Cross-scale and cross-region coupling panel

Key questions:

- What do we need to understand to about cross-scale and cross-region coupling to enable predictive capability of the state of the Magnetosphere/ITM?
- What are the research needs to make progress on that understanding?

Moderator: Endawoke Yizengaw, Committee

***Joshua* Semeter**	*Boston University*	*Professor*
Astrid Maute	HAO/NCAR	*Project Scientist*
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Space Weather Operations and Research Infrastructure Workshop: Phase II, Monday April 12, 2022, 1140 ET

What do we need to understand about cross-scale and cross-region coupling to enable predictive capability of the state of the Magnetosphere/ITM?

Proposed Definitions:

- *Cross-scale coupling:*

  Dynamics at one spatiotemporal scale define boundary conditions for another scale governed by different physics (e.g., MHD kinetic)

- *Cross-region* ↔ *coupling:*

  Coupling between geophysical domains demarcated by a change in physical description
  (e.g., solar wind – magnetosphere,
  ring current – plasmasphere)

Josh Semeter, Boston University, 12 April 2022

Cross-Scale Coupling: Energy Perspective

Mode of energy transport	Cross-scale boundary	Change in physics	Significance
1. Plasma sheet injection, energization, and dissipation	Mesoscale dynamics (1 Re X 1 minute)	Global MHD → 'kinetic' MHD (embedded test particle or PIC simulation)	Ring current dynamics poorly understood. Role of localized injections, waves and instabilities on storm development not known.
2. Substorm onset	Plasma sheet thickness $\sim$ Ion Larmour radius	Tail reconnection, particle acceleration, breakdown of field theory	Major mode of internal energy release in the geospace system.
3. Alfvén waves	Wavelength $<$ electron inertial length	Change in dispersion relation, MHD→ kinetic.	Dominant mode of energy transport. Dispersion leads to 100-meter variability in precipitation, ionization, and conductivity.
4. Joule heating	Polarization *E*-fields caused by sub-grid variability in conductance.	E-field variability that is either unresolved by the physics model, or undersampled by observations.	Misrepresentation of Joule heating rate. Both over-estimation or under-estimation possible.
5. E-region turbulence (SAID, electrojets, arc boundaries)	$E > 50$ mV/m	Destabilization of modified two-stream instability → nonlinear currents, anomalous heating.	Alters macroscopic conductance seen by magnetosphere.
6. Equatorial Plasma bubbles	Irregularity scale near Ion Larmour radius	Non-Maxwellian distributions, dissipation through kinetic instabilities.	Broad-band RF scintillation.
7. RF wave propagation through disturbed ionosphere.	Ionospheric irregularities $<$ Fresnel scale (~300 m)	Ionosphere transitions from refractive to diffractive medium	Stochastic amplitude modulation ('scintillation') and rapid phase fluctuation (loss-of-lock)

Alfvén waves

Dominant mode of electromagnetic energy transfer between the magnetosphere and the ITM system.

Dispersionless-to-dispersive transition occurs in the near-Earth magnetosphere as transverse wavenumber spectrum broadens due to:

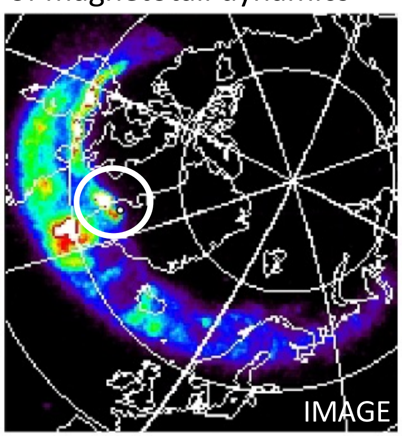
- Mode coupling
- Propagation thru inhomogeneities
- Impulsive excitation (substorms)

$$\omega^2 = k_z^2 v_A^2 \quad \leftrightarrow \quad \omega^2 = \frac{k_z^2 v_A^2}{1 + k_\perp^2 \lambda_e^2} \qquad \lambda_e = \frac{c}{\omega}$$

Consequences are profound, and yet not captured in predictive models:

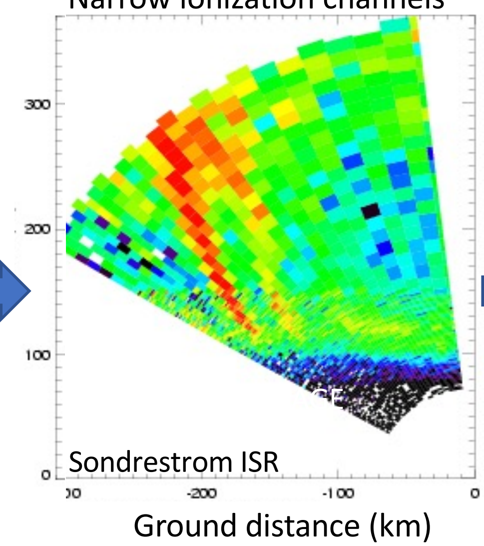
- Ionizing precipitation at ~100-m scales
- Extreme structuring of conductance field, producing unresolved polarization electric fields.
- Misrepresentation of Joule heating ($\sigma_p E^2$)
- Excitation of E-region turbulence (next slide)
- Reflection and damping of Alfvénic disturbances over minutes time-scale.
- Topside transverse heating leads to ion outflow.

PBIs and streamers: projection of magnetotail dynamics

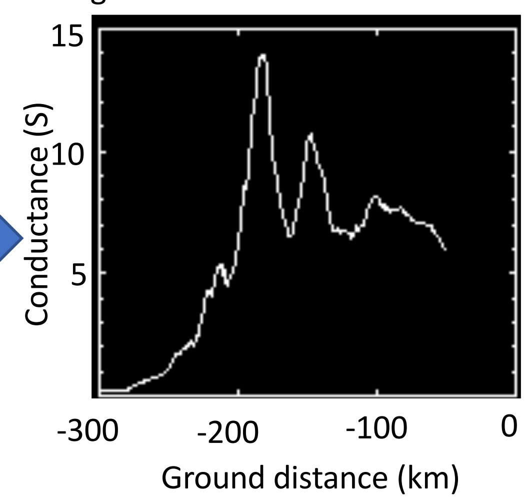


Broad-band, highly structured, precipitation.

