Inputs for Magnetosphere Models

Determining what you need and how it impacts simulation results

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This Lecture:

Definitions & Assumptions For This Lecture

- Models can be first-principles-based or regression-based (but focus will be on FPB)
- Magnetosphere models can be *any* model of the magnetosphere or its parts. Think beyond global MHD!
- Model inputs refers to any model requirement, not just solar wind.
- This talk is designed for model users, not *developers* or *power users*.

Learning Objectives: *in 50 minutes, you will be able to…*

- Identify inputs required for a given magnetospheric model
- Recognize how inputs can impact a numerical simulation
- Given research goals, critically assess the strengths and weaknesses of the set of model inputs used for the study

What are *Inputs*?

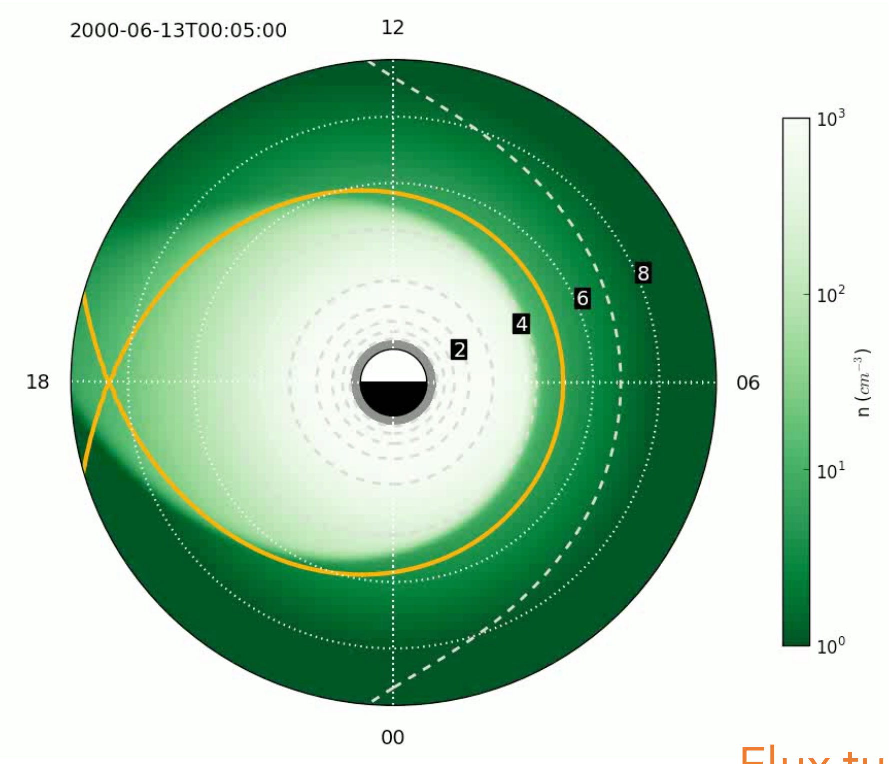
Inputs are anything you need to run your model

- Initial Conditions
- Boundary Conditions
- Source & Loss Terms
- Variables not explicitly solved by numerical scheme
- Values used to create regression-based models (*features* in ML parlance)
- Configuration and parameter set of the numerical scheme, including spatial grid, solver order, time-stepping scheme, *etcete*

Model config is a *huge* topic that requires its own deep-dive.

It is a critical step in scientific investigations!

A Case Study: DGCPM



Flux tube content (n electrons)

$$\nabla \cdot (\overrightarrow{U_\perp} N) + \frac{\partial N}{\partial t} = S_{\mathrm{iono}}$$

$\vec{E} \times \vec{B}$ drift (km/s)

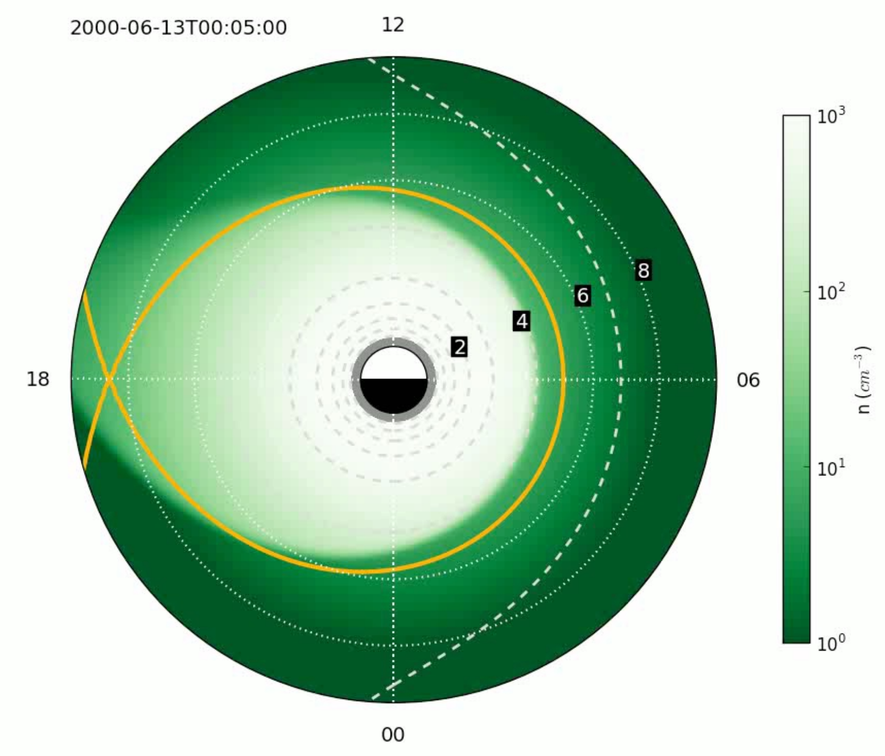
Ionosphere refilling (N/s)

The Dynamic Global Core Plasma Model is a model of equatorial plasmasphere content.

- Simple continuity equation for N: flux tube content (electrons per flux tube) as a function of local time, L-shell, and time.
- Solves for N using a second-order upwind scheme with a Superbee limiter.
- Assumes a dipole field.
- Ionosphere refills flux tubes on dayside (S_{iono}).

What are the inputs to this model?

Case Study: DGCPM Inputs



$$\nabla \cdot (\overrightarrow{U_\perp} N) + \frac{\partial N}{\partial t} = S_{iono}$$

What are the inputs to this model?

Initial conditions:

N at all local times and L-shells

Boundary conditions:

None: outer boundary is lossy, Neumann inner boundary

Source & ~~Loss~~ Terms:

Refilling via *Carpenter & Anderson*, 1992

Variables not solved for:

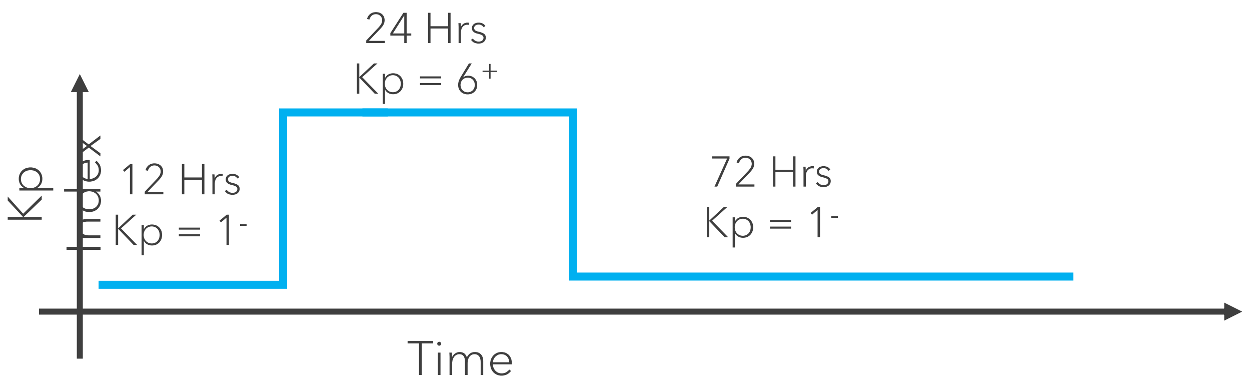
$\overrightarrow{U_\perp} = \vec{E} \times \vec{B}$

Input data for relationships:

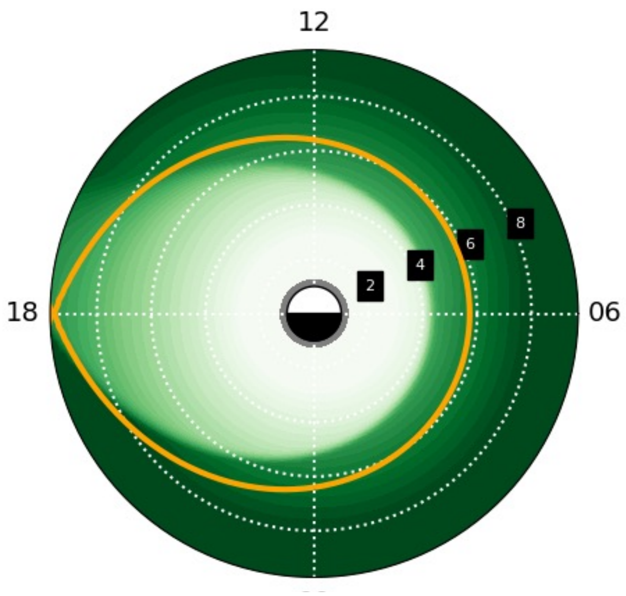
None.

