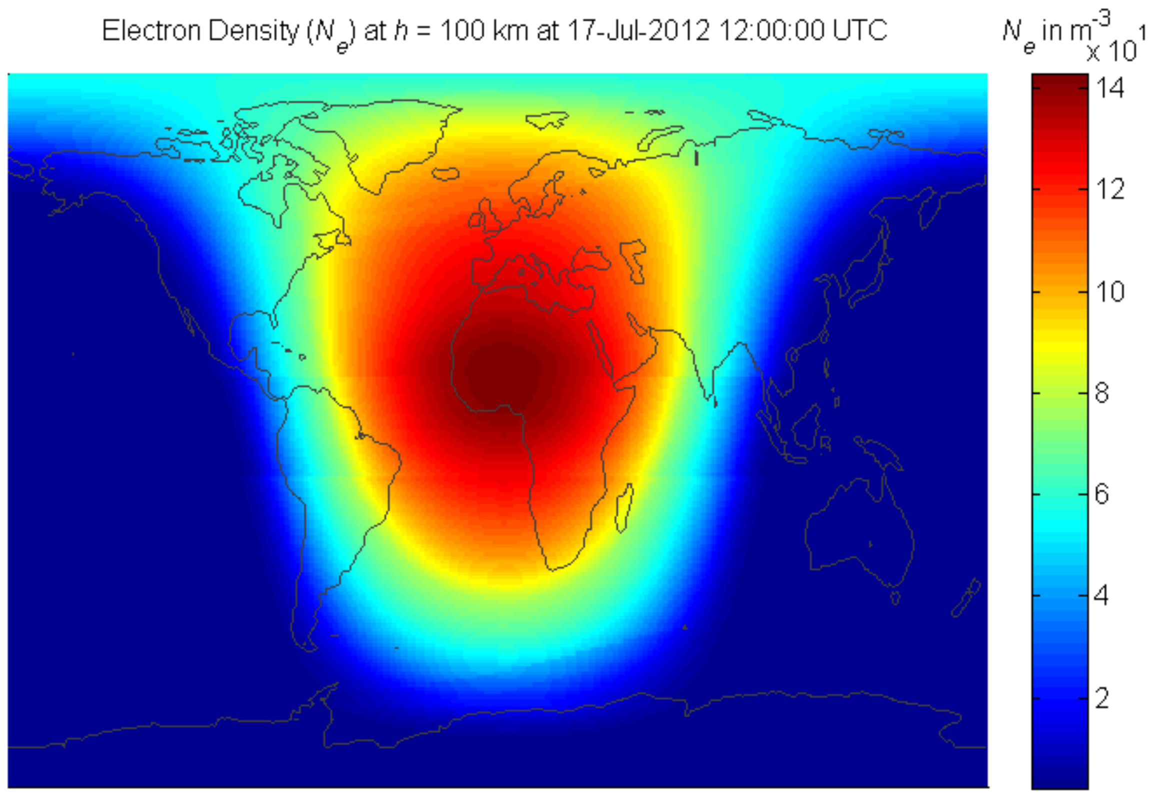


Source: Numerical values extracted from LWPC for VLF propagation.

Magnetized Ionospheric Plasma Algorithm Input

International Reference Ionosphere (IRI):

- Provides global electron density & ion composition estimates vs. altitude and position
- Data sources include ionosondes, incoherent scatter radars, in situ measurements, etc.

