Impacts of Extreme Space Weather Events on Power Grid Infrastructure: Physics-Based Modeling of Geomagnetically Induced Currents (GICs) During Carrington-Class Geomagnetic Storms

PI: Michael Henderson (ISR-1) **Co-PI: Michael Rivera (A-1)**

Co-Investigators:

ISR-1:
Vania Jordanova
Steve Morley
Jesse Woodroffe
Miles Engel (PD)

A-1:
Russell Bent
Scott Backhaus

USGS:
Jeff Love*

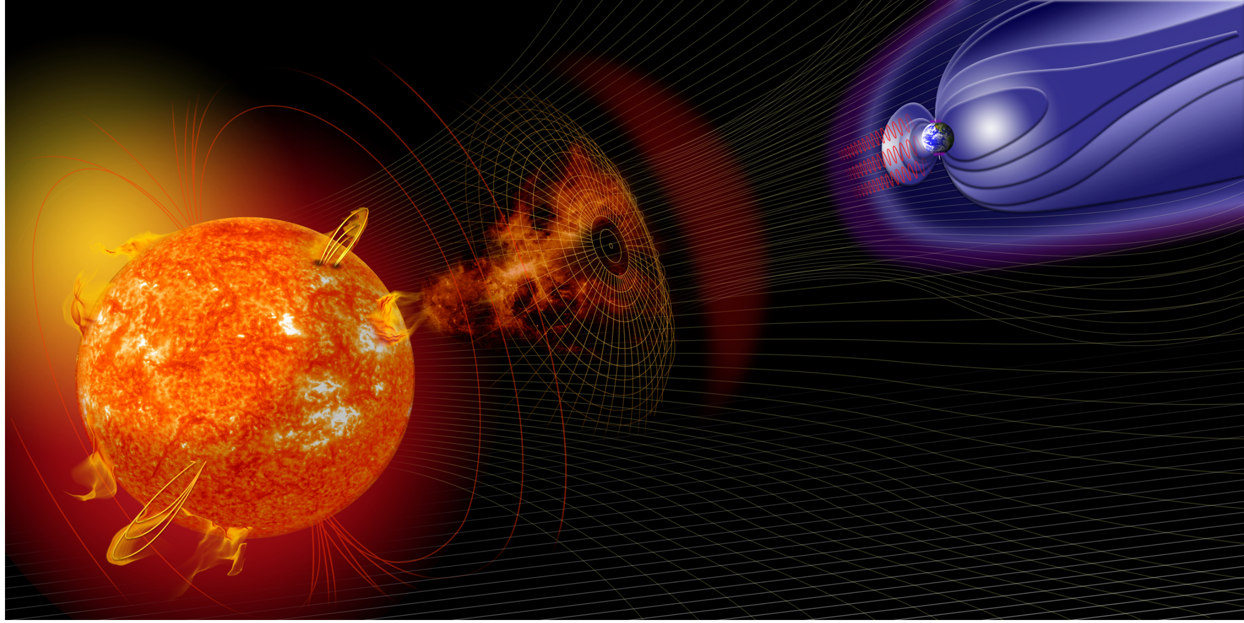
ISR-2:
Chris Jeffrey

U Michigan:
Dan Welling
Gabor Toth

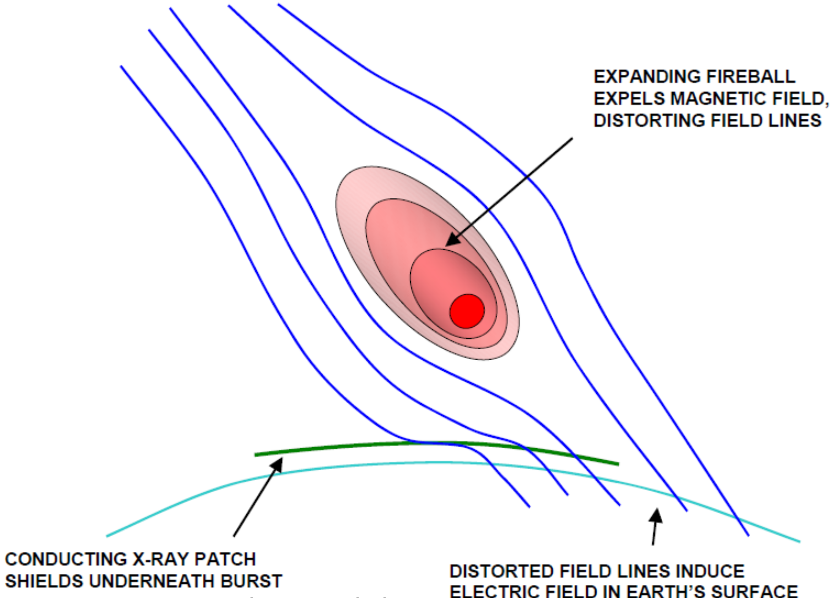
T-5:
Humberto Godinez
Gian Luca Delzanno

APL:
Brian Anderson*

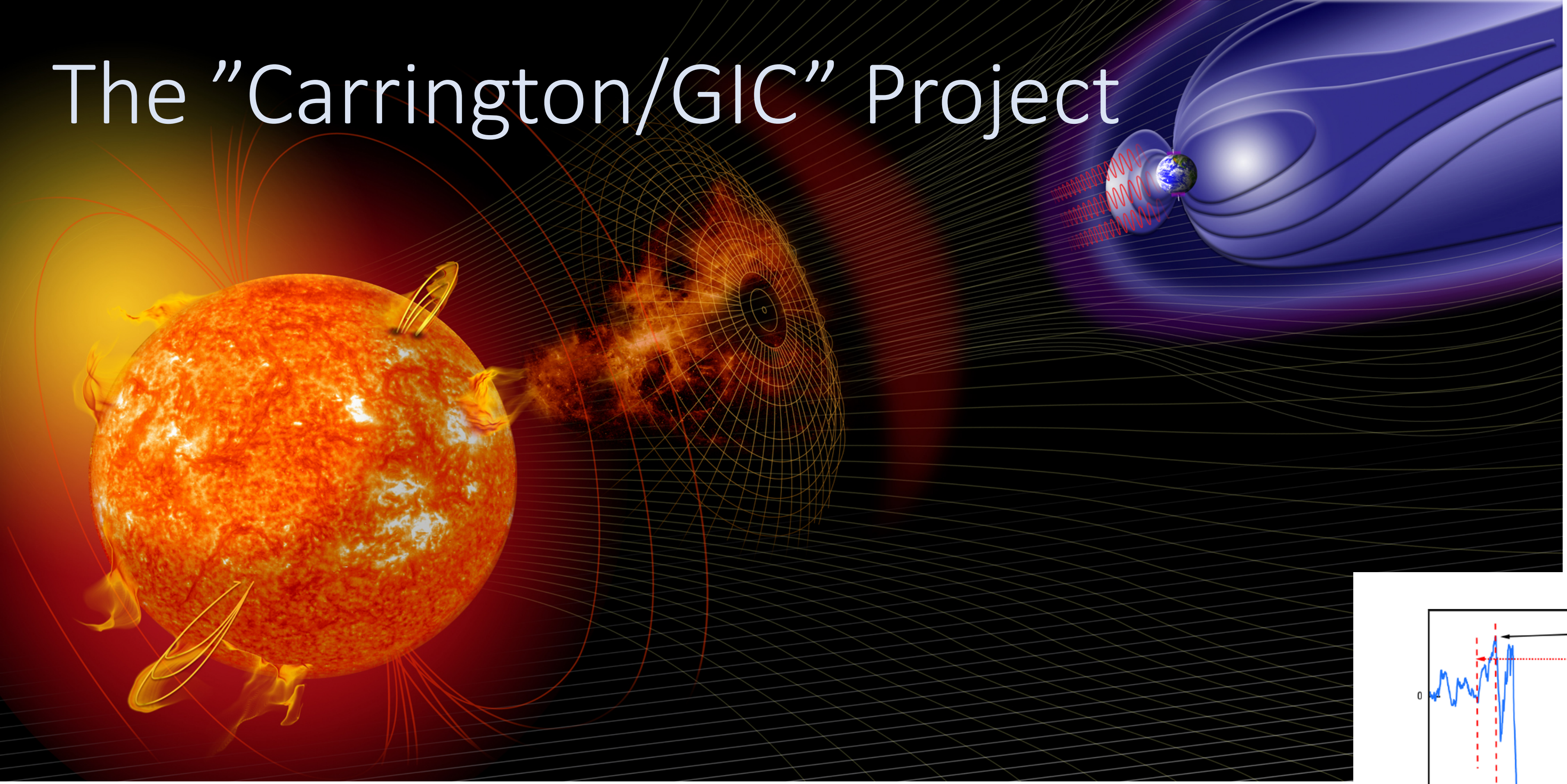
Geo-Magnetic Disturbances (GMDs) can come from Space Weather or EMP/E3



- GMDs can come from storms (CMEs.) Perturbations are at and above ionosphere.
- Or nuclear explosions. Perturbations are between ground and ionosphere.
- The perturbations detected on the ground are similar for both sources and can impact power distribution systems similarly.

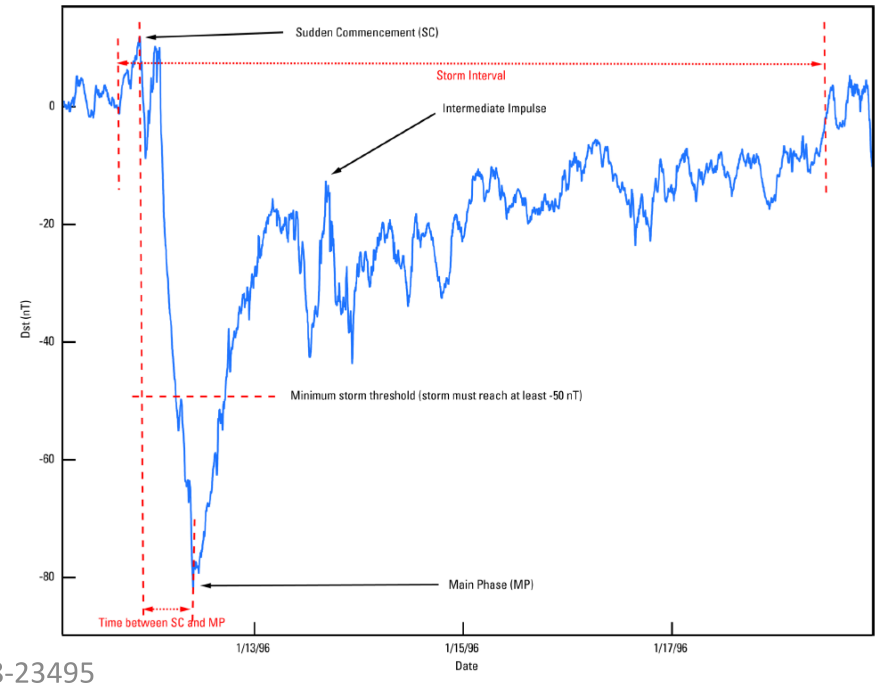


The "Carrington/GIC" Project



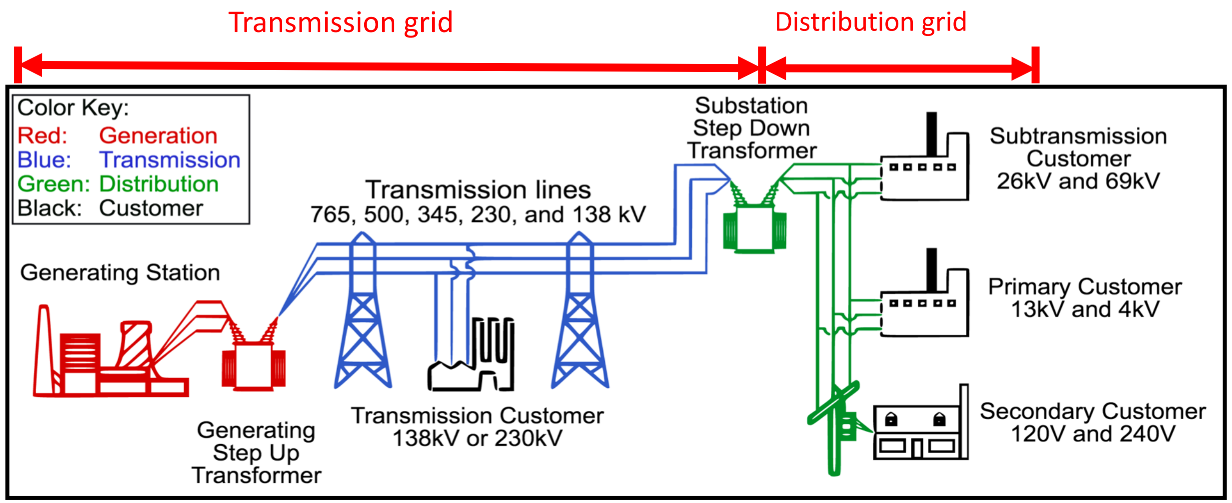
Ultimate goals are to:

- Simulate a Carrington-class storm.
- Assess its impacts on power grid infrastructure.
- Develop mitigation strategies.

