Electrojet turbulence: recent progress in understanding the Farley-Buneman instability

Electrojet Turbulence: Recent Progress in Understanding the Farley-Buneman Instability

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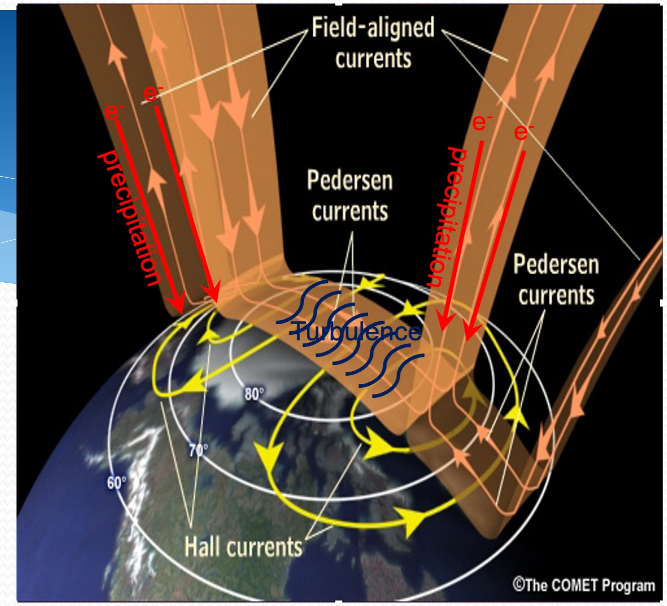
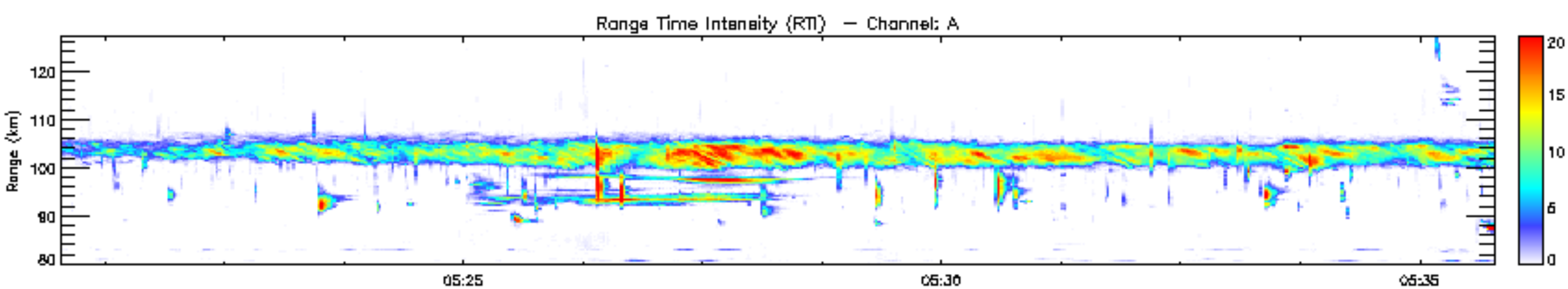
CEDAR/ISR Workshop 2024

Center for Space Physics

Electrojet irregularities: Collisional Plasma Waves

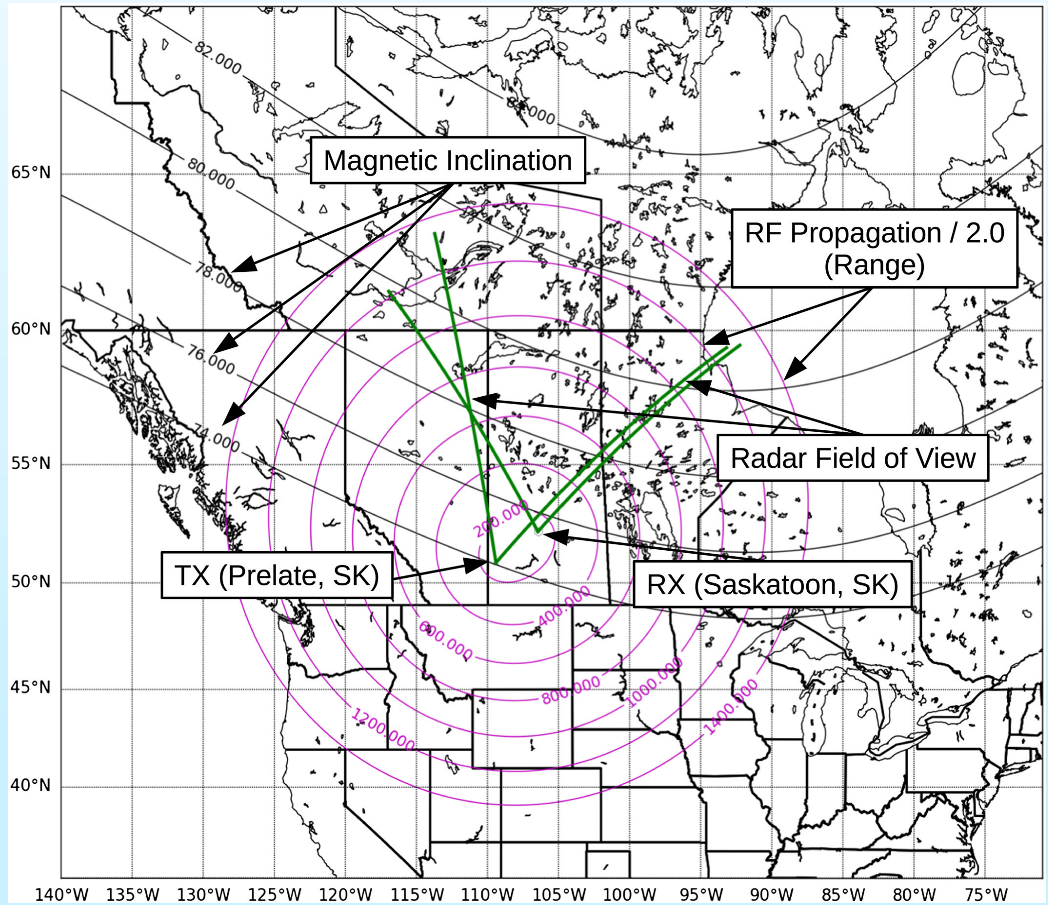


- Radar Reflections from E-region ionosphere (90-140 km)
- What type of waves?
  - Steaming instability: Farley-Buneman Waves
  - Gradient Drift Waves
  - Meteor Trail Turbulence
- Where do they exist?
  - Partially Ionized, Cold Plasma
  - Region with strong electric fields (or neutral winds)
- How are they detected:
  - Radar Echoes (Types I-IV)
  - Rocket Data



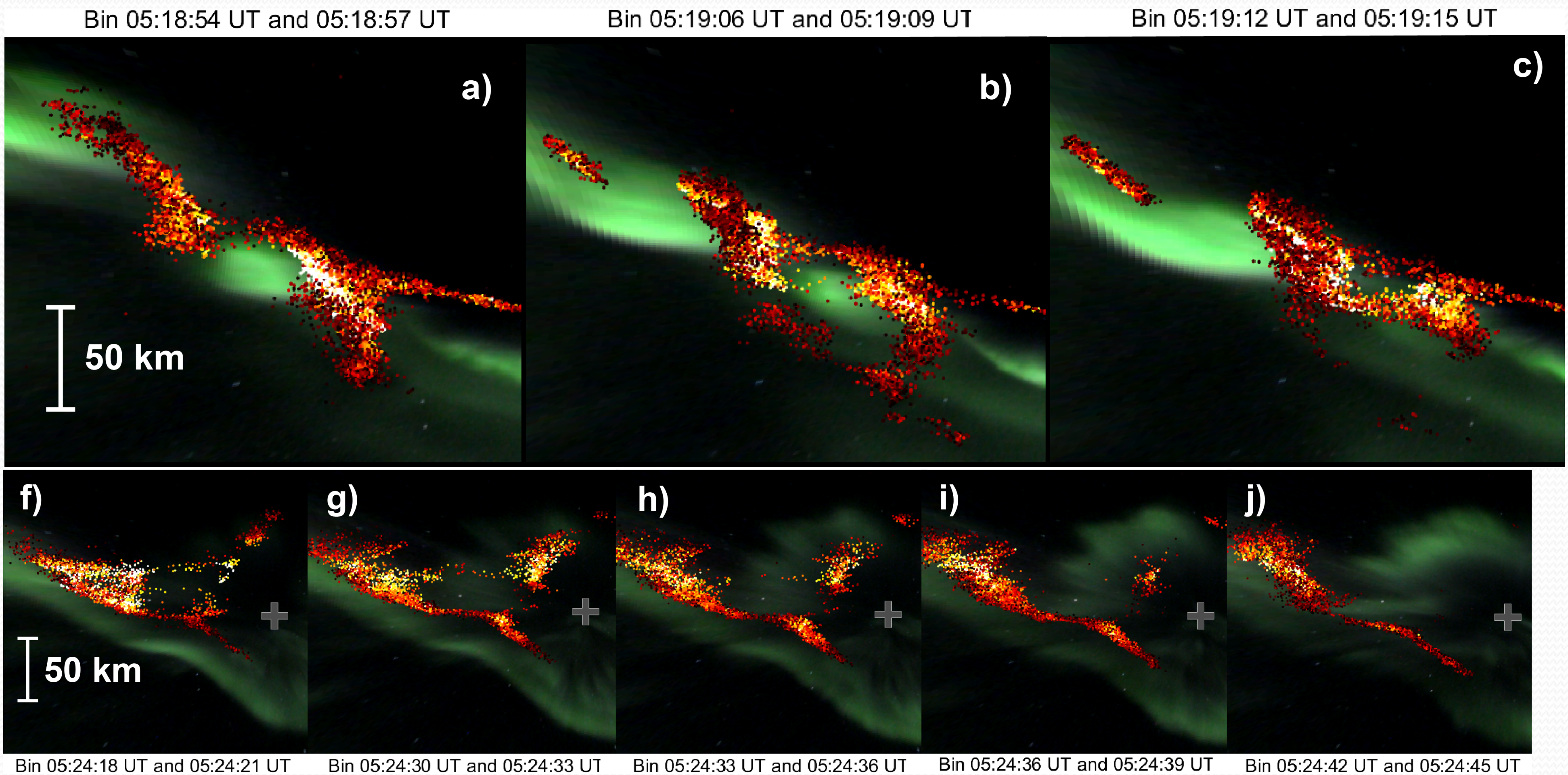
Electrojet Turbulence (ET) Observations by ICEBEAR

ICEBEAR: An All-Digital Bistatic Coded Continuous-Wave Radar for Studies of the E Region of the Ionosphere



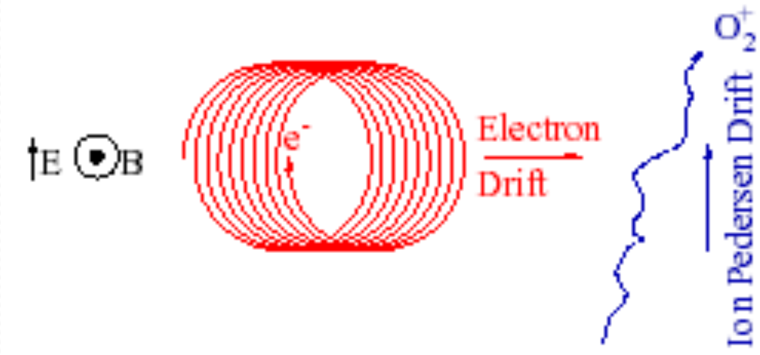
Radio Science, Volume: 54, Issue: 4, Pages: 349-364, First published: 15 April 2019, DOI: (10.1029/2018RS006747) by Devin Huyghebaert, Glenn Hussey, Juha Vierinen, Kathryn McWilliams, J.-P. St-Maurice