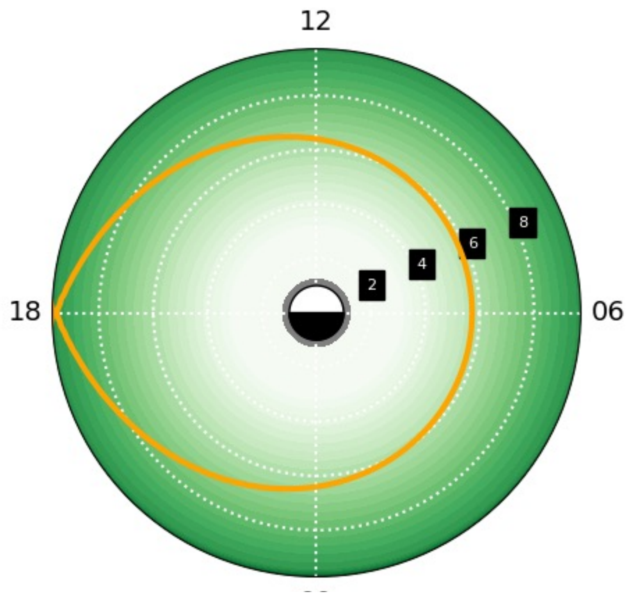
Initial Condition Choices Impact Simulations

- Let's run DGCPM for a synthetic storm:

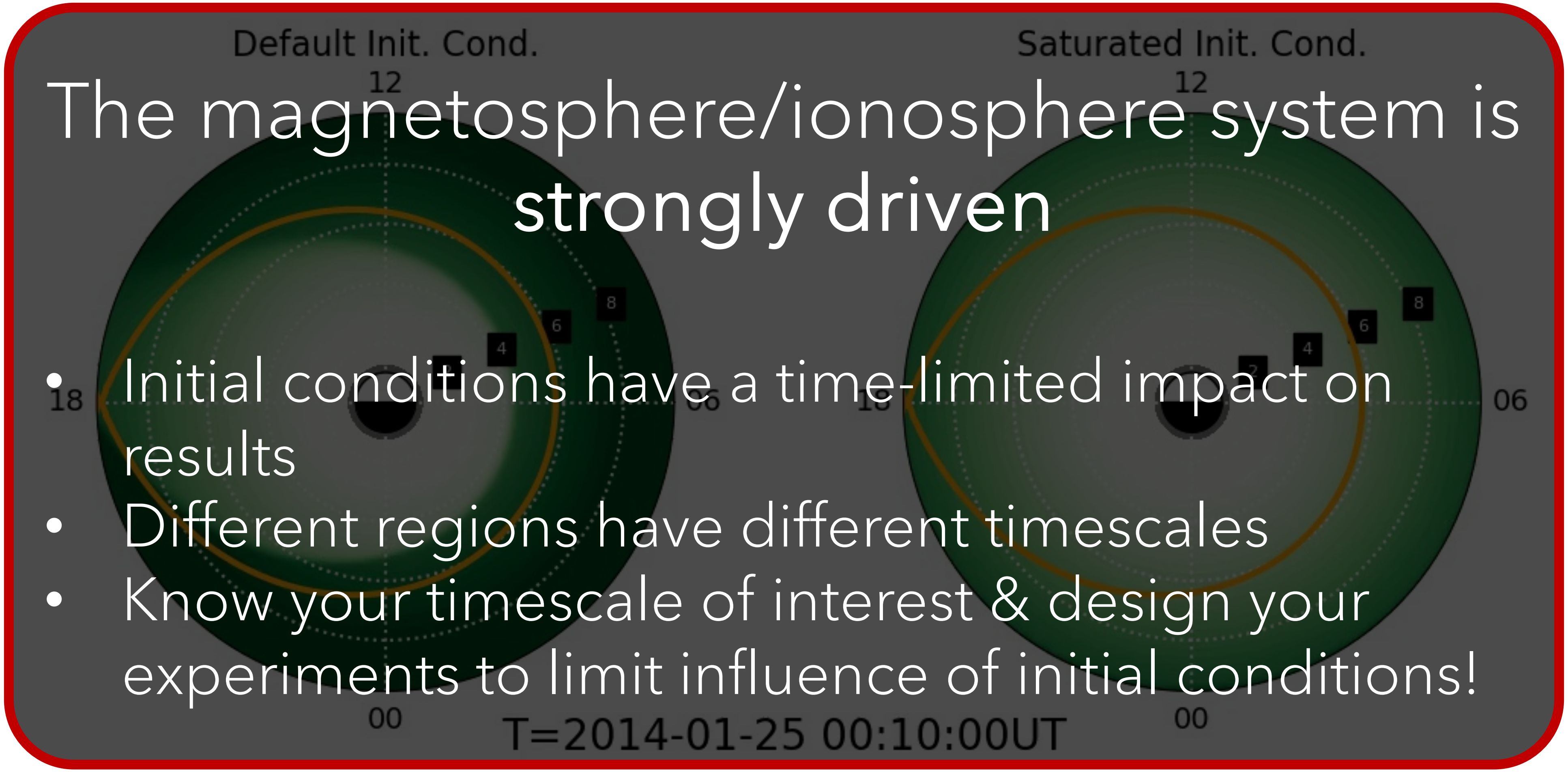


- Let's use two choices for initial conditions:





Initial Conditions in DGCPM



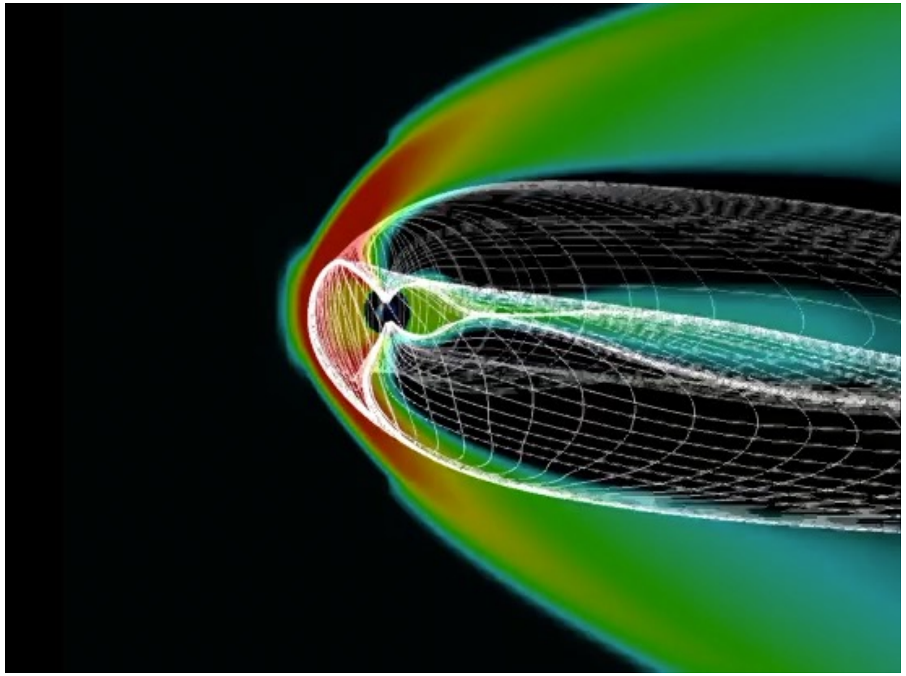
The magnetosphere/ionosphere system is **strongly driven**

- Initial conditions have a time-limited impact on results
- Different regions have different timescales
- Know your timescale of interest & design your experiments to limit influence of initial conditions!

Building Initial Conditions in Magnetosphere Models

- BATS-R-US employs a “steady state” mode to build initial condition
  - Uniform density, dipole magnetic field, zero flow.
  - Solar wind conditions corresponding to run start applied at upstream boundary
  - Code iterates without advancing time until pseudo steady state obtained
- LFM/Gamera uses 12+ hour preconditioning period
  - Solar wind density & velocity held constant
  - IMF begins northward, turns southward for several hours, then northward again.
- Inner magnetosphere models (ring current, rad belt, plas sphere) use quiet time conditions built from observation statistics
- Thermosphere models (e.g., GITM) will begin simulation 1-2 days before period of interest to wash out simple initial conditions.

Case Study: Global MHD



$$\frac{\partial \rho}{\partial t} + \nabla(\rho \bar{u}) = 0$$

$$\rho \frac{\partial \bar{u}}{\partial t} + \rho \bar{u} \cdot \nabla \bar{u} + \nabla p - \bar{J} \times \bar{B} = 0$$

$$\frac{\partial p}{\partial t} + \bar{u} \cdot \nabla p + \gamma p \nabla \cdot \bar{u} = 0$$

$$\frac{\partial \bar{B}}{\partial t} - \nabla \times (\bar{u} \times \bar{B}) = 0$$

Global MagnetoHydroDynamics can solve for the dynamics of the whole magnetosphere

- Continuity equations for mass, momentum, and energy
- Induction equation ties $\bar{B}$ and $\bar{u}$
- 8 state variables:

$\rho \rightarrow$ mass density, $(\frac{kg}{m^3})$

$p \rightarrow$ thermal pressure, (Pa)

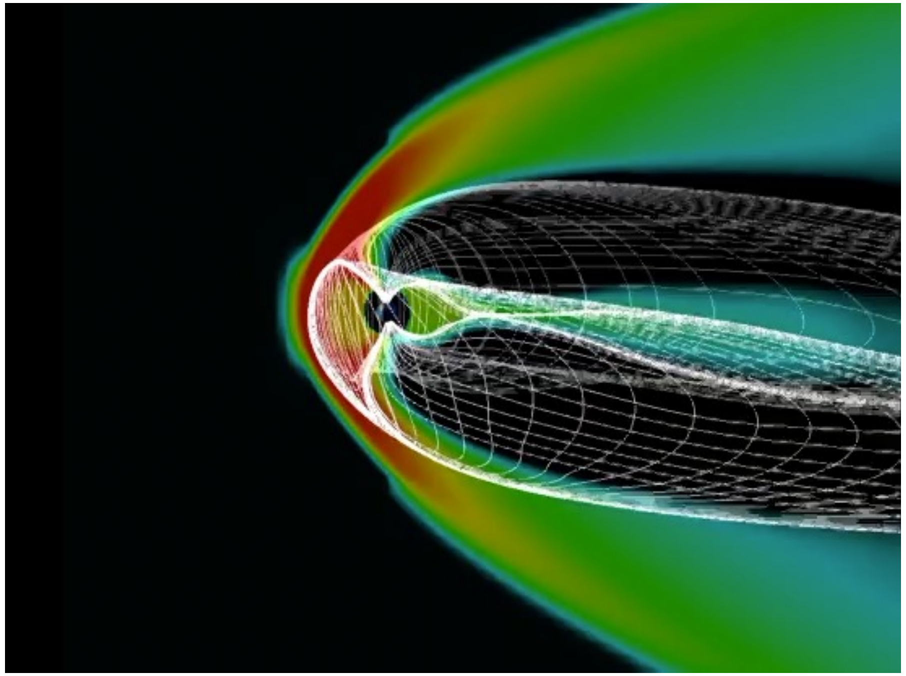
$\bar{u} \rightarrow$ bulk velocity, $(\frac{m}{s})$

$\bar{B} \rightarrow$ magnetic field, (T)

- Many implementations (OpenGGCM, GAMERA, BATS-R-US)

What are the inputs to this

Case Study: Global MHD



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$$\frac{\partial p}{\partial t} + \bar{u}\cdot\nabla p + \gamma p\nabla\cdot\bar{u} = 0$$

$$\frac{\partial \bar{B}}{\partial t} - \nabla\times(\bar{u}\times\bar{B}) = 0$$

What are the inputs to this model?