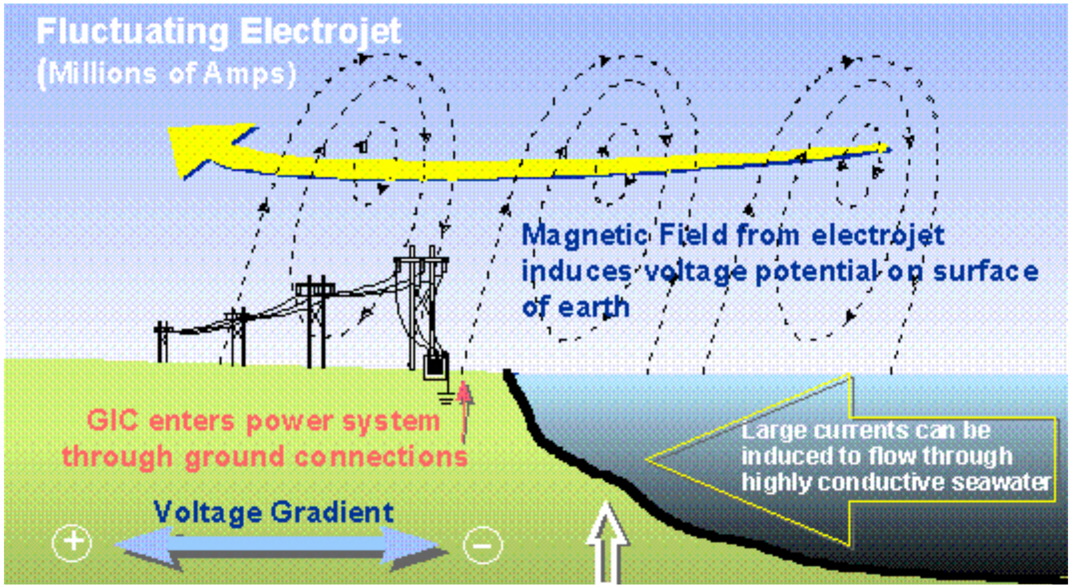


ccmc.gsfc.nasa.gov/modelweb/ionos/iri.html

Topic 1: Geomagnetically-Induced Current (GIC) Hazards to Electric Power Grids

- Flow along electric power-transmission systems and other electrically-conducting infrastructure

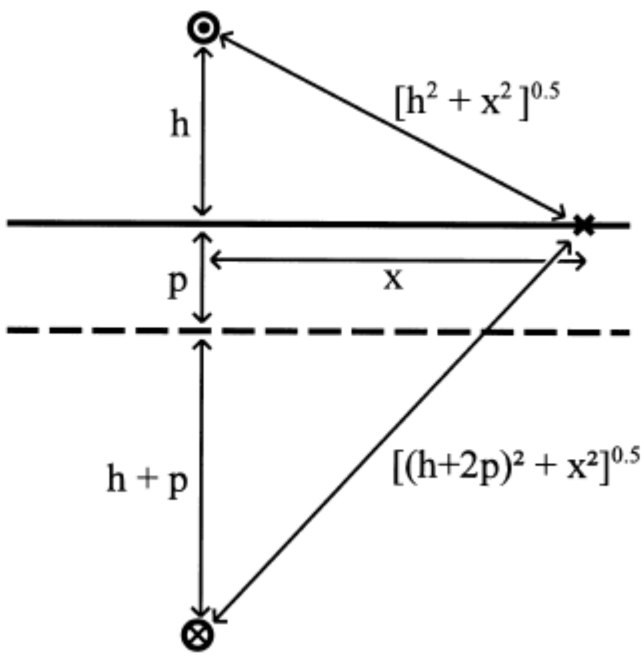
- On average, 200 days of strong to severe geomagnetic storms that could produce GICs can be expected during a typical 11-year solar cycle [DoE-NERC, 2010]