Auroral Precipitation & E-Region Coherent (Icebear) Echo Observations

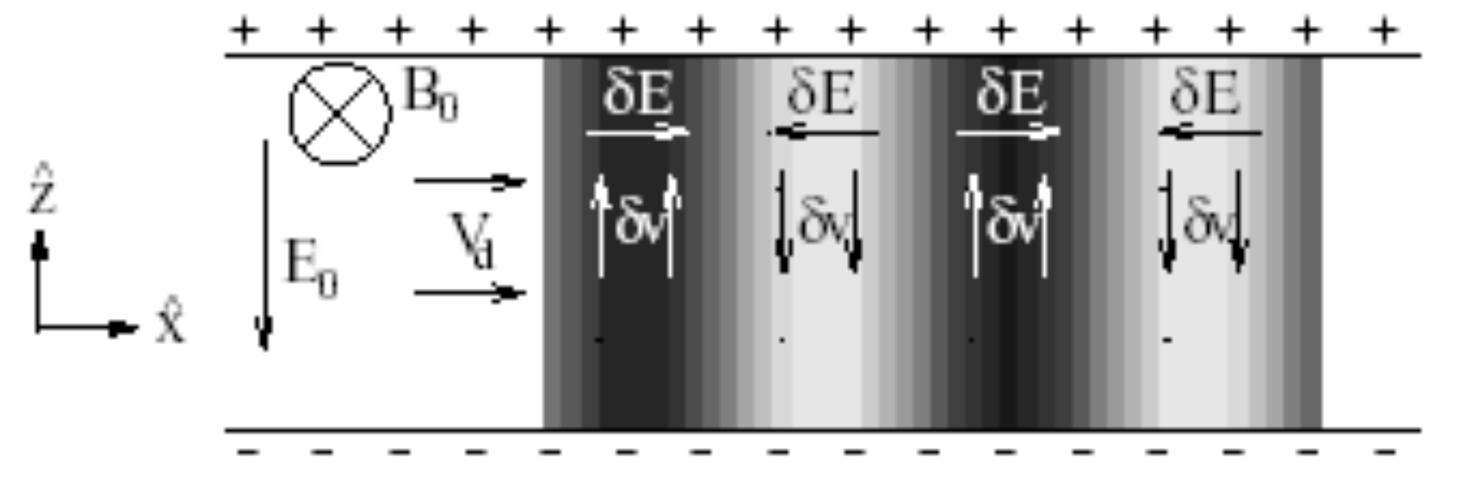


What are Farley- Buneman (FB) Waves?

- Ions & Electrons respond differently to fields
  - Electrons remain magnetized: ***E*x*B*** drift
  - Ions demagnetized by collisions: flow along ***E***
- If $V_e > C_s$, streaming instability develops



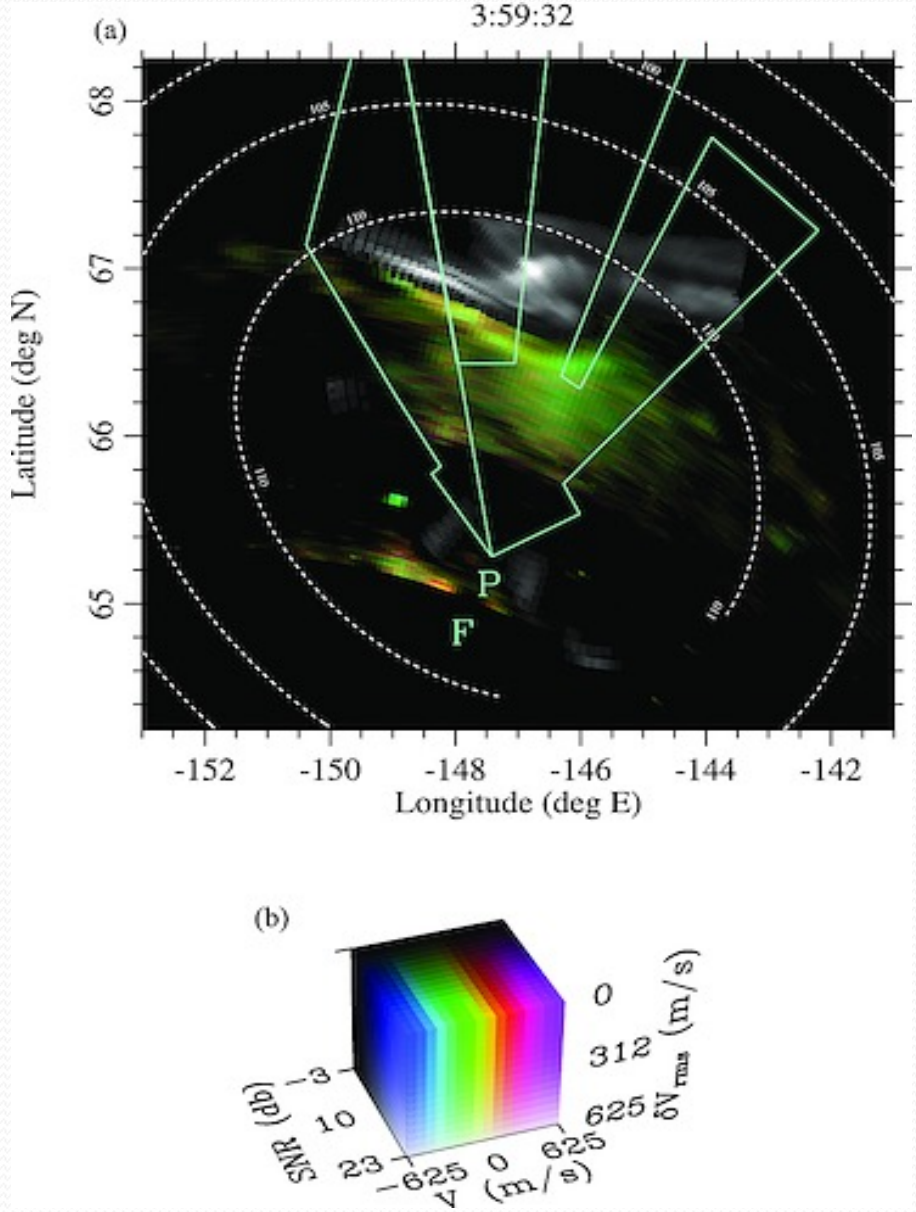
Modified two-stream or Farley-Buneman Instability



So What? Why do FB Waves Matter?

- Causes Strong Radar Reflections:
  - Enables monitoring of energetic processes
  - Doppler and location are an ITM diagnostics
- Equatorial: A number of diagnostics
- Auroral:
  - Diagnostic
  - Electron Heating
  - Anomalous Conductivity impacts entire MIT system

Homer Alaska Doppler Imaging of FB Waves



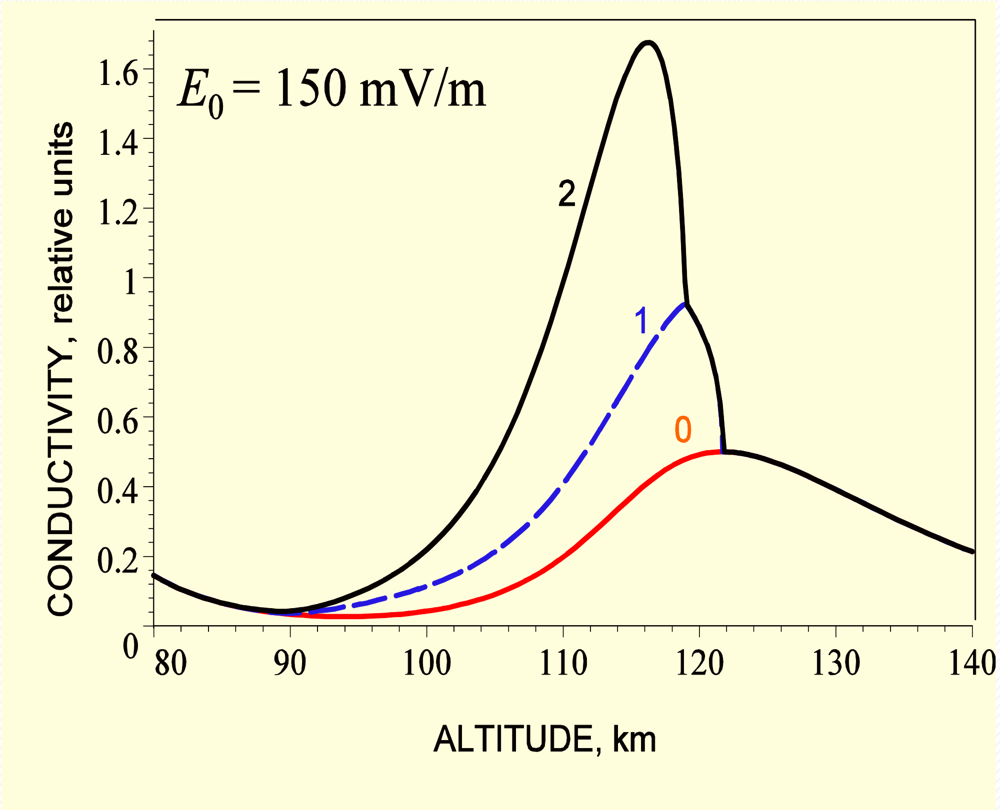
Electrojet PIC Simulations show how turbulence modifies conductivity

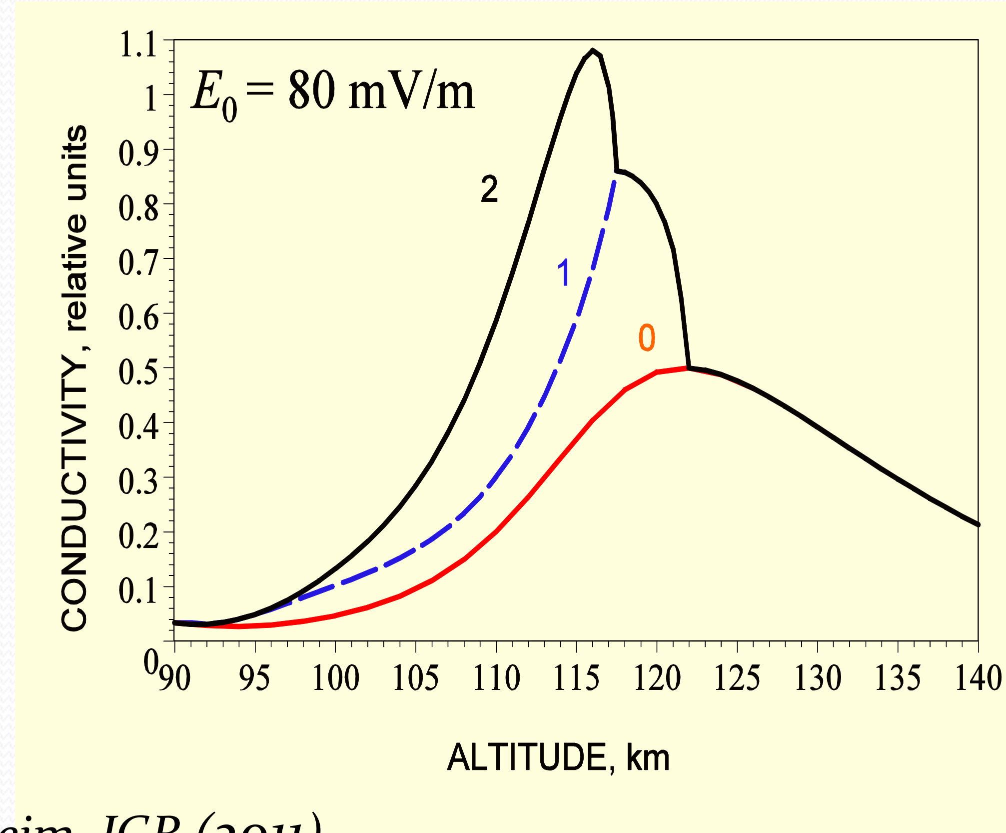
Instability-driven plasma turbulence drives:

- Turbulent electrostatic fields create wave-induced nonlinear currents (NC).
- Anomalous electron heating (AEH) reduces recombination, leading to plasma density increases.