Narrow ionization channels



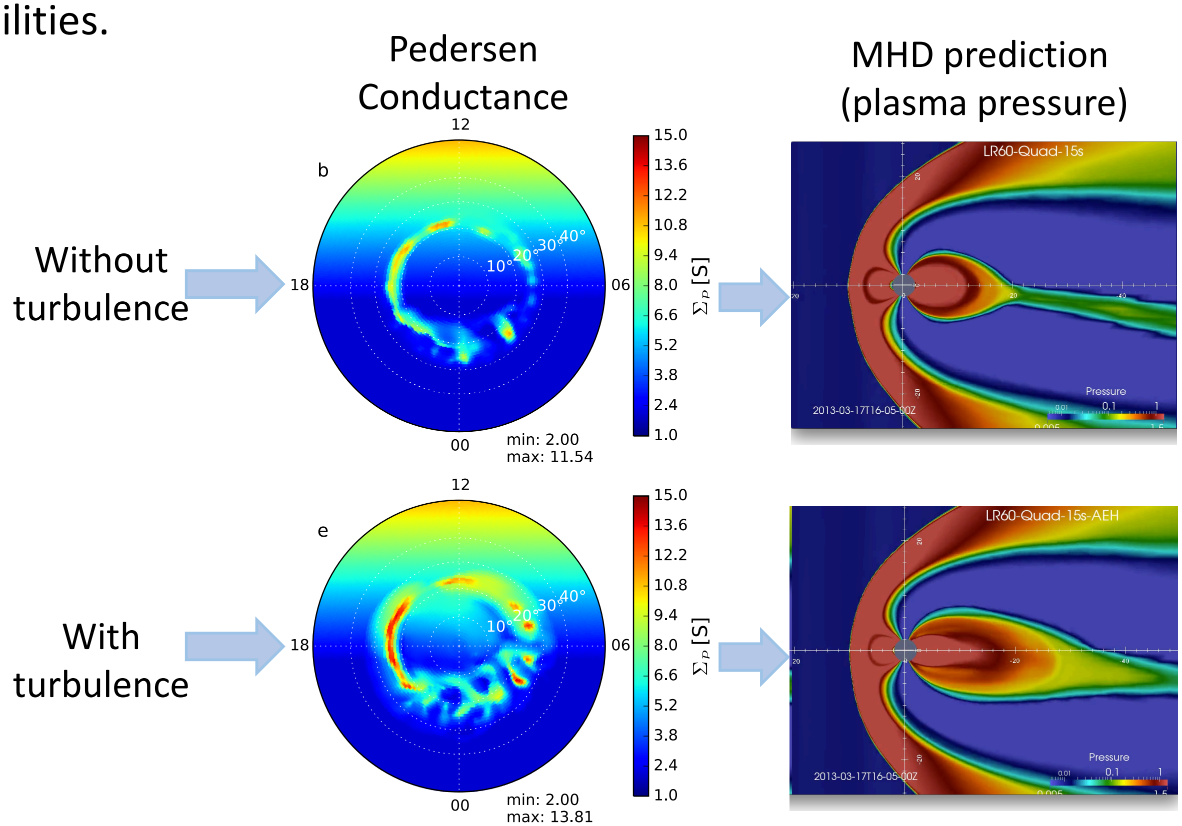
Highly structured conductance field, in regions of intense FACs.



E-region turbulence

Ionospheric micro-scale turbulence should have significant macro-scale effects on the geospace system. These effects are not captured in predictive models and are incompletely measured by current sensing capabilities.

The figure shows predicted impact of E-region streaming instabilities on the global magnetosphere. The enhanced effective conductance is due to non-linear currents and anomalous electron heating caused by Farley-Buneman instability.



Wiltberger et al., JGRA 2017]

Turbulence is ubiquitous in the disturbed Solar Wind – Magnetosphere – ITM system. Hybrid fluid-kinetic models and new data assimilation approaches are needed for next generation predictive modeling.

Research paradigm: The ITM as projection

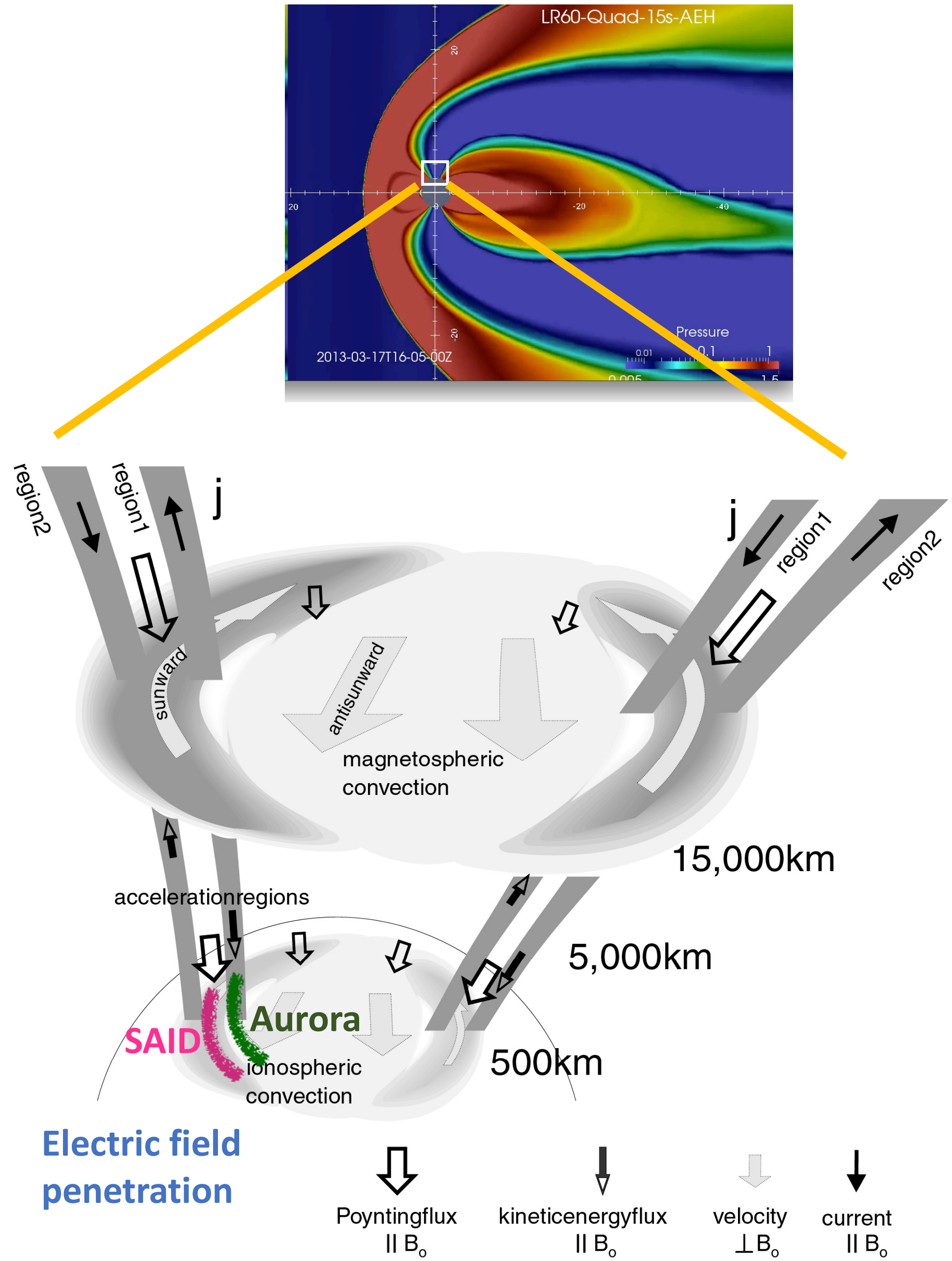
We will never obtain in-situ samples of the geospace system sufficient density.

