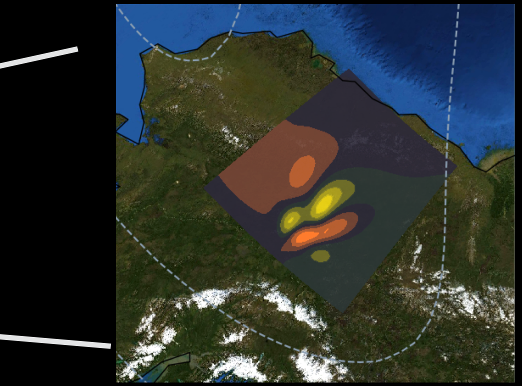


Investigating Meso-Scale Drivers and their effects on the Ionosphere-Thermosphere System

Dogacan Su Ozturk

Team Members: Olga Verkhoglyadova (JPL), Xing Meng (JPL), Josh Semeter (BU), Roger Varney (SRI), Ashton Reimer(SRI)

Jet Propulsion Laboratory
California Institute of Technology

Outline for the Talk

Introduction:

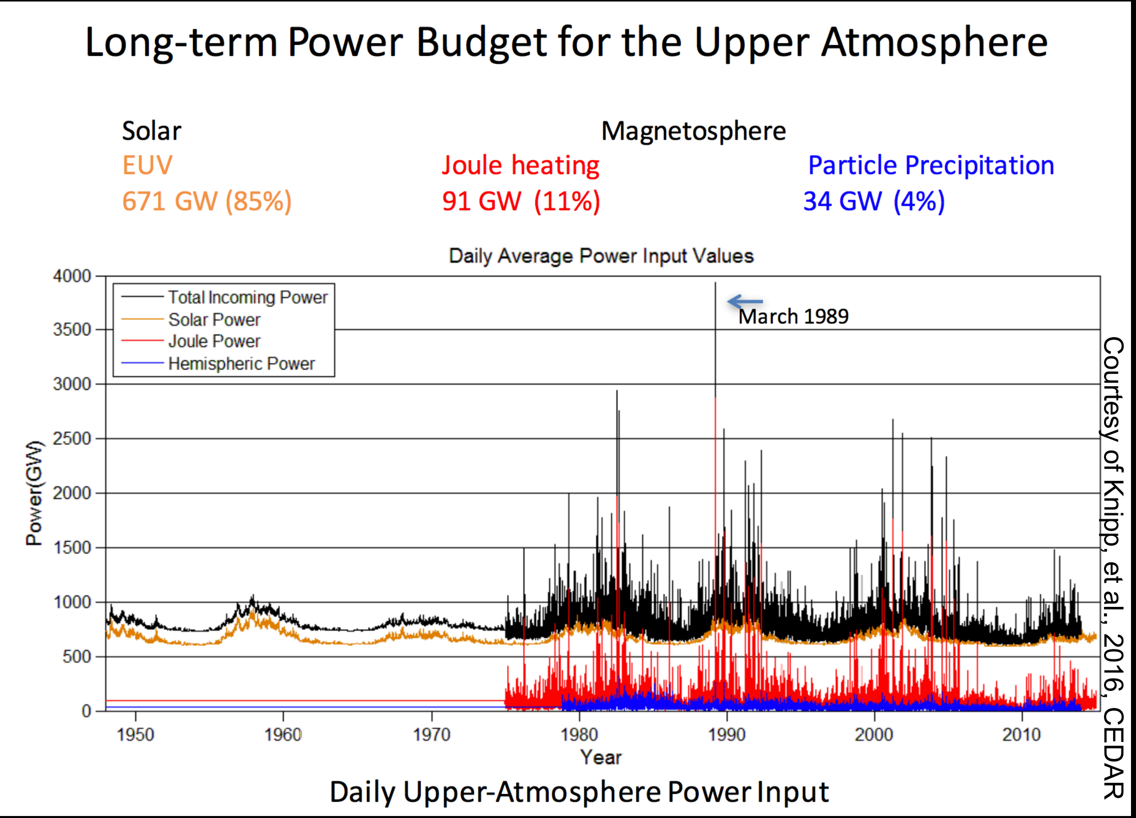
- Energy budget of the high-latitude I-T
- Models of energy transfer from Magnetosphere
- Meso-scale drivers
- Wave contribution to I-T energy budget

Introduction → Methodology → Results → Discussion → Future work

Introduction I: Energy budget of the high-latitude I-T

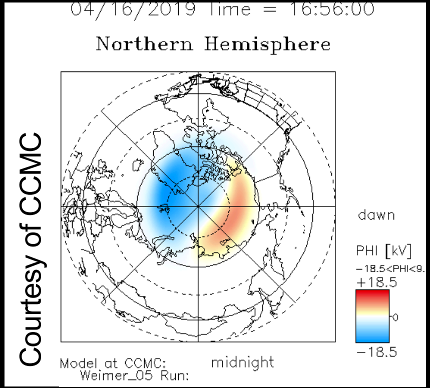
- Solar EUV is the dominant energy source for the I-T system.
- Joule heating ($\sigma_p E^2$) and particle precipitation are important during periods of high solar activity.