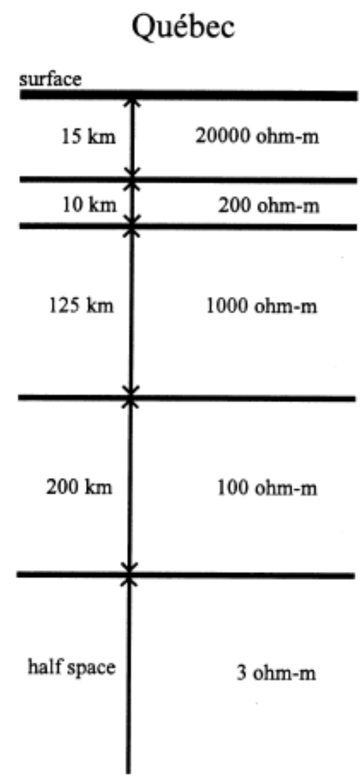


J. Kappenman

Current Approaches for Estimating Surface-Level EM Fields for GIC Calculations

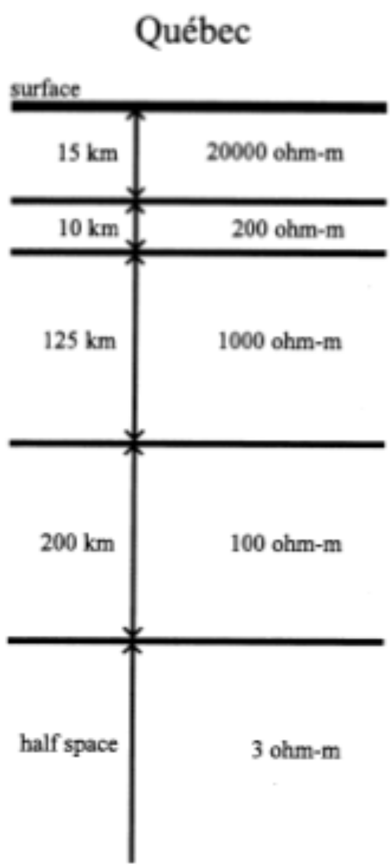
- Biot-Savart Law
- Complex-image theory
- Method of auxiliary sources
- Plane-wave method
- Finite element method





These approaches involve localized solutions, simplified geometries, simplified physics, steady-state conditions, etc.

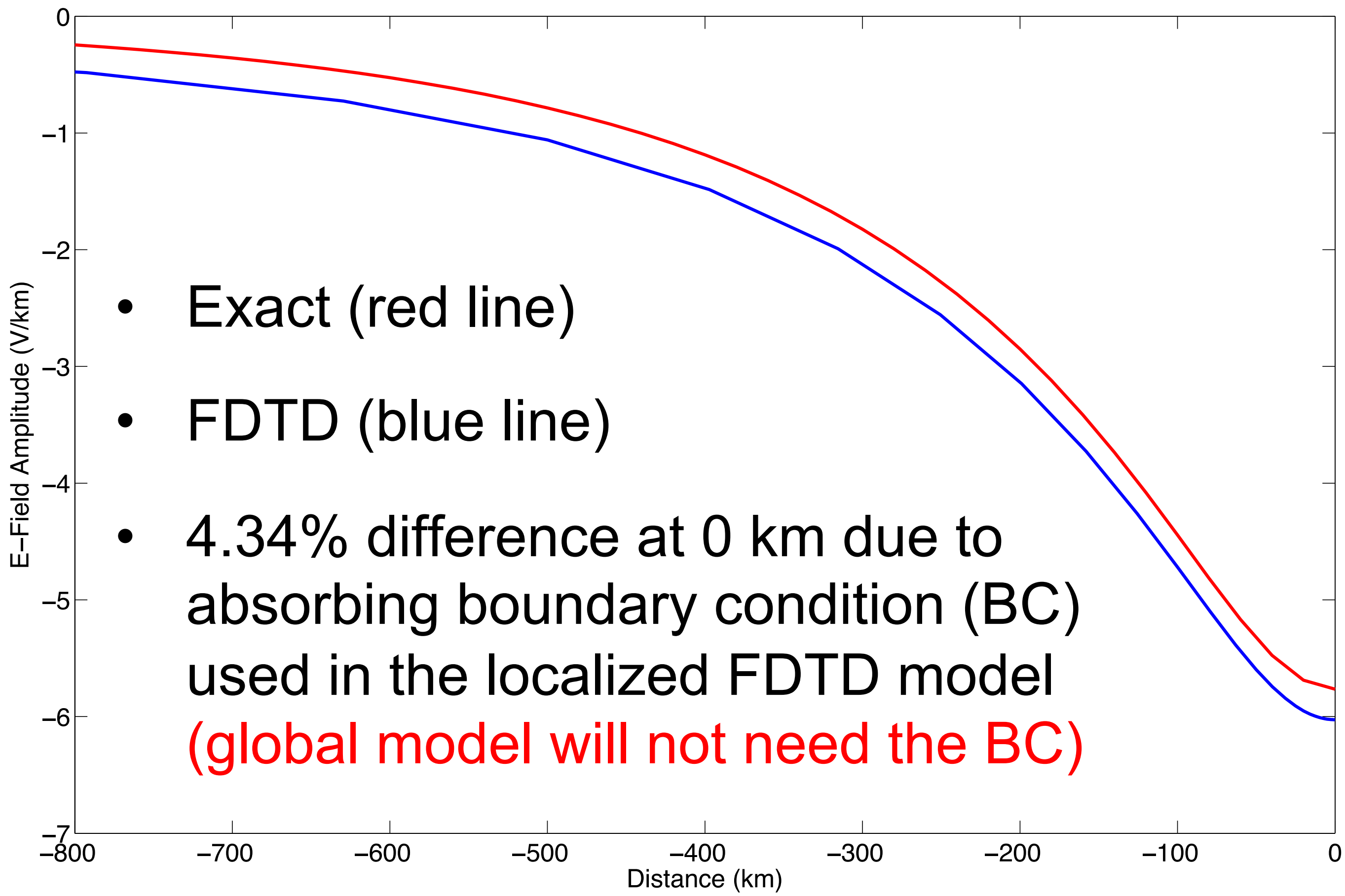
Initial Validation of FDTD Applied to GICs