Initial conditions:

Uniform initial with wind-up phase

Boundary conditions:

Must set all 8 state variables at inner and outer boundaries

Upstream & downstream: inflow & outflow, otherwise float

Source & Loss Terms:

None for ideal MHD

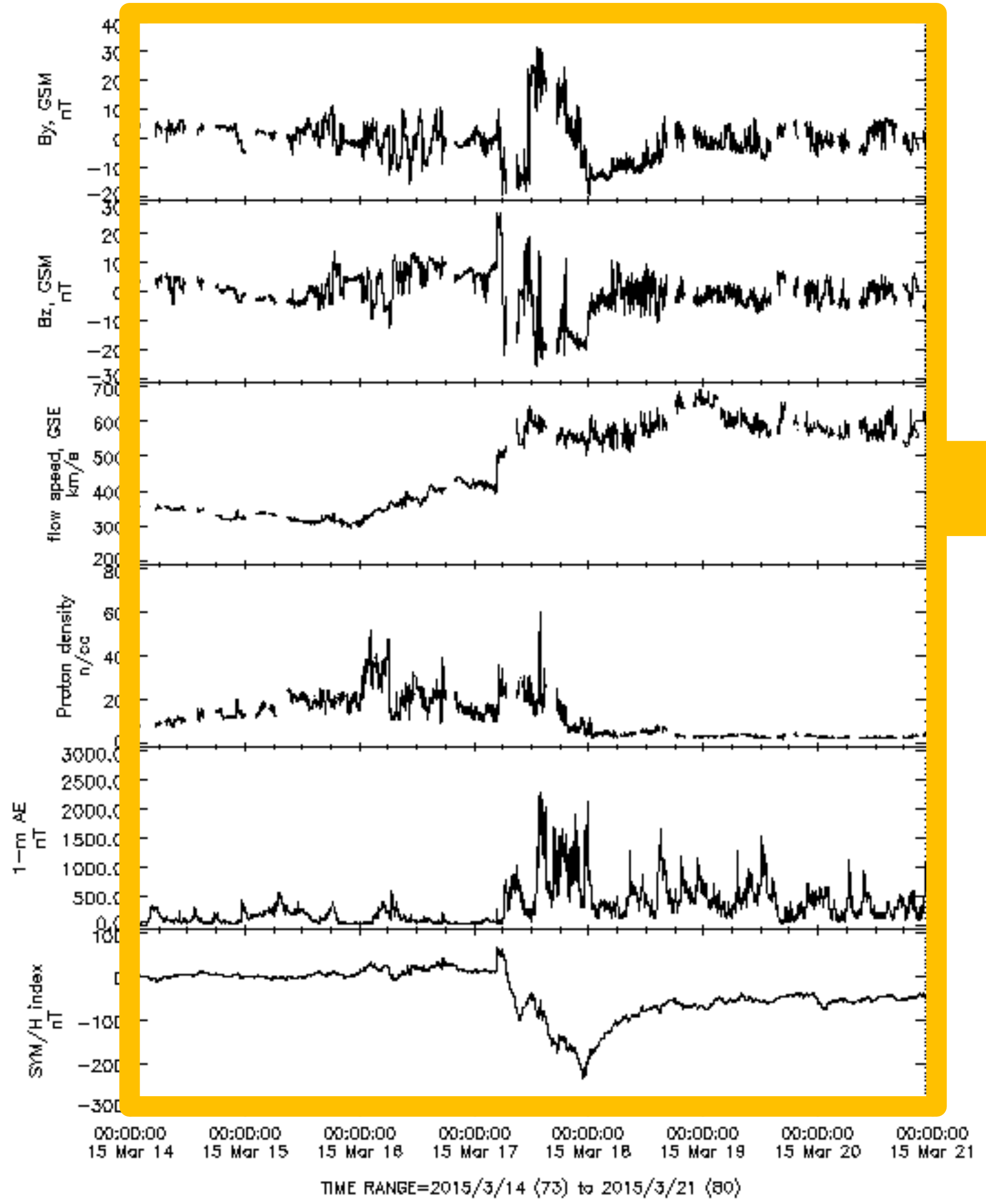
Variables not solved for:

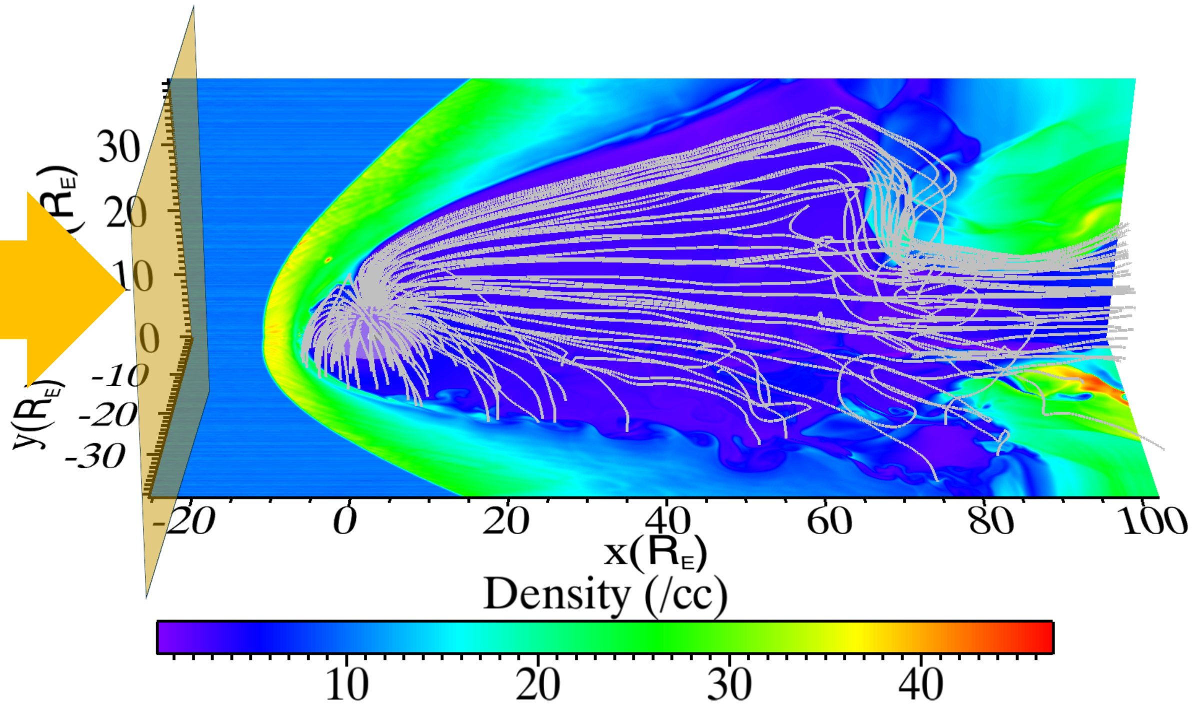
None (yet).

Input data for relationships:

None (yet).

Upstream Boundary Conditions: Solar Wind & IMF





Obtaining Upstream Boundary Conditions

Get Solar Wind & IMF Values

- L1 observations (ACE, DSCOVR): CDAWeb or OMNIWeb
- Near-bowshock values (e.g., Cluster, THEMIS, Geotail, etc): CDAWeb or mission websites
- …or just make'em up!

Propagate Values to Mag'Sphere

- The solar wind must travel from point of observation to nose of bowshock.
- Several methods: ballistic, phase-front-angles, 1D MHD, etc. OMNI uses PFAs.

Adapt to MHD code & Run

- Rotate to desired coordinate system.
- Upstream inputs are usually interpolated in time as MHD timesteps can be sub-second.

Obtaining Upstream Boundary Conditions

Get Solar Wind & IMF Values

Are there data gaps?
What is the time resolution?
Did we measure what hit Earth?