An achievable objective is a complete understanding how the physics is projected into the ITM system, and how to interpret this projection quantitatively.

The projection accessible to ground-based networks presents a rich admixture of cross-scale and cross-region dynamics.

Fully exploiting this paradigm requires new collaborations and convergent thinking:

- Applications of data fusion and inverse theory to heterogeneous observations.
- New applications of predictive filtering
- Applications of information theory
- AI and machine learning applied to collaborative measurements from ground and space.
- Merging mathematical and physical models
- New collaborations with CS, engineering, statisticians, data scientists.



Ionospheric electrodynamics across regions & scales

1. What do we *need to understand about cross-scale and cross-region coupling* to enable predictive capability of the state of the Magnetosphere/ITM?
2. What are the *research needs* to make progress on that understanding?

- Research and modelling perspective limited to the ionosphere & thermosphere
- Focus on meso 10s-100s km and large scale > 100s km, temporal scales > 1min (not small scale)
- I interpret "enable predictive capabilities" widely as gaining more insights into the important influences and factors leading to space weather effects but not doing predictive modelling.

NCAR

Astrid Maute, High Altitude Observatory/NCAR, Boulder CO, USA

NSF

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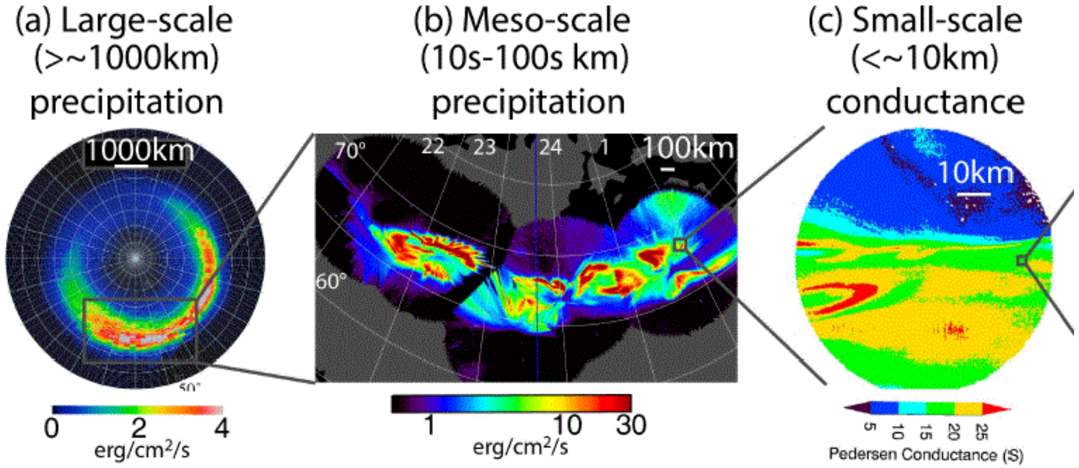
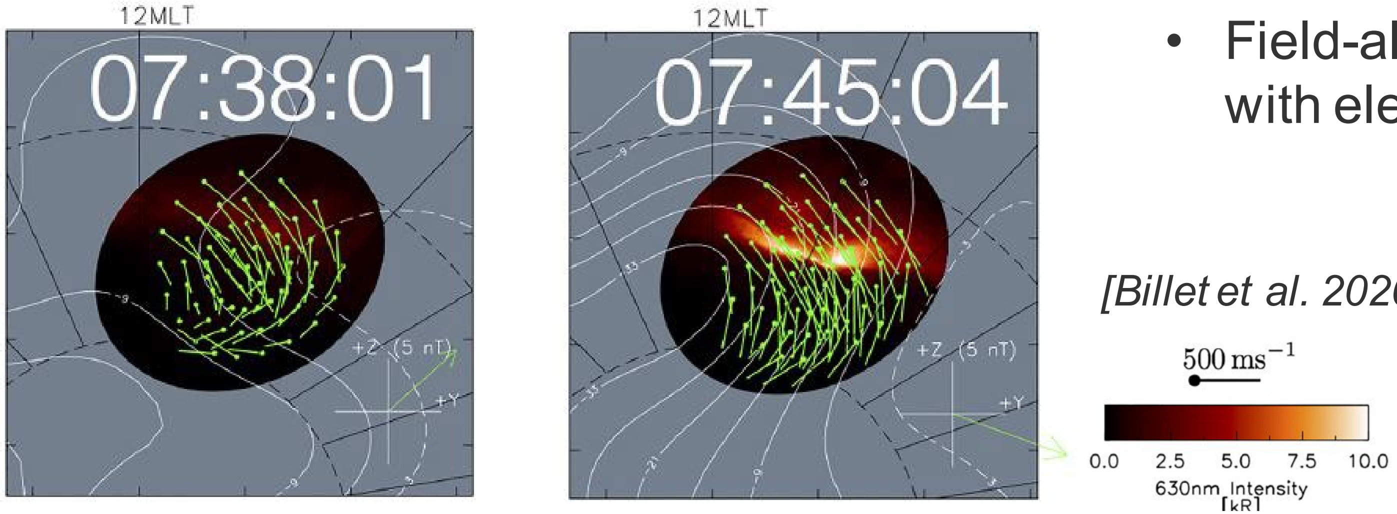
Mesoscale electrodynamics in MI coupling