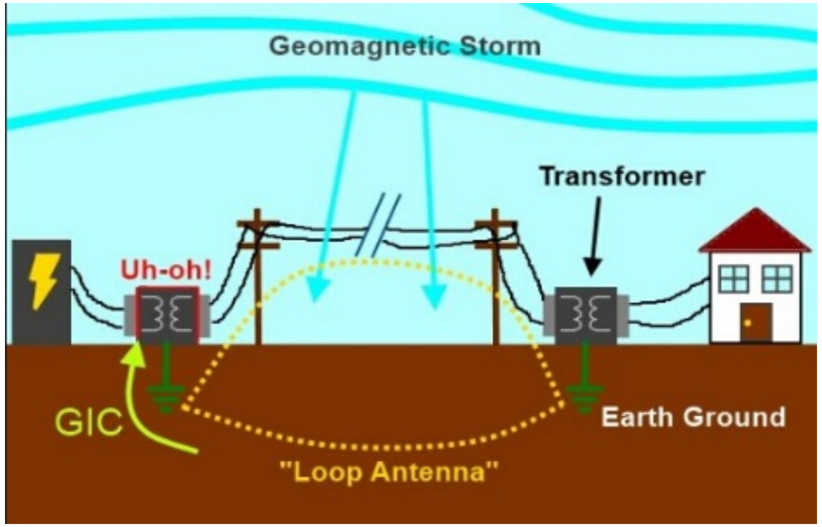


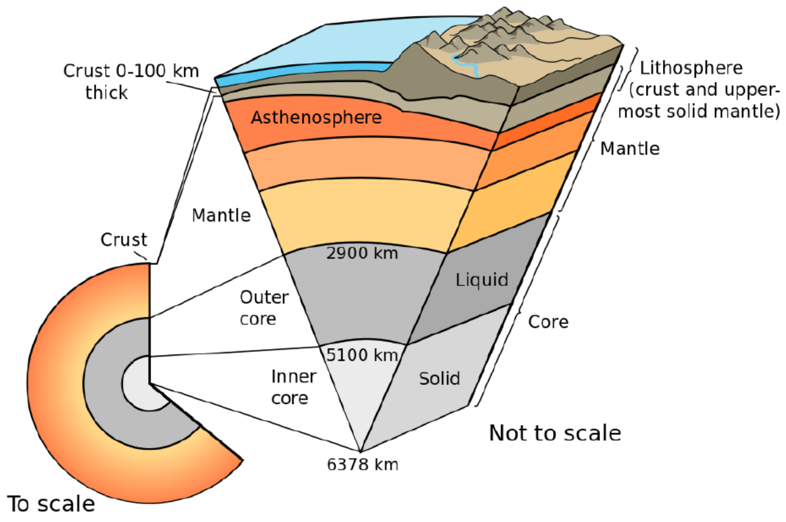
- The strongest geomagnetic storms are due to CME impacts.
- The magnetopause becomes severely compressed on the dayside. For large events this breaks many existing models.
- The nightside tail dynamics become dramatically enhanced due to magnetic reconnection in the "tail". Substorm physics and coupling to the inner magnetosphere is still not well represented in the global models.

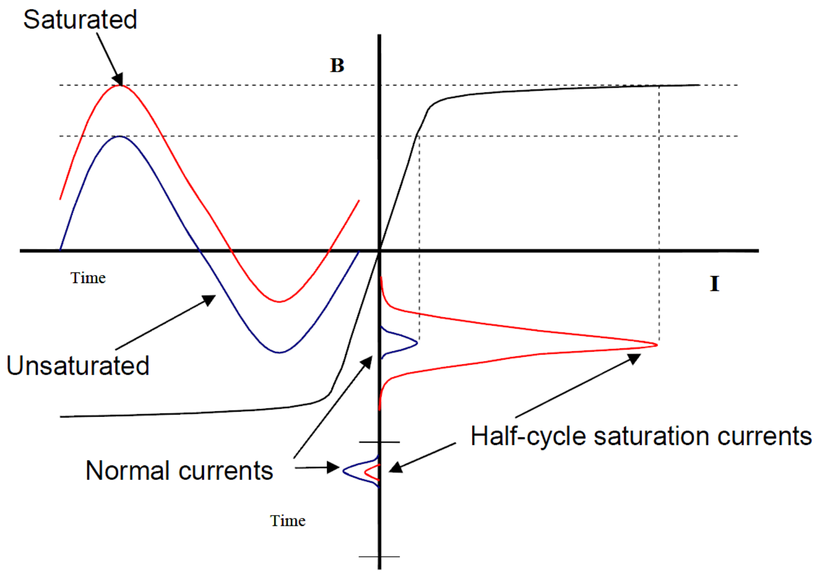
Power Grid Basics and and Geo-magnetically Induced Currents (GICs)



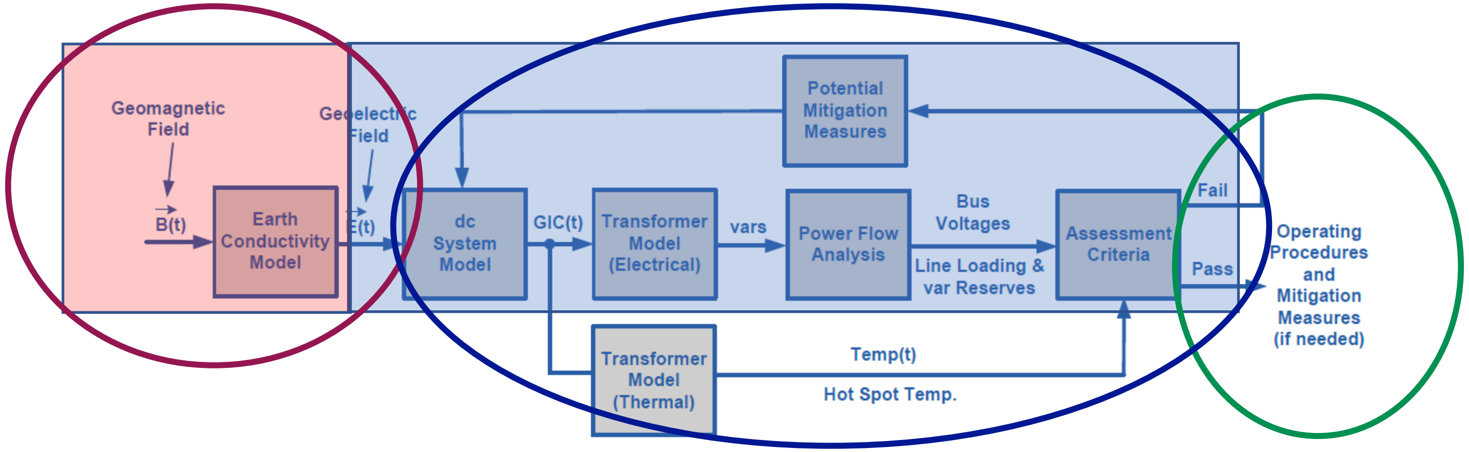
- Generator Step-Up (GSU) and Substation Step-Down Transformers are the most susceptible.
- They are grounded and form large "loop antennas" in which GMDs induce currents to flow (called GICs.)
- Characteristics of the GMDs and of the 3D ground conductivity plays a crucial role in the complex interaction.
- GICs produce (quasi-) DC-offsets and transformer saturation. This can lead to: potentially catastrophic heating and; harmonic generation that can interfere with the proper operation of protective devices.







Current NERC GMD event planning work flow (TPL-007-1)



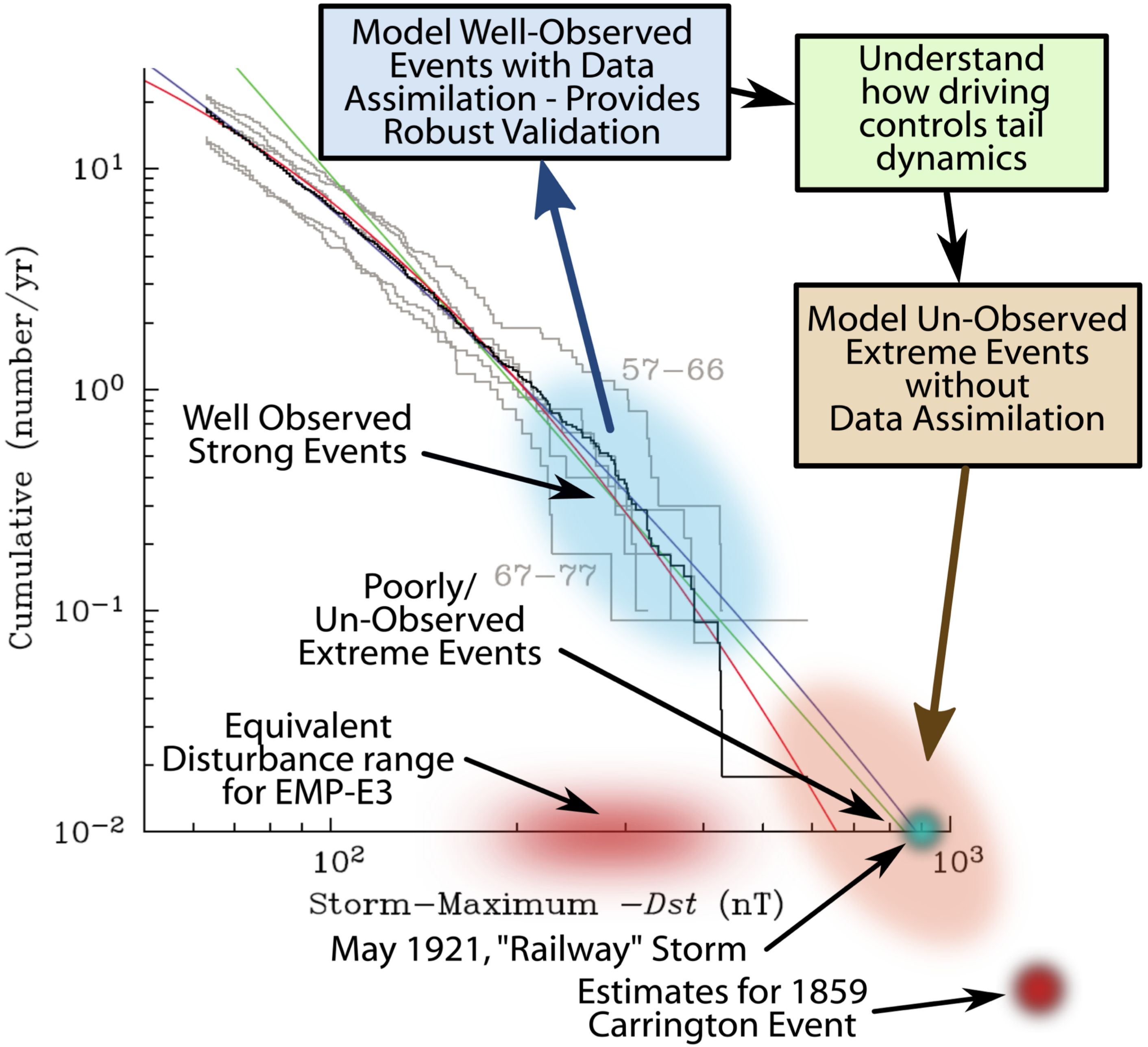
- Capturing space weather to the ground-level electric field has three basic steps that scales a measured event (1989 QH) to the region of interest:
    1. Approximate the strength of a 1 in 100 year storm
    2. Scale storm strength by 1D local ground conductivity
    3. Scale storm strength by magnetic latitude

- The resultant uniform electric field is applied to the transmission network of interest and impacts are assessed.

- Mitigation measures are introduced “by hand” until a network configuration that is stable to induced GIC is found.

Main Goals of the LANL Carrington/GIC Project

- Improve models to accommodate extreme storm conditions.
- Use observations to guide model solutions for well-observed weak to strong events. Scale up to Carrington-class events.
- Improve dB/dt calculations on the ground.
- Assess impacts on power grid infrastructure from Carrington-class storm events.
- Actively determine power grid network configurations that optimize resiliency to GICs.



How do you Validate a Modelled Carrington-Class Event?

Short answer: You cant really.