Propagate Values to Mag'Sphere

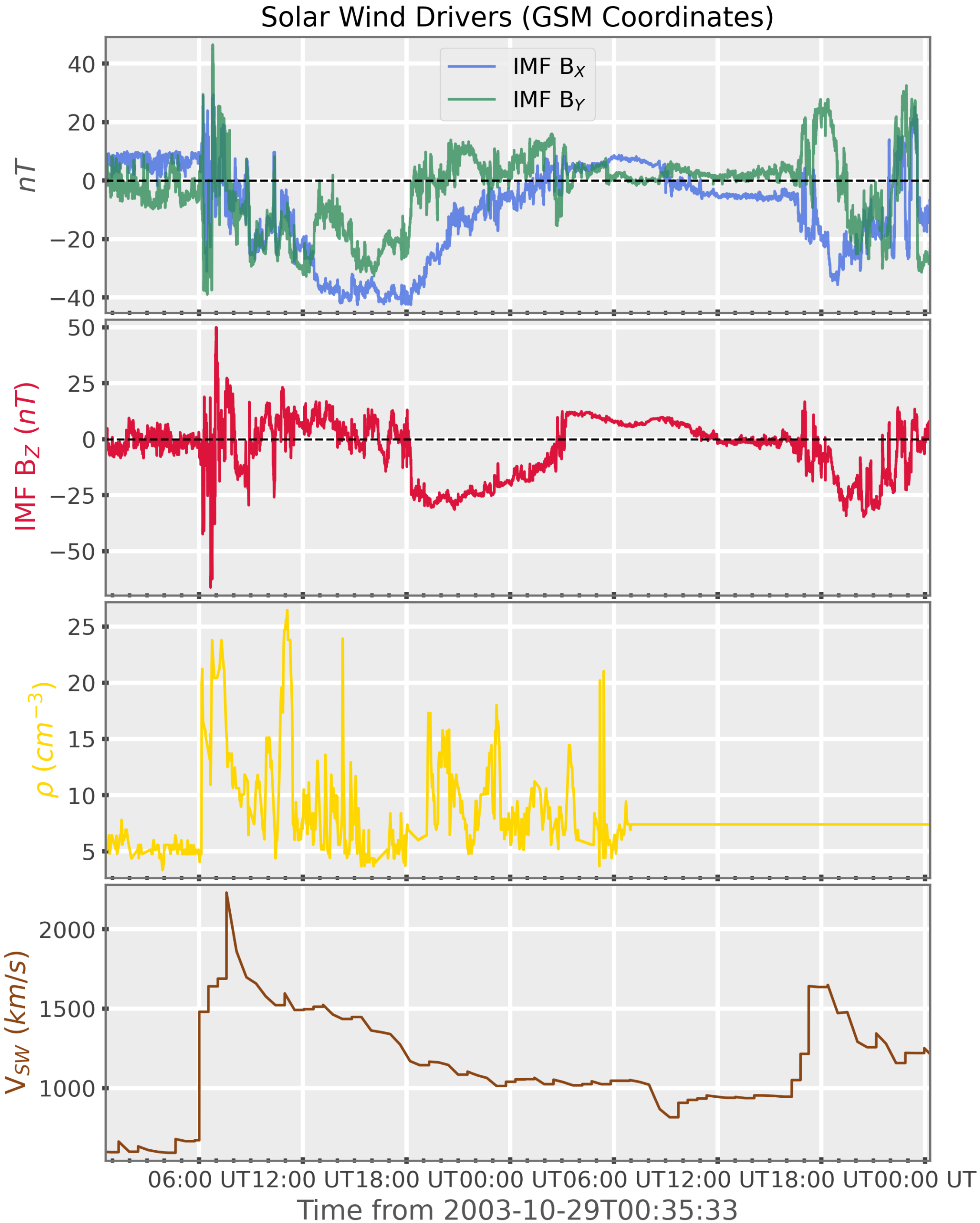
Is the propagation high quality?
Did values *evolve* from L1 to Earth?

Adapt to MHD code & Run

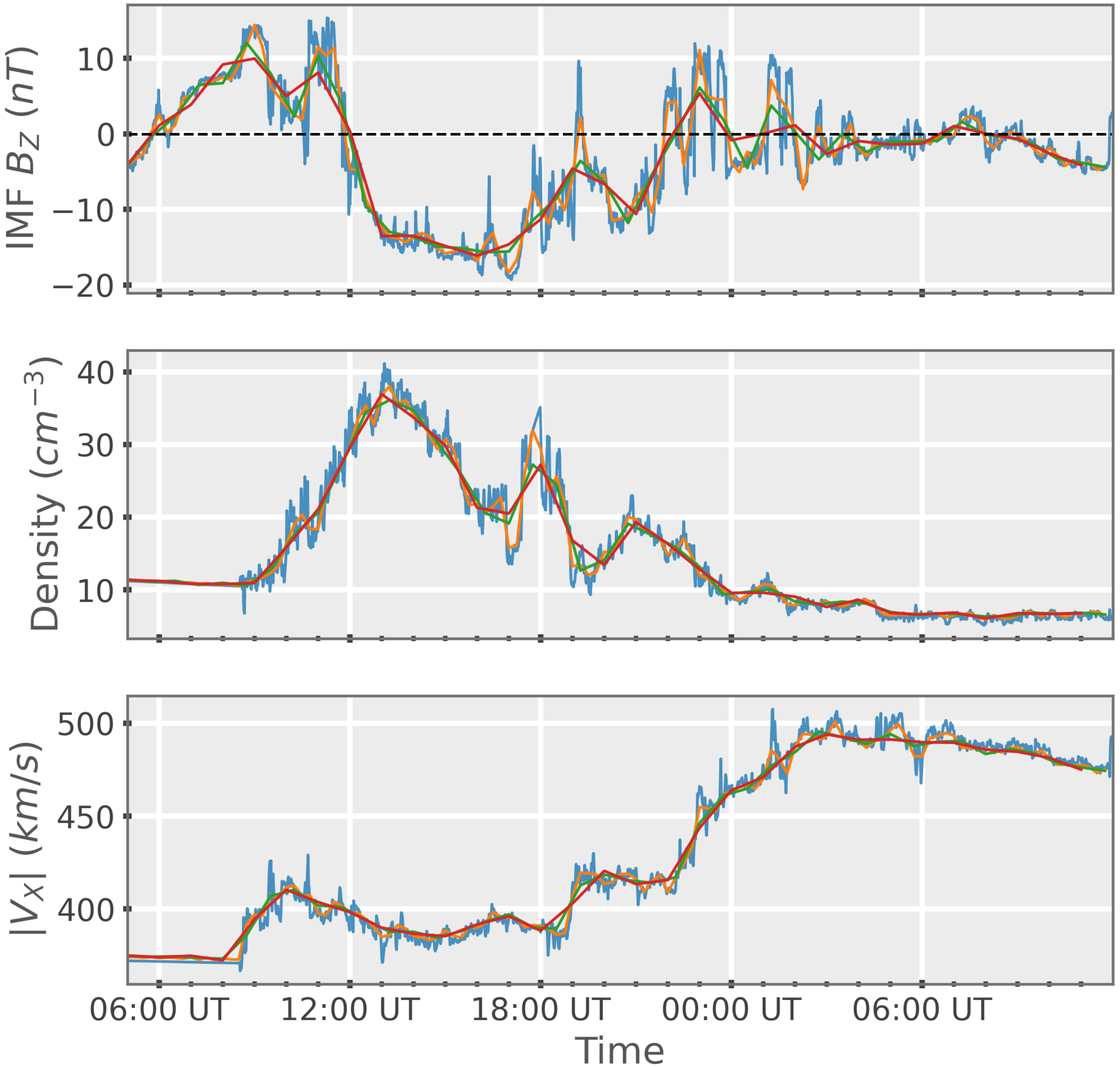
Is the model configuration appropriate for the input data set?

Data Quality Challenges

- L1 observations are often riddled with data gaps.
- During active times, instrument contamination (e.g., ACE SWEPAM) can invalidate large periods
- Famous example: Oct. 2003 "Halloween Event"
- Mitigating strategies:
  - Do not rely purely on OMNIWeb
  - Consider multiple data sources
  - Talk to instrument PIs
- Do these data gaps matter?
  - Depends on your use case!



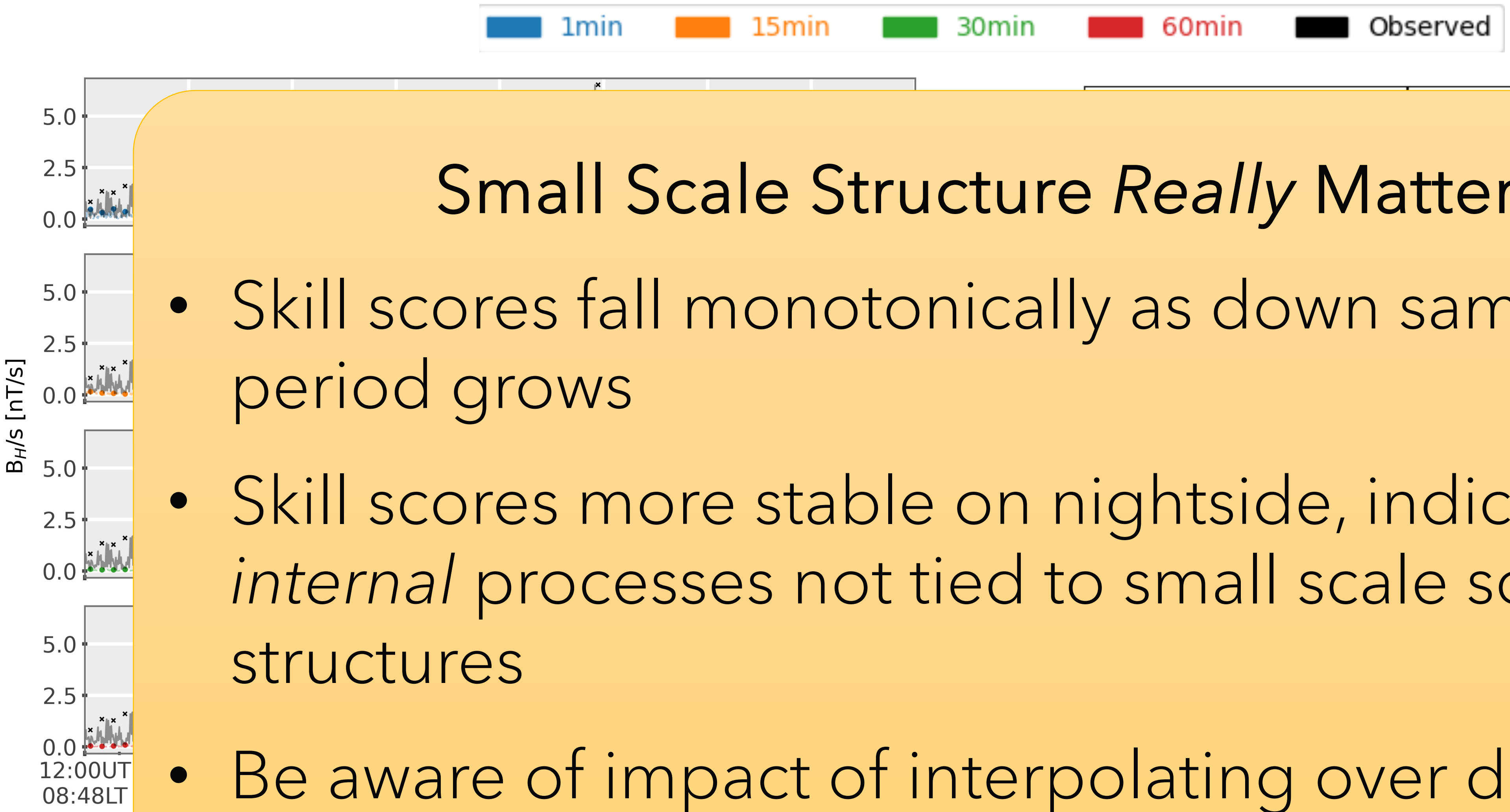
Small Scale Features: Do the wiggles matter?