[Nishimura et al. 2019]



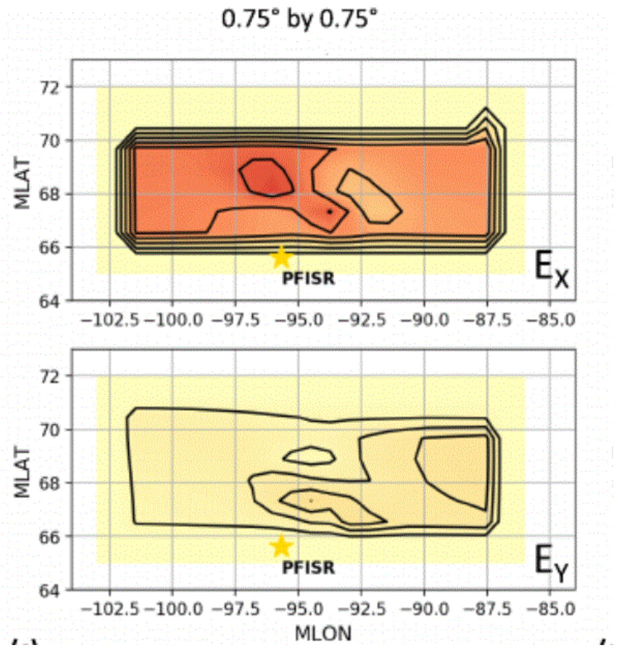
[Billet et al. 2020]

- Without mesoscale electric field the Joule heating is underestimated by ~50%.
- Mesoscale precipitation can account for 25-50% of total precipitation energy input during active times.
- Neutral winds in F-region respond within minutes to magnetospheric forcing associated with aurora down to scales of 100km and can reduce the local Joule heating.
- Field-aligned current & its variability consistent with electric field & conductivities.

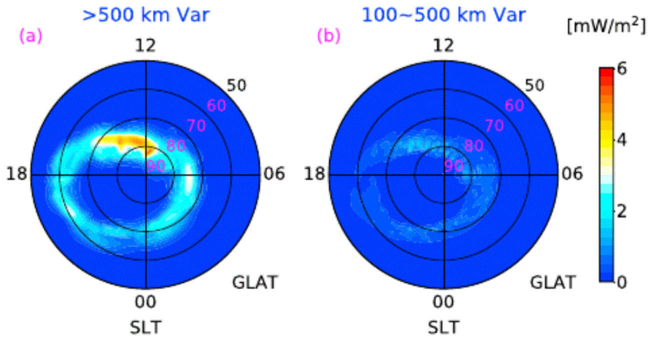
Regional self-consistent observations of ion drift , particle precipitation, FAC, E- & F-region neutral wind.

Including mesoscale features in simulations

Include PFISR electric fields



Include large and mesoscale FAC variability



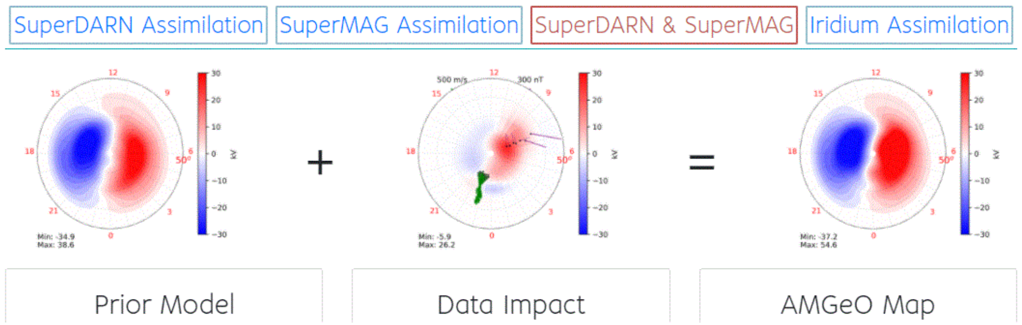
[Zhu et al., 2019]

High-latitude Input for Mesoscale Electrodynamics (HIME)

[Öztürk et al., 2020]

- Improve empirical models to make them self-consistent between electric field, FAC, auroral particle precipitation and consider both hemispheres as well as longitude.
- Regional inclusions of data – being flexible in location, boundary conditions, consistency of scales.
- Data assimilation
- Include the effect of the neutral wind dynamo

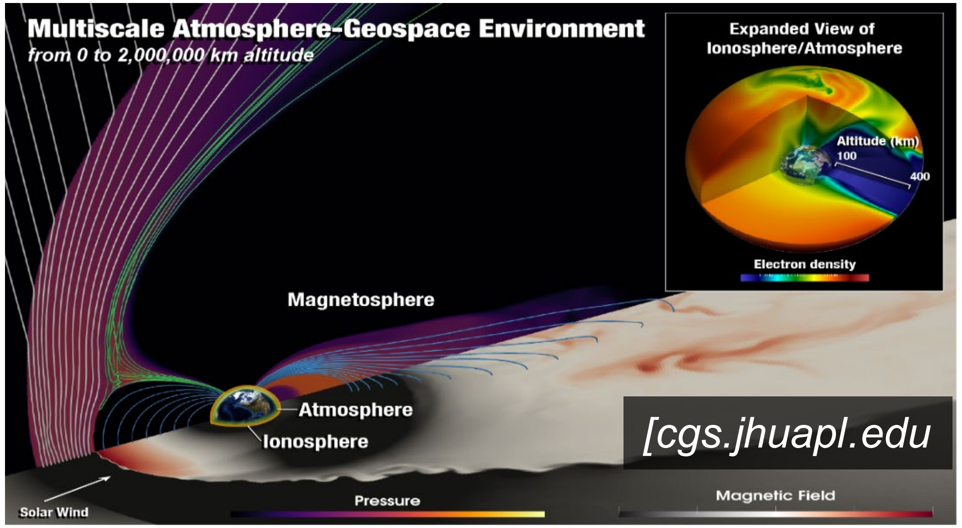
Making AMGeO Maps



Need methods to ingest diverse, self-consistent datasets into models.