These microscopic processes modify global-scale macroscopic ionospheric conductances

Anomalous Pedersen Conductivity





Dimant and Oppenheim, JGR (2011)

0: Undisturbed ("normal") conductivity

1: Anomalous conductivity with nonlinear current (NC)

2: Anomalous conductivity from NC + Anomalous Electron Heating (AEH) effect

A Model of FB Turbulence modified Heating and Conductance

- Current Model: Parameterized Effects of Turbulence
  - Heating:

$$Q_a = \frac{m_e \upsilon_e n_0 E^2}{B^2} + \frac{m_i \upsilon_i n_0 \kappa_i^2 (E - E_1)^2}{(1+\kappa_i^2)B^2}\left(\frac{E}{E_1}(1+\psi) - 1\right) H(E - E_1) H(h_{MB} - h),$$

$$\psi = \frac{\upsilon_e \upsilon_i}{\Omega_e \Omega_i} = \frac{m_e \upsilon_e m_i \upsilon_i}{e^2 B^2}, \quad \kappa_i = \frac{\Omega_i}{\upsilon_i} = \frac{eB}{m_i \upsilon_i}. \quad E_1 = (1+\psi)\sqrt{\frac{K_b(1+\kappa_i^2)}{1-\kappa_i^2}\left(\frac{T_e + T_i}{m_i}\right)} B,$$

Dimant & Oppenheim 2011; Liu+2016

  - Anomalous Pedersen Conductivity from electron NC

$$\Sigma_P^{ET} = \begin{cases} \Sigma_P^O (1 + 0.01(E - 35) + 1.3 \cdot 10^{-5}(E - 35)^2) & E > 35(\text{mV/m}) \\ \Sigma_P^O & E \leq 35(\text{mV/m}). \end{cases}$$

  - Added to MAGE Geospace Simulator
    - [Dimant & Oppenheim 2011; Wiltberger et al. 2017; Dong et. al. 2024]
- Only applies for moderate to large storms but not for:
  - Super Storms
  - STEVE events
- Plan: Add to other codes (GEMINI) Extend to stronger fields from larger events

Recent Analysis:

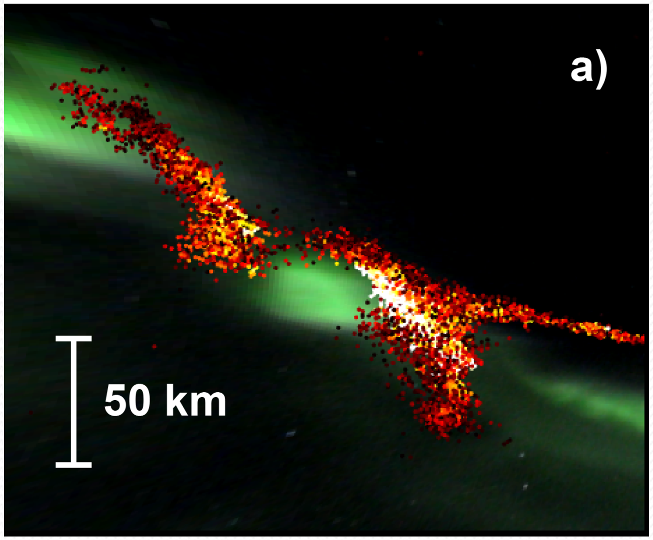
FB waves impacted by Precipitation

Effects of Electron Precipitation on E-Region Instabilities: Theoretical Analysis

Y. S. Dimant[1], G. V. Khazanov[2], and M. M. Oppenheim[1]

[1]Center for Space Physics, Boston University, Boston, MA USA
[2]NASA Goddard Space Flight Center, Greenbelt, MD USA

Bin 05:18:54 UT and 05:18:57 UT



Key Points:

- During geomagnetic storms, strong electric fields and intense electron precipitation frequently overlap in the E-region ionosphere.
- Without precipitation, strong electric fields drive E-region instabilities, leading to plasma turbulence and increased conductance.
- Strong electron precipitation dramatically raises the instability threshold, largely suppressing the instability inside the auroral regions.

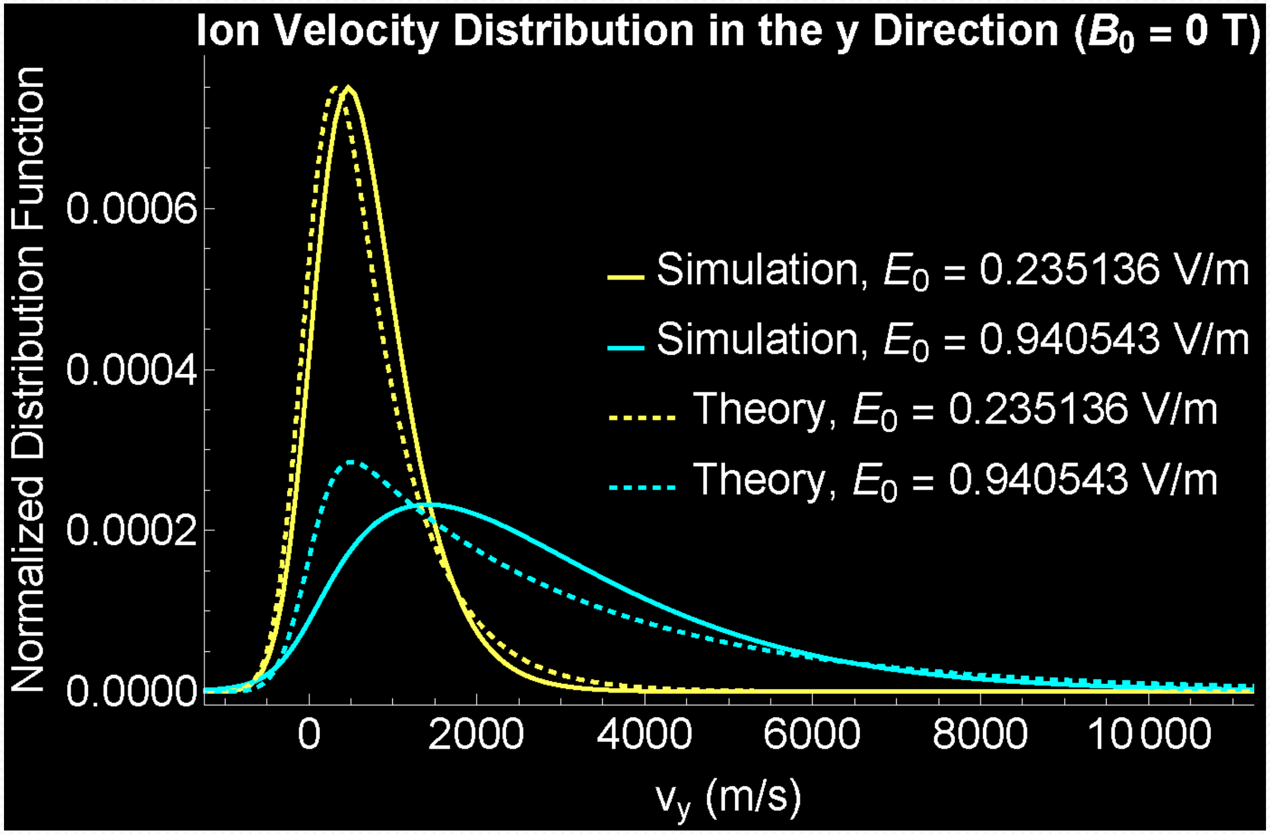
Problem: We know from radar measurements that Farley-Buneman Turbulence is intense during strong precipitation (ie., storms)

(doi: 10.1029/2021JA029884)

New Directions in Auroral FB Studies

- Strong Stormtime E-fields will Distort Plasma Distribution from Thermal

parallel to E_0:



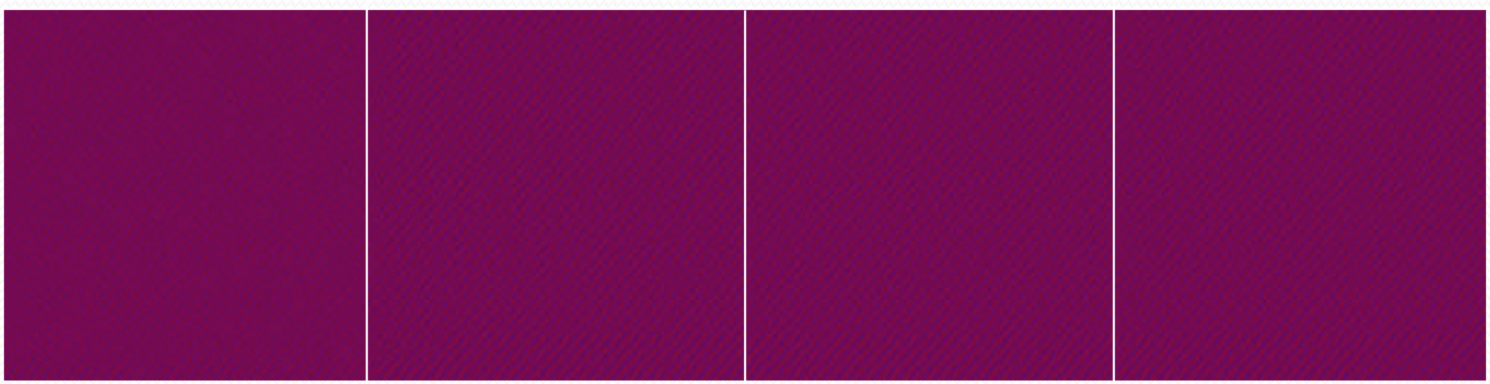
- Modify:
  - FB Instability
  - Heating and Conductivity
- Study with:
  - Theory
  - PIC Simulations

See Save Koontaweepunya's Poster on Wed.