Data gaps can be solved by interpolation, but this removes structure.

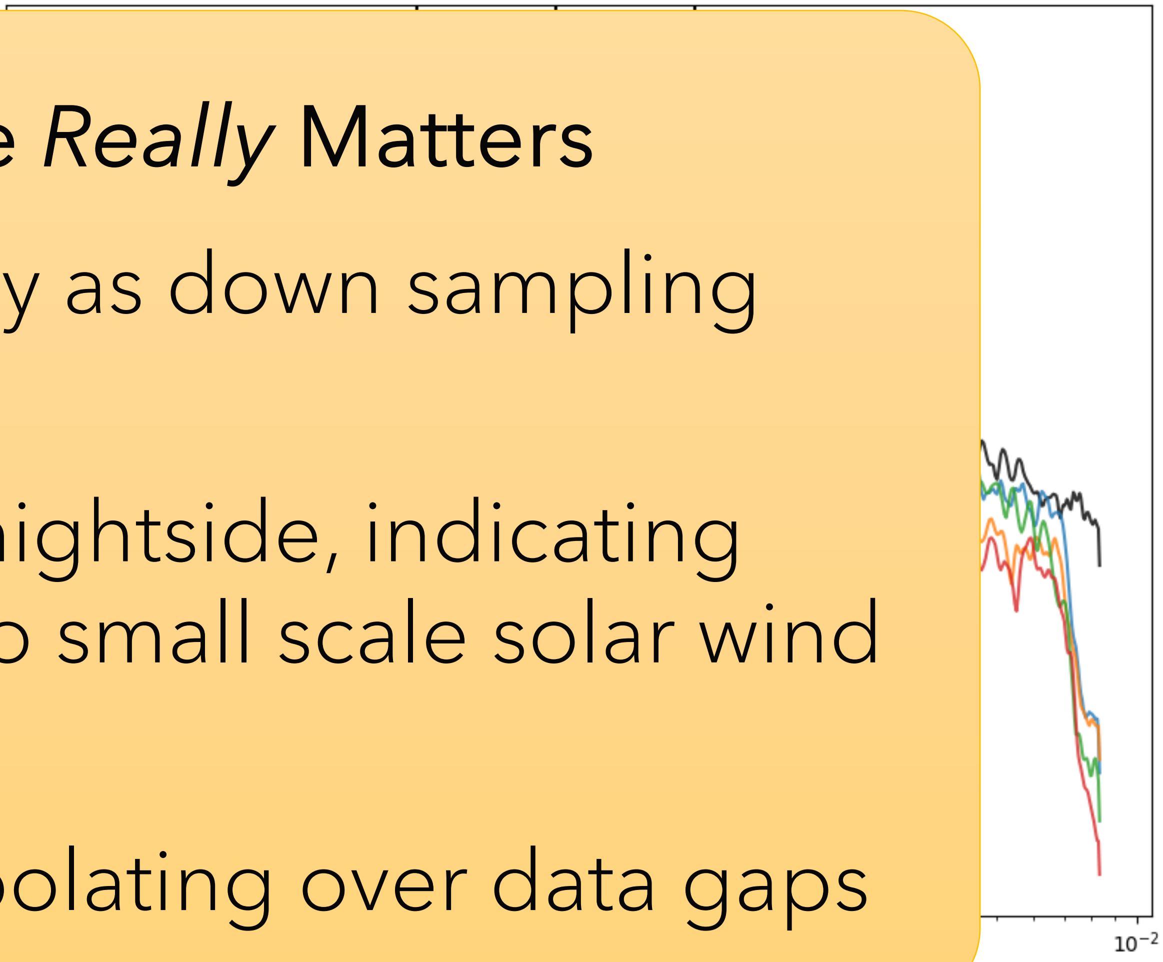
How much does *down sampling* or smoothing affect results? Let's test:

- Repeat SWPC/CCMC validation challenge, increase number of magnetometers
- For each storm, down sample 1min solar values to 15, 30, and 60 minutes
- Simulate storms, compare forecasts to observations, calculate metrics

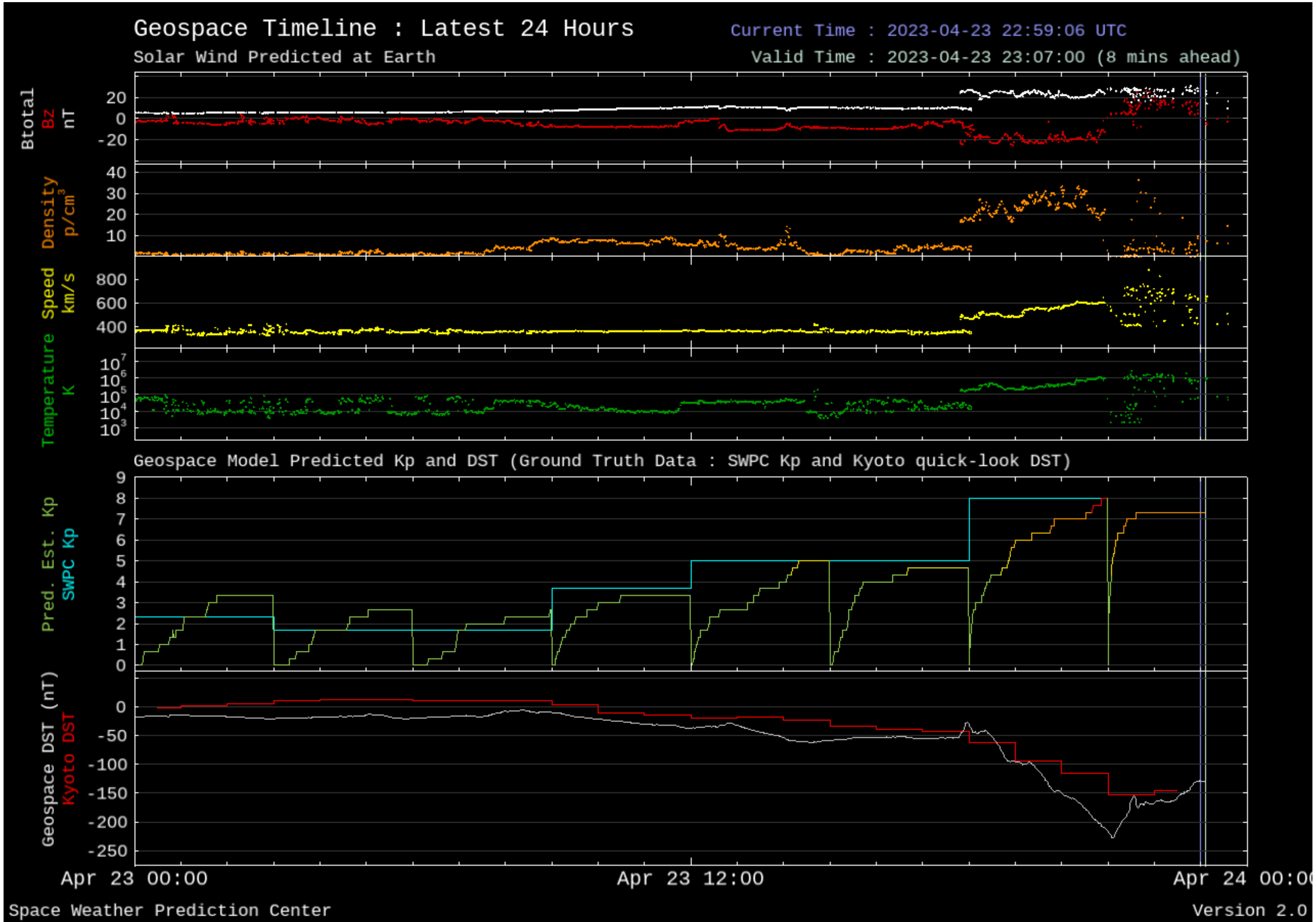


Small Scale Structure *Really* Matters

- Skill scores fall monotonically as down sampling period grows
- Skill scores more stable on nightside, indicating *internal* processes not tied to small scale solar wind structures
- Be aware of impact of interpolating over data gaps