- Infinite line current 100 km above the Earth's surface
- 1 million amps
- Period of 5 minutes

Source: Boteler & Pirjola, *Geophys. J. Int.*, 132:31-40, 1998.

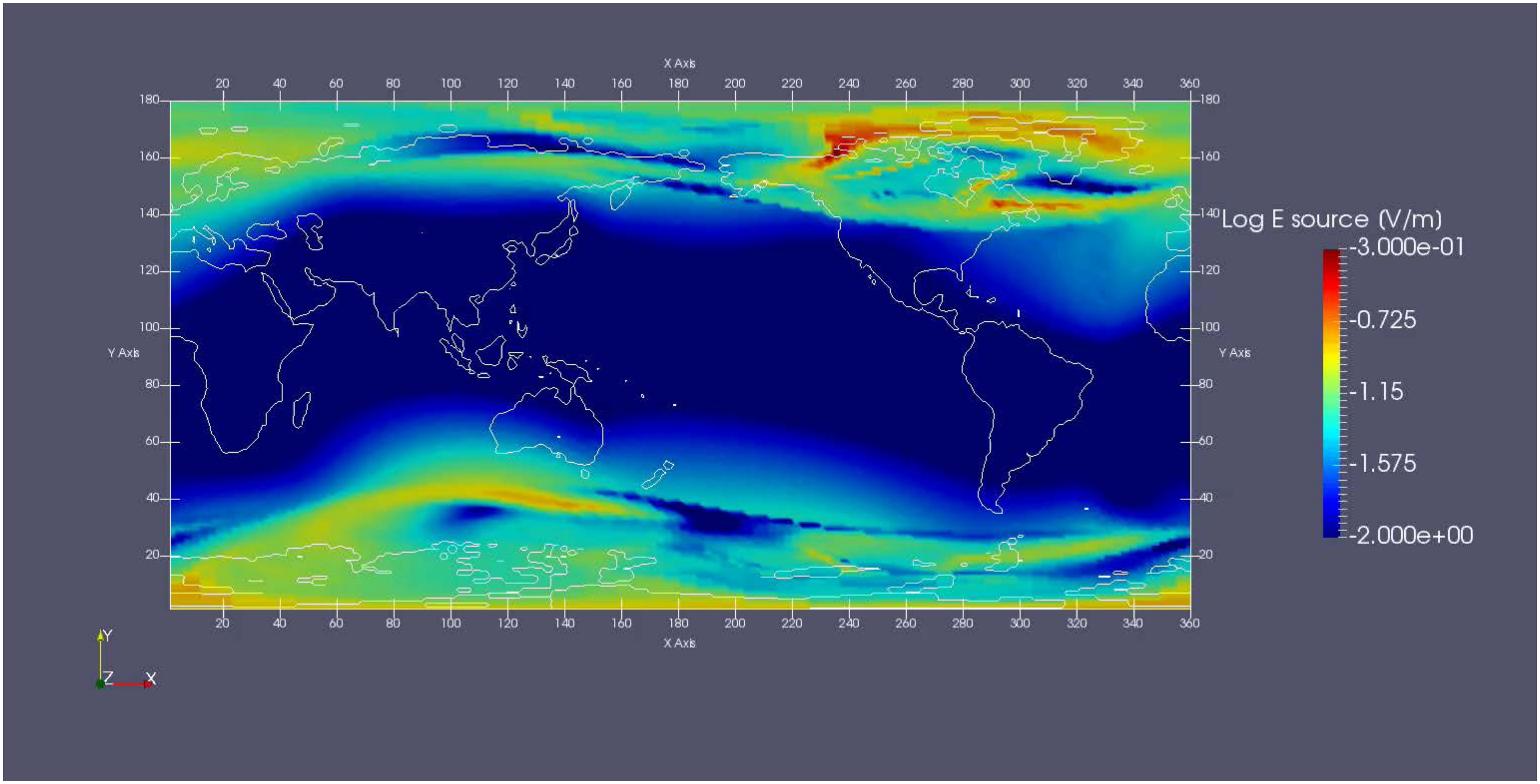
Comparison of FDTD with Exact Analytical Solutions