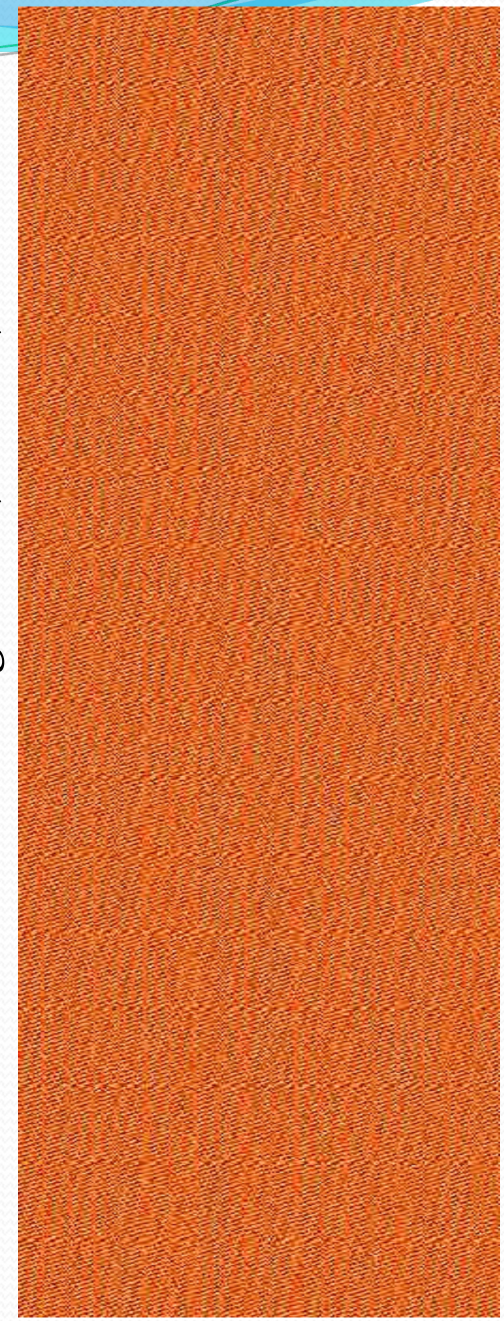
New Directions in Auroral FB Studies II

- Full PIC Simulations of auroral section
- Changing Collision rate in Vertical direction
- Still way too small

4 Cross sections perp to B



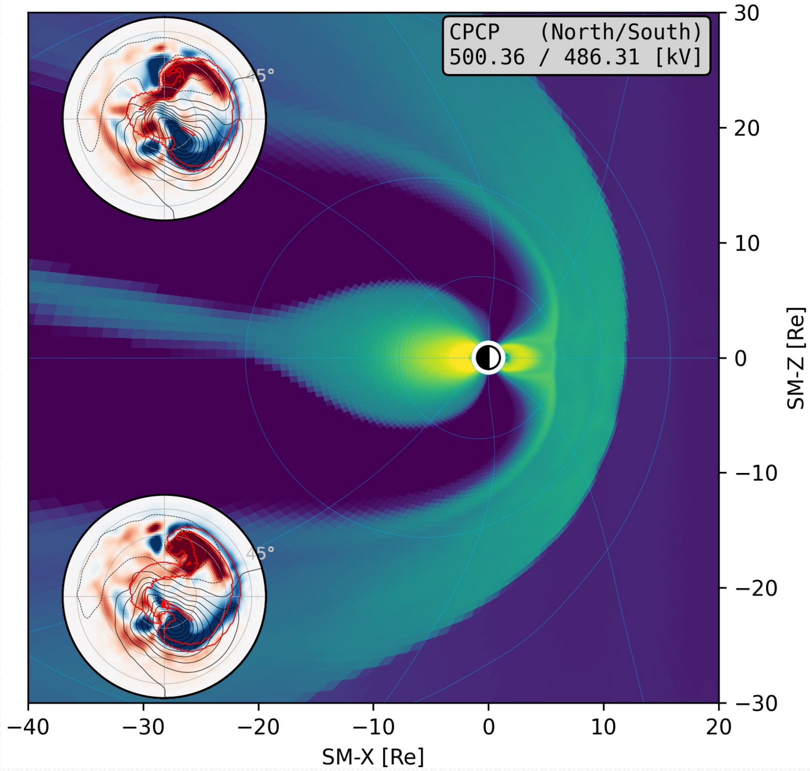
Along B → (vertical)



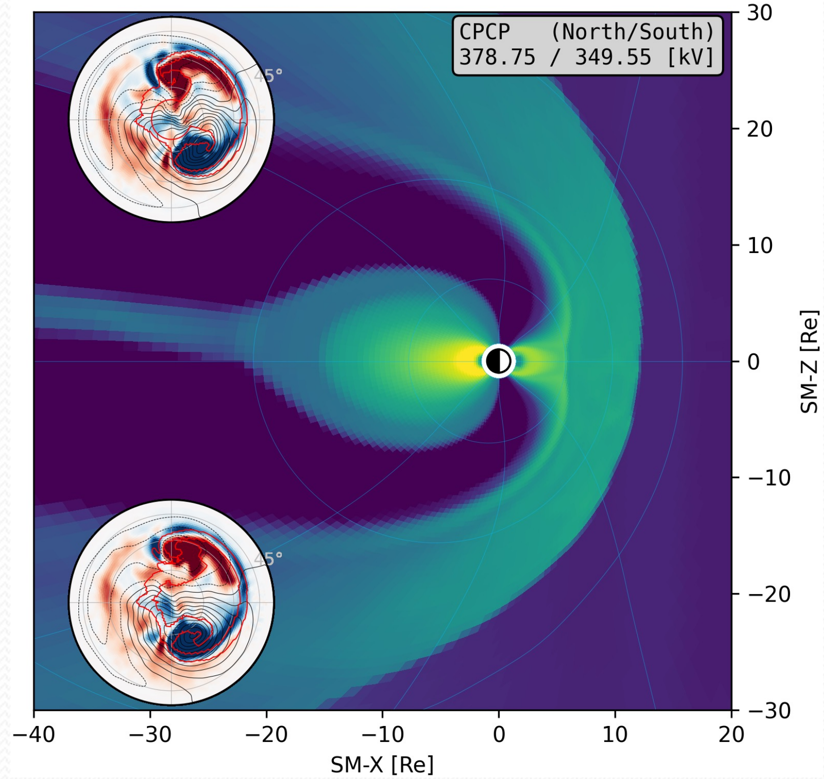
Perp to B

Electrojet Turbulence (ET) effects on the magnetosphere: MAGE Geospace Simulations

without ET

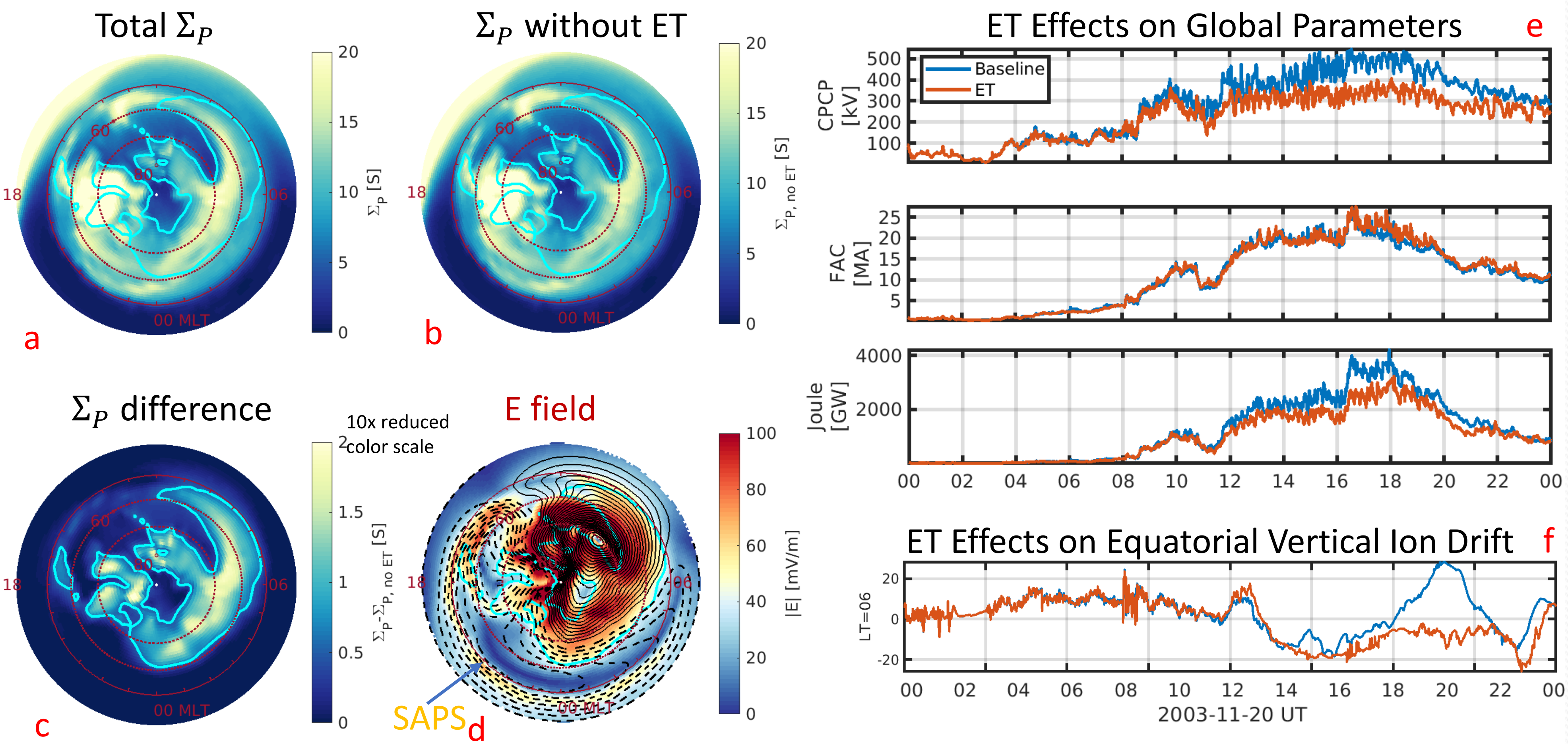


with ET



- Enhanced conductance due to ET effects causes a more dipolar nightside magnetic field and a stronger ring current pressure during storm main phase.