[Provided by Tomoko Matsuo et al. https://amgeo.colorado.edu/]

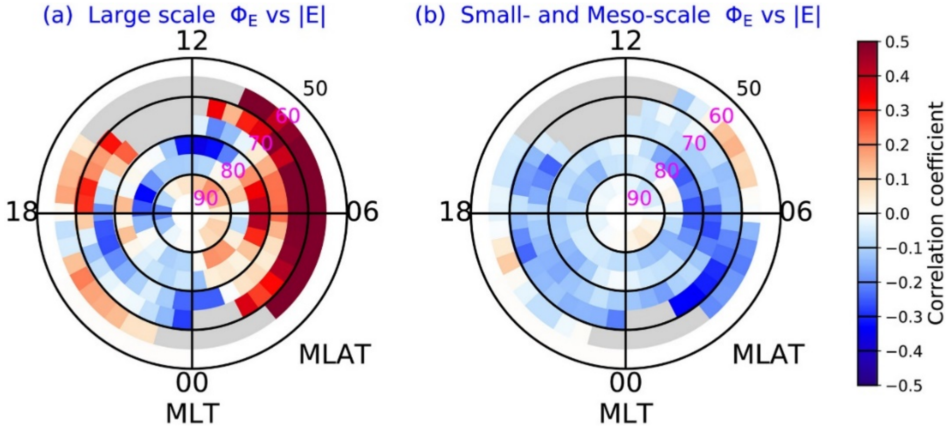
Ionospheric electrodynamic across regions



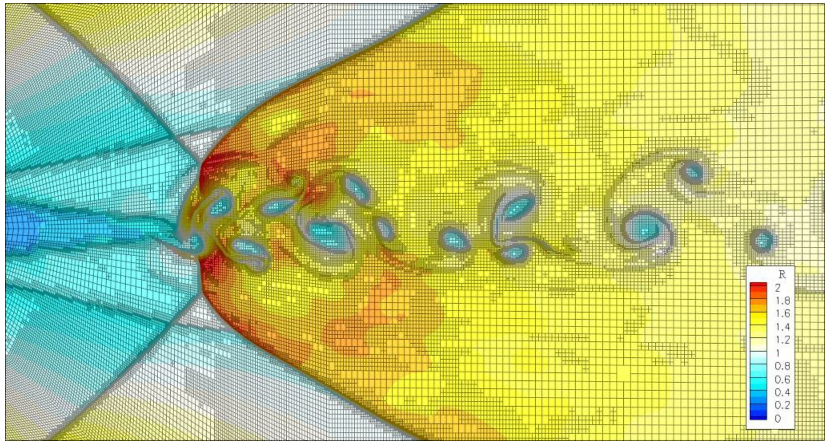
[cgs.jhuapl.edu

- Couple the appropriate scales across physical domains.
- Be aware of the used geomagnetic main field(s).
- Voltage versus current generator type depends on scale size.
- Transition of open and closed field-line region – does it have to be a circle?
- Learn from other field which has used adaptive grid refinement.

Correlation between electric field & particle energy flux



voltage generator type current generator type [Zhu et al, 2019]



[Papoutsakis et al, 2018]

ITM CROSS-SCALE COUPLING: IRREGULARITIES

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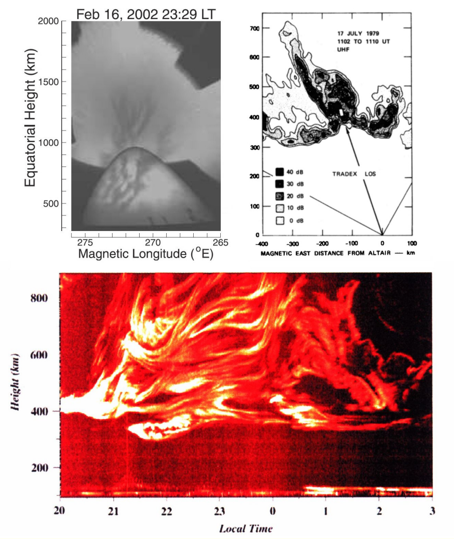
Space Weather Operations and Research Infrastructure Workshop: Phase II
April, 2022

EXAMPLE: EQUATORIAL SPREAD F

- $>$ top left: optical emissions observed from Mount Haleakala 10s km irregularities
- $>$ top right: 11 cm radar backscatter from Kwajalein
- $>$ bottom: 3 m radar backscatter from Jicamarca
- $>$ hierarchy of instabilities suggested to explain range of irregularities (Haerendel 1973)



CROSS-SCALE COUPLING

$>$ cross-scale (spans 6 orders of magnitude)

  spatial (10s cm to 100s km)

  temporal (msec to hrs)

$>$ different physical equations needed

  – small-scale:

    kinetic theory ($\lambda \lesssim \rho_i$)

  – mid- to large-scale:

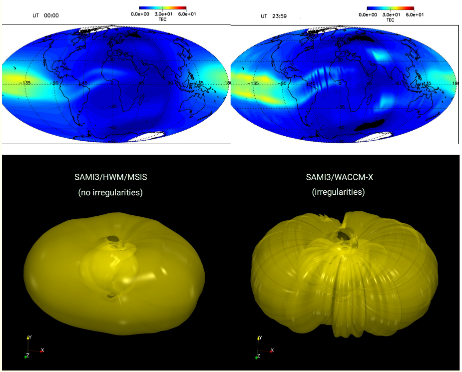
    fluid theory ($\lambda > \rho_i$) (finite Larmor radius effects)