- Exact (red line)
- FDTD (blue line)
- 4.34% difference at 0 km due to absorbing boundary condition (BC) used in the localized FDTD model (global model will not need the BC)

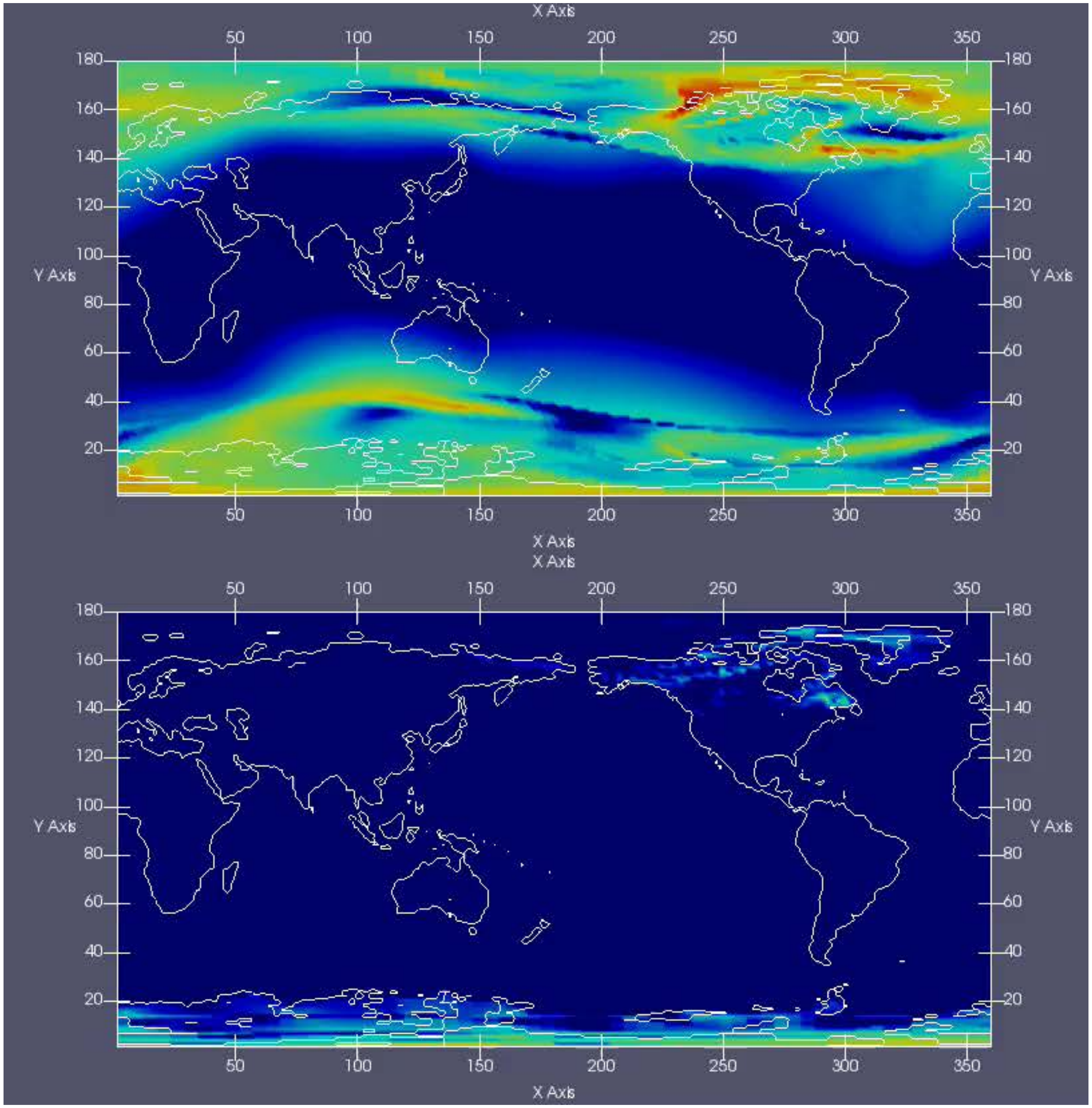
Source of red line: Boteler & Pirjola, *Geophys. J. Int.*, 132:31-40, 1998.