Impact of Electrojet Turbulence (ET) on Ionosphere

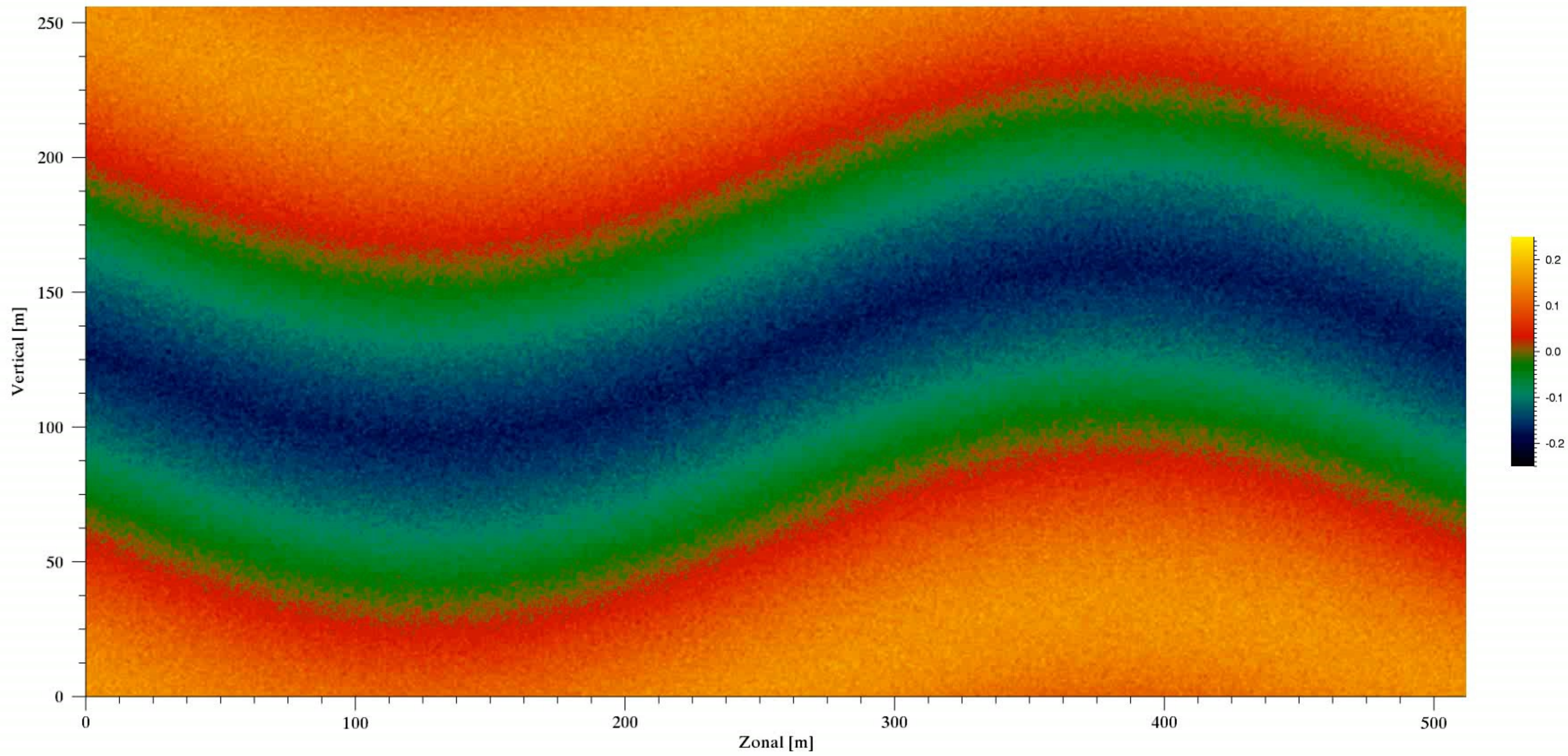


- *ET has major impacts on dawnside where fields are large*
- *CPCP is reduced by ~1/3 during storm peak with ET effects enabled.*
- *Hemispheric Joule heating rate is reduced by ~1/3.*

Other Effects of **Equatorial** Turbulence

- Gradient Drift Driven Turbulence

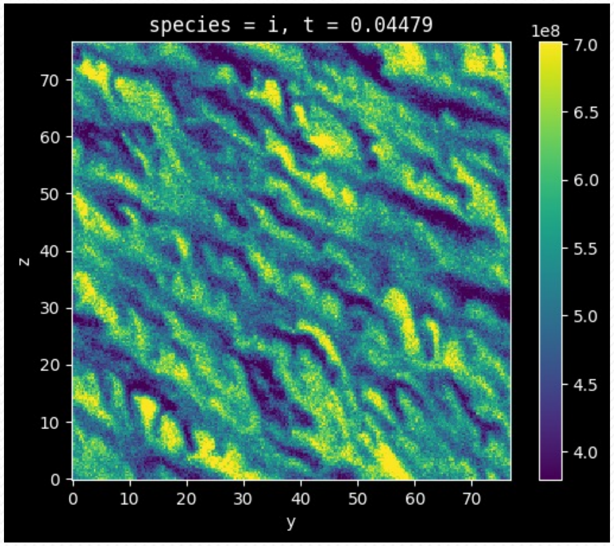
2-D Hybrid Simulations



- Pure Farley-Buneman (Top side or counter Electrojet)
- Other effects?

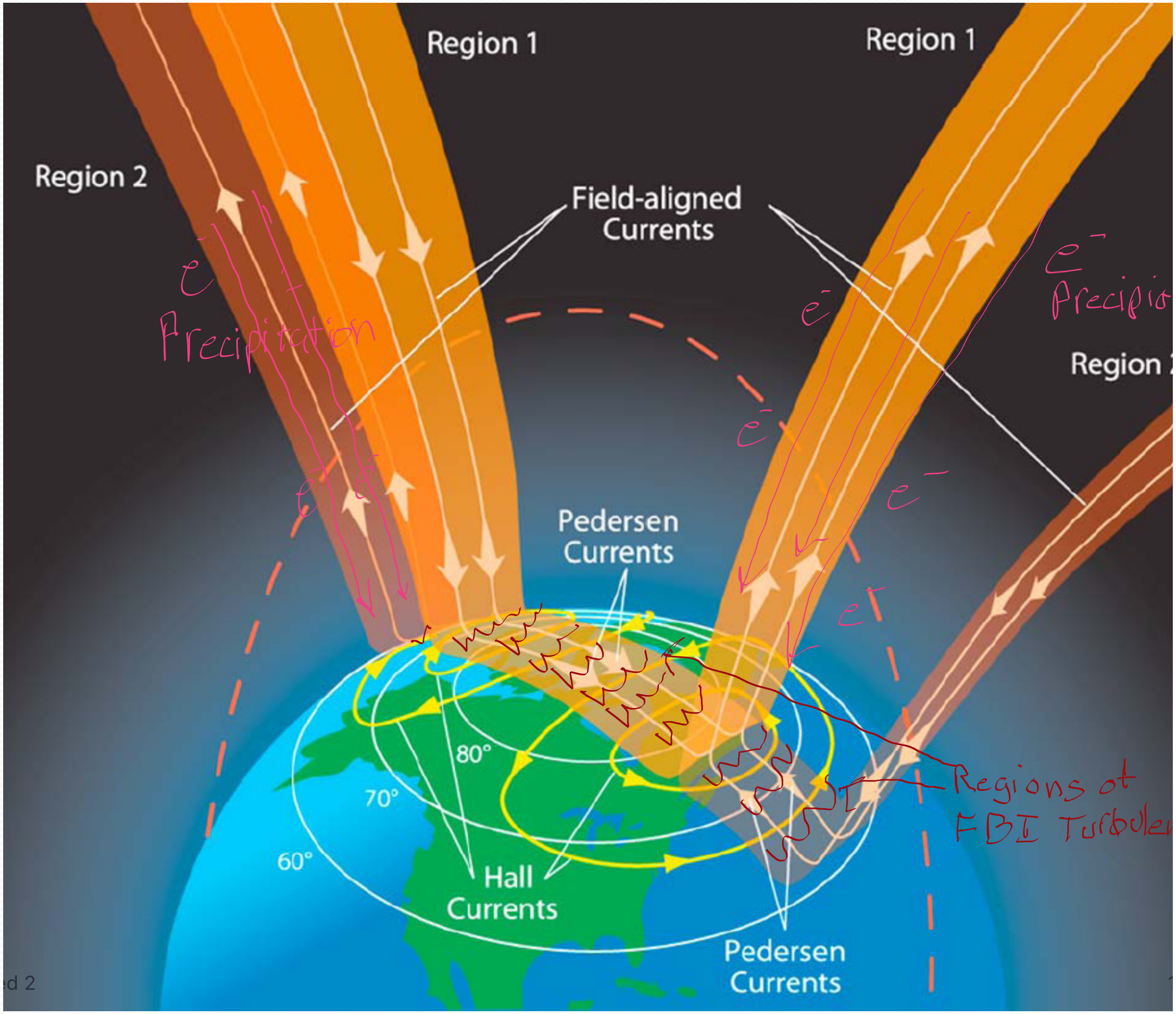
Conclusions

- Good Progress!
- Still Many questions:
  - How does the ET behave in full 3-D?
    - Don't understand how waves behave along B.
    - 3D turbulence not fully characterized.
  - Auroral:
    - Strongly Driven FB
    - Effects of Gradients and other contributors
  - Equatorial
    - See above
    - Variations with altitude
- Need: Observations, Simulations and Theory working together!



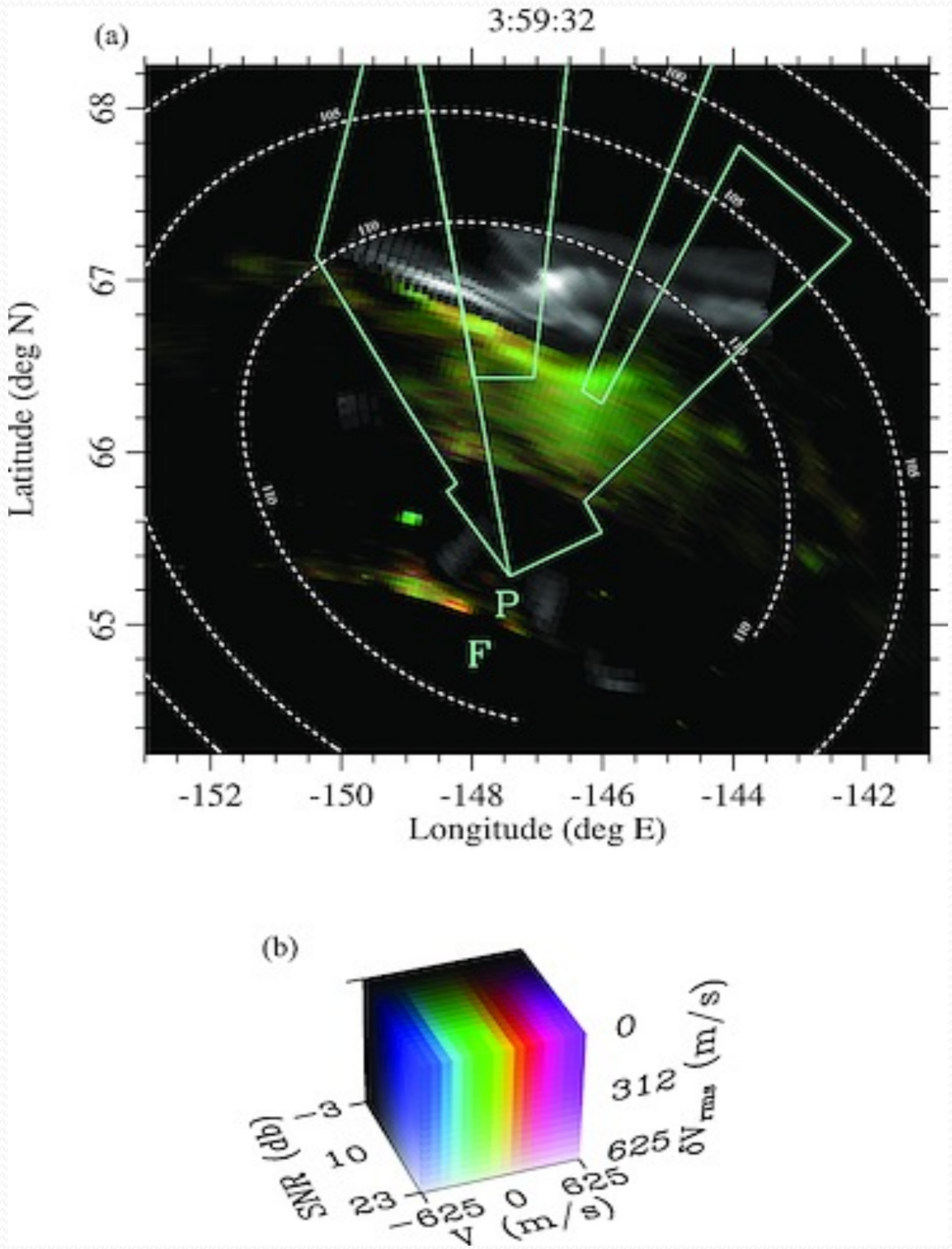
E-region turbulence modified by Precipitation