Electromagnetic energy from the magnetosphere (source) → Joule heating at the I-T (sink)

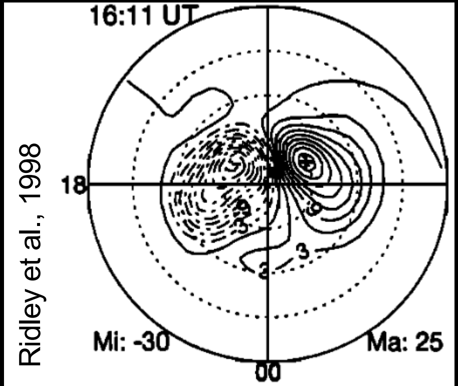


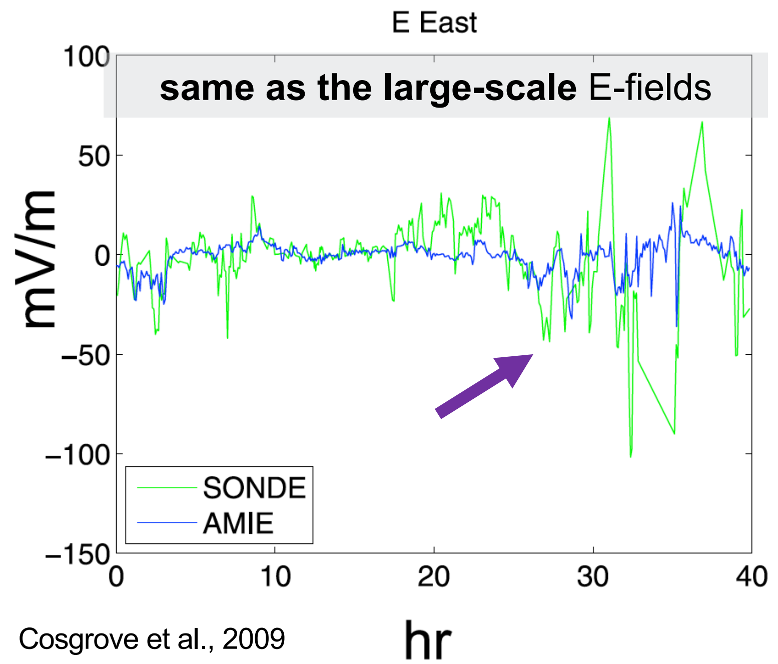
Introduction II: Estimating the Energy Transfer from Magnetosphere

Weimer Model :



AMIE Model:





Not resolving meso-scale electric field variability (temporal + spatial) → underestimated Joule Heating

- Traditionally, conductivity and electric fields are estimated through empirical models.
- Current models can not resolve the meso-scale structures but significant work is ongoing*.

*[Codrescu et al. 2008; Deng et al. 2009; Matsuo & Richmond 2008; Zhu et al. 2018].

Introduction III: Meso-scale drivers

Spatial scale between 100-250 km, temporal scale below 15 minutes

- **Direct Current (DC):** Quasi-static (>15 minutes), time-dependent terms neglected, large-scale (>250 km), estimated with empirical models
- **Alternating Current (AC):** Dynamic (< 15 minutes), allows for wave solutions, **meso- (250-100 km)** and small-scale (<100 km)

$$B = B_0 + \tilde{B}$$
$$E = E_0 + \tilde{E}$$

DC AC

→ Energy deposition from magnetosphere = $Q_s + Q_w$

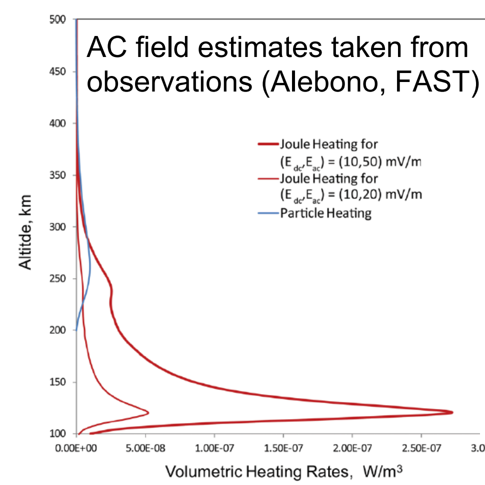
Verkhoglyadova et al., 2018 and references therein

Introduction IV: Wave contribution to I-T Energy Budget