Realistic 3-D Disturbed Ionospheric Currents are the Sources of EM Waves in the Global FDTD Grid

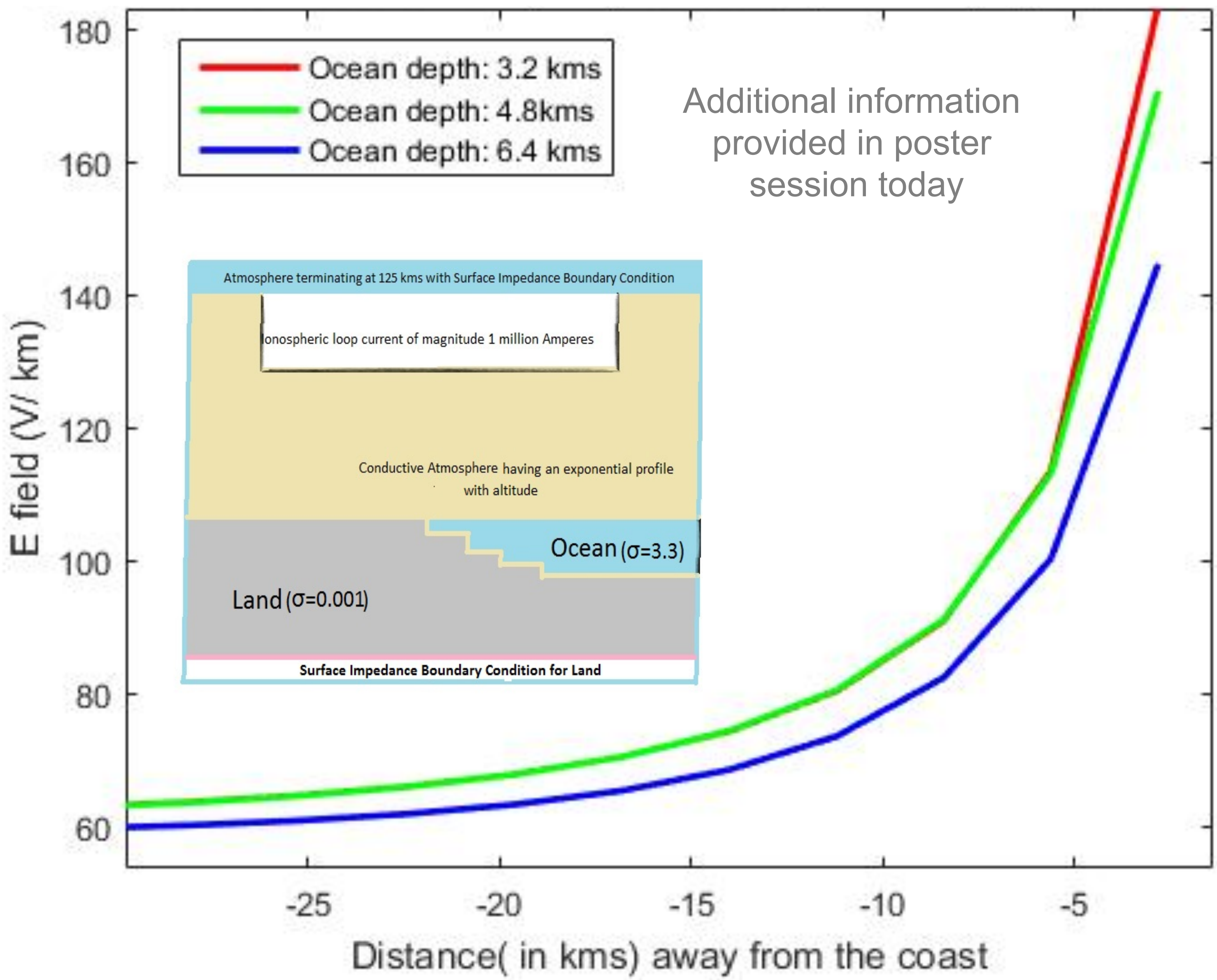


BATS-R-US data courtesy of Daniel