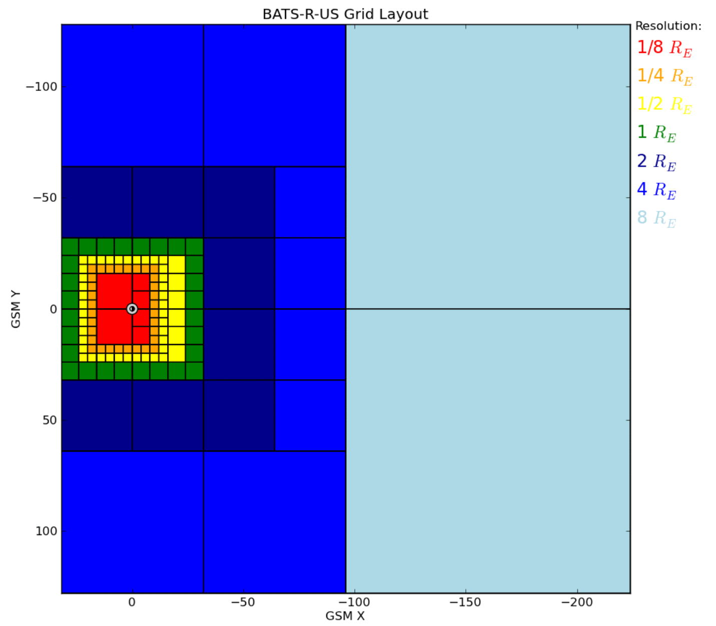
Next best thing:

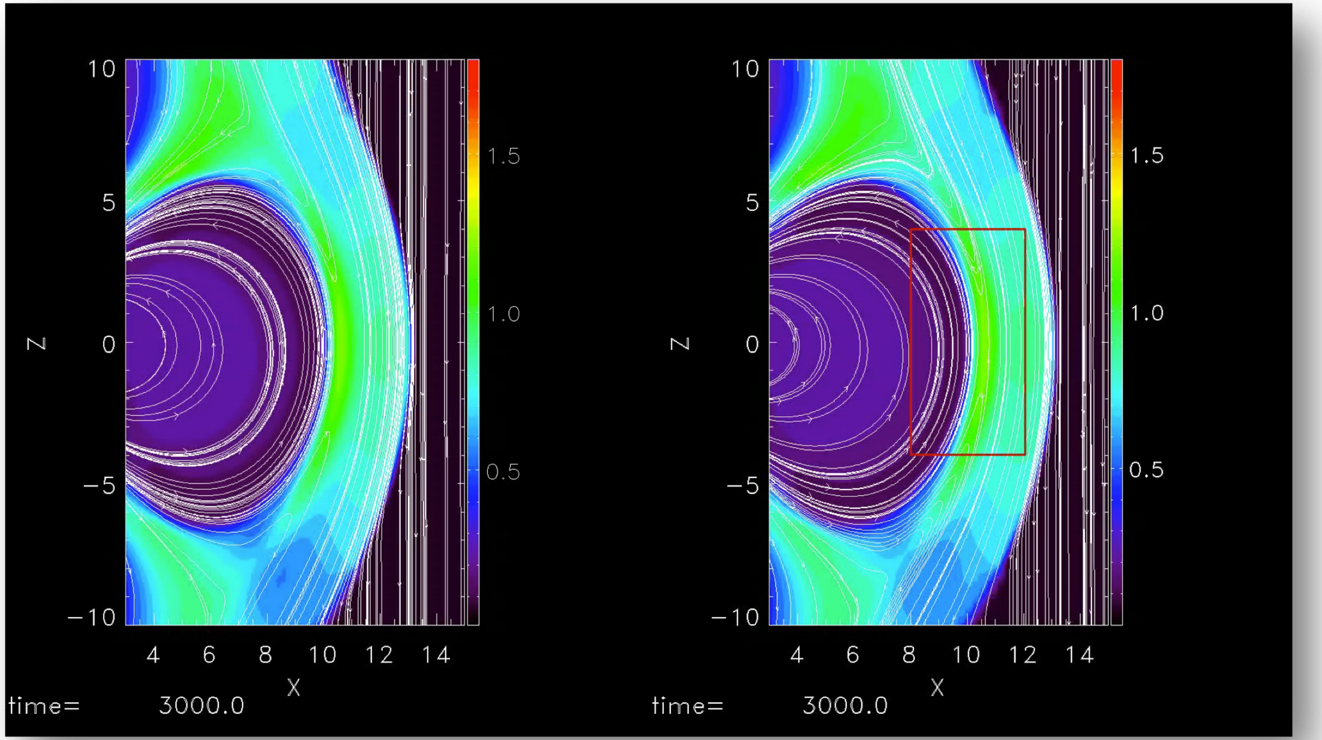
- Improve models so they have a chance with the extreme events.
- Learn how to scale up to a Carrington-class event by modelling well-observed large events.
- Include uncertainties via ensemble modelling.

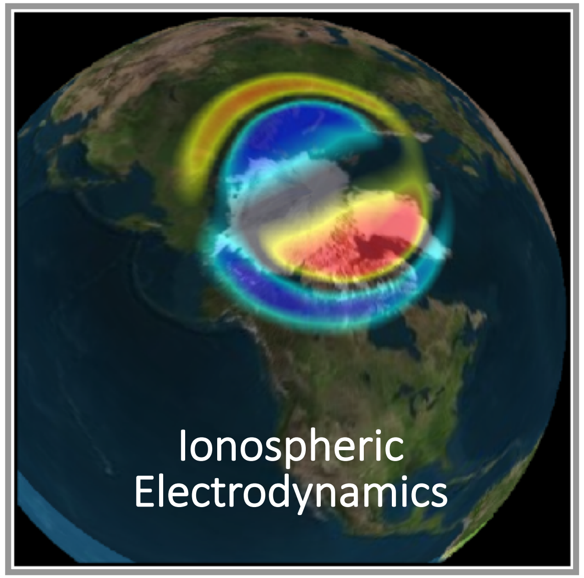
Potential problem: “New” exotic mechanisms/instabilities may occur during Carrington-class events that the models can’t handle.

Model Improvements

- Use Adaptive Mesh Refinement (AMR) to track the magnetopause with sufficient resolution during the rapid push-in.
- Embed 3D PIC (iPIC3D) at moving magnetopause to more accurately model the dayside reconnection. Validation efforts using MMS data underway.
- Add ionospheric conductivity enhancements and FACs from inner magnetospheric model, RAM/SCB.



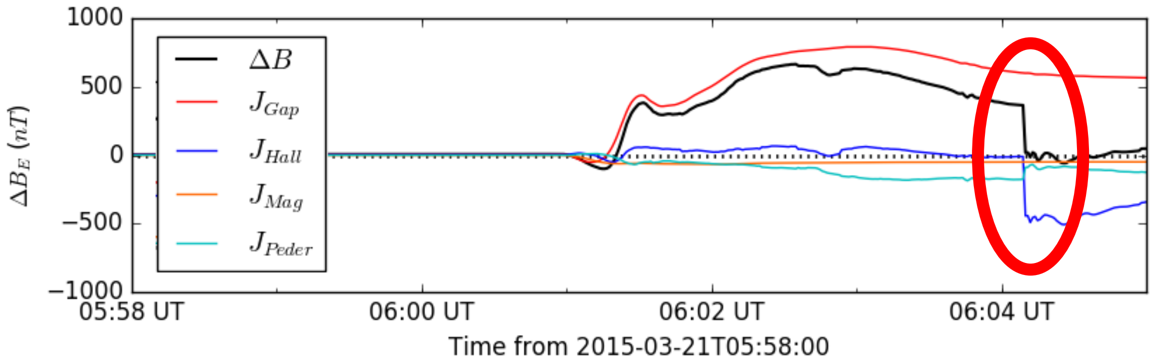


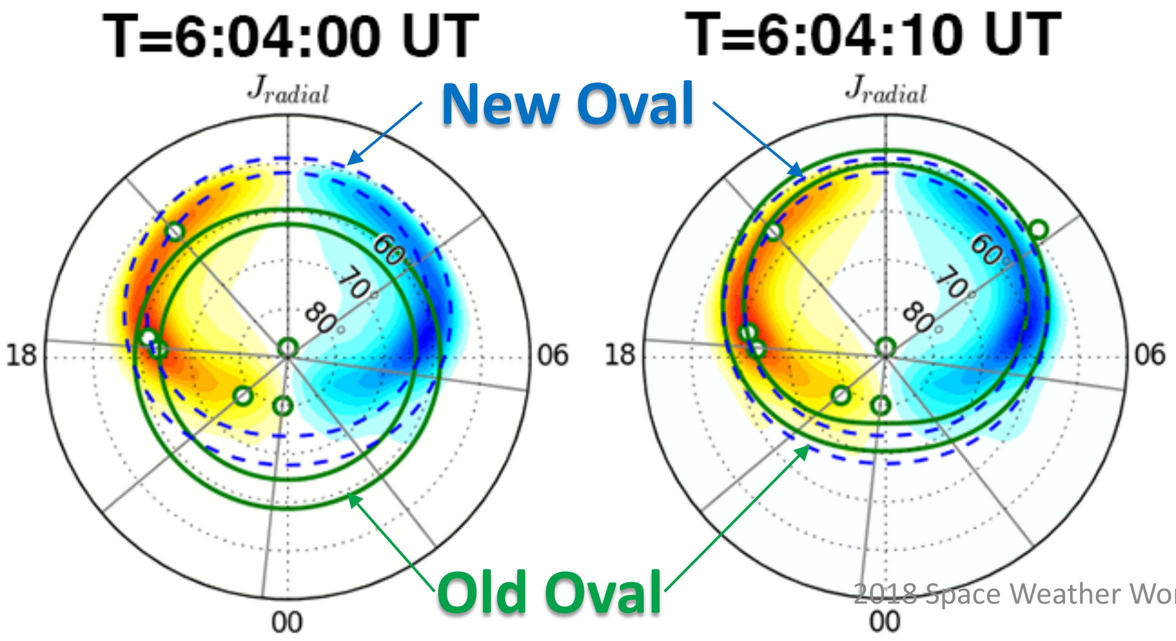


- Improved Ionospheric conductance model. Currently based on limited data, during relatively quiet time intervals.

SWMF Model Development: Improving Conductance Model

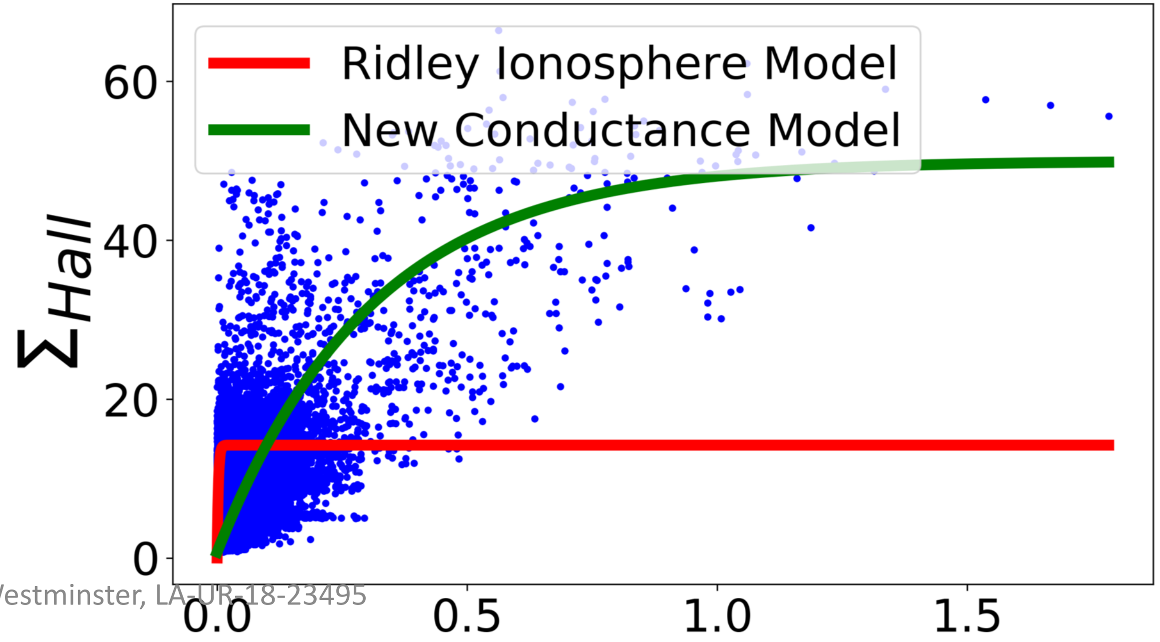
- "Jumps" in auroral oval during extreme events fixed





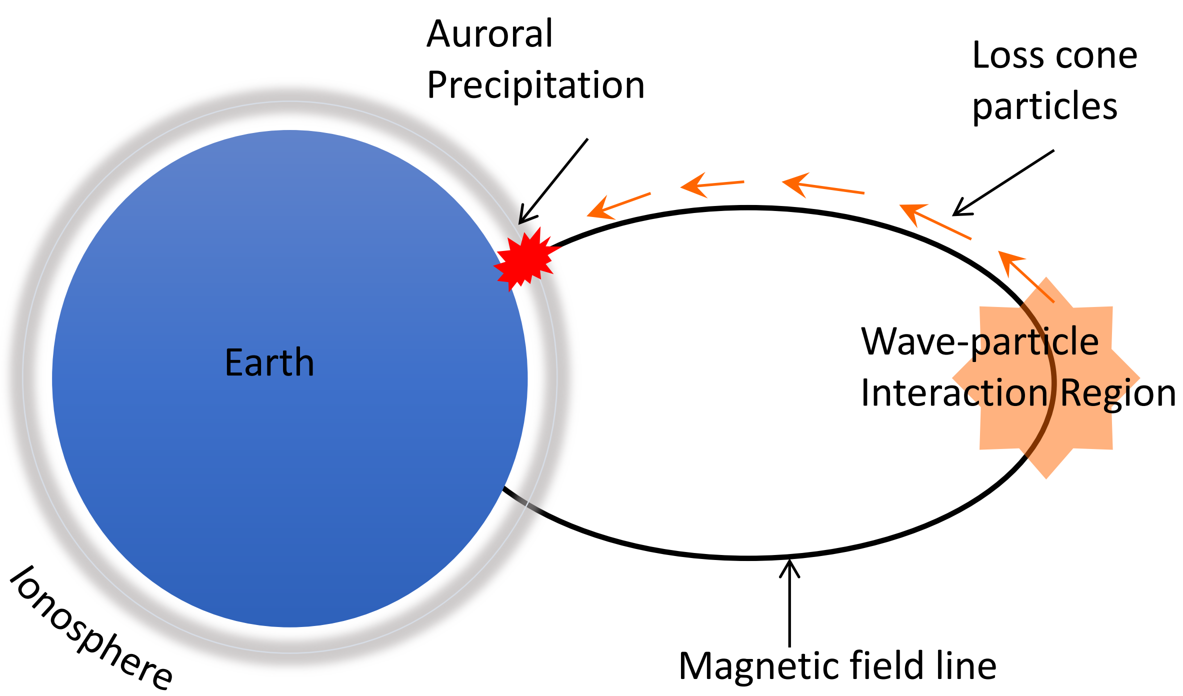
Empirical ionospheric conductance model expanded & improved