More on Instrument Limitations

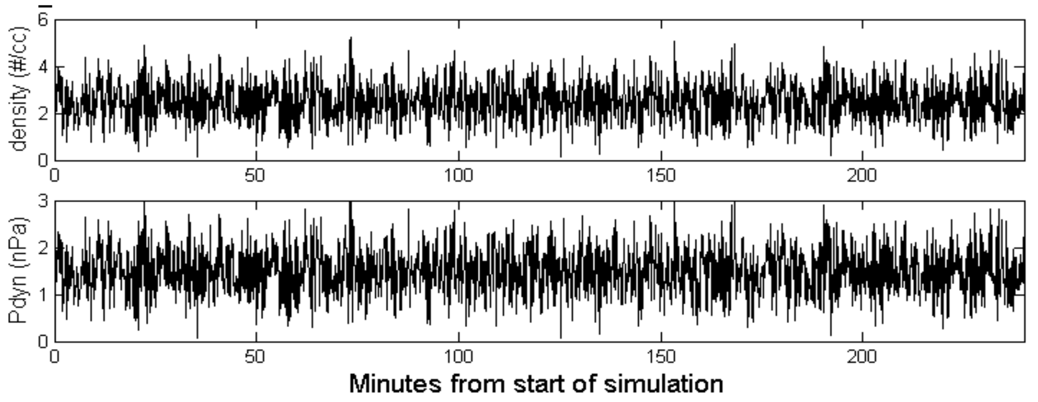


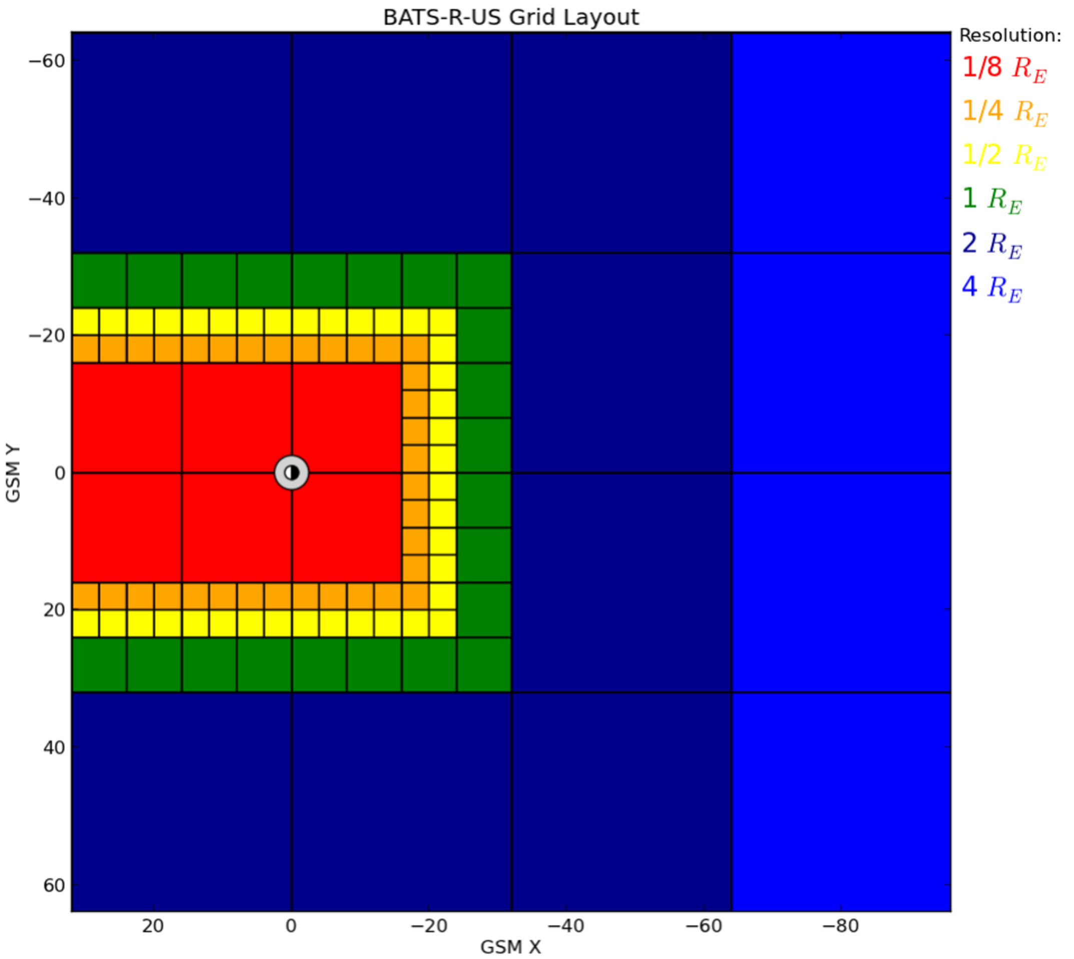
Model Considerations – An Anecd

- Mike Hartinger & I wanted to simulate ULF waves and reproduce *Claudepierre et al.*, 2009.
- BATS-R-US would not produce ULF waves using the same inputs.
- Problem was the grid!
- Spacing must meet Nyquist requirement for input wavelengths.

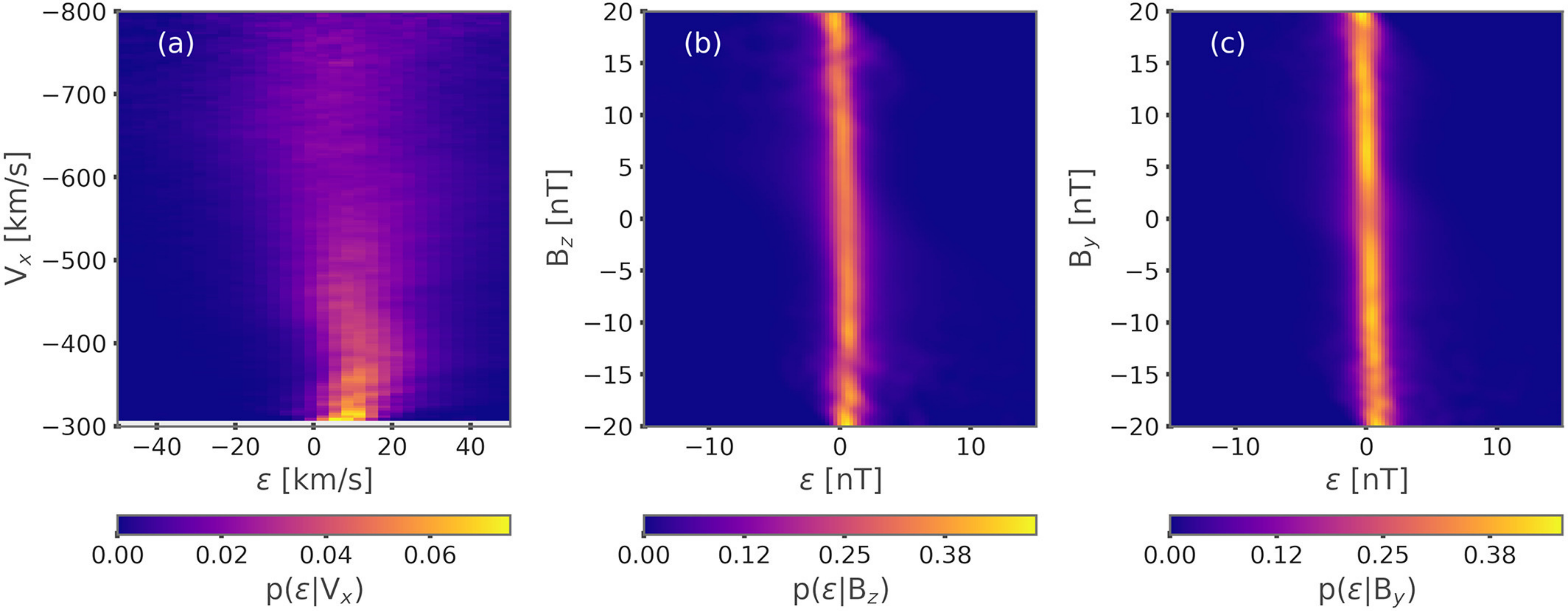
Other common considerations:

- Can model handle significant IMF BX?
- Are all state variables included (e.g., multifluid or anisotropic MHD)?





Propagation & Observational Limitations



Morley et al., 2018

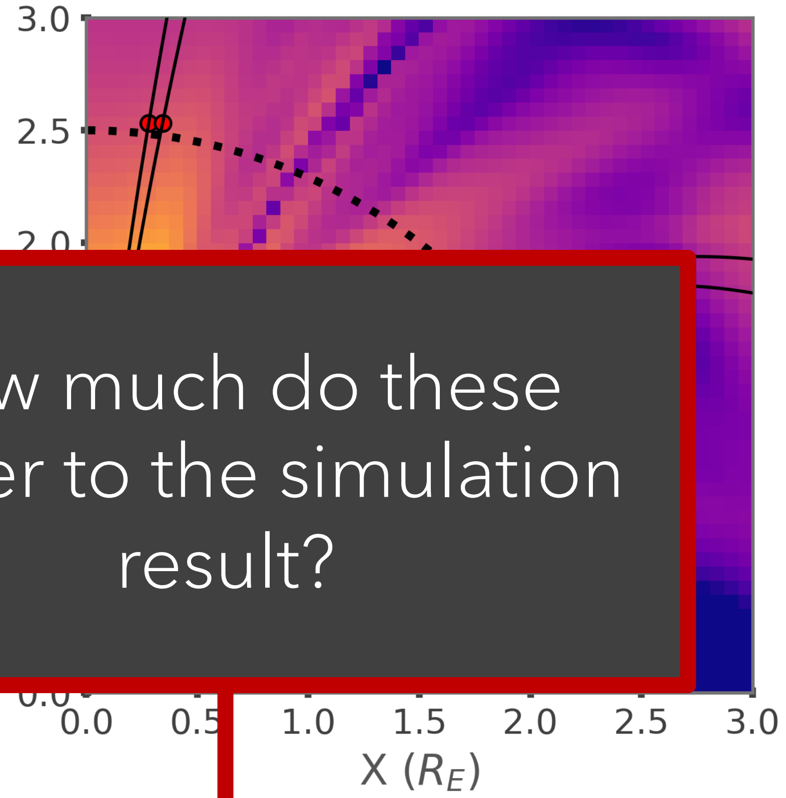
Upstream Boundary Conditions: Key Takeaways

- Keep in mind the goals of your study: what types of features or processes are important to you?
- Assess upstream data thoroughly – look for gaps or poor-quality values.
- Consider different sources than just OMNIweb.
- Be honest in your presentations and publications: what are the limitations of the upstream data?
- Seek a domain expert (e.g., an instrument PI or model developer) to help

Inner Boundary Conditions

MHD inner boundaries for geospace are typically spheres of radius 2-3 RE

Sometimes known as the "gap region" between mag'sphere & ionosphere.



How much do these matter to the simulation result?