- Both precipitation and turbulence modify conductance
- Evidence that regions of intense precipitation have less turbulence



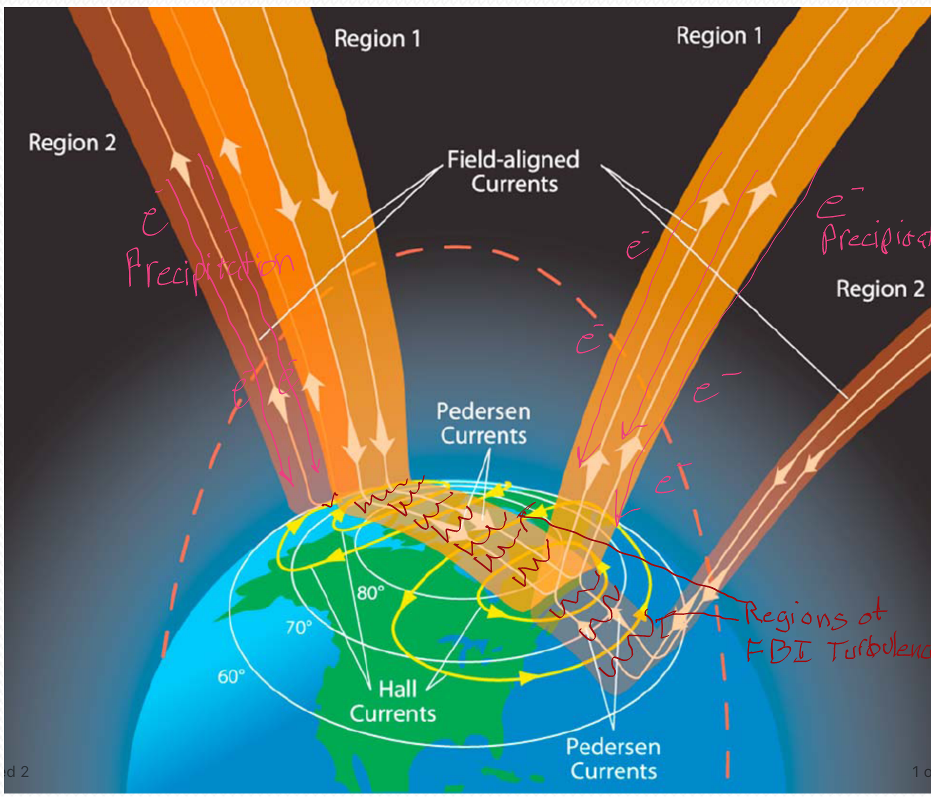
Comparing radar and all-sky auroral imagery

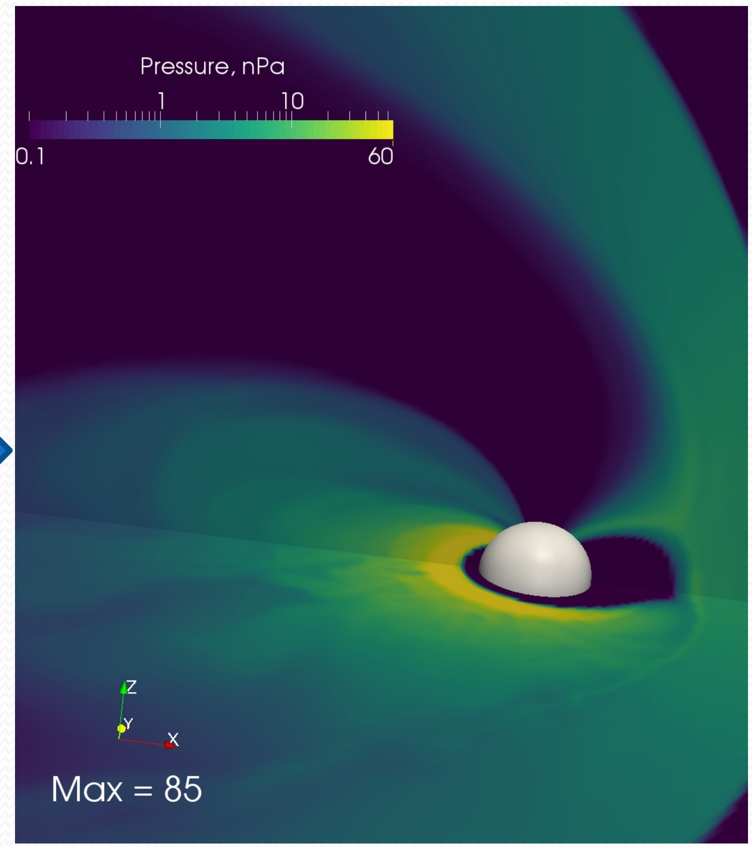
- Radars directly measure FB waves (when looking perp to B)
- All Sky images show the FB waves surrounding but not overlying Aurora
- Image Notes:
  - Radar data are represented by colored pixels
  - Optical imagery from all-sky imager is in gray shades.
  - White contours show the altitude where rays from the Homer radar are perpendicular to B,
  - Cyan lines outline the rocket launch zones from the Poker Flat Rocket range.



From: *Comparing VHF coherent scatter from the radar aurora with incoherent scatter and all-sky auroral imagery* by D. Hysell, R. Miceli, J. Munk, D. Hampton, C. Heinselman, M. Nicolls, S. Powell, K. Lynch, M. Lessard
JGR, DOI: (10.1029/2012JA018010)

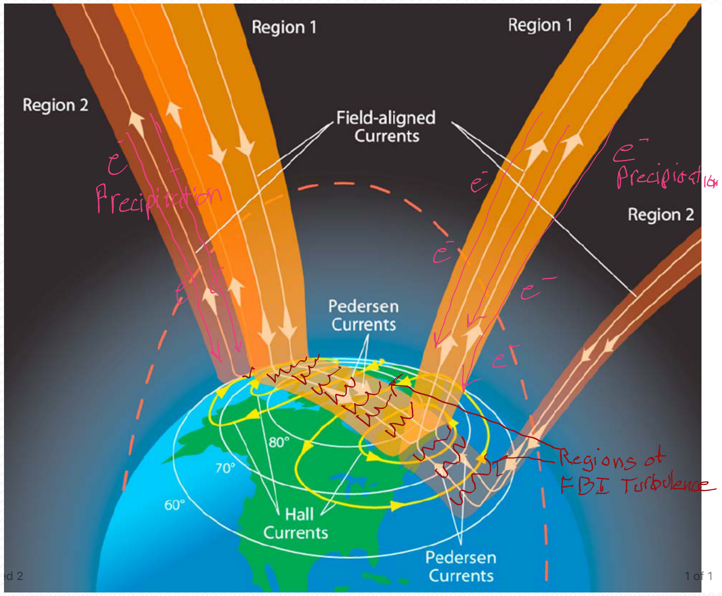
Effects I & II: Impacts on Storm-time Geospace Modeling

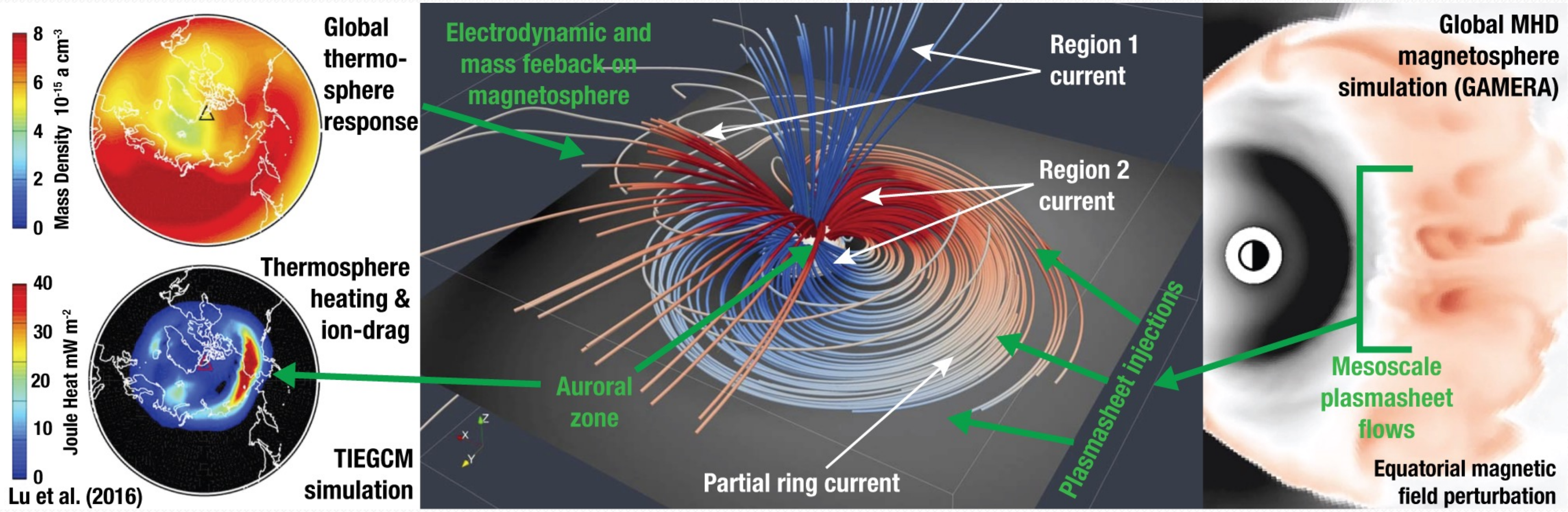




Conclusions

- Improving Conductance Calculations for Global Models:
  1. Lower Ionosphere turbulence
  2. Electron precipitation
- Global Modeling with MAGE
- Essential to modeling Storms