Welling, University of Michigan

Global Surface EM Fields Calculated vs. Time



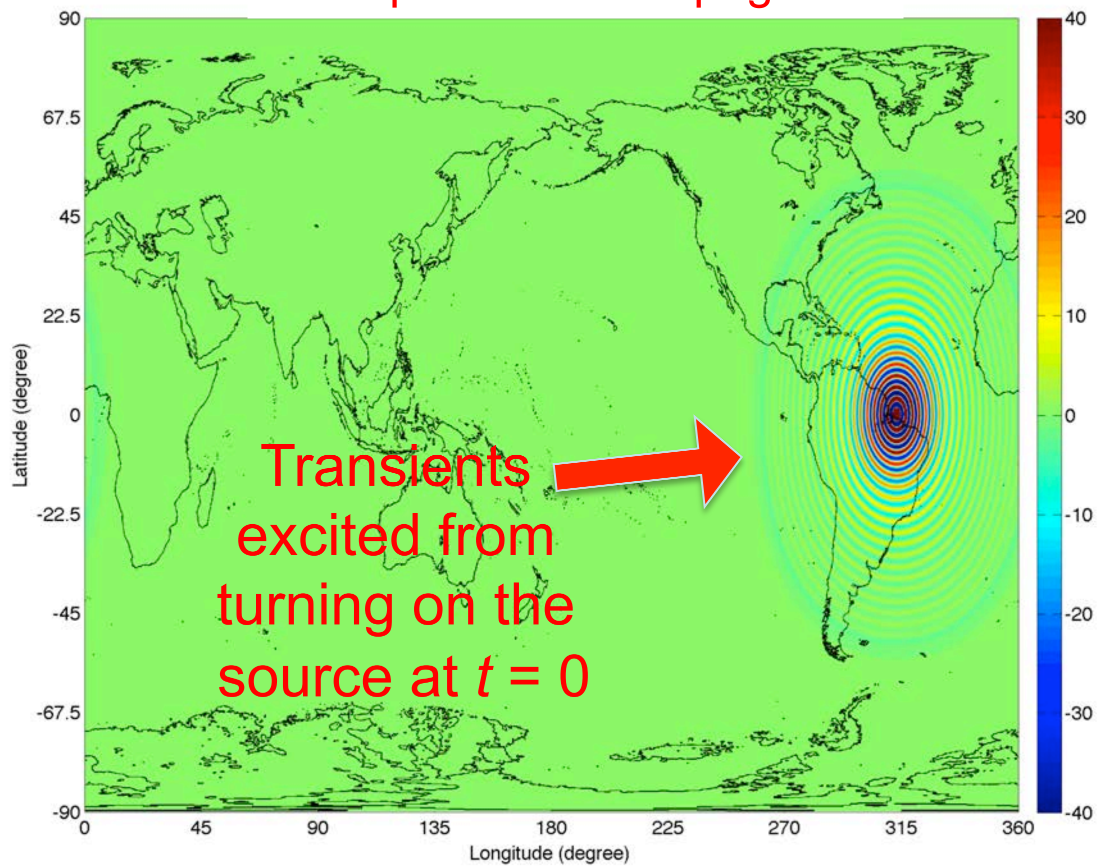
Potential Hazards Posed by Ocean-Continent Boundaries