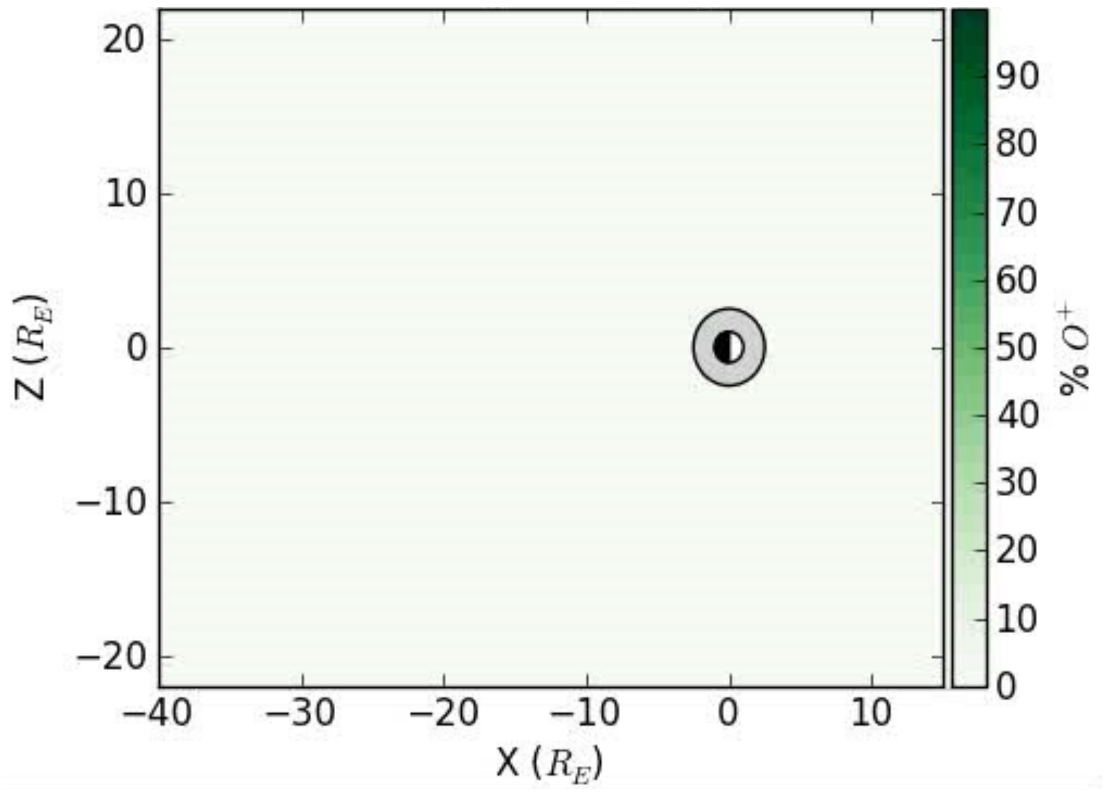
Along the I.B., we need to set valu

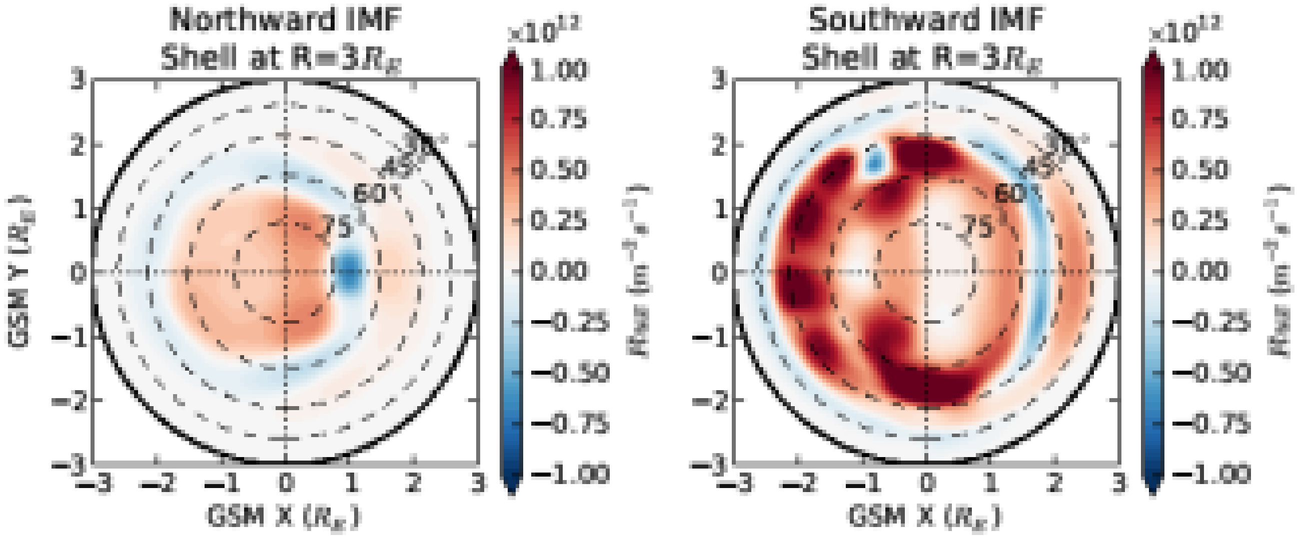
Variable	Typical Approach
Mass Density & Pressure (ρ, p)	Either set constant values or "hard wall" boundary
Magnetic Field ($\bar{B}$)	Dipole magnetic field (with or without tilt!)
Radial Velocity (c)	Set to zero.
Tangential Velocity ($\bar{u}_\perp$)	Set to match ionosphere convection velocity

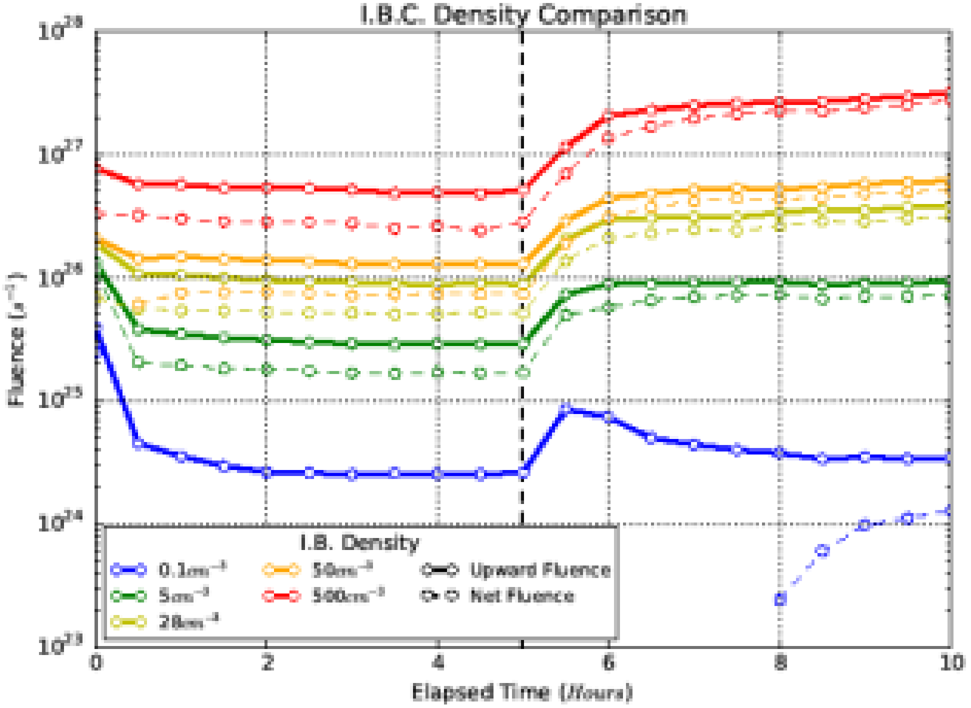
Inner Boundary Conditions: Mass Density

Even if $u_r = 0$, Dirichlet IBCs in ρ_{IB} yields *dynamic* plasma outflow…

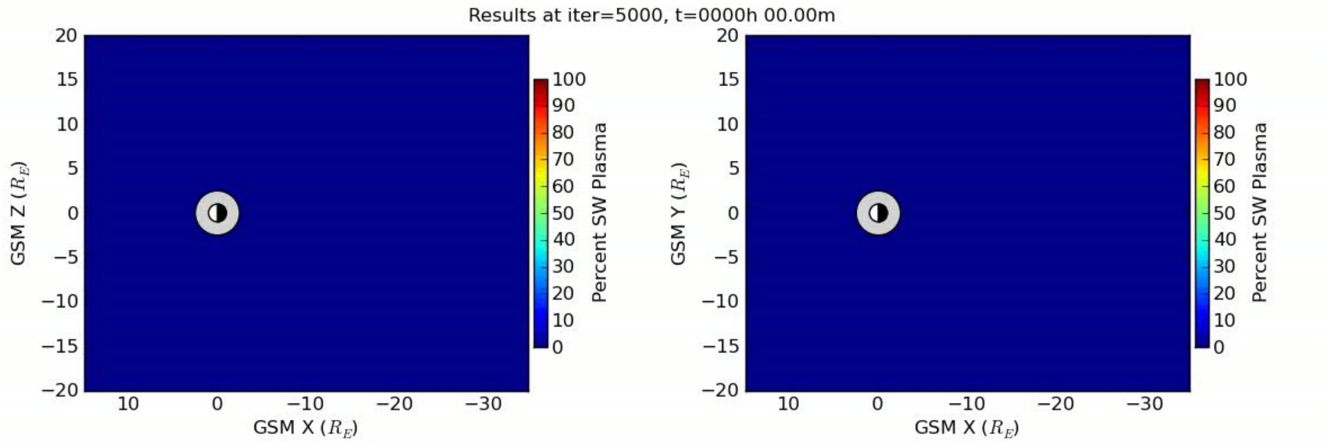
…that scales with ρ_{IB} and activity…



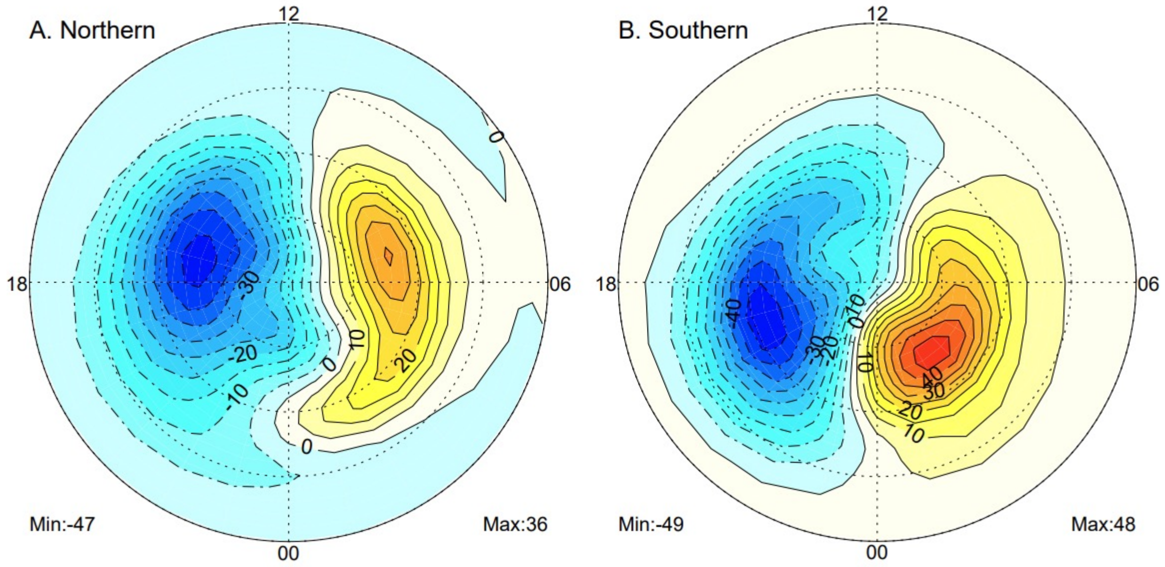




Consequences of ρ_{IB}



Case Study: Ionospheric Electrodynamics Solvers



Electric potential (kV)

$$J_R = \nabla_\perp(\bar{\bar{\Sigma}} \cdot \nabla_\perp \Phi)$$

Field-Aligned Currents (A/m^2)