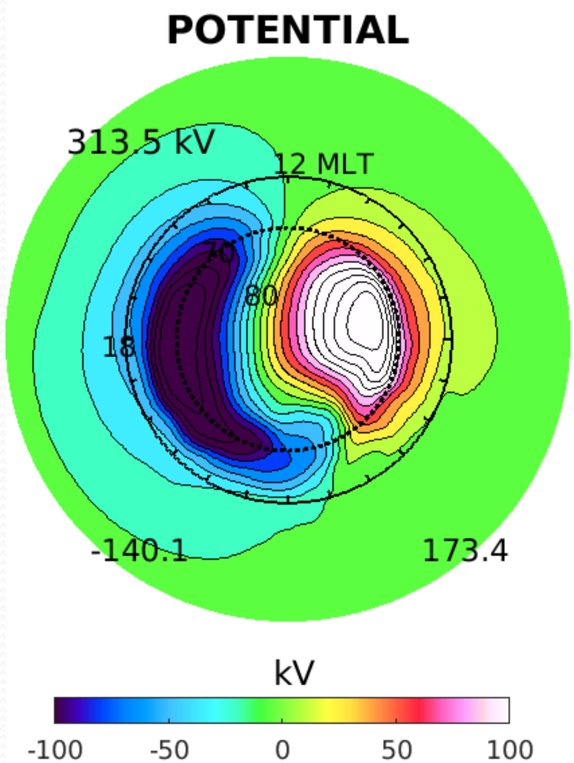




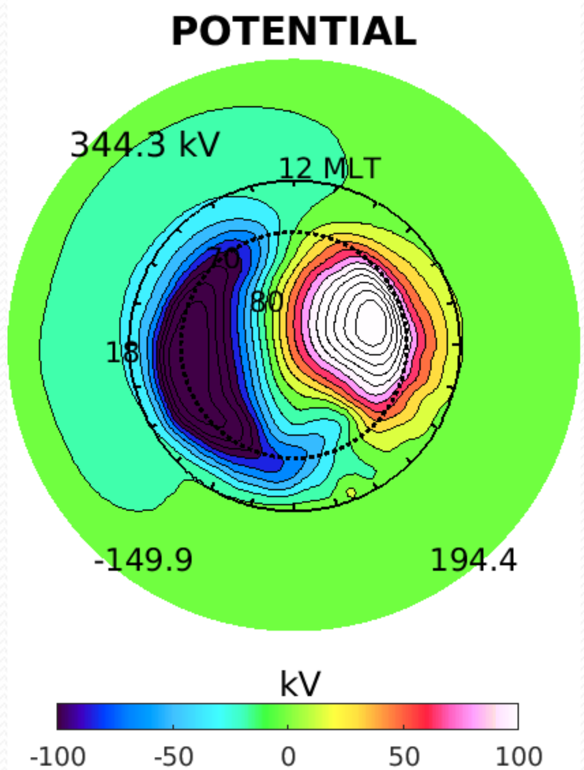
Adding Kinetic Precipitation and AEH to TIEGCM simulations