Topic 2: Space Weather Effects on Very Low Frequency Propagation

- Increased the global FDTD grid resolution from ~40 x 40 x 5 km down to ~1.25 x 1.25 x 3 km
- Model from the Earth's surface to an altitude of +100 km
- Propagated frequencies up to 11 kHz so far

Example Global Propagation

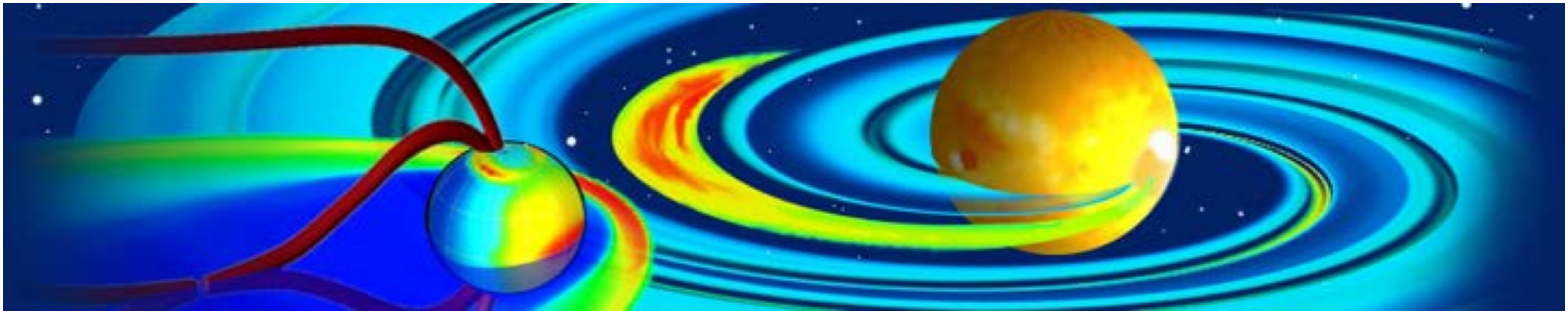


Advantages of using BW in Our Research

- Increase the grid resolution to ~1 x 1 x 3 km worldwide (previous resolution was 40 x 40 x 5 km).
  - Simulate frequencies up to ~20 kHz for the first time on a global scale
  - Provide location-specific space weather hazard information:
    - Ocean-continent boundary effects (requires high resolutions near boundaries)
    - Regions of low conductivity rock
    - Realistic 3-D disturbed ionospheric currents
    - Day vs. night
    - Polar regions vs. equatorial regions

Nominal Lateral Resolution	# Cells in East-West Direction along Equator	# Cells in North-South Direction	Total Cells per Radial Coordinate	Maximum Δt (assuming 1 km radial resolution)
300 m x 300 m	131,072	65,536	6,698,637,136	0.37 μsec
600 m x 600 m	65,536	32,768	1,674,680,144	0.73 μsec
1.2 km x 1.2 km	32,768	16,384	418,649,936	1.3 μsec

Global FDTD Model at CCMC



We are working to make our FDTD global Earth-ionosphere models available through the NASA's Community Coordinated Modeling Center (CCMC), joining a wide range of sun-to-earth models.

- Researchers around the world can request simulation runs
- An executable is used to run the requested simulation

http://ccmc.gsfc.nasa.gov/index.php

Conclusion

- BW has been instrumental in allowing us to model the global Earth-ionosphere waveguide at unprecedented detail. For the first time, we were able to model frequencies in the very low frequency range (3 – 30 kHz) on a global scale.
- Ongoing access to petascale supercomputers will allow us to further improve our hazard predictions, by allowing us to extend the model through the ionosphere, couple to models of the magnetosphere, etc.

Acknowledgements

- Blue Waters sustained-petascale computing project, supported by NSF (OCI-0725070 and ACI-1238993) and the State of Illinois. (Through NSF award number ACI-1440023).

- DARPA and Air Force research grants.

- National Science Foundation CAREER Award (2010 – 2015, #AGS-0955404).

- University of Utah's Center for High Performance Computing.

Jamesina J. Simpson, Associate Professor
ECE Dept., University of Utah
Salt Lake City, UT USA
Email: jamesina.simpson@utah.edu
URL: www.ece.utah.edu/~simpson