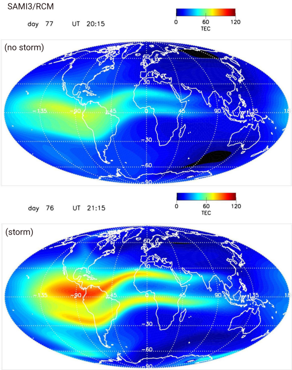
    fluid theory ($\lambda >> \rho_i$) (no finite Larmor radius effects)

CROSS-REGION (SPATIAL) COUPLING

example of current status

> lower atmosphere $\rightarrow$ ionosphere/plasmasphere (left)
> high-latitude $\rightarrow$ low-latitude (right)





CROSS-COUPLING ISSUES

physics

- $>$ different equations needed
  - kinetic and fluid models
- $>$ 2D vs 3D electrodynamics:
  - controls scale-size of irregularities mapping along B
  - new instabilities
- $>$ global electrodynamic model: i.e., high-latitude $\rightarrow$ low-latitude
  - penetration electric fields
  - stormtime dynamo fields

methodology

- $>$ usual suspects
- $>$ 'new and/or improved' coupled computer models

  e.g., atmosphere/ionosphere scale sizes down to 100s m (scintillation causing irregularities)
- $>$ sub-gridding for small-scale physics
- $>$ embed PIC code in fluid code

Research Needs for Cross-Scale and Cross-Region Coupling

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12 April 2022

Space Weather Workshop Phase II

Q1: What do we need to understand to about cross-scale and cross-region coupling to enable predictive capability of the state of the Magnetosphere/ITM?

a) The role that "mesoscale" injections of plasmasheet particles play in energetic particle dynamics in the inner magnetosphere (i.e., ring current and radiation belt)

b) The significance of energetic particle precipitation (EPP) as a facilitator of MI-coupling

c) An improved understanding of cold plasma evolution/energization/journey on a global scale

……

a) Mesoscale injections of plasmasheet particles

- Mesoscale particle injections
  - ~1 Re (spatial)
  - ~1 minute (temporal)
- Cross-region coupling
  - Plasmasheet -> inner magnetosphere
- Cross-scale coupling
  - Mesoscale -> synoptic (e.g., global ring current)
  - Mesoscale -> kinetic (e.g., plasma instabilities -> waves)

LFM Global MHD Simulation

Wiltberger+ [2015]

a) Mesoscale injections of plasmasheet particles

- We need to better understand the role that mesoscale injections of plasmasheet particles play in energetic particle dynamics in the inner magnetosphere (i.e., ring current and radiation belt)

- Is the ring current is built up through enhanced global convection? Or through a series of localized injections? Or some combination of both?

- To estimate the contribution of localized injections/mesoscale transport to the global ring current requires a number of assumptions to be made which are not well constrained (by observations or models)

- This knowledge gap limits our ability to model and predict ring current evolution and, thus, the development of geomagnetic storms

a) Mesoscale injections of plasmasheet particles

Q2: *"What are the research needs to make progress on that understanding?"*

We need:

- To measure injections in-situ and distributed over a broad region of the nightside plasmasheet
- To have simultaneous global imaging of the nightside region
- To have simultaneous in-situ measurements of the ring current and radiation belt particles
- To coordinate these measurements with a robust modeling program (e.g., MHD-test particle simulations, global MHD with embedded PIC)

How to advance our understanding of cross-scale/cross-region coupling

Improvements in the accuracy global geomagnetic field models

- Magnetic field mapping touches essentially all areas of M/ITM research and plays a crucial role in coupling studies

- Our understanding of magnetospheric coupling processes can be limited by uncertainties in mapping via the magnetic field models that are used to link different regions (e.g., plasmasheet-to-ionosphere).

<u>Coordinated</u> multipoint observations distributed widely over the M/ITM system

- The Heliophysics System Observatory (HSO) isn't providing us with what we need
  - The HSO has not been strategically planned from a systems science perspective
  - We have several individual multipoint missions, but they more or less operate independently of one another
  - The HSO needs to be planned from the start with a global, holistic view of coupling in the M/ITM system and built up progressively in pieces
  - In addition, both ground assets and modeling must be considered and included when formulating and implementing this approach

- Similarly, we need to continue to advocate for sensors on operational missions
  - Even simple/low-cost sensors on proliferated operational satellites can provide important and scientifically useful data
  - e.g., the energetic particle sensors on POES and DMSP, which have enabled advances in our understanding of MI coupling
  - It is vital to maintain the long-term continuity of these types of measurements and establish new programs

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Research Needs for Cross-Scale and Cross-Region Coupling

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1. *"What do we need to understand to about cross-scale and cross-region coupling to enable predictive capability of the state of the Magnetosphere/ITM?"*
2. *"What are the research needs to make progress on that understanding?"*