Cross-Polar-Cap Potential

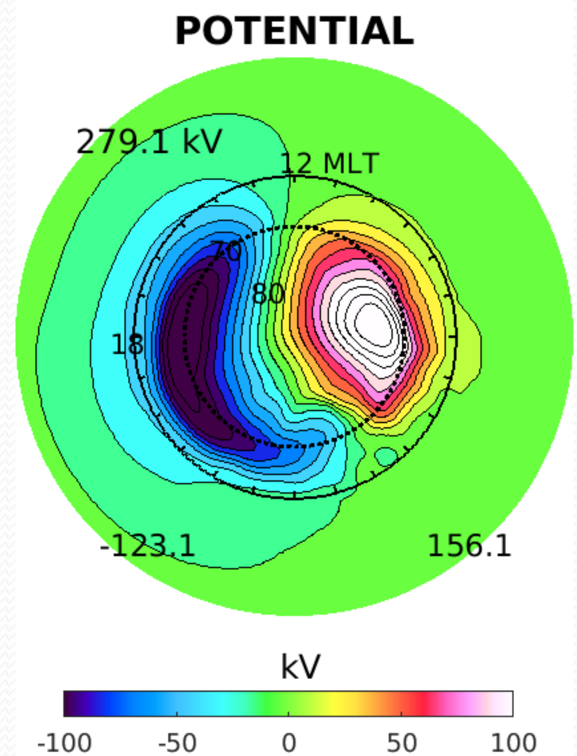
Baseline



With Precipitation

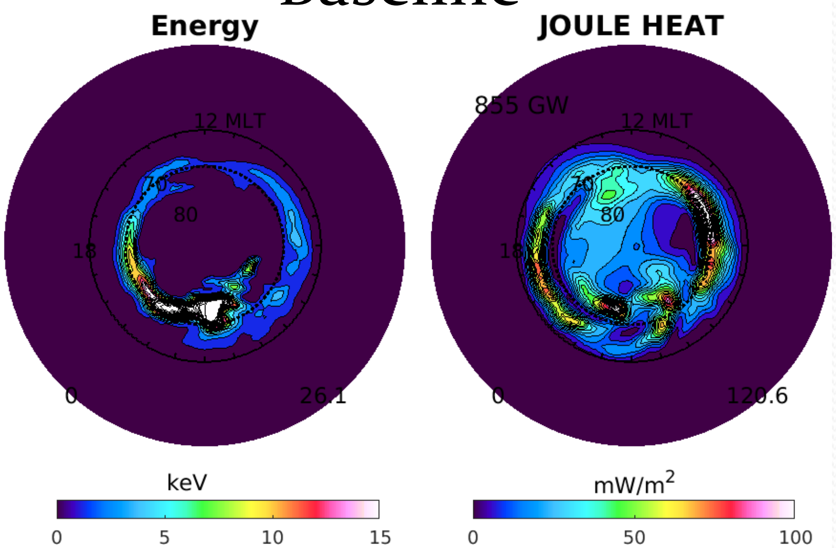


With Precipitation and AEH

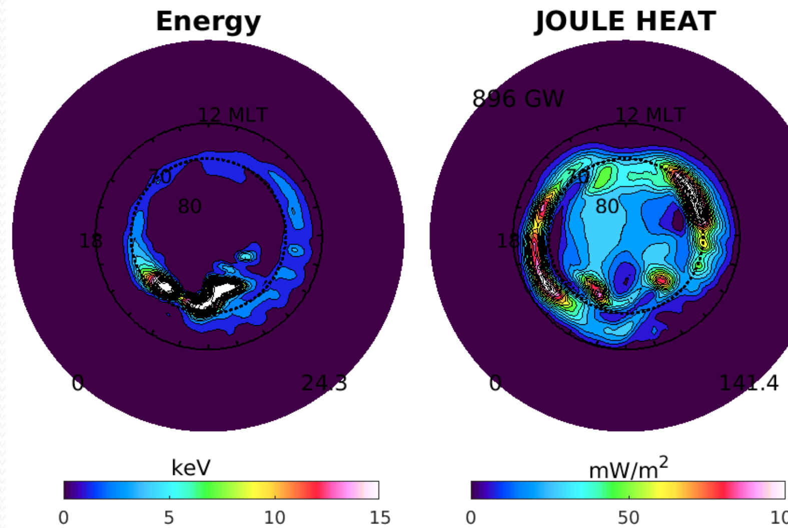


More Diagnostics

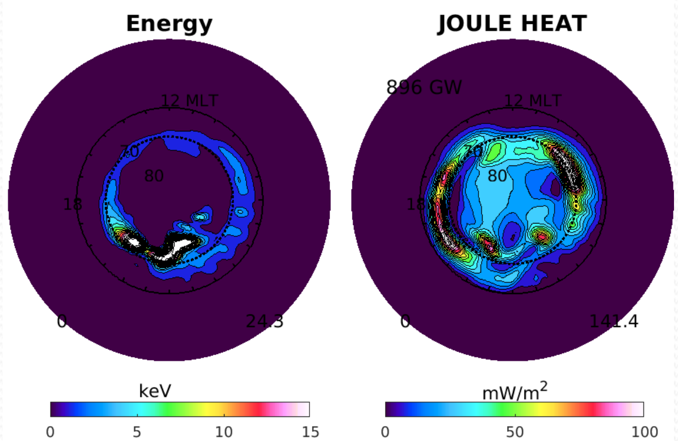
Baseline



With Precipitation

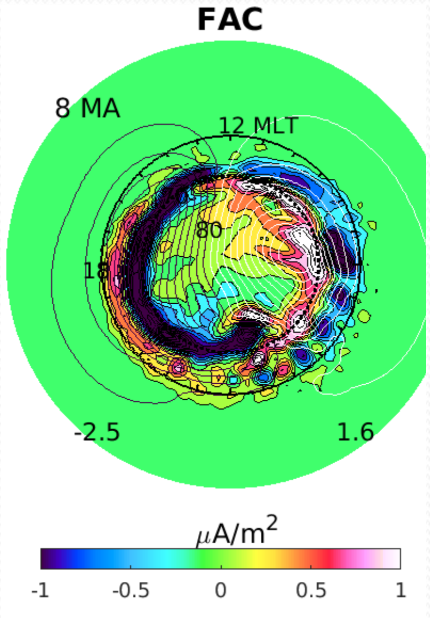


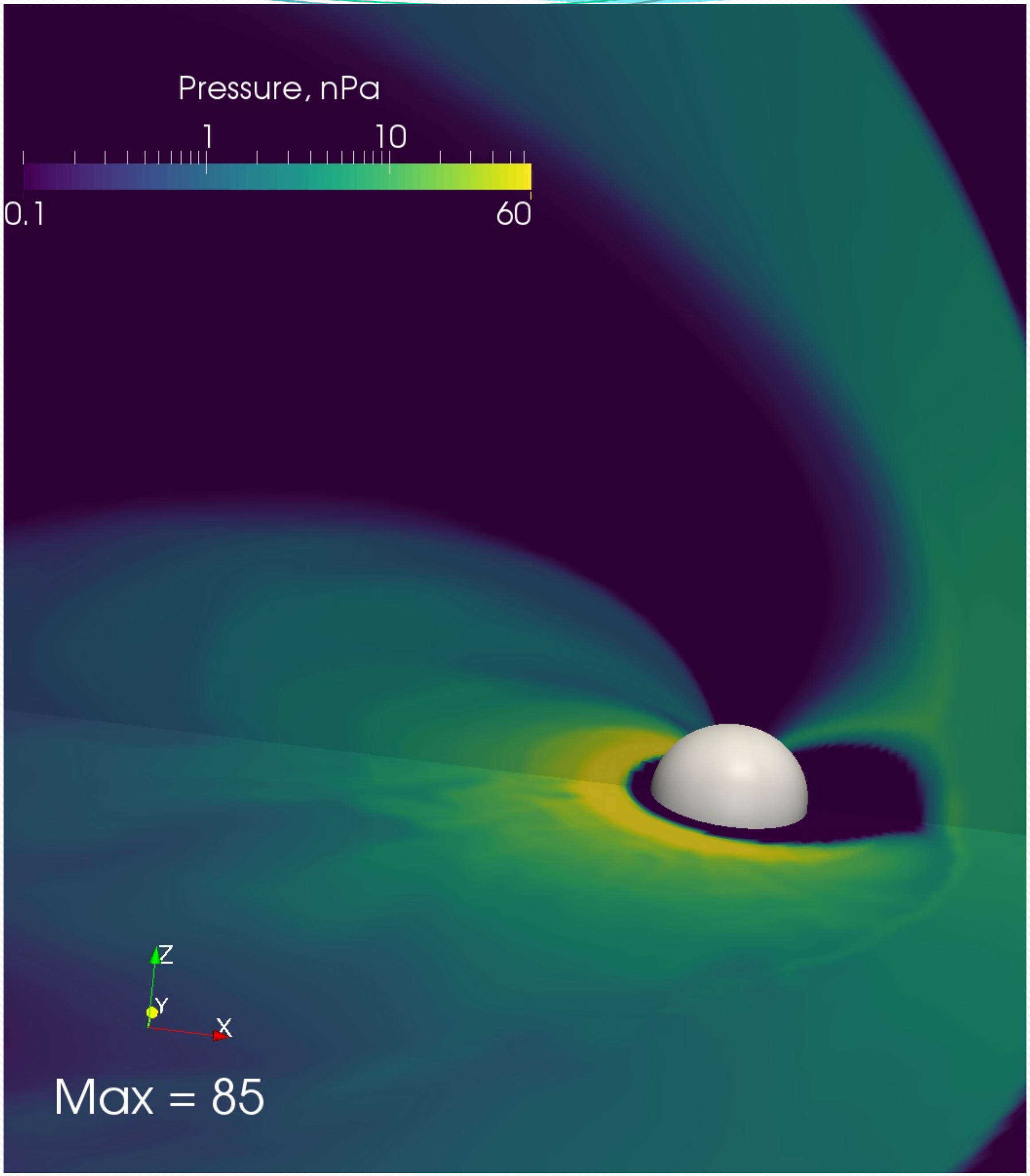
With Precipitation and AEH



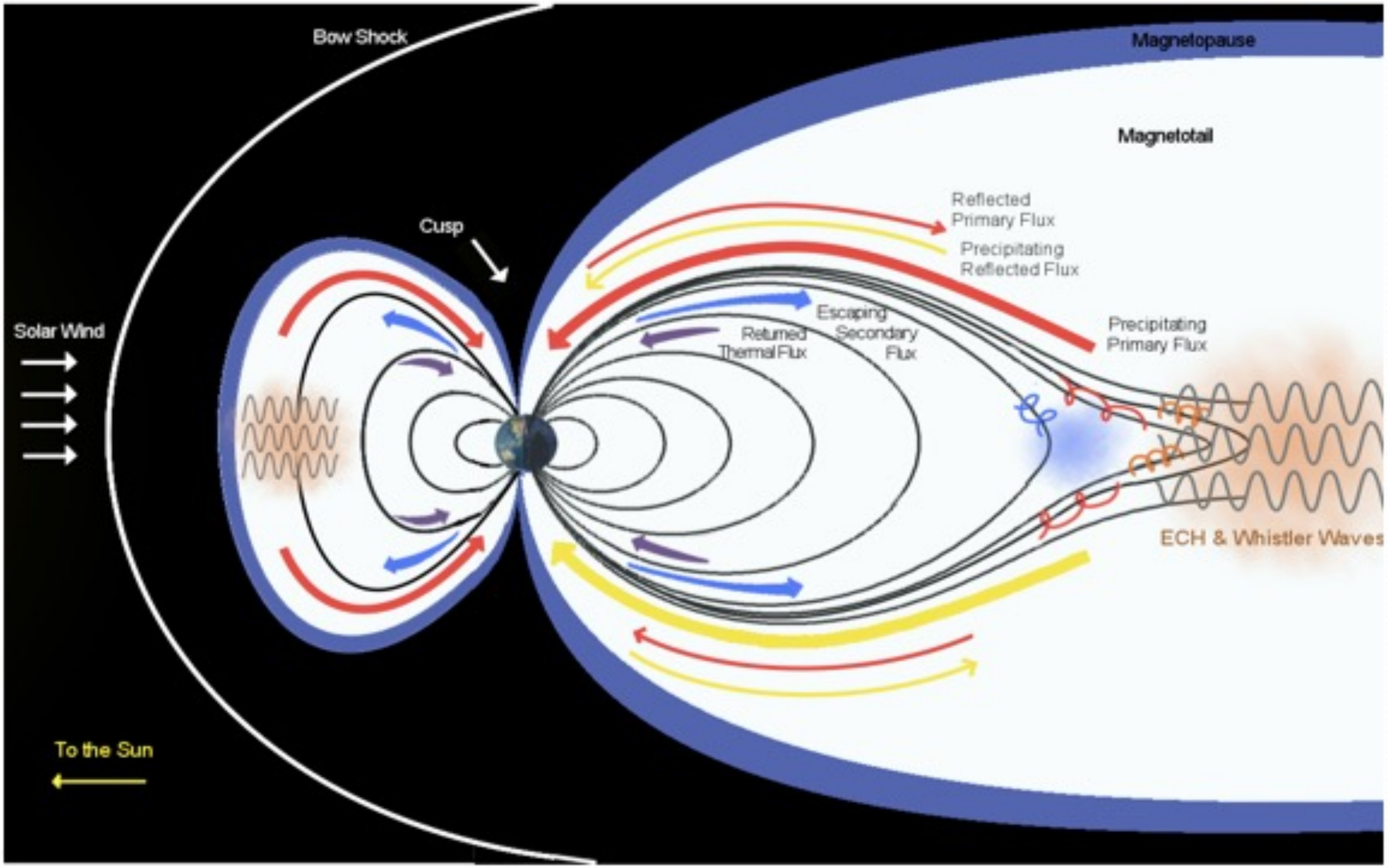
Conclusions

- Kinetic Effects Matter to Conductances
- Conductances Affect MIT Simulations



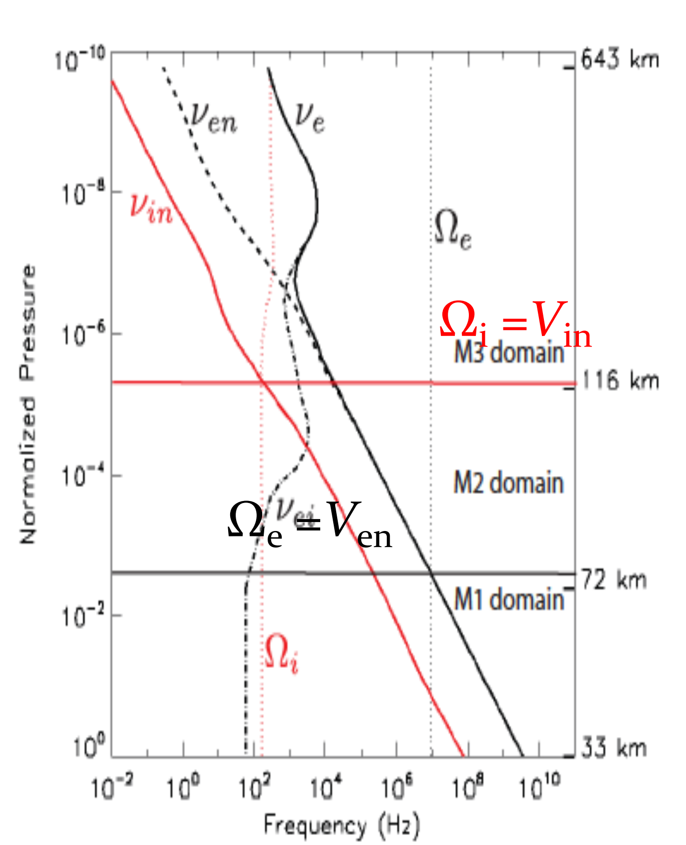


Magnetosphere-Ionosphere SE Coupling in Aurora: Precipitation



Where and When FBI Occurs

Leake et al., 2014, Space Sci. Rev.



- E-region ionosphere (90-130km):
- Dominant collisions with neutrals

*Magnetized electrons: **E x B** drift*

Unmagnetized ions: attached to neutrals

Magnetized electrons ($\Omega_e \gg \nu_e$)

Unmagnetized ions ($\Omega_i < \nu_i$)

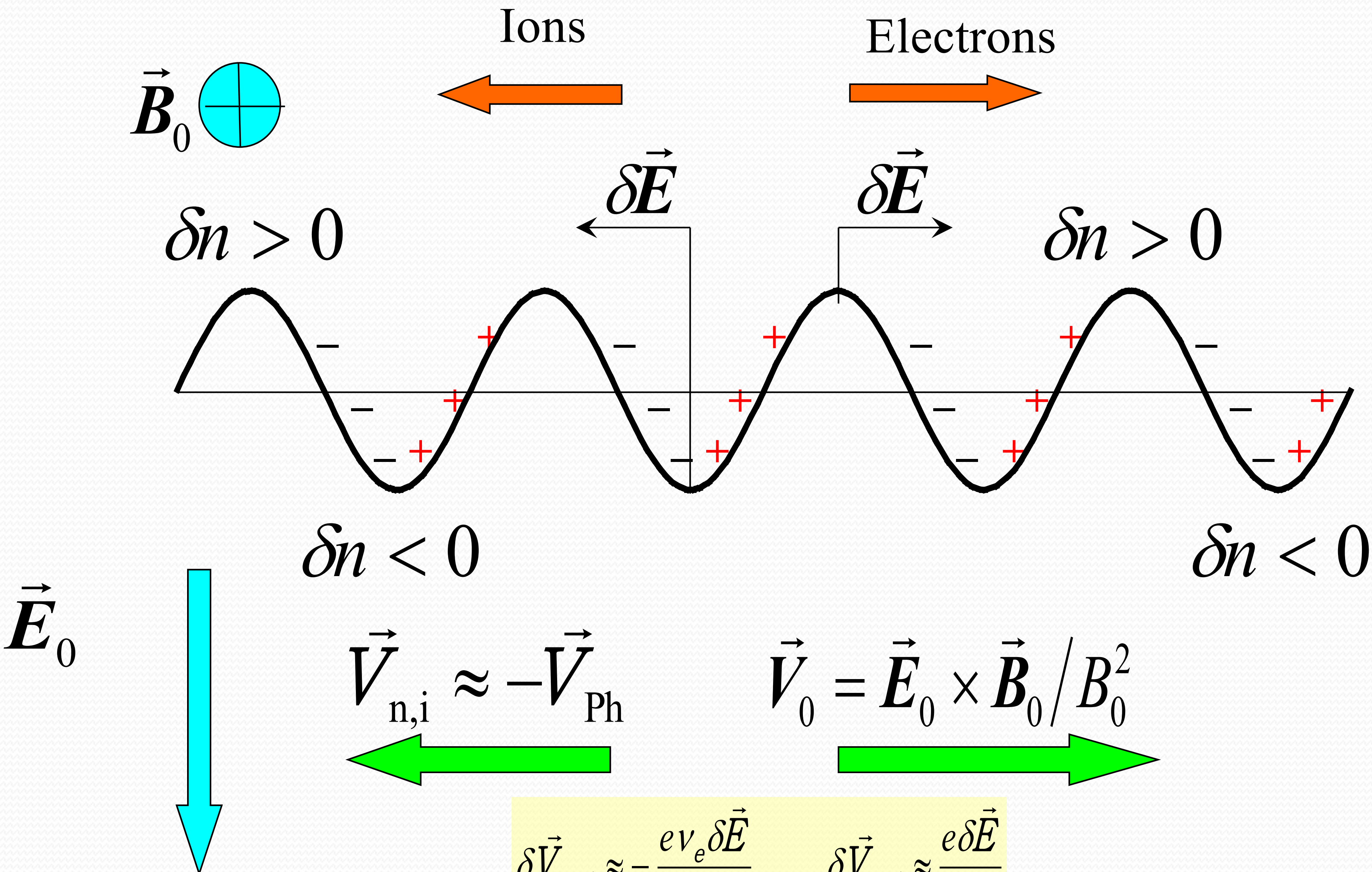
$\Omega_{e,i}$ - gyrofrequency

$\nu_{e,i}$ - collision frequency

Farley-Buneman (modified two-stream) Instability

Difference in drifts of electron and ion should exceed the local ion acoustic speed.

Quasi-stationary waves



$$\delta\vec{V}_{ePed} \approx -\frac{e\nu_e \delta\vec{E}}{m_e\Omega_e^2}, \qquad \delta\vec{V}_{iPed} \approx \frac{e\delta\vec{E}}{m_i\nu_i}$$