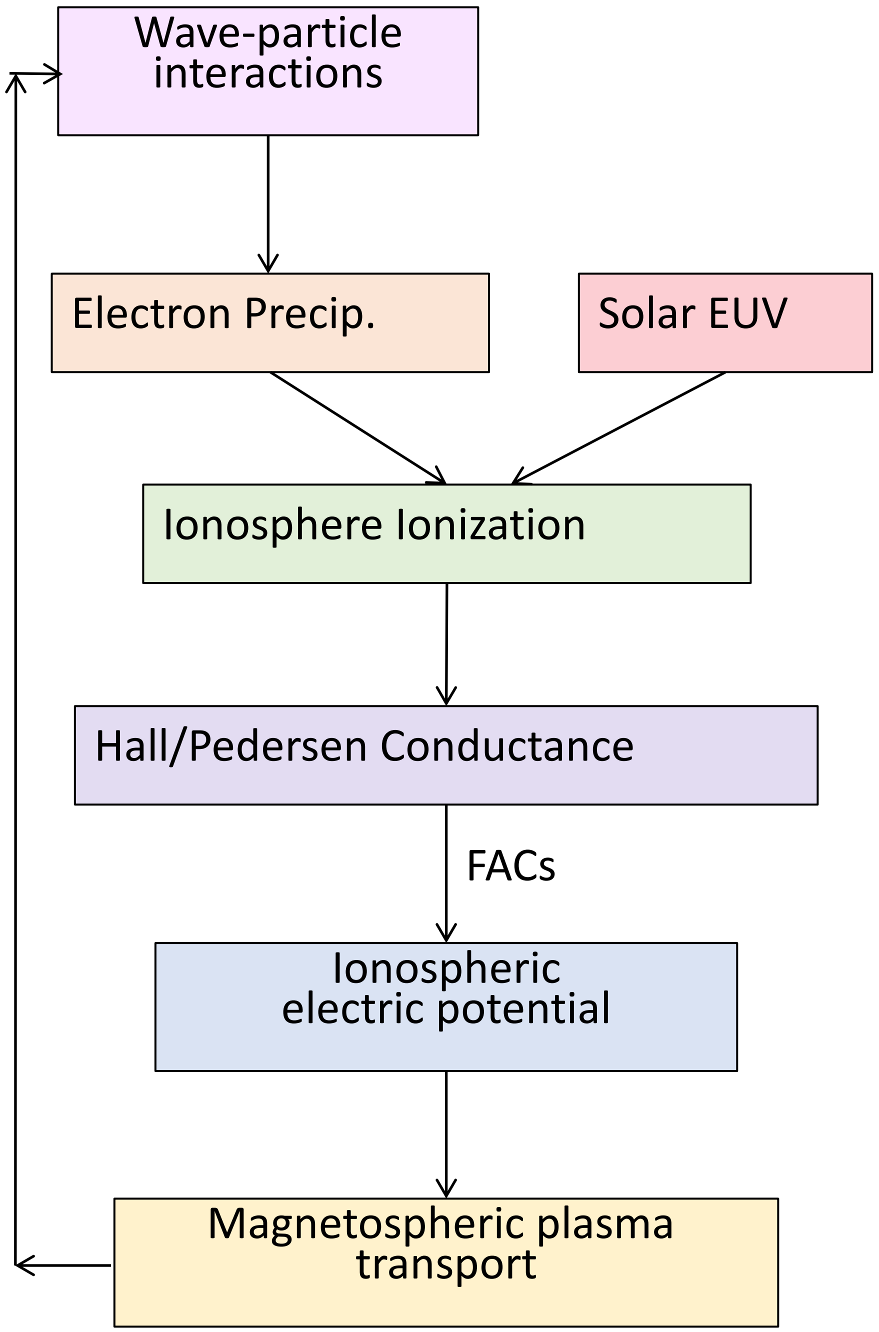
Old model	New Model
1 month of AMIE data (Jan. 1997)	1 year of AMIE data (2003)
$\Sigma = \Sigma_0 e^{-AJ_\parallel}$	$\Sigma = \Sigma_0 - \Sigma_1 e^{-AJ_\parallel}$



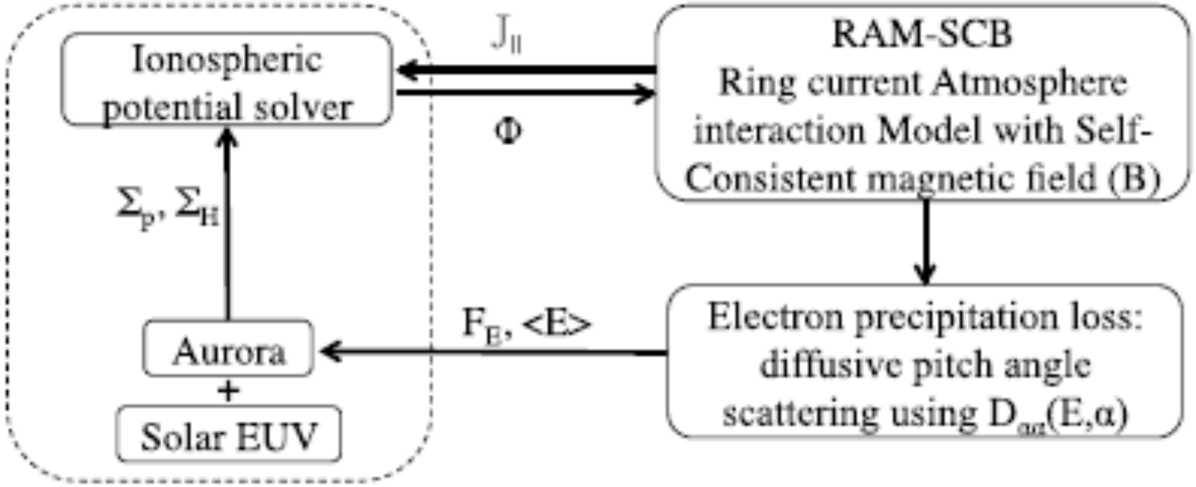
RAM/SCB Model Development

- Add missing inner magnetosphere-ionosphere coupling.
- Add wave-particle interactions to drive precipitation which contributes to ionospheric Hall/Pedersen conductivities.
- Allows FACs and Electric potential to feed back to magnetospheric transport codes.
- Particularly needed during extreme storm intervals when activity moves closer to the Earth (i.e. equatorward in ionosphere.)

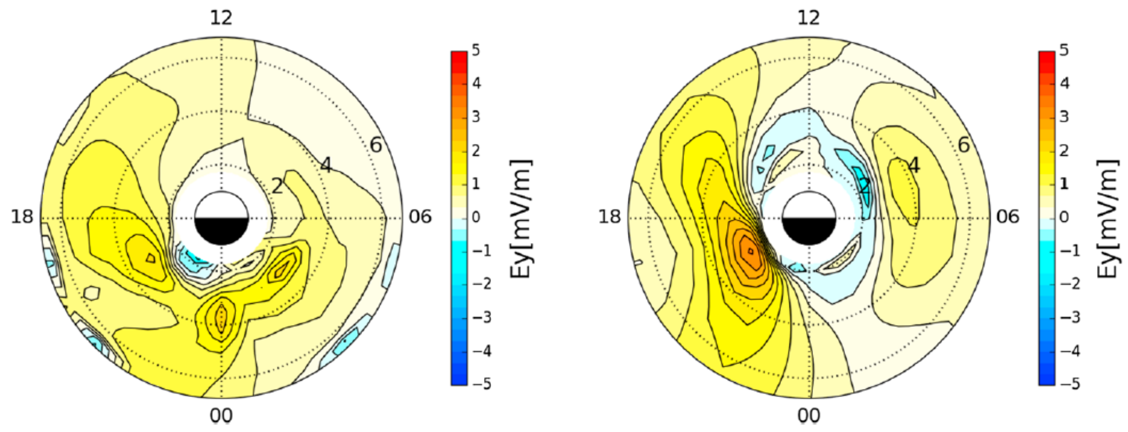




RAM-SCB: Two-way Coupling Between Ring Current and the Ionosphere



- The dashed box indicates the implementation of the self-consistent electric field using inputs of $J_{||}$ and precipitation energy flux F_E from the kinetic ring current model



Self-Consistent E

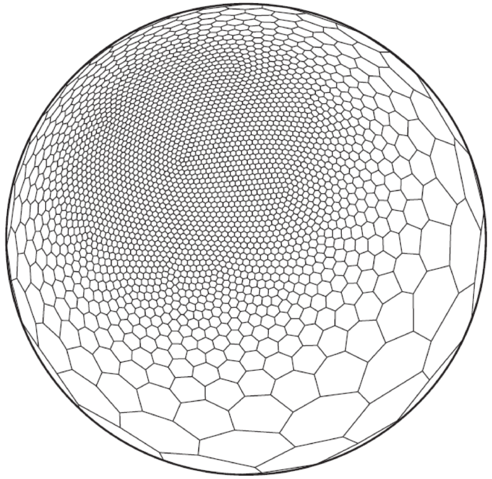
Weimer E

- The self-consistent RAM-SCB electric potential contours show more substantial skewing toward post-midnight
- The Weimer potential is based on statistical observations and cannot represent the feedback effects and is less shielded

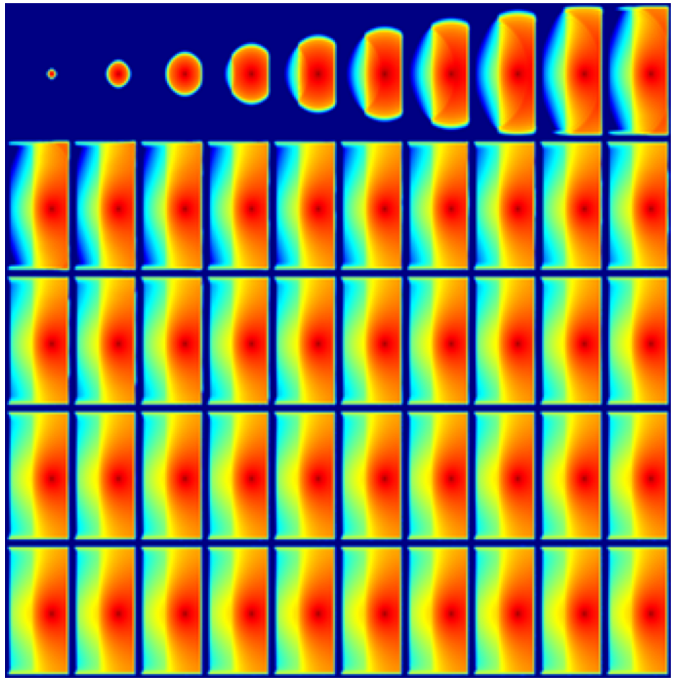
LanlGeoRad: Improved dB/dT Calculations

- Current state-of-the art is to compute Delta-B on the ground using Biot-Savart integrals over 4 different current systems (Ionospheric Hall &Pedersen, Magnetotail, and Gap region currents).
- Instead of this, we are developing a Finite-Difference Time-Domain (FDTD) model to propagate disturbances to the ground: LANLGeoRad.
- Variable resolution spherical Voronoi mesh. (Machinery developed by LANL's COSIM team.)
- Grid starts at the top of the BATSRUS gap region and extends down into the conductive Earth.
- 3D ground conductivities are required as inputs.

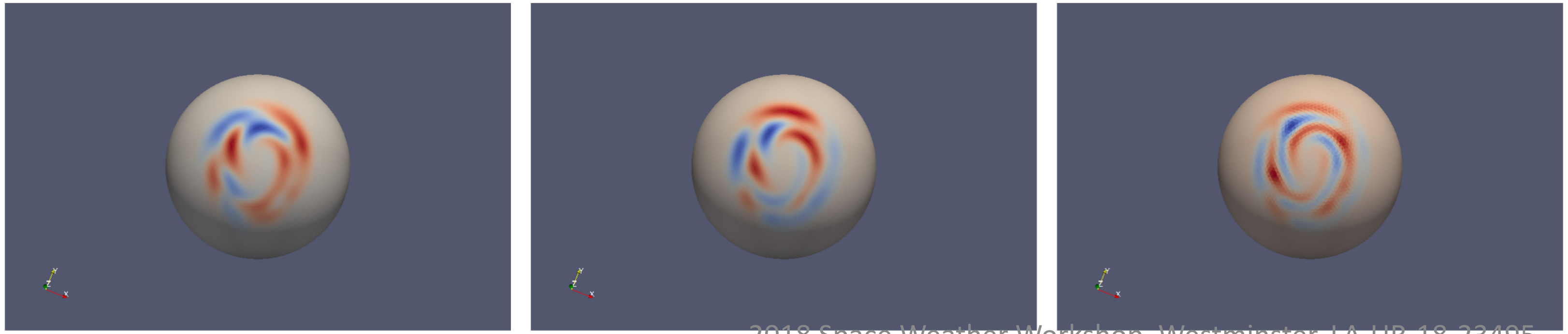
LANL's Climate, Ocean and Sea Ice Modeling (COSIM) program has developed technology to generate Voronoi Tessellations on Spheres with High Resolution Region.