We are trying to predict a wide range of regimes

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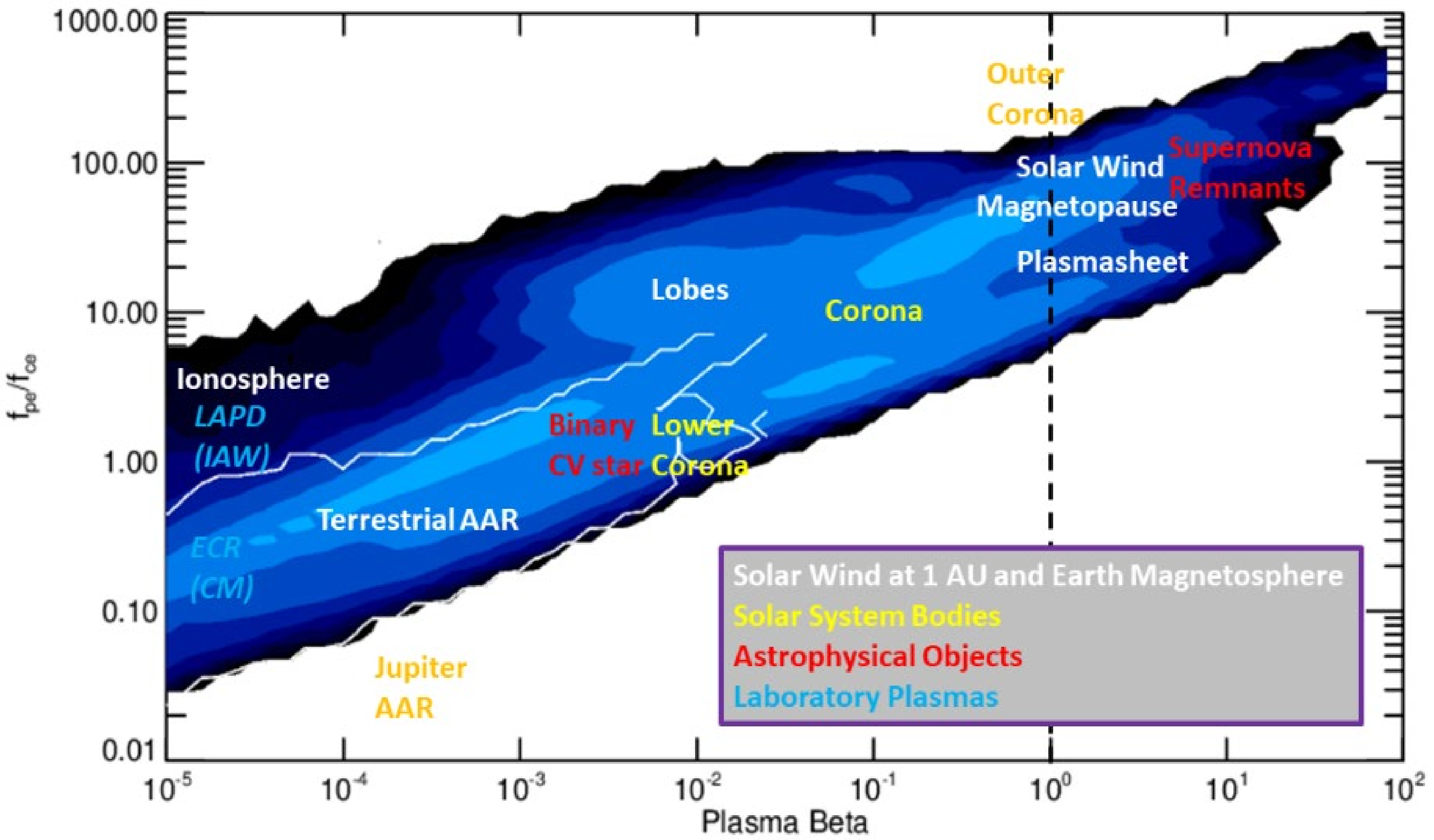
- Magnetically-dominated and plasma dominated regimes are coupled
- No one simulation can cover all energy ranges
- ALL plasma is relevant from cold to relativistic
- Inside the magnetosphere there are direct and indirect energy pathways between regions
- Feedback is crucially important



1. *“What do we need to understand to about cross-scale and cross-region coupling to enable predictive capability of the state of the Magnetosphere”*

New modelling advances open new questions

How storage and release of energy occurs inside the unmodelled region is…unknown.

IF we want to understand the magnetosphere and ionospheric responses then we must understand the substorm

1. Predicting cross-scale M-I coupling

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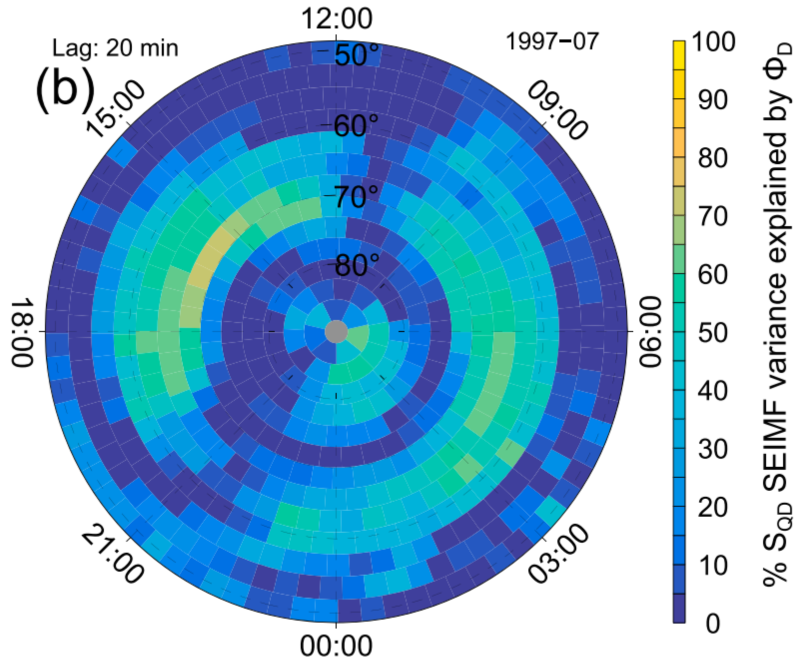
- Solar wind energy input can only account for 50-60% of variability in the ionosphere
- The substorm is the major unknown source of variability in the Earth's magnetosphere
- Why do we care about the substorm?
  - Directly related to GICs
  - Deposit energy into ionosphere via EPP/JH
  - Power the radiation belts and ring current
- We cannot predict when and where
- Do we need to?



Shore et al. [2019]

The *other* problem with predicting M-I coupling is that for the radiation belts.....