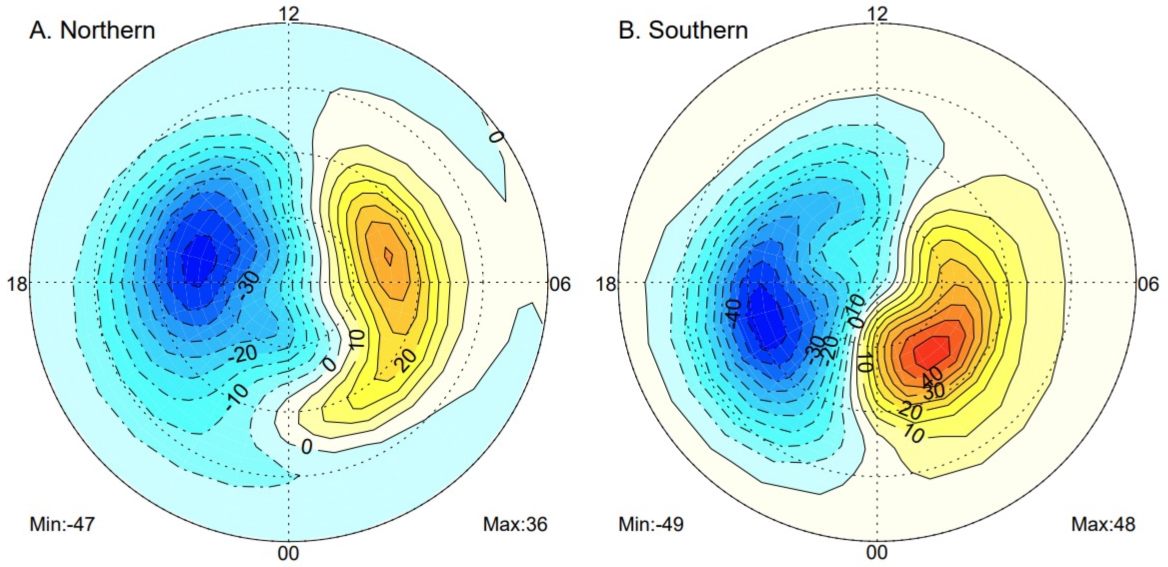
Conductance (S)

Ionospheric Electrostatic Solvers obtain the ionospheric potential given FACs and conductance.

- Given FAC pattern (J_R) and ionospheric conductance ($\bar{\bar{\Sigma}}$), solves a Poisson-like equation for the ionospheric potential, Φ
- An iterative minimal residual method to converge to a solution.
- Coupled to MHD to set the $\bar{u}_\perp$ inner boundary conditions

What are the inputs to this model?

Case Study: Ionospheric Electrodynamics Solvers



$$J_R = \nabla_\perp(\bar{\bar{\bar{\Sigma}}} \cdot \nabla_\perp \Phi)$$

What are the inputs to this model?

Initial conditions:

Iterative model/not time dynamic

Boundary conditions:

Zero Φ at the equator

Source & Loss Terms:

None.

Variables not solved for:

J_R from global MHD

$\bar{\bar{\bar{\Sigma}}}$ from 🪄 🎩

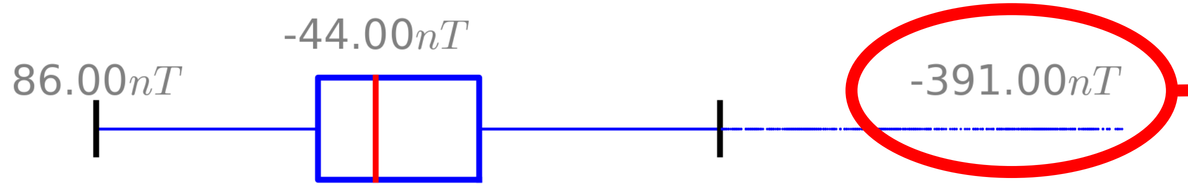
Input data for relationships:

$\bar{\bar{\bar{\Sigma}}}$, based on empirical relationships

Range of Empirical Inputs

Input Conditions: Sym-H

SWPC Events



"Halloween Storm"
Oct. 29, 2003

WEIMER

Nov. 20, 2003

WEAKER
ACTIVITY
BIAS

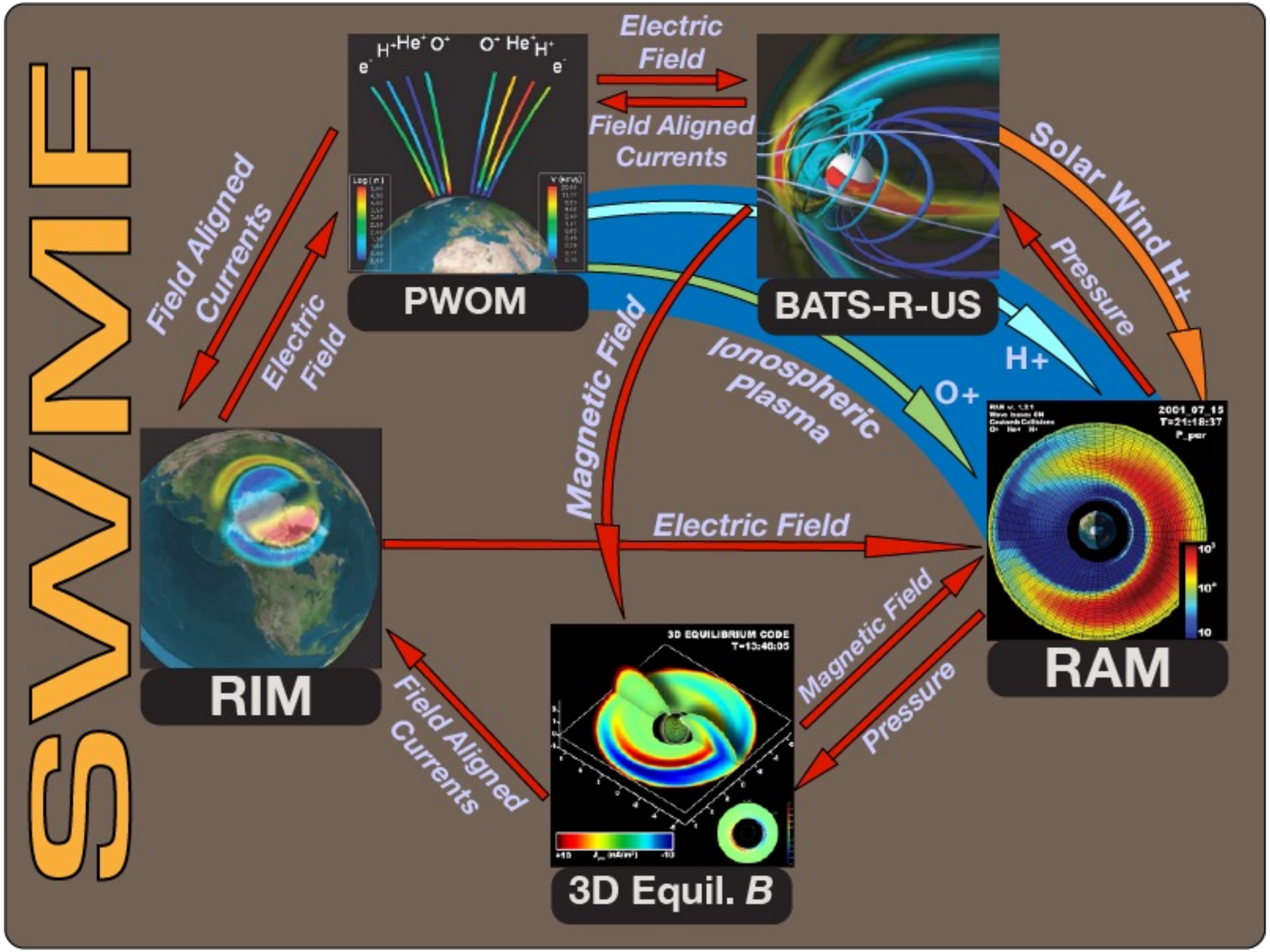
NO
EXTREMES

LFM &
OpenGGCM

Stronger Activity ⟶

Welling et al., Space Weather, 2017

Model Coupling



Final Take-Aways

- Model inputs are any values or data sets required to run a simulation or build an empirical/ML relationship
  - These can include upstream values, boundary conditions, *anything* the code doesn't explicitly solve for.
  - Think beyond solar wind and upstream values! Codes have MANY inputs!
- All inputs have consequences on model results
  - Critically consider the role each choice may have.
  - When reporting results, be open and honest about input limitations.
- Evaluate everything with respect to the goal of the study
  - Is a limitation of a given input likely to be a 1st order effect?
  - Is a given limitation relevant to the processes being studied?