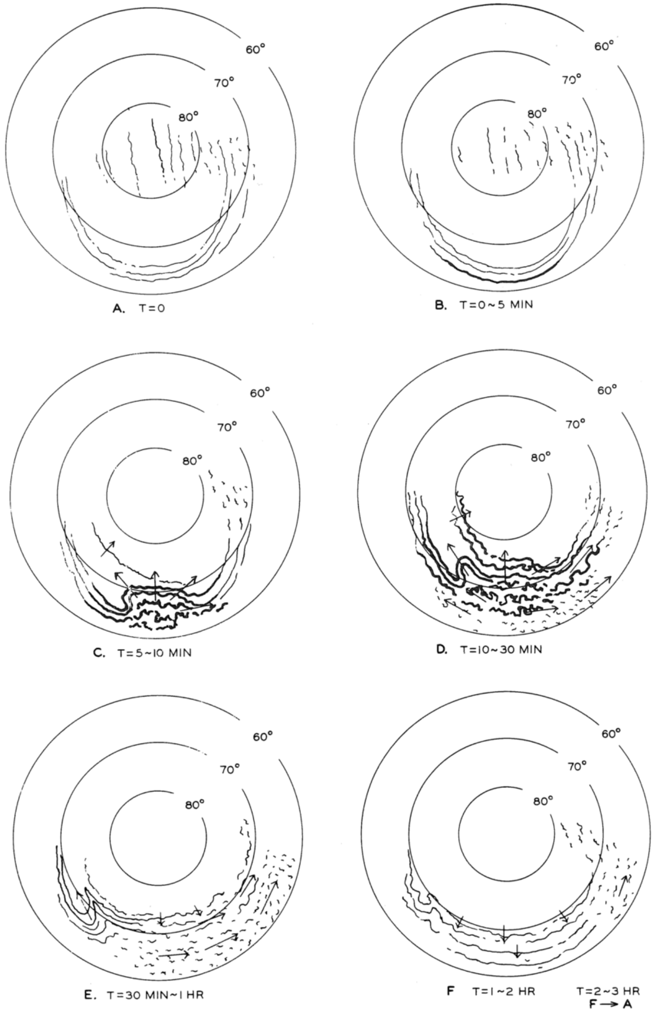
Initial testing: a line current turning on. 2-D height profiles of electric field



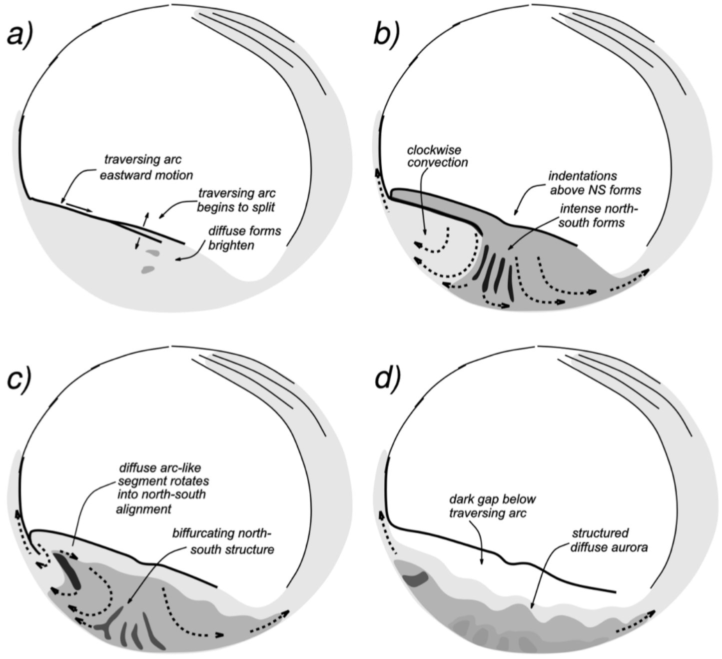
Initial testing of magnetic perturbations resulting from realistic steady-state empirical currents. Ongoing work being performed to validate against Biot-Savart results.

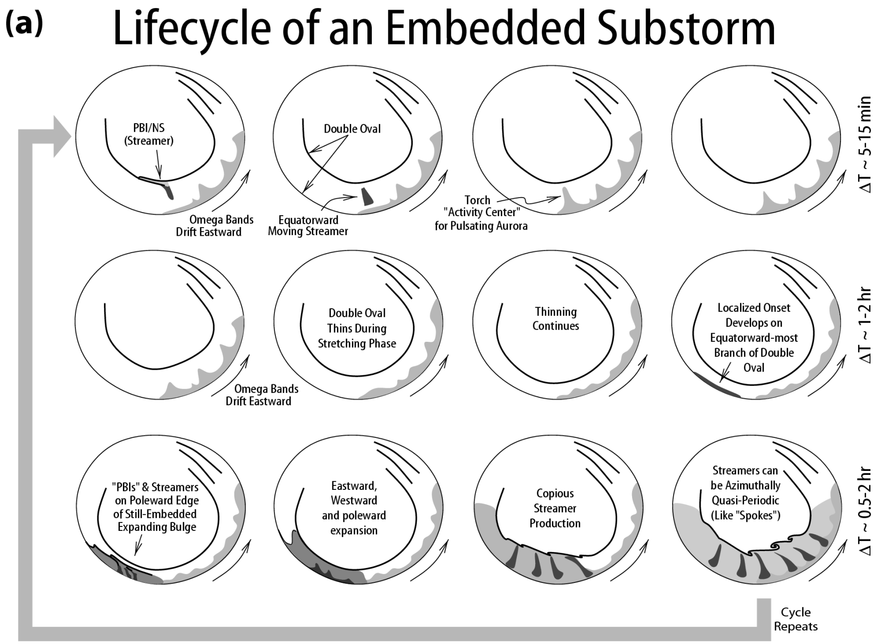


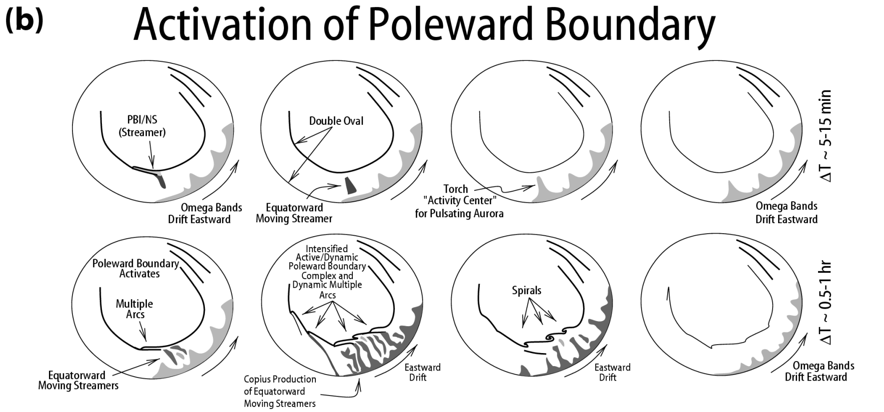
Observations: What physical processes control when and where the most intense and highly localized GMDs occur during storms?



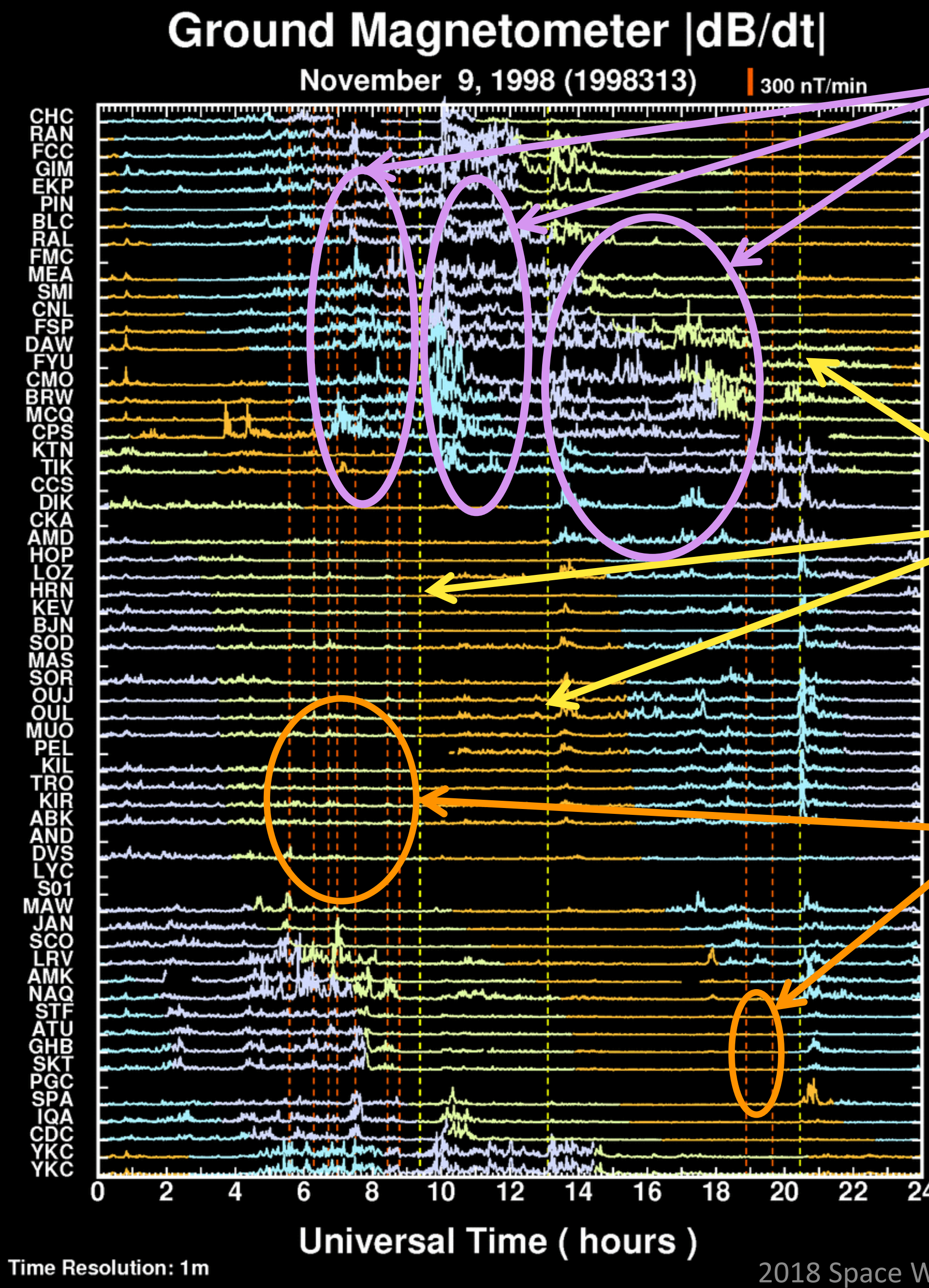
Akasofu, [1964]



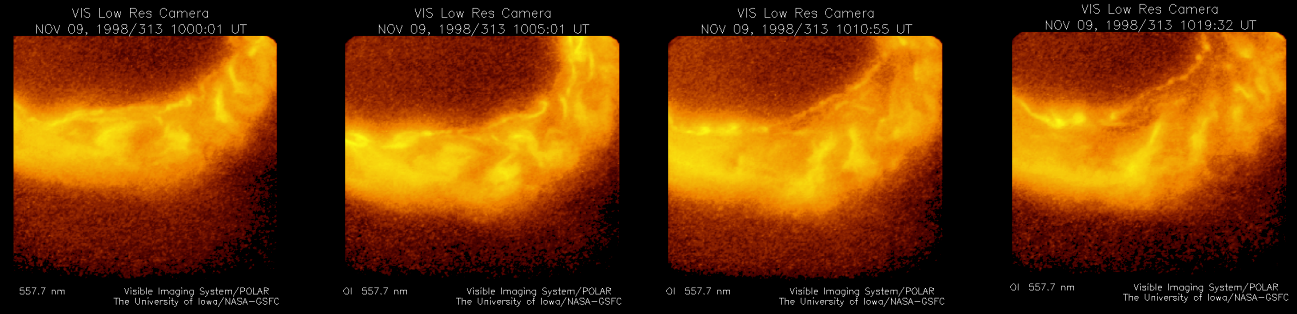




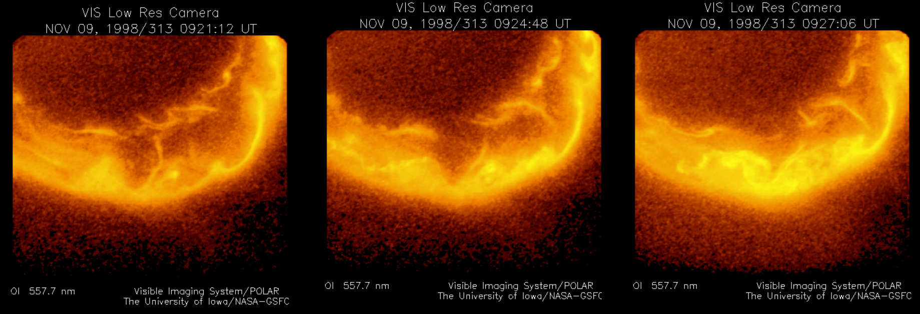
- A number of smaller-scale impulsive auroral disturbances commonly occur during storms: substorm onsets, pseudo-breakups, streamers, and omega bands.
- We are currently exploring which of these are associated with the most significant levels of |dB/dt| on the ground.



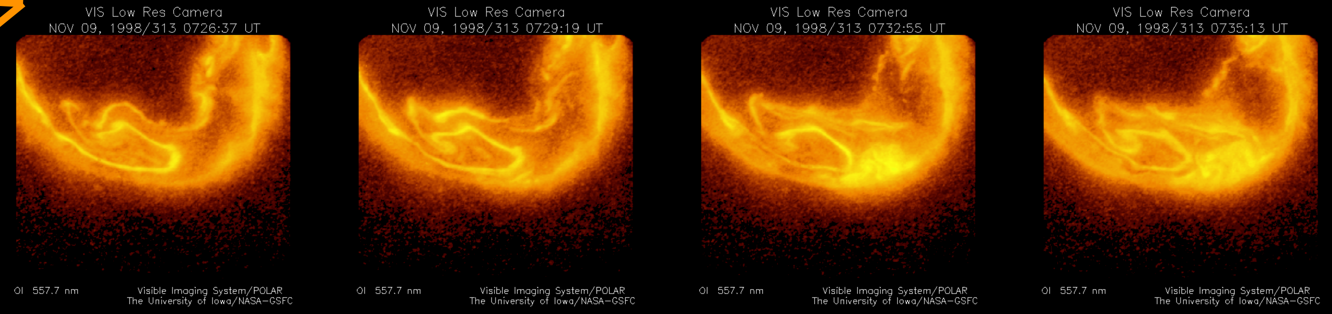
Streamers / Omega Bands (largest, most-sustained dB/dt)



Substorm Onsets

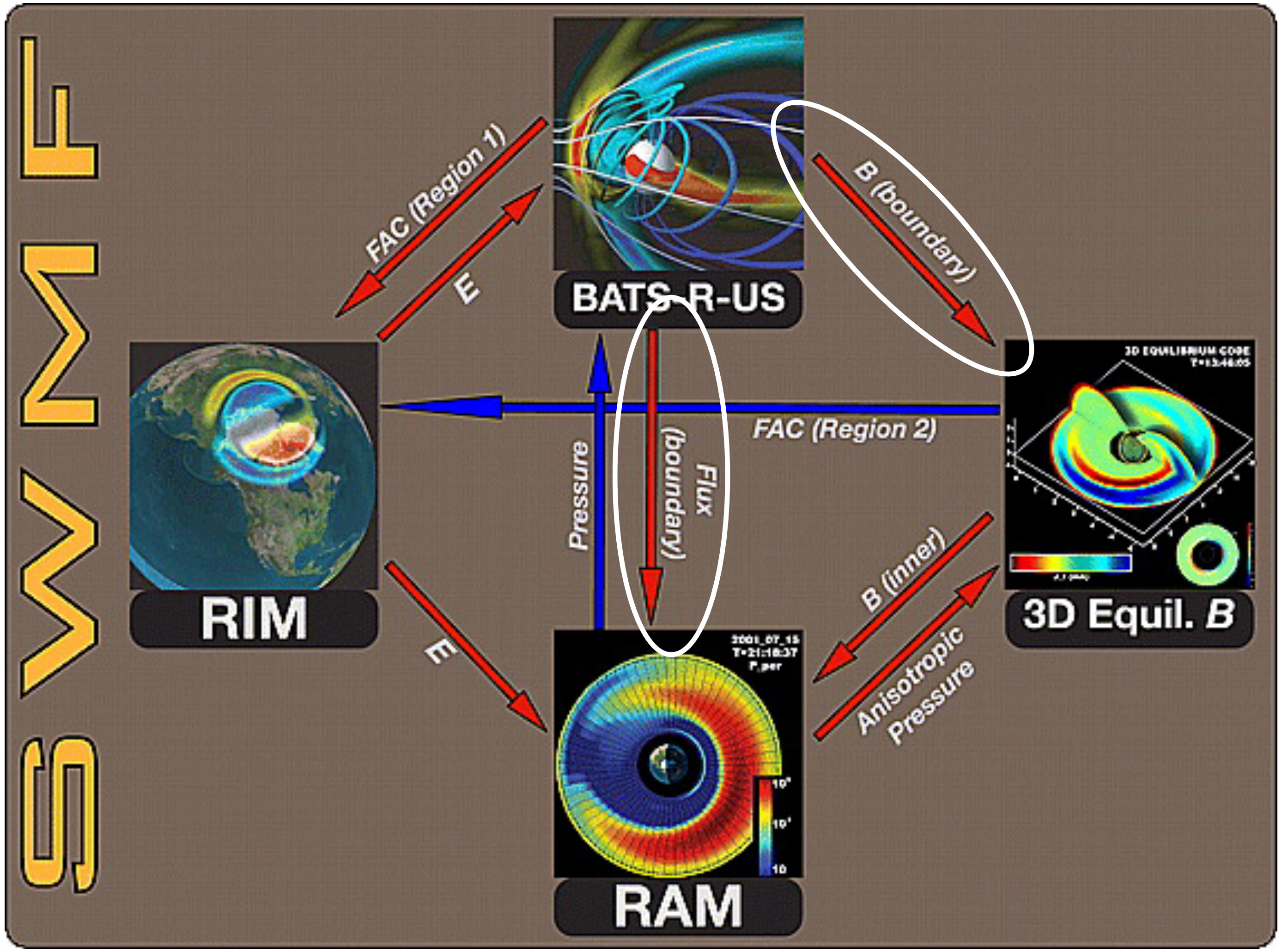


Pseudo-breakups



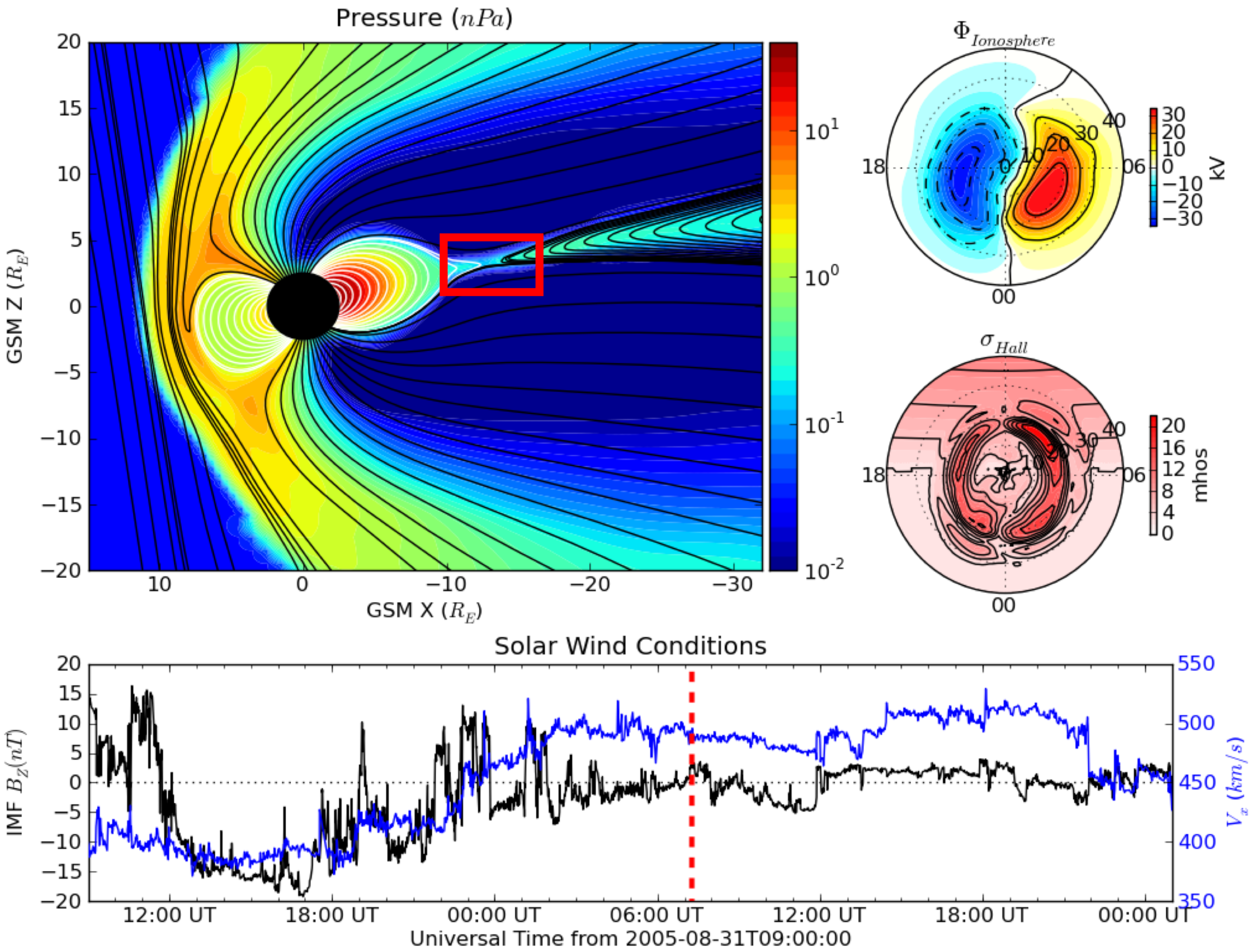
PBIs, streamers, omega bands can produce large, localized, sustained dB/dt → We need to model flow bursts reasonably well. But they are likely to be stochastic!

Data Insertion/Assimilation for RAM-SCB and SWMF



- We are developing a novel method for data insertion in the coupled SWMF/RAM-SCB codes.
- Use data fitted empirical magnetic field models (e.g. Brito and Morley 2017) to provide the “B (boundary)” link instead of getting it from SWMF. And LANL/GEO data to provide the “Flux (Boundary)” link. Can also “blend” BATS-R-US and data sources.
- RAM evolves pressure and feeds back to SWMF.
- Ingestion of **B** and particle data in this manner will force both coupled models to conform better to the observations.

SWMF Magnetotail Tuning

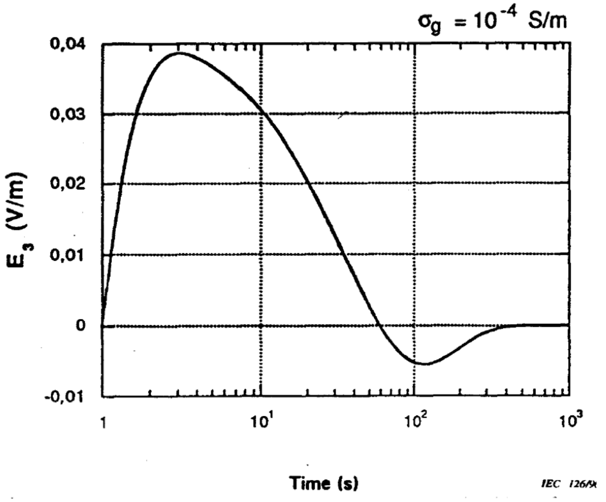


- Flows in the Magnetotail impact auroral zone field lines.
- Tune SWMF to adjust reconnection locations (e.g. via anomalous resistivity) to better match observations.
- Parameterization or characterization of this relationship will (hopefully) enable us to extrapolate to Carrington-class simulations.

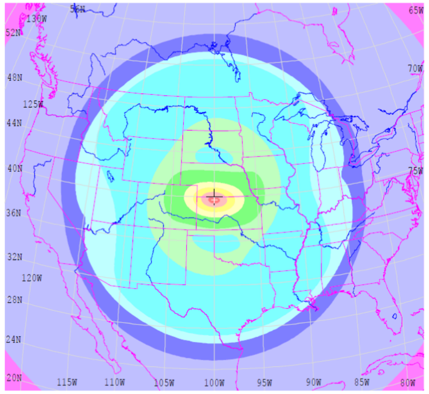
Impacts of Geomagnetic Disturbances on the Ground: EMP/E3 Coupling to Texas 2000 Bus Model

- Initial work uses model EMP/E3 disturbances to exercise the power flow solver to obtain GICs on a network model.
- Initial end-to-end analysis was also recently performed using SWMF GMD outputs. A "version 1.0" of the overall project task connectivity has been completed.

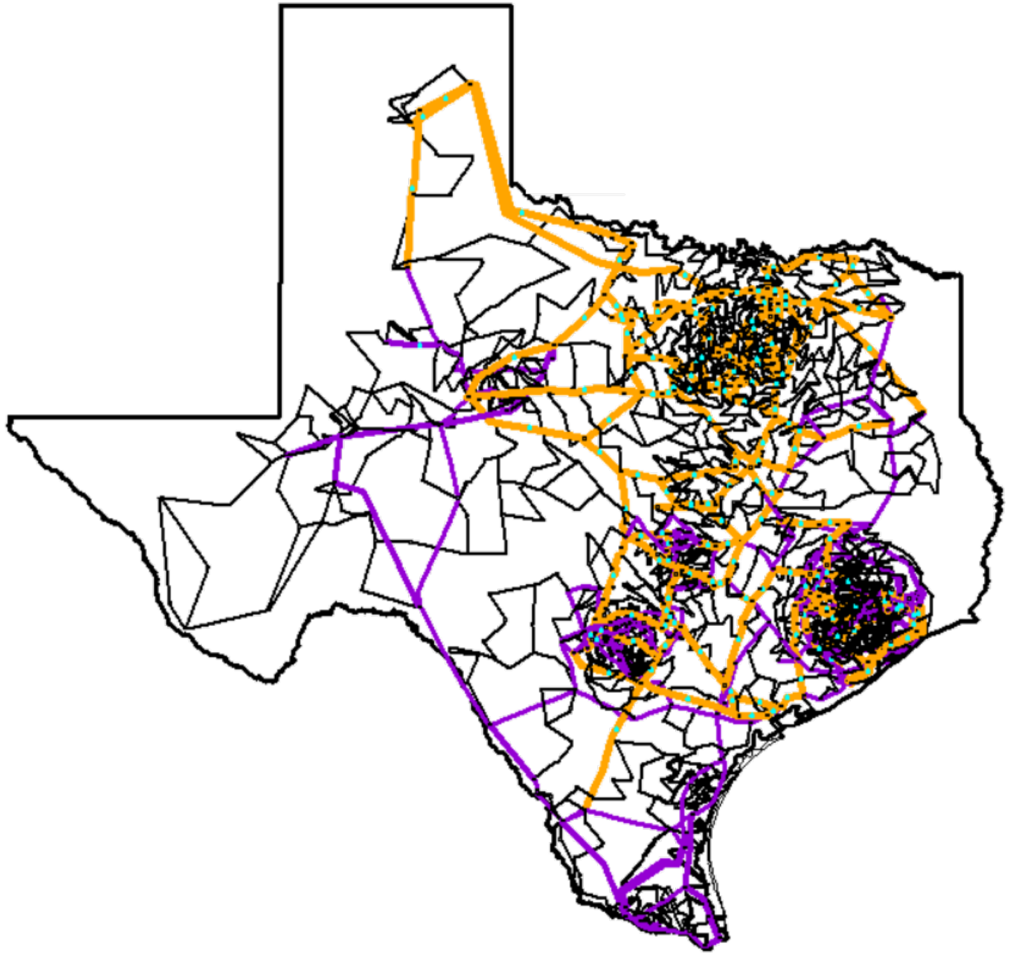
IEC de facto standard



+

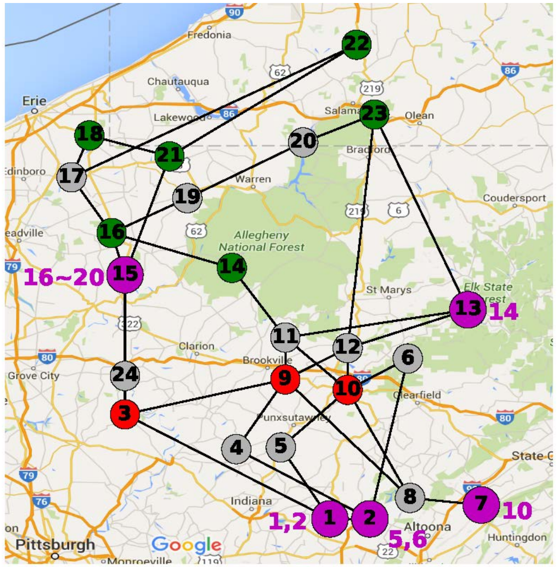


Texas 2000 Bus Model

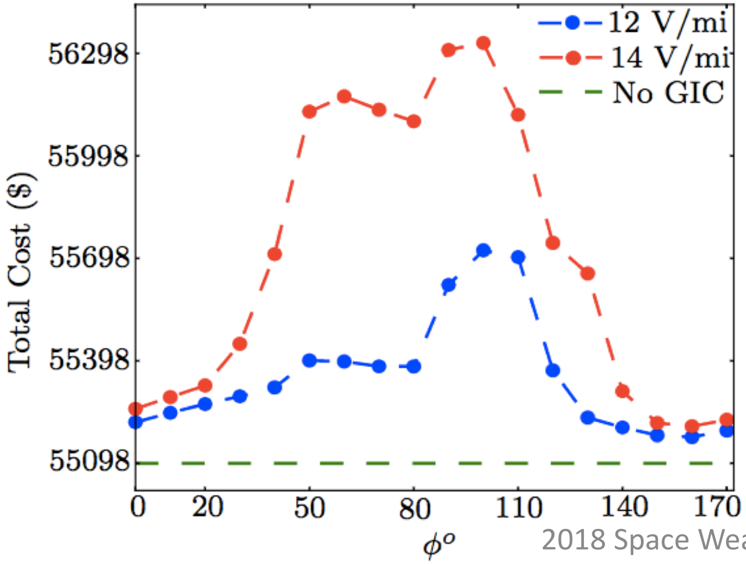


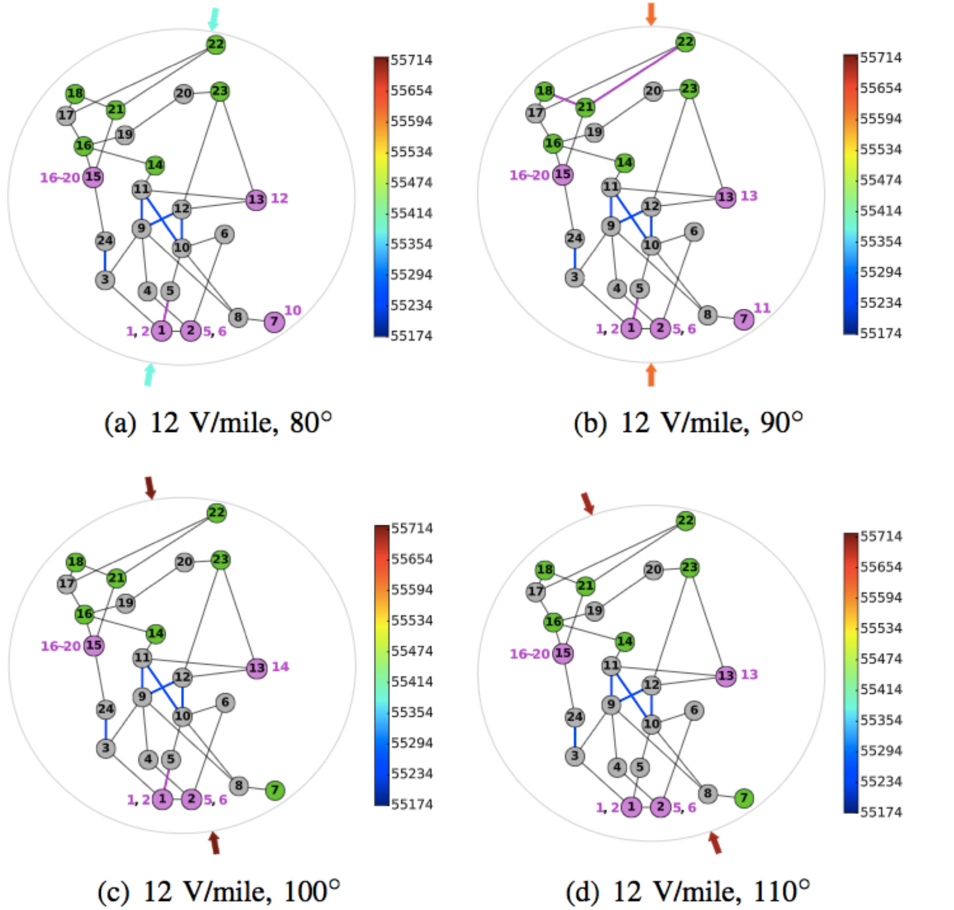
Optimizing Resilience of Power Distribution Systems

Hypothetical transmission network arb. placed in western Pennsylvania



Cost to Mitigate via Network Control (line switching, increased gen., load shedding)





(a) 12 V/mile, 80°

(b) 12 V/mile, 90°

(c) 12 V/mile, 100°

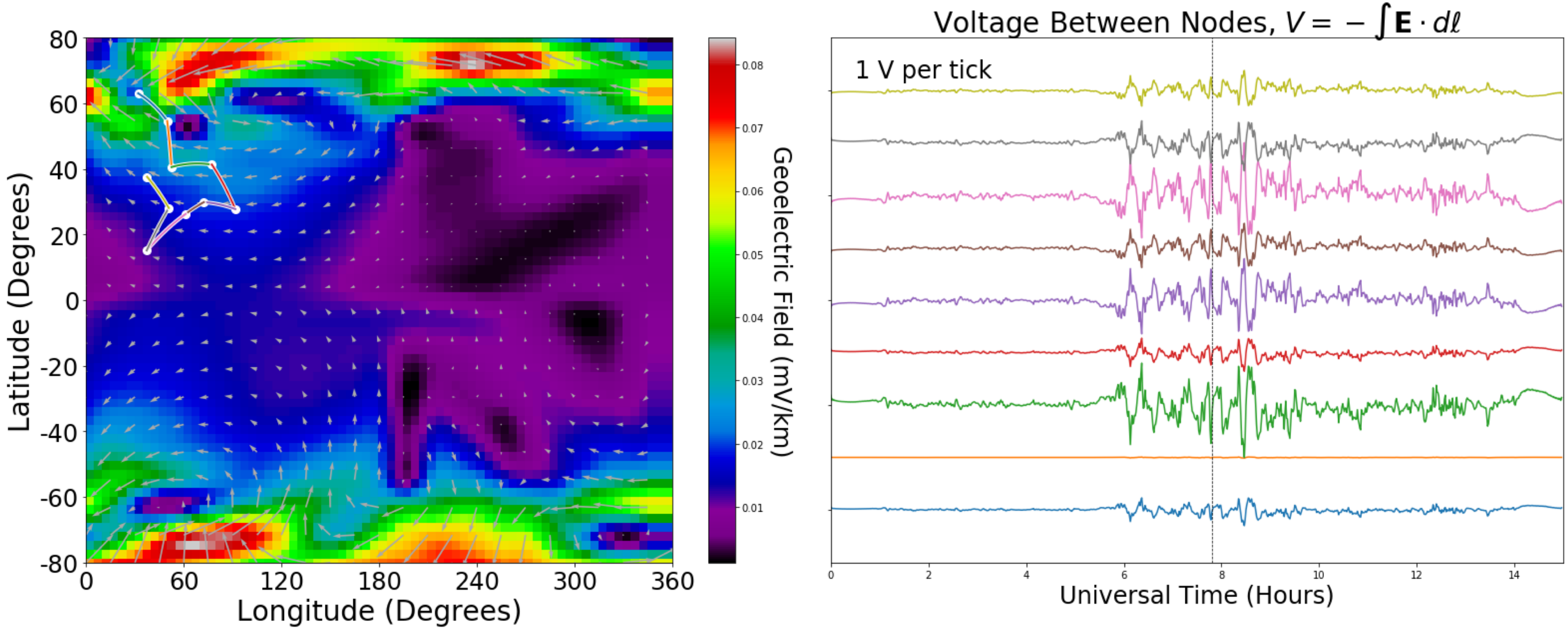
(d) 12 V/mile, 110°

Switched off lines are colored magenta and the IDs of unused generators are labeled beside their connected substations

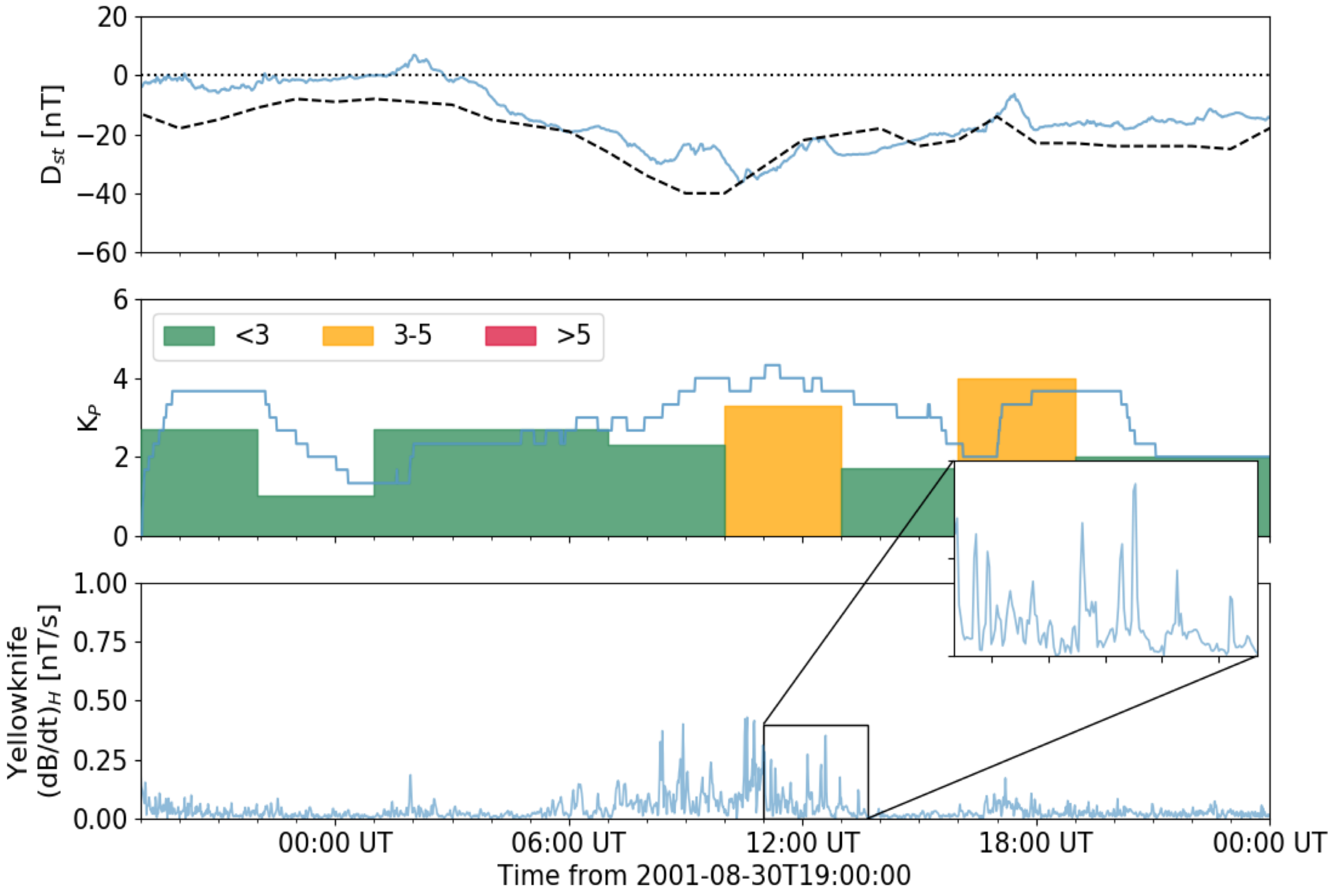
M. Lu, H. Nagarajan, E. Yamangil, R. Bent, S. Backhaus, A. Barnes, (2017), *Optimal Transmission Line Switching under Geomagnetic Disturbances*, IEEE Transactions on Power Systems, to appear

SWMF Geo-Electric Field and Voltages at Power Grid Nodes

- Computation of voltages at arbitrary locations on the Earth using SWMF.
- This example uses simple random network and 1-D ground conductivity model, but it is setup to also use full 3-D impedance tensors and/or conductivity depth profiles.

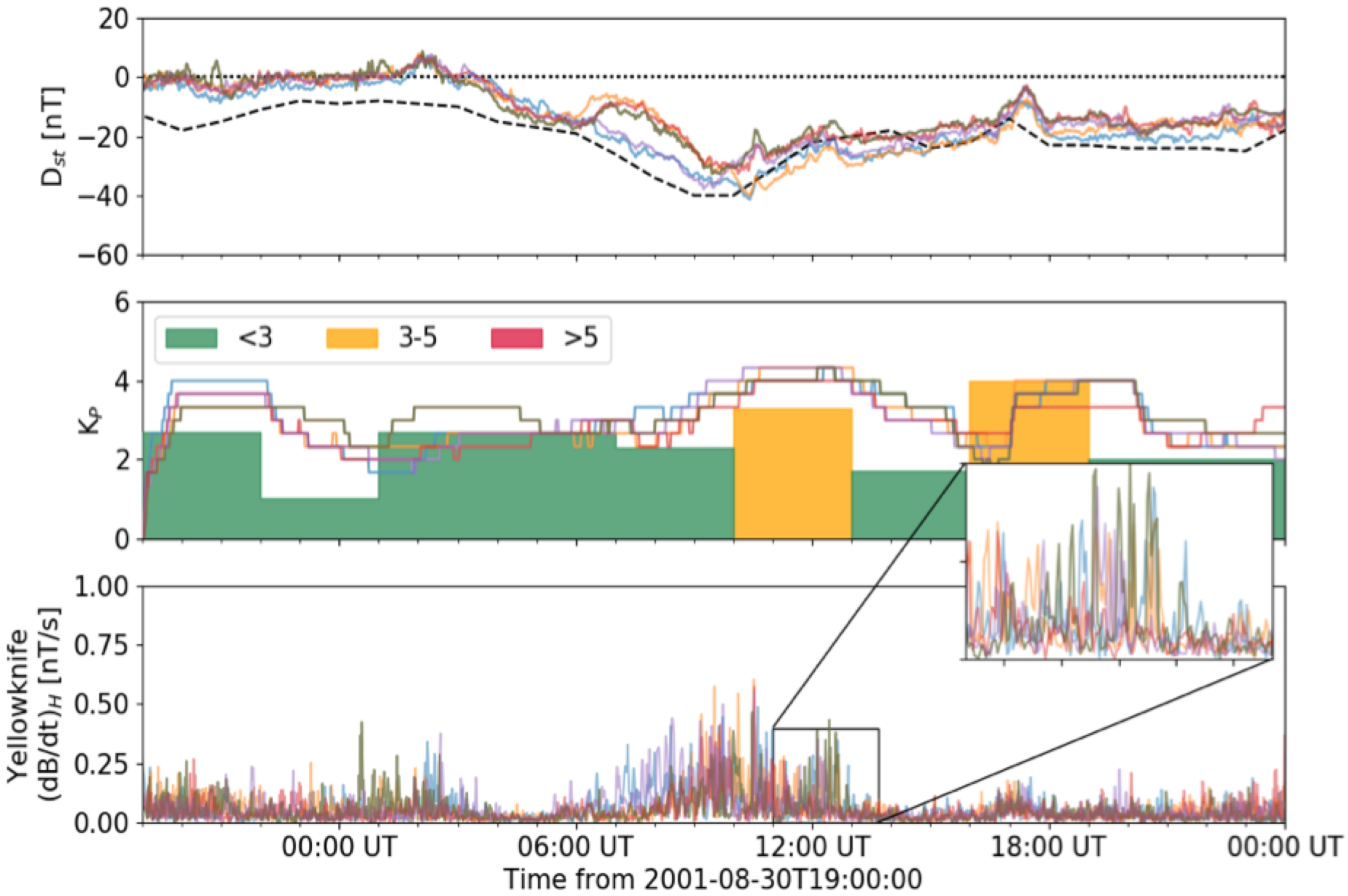


Ensemble Modelling



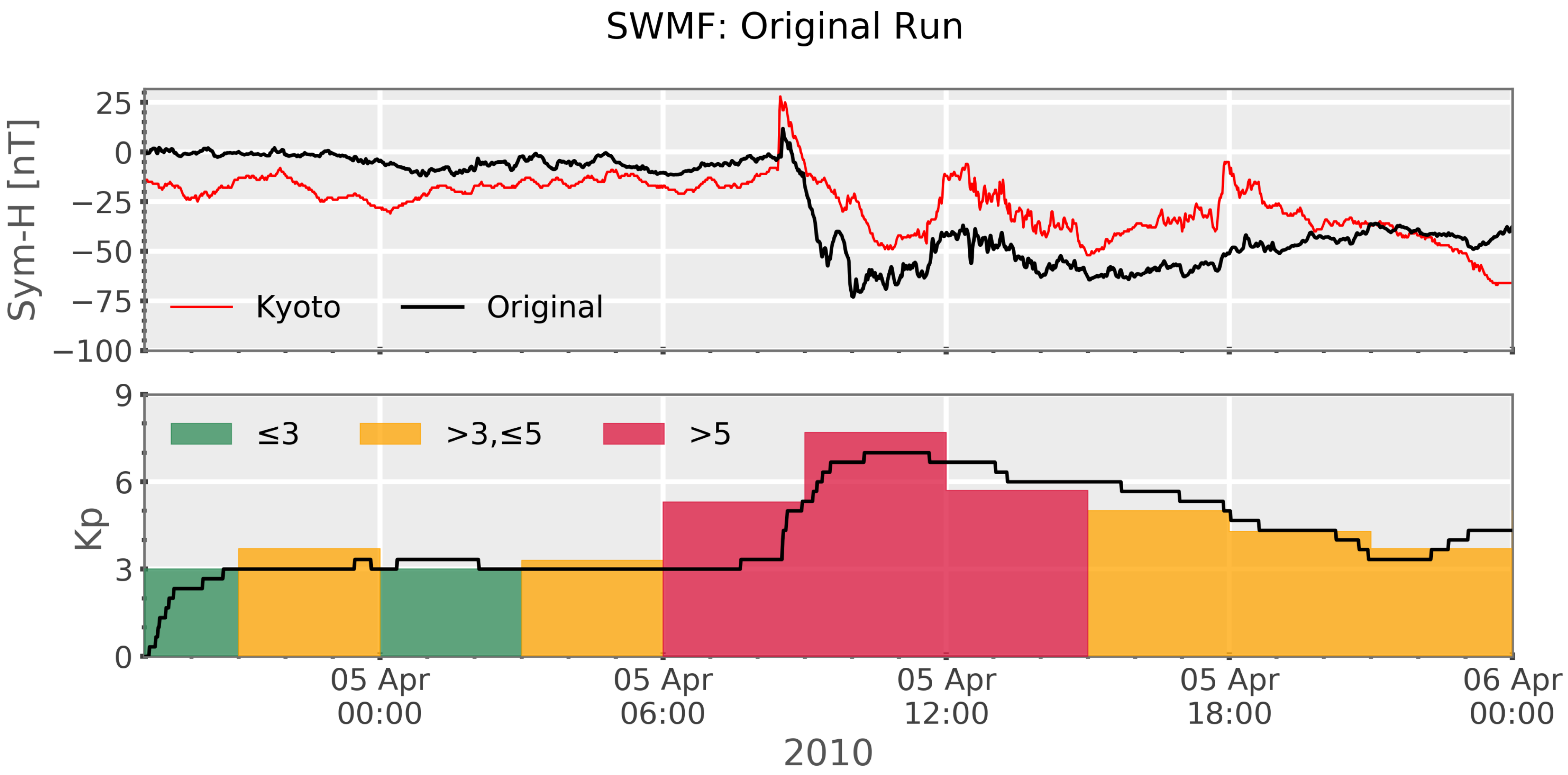
- Both the magnetosphere and power grids are complex and may react sensitively to changes in input.
- Ensemble modeling allows us to explore these sensitivities and understand better which "knobs" we need to be able to turn to fit the observations.

Ensemble Modelling

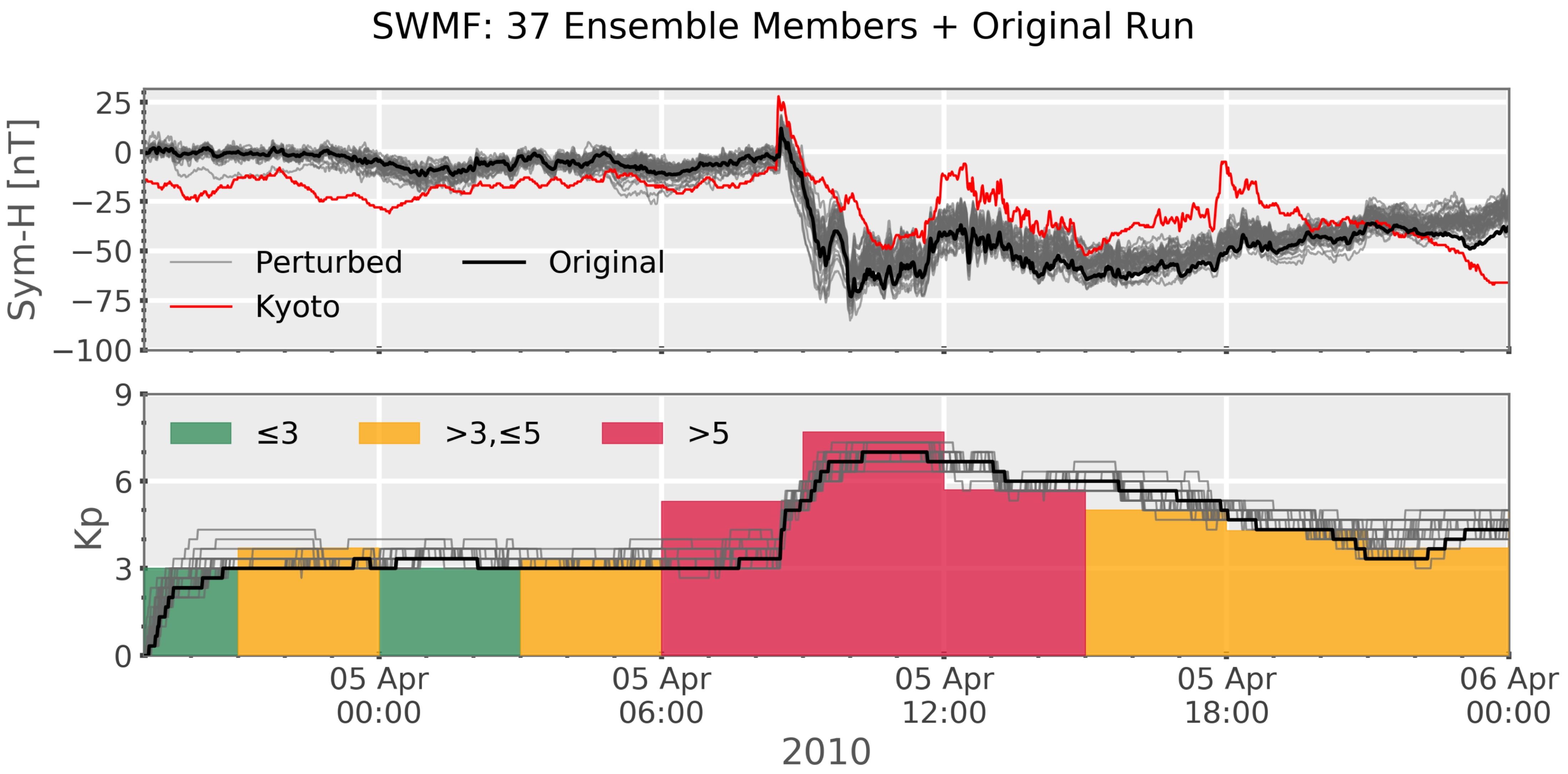


- Both the magnetosphere and power grids are complex and may react sensitively to changes in input.
- Ensemble modeling allows us to explore these sensitivities and understand better which “knobs” we need to be able to turn to fit the observations.

Ensemble Modelling – SWPC Challenge Event #5



Ensemble Modelling – SWPC Challenge Event #5



Summary

- Carrington/GIC is a large project (LANL, U. Michigan, USGS) to:
    1. simulate a Carrington-class storm (Dst ~ -1800nT)
    2. assess impacts on power grid infrastructure (develop new physics-based benchmarks)
    3. develop mitigation strategies via active network control
- Ionospheric conductances used in SWMF are being redefined using much more data and will be further binned by driving.
- FDTD EM propagator (LanlGeoRad) being is developed to replace the Biot-Savart method currently used to compute dB/dt (will use full 3D ground conductivities where available.)
- The largest and most sustained |dB/dt| signals appear to be associated with time periods dominated by streamers/omega band types auroral forms. This implies that we need to be able to model flow bursts that penetrate towards the inner magnetosphere.
- We have developed a novel approach (via data inputs to improved RAM-SCB model) for assimilation of data into the coupled SWMF.
- SWMF GMDs are now coupled to LANL power grid analysis and optimization codes and we have the machinery in place to generate ensemble runs.