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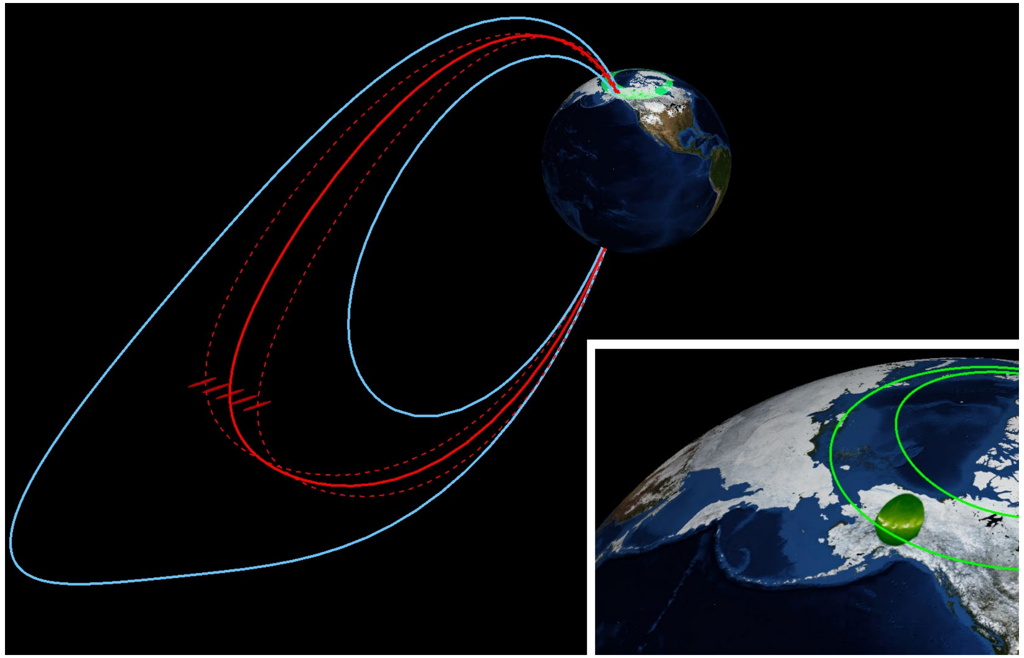
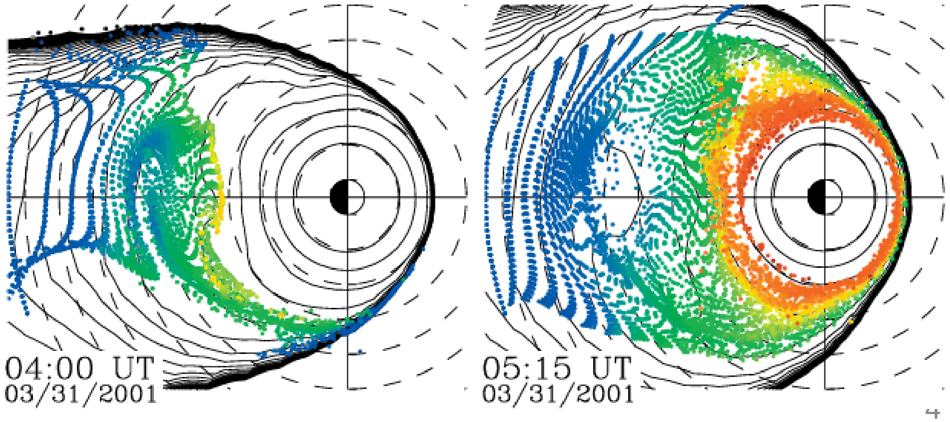
- we need to understand how the magnetotail feeds the radiation belts
    - cold plasma (~eV) for reconnection, substorms, wave propagation and wave-particle interactions
    - warm plasma (~keV) for wave-particle interactions, wave propagation and spacecraft charging
    - relativistic plasma (~MeV) for single event upsets
- we need multi-point measurements to compare our predictions with our data-driven models, else we cannot verify

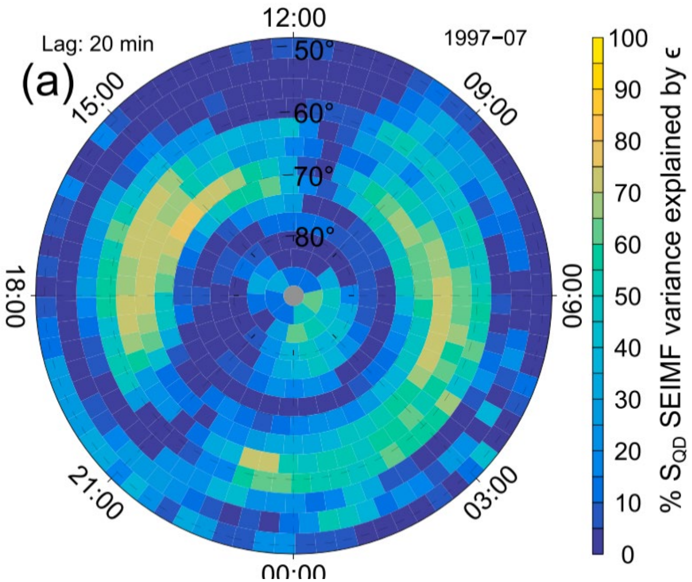


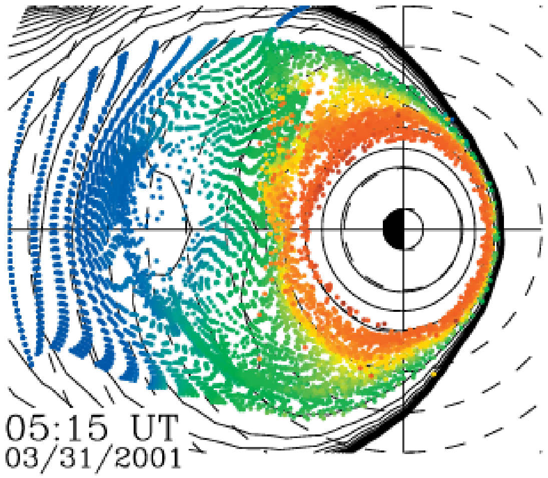


Elkington et al. [2003]; Kalmoni et al [2019]

2. "What are the research needs to make progress on that understanding?"

- New point measurements in the key regions of geospace to both drive and test models
    - Continuous ground-based measurements as key global measurements
    - More single point measurements e.g., hosted P/L
- Turning new data into realistic models of plasma behaviour
    - The substorm
    - Cold plasma
    - Warm plasma
    - Relativistic plasma
- What can you predict deterministically and what is best described by probabilistic models?
    - Relative to things we do know like storms/substorms





Elkington et al. [2003]; Shore et al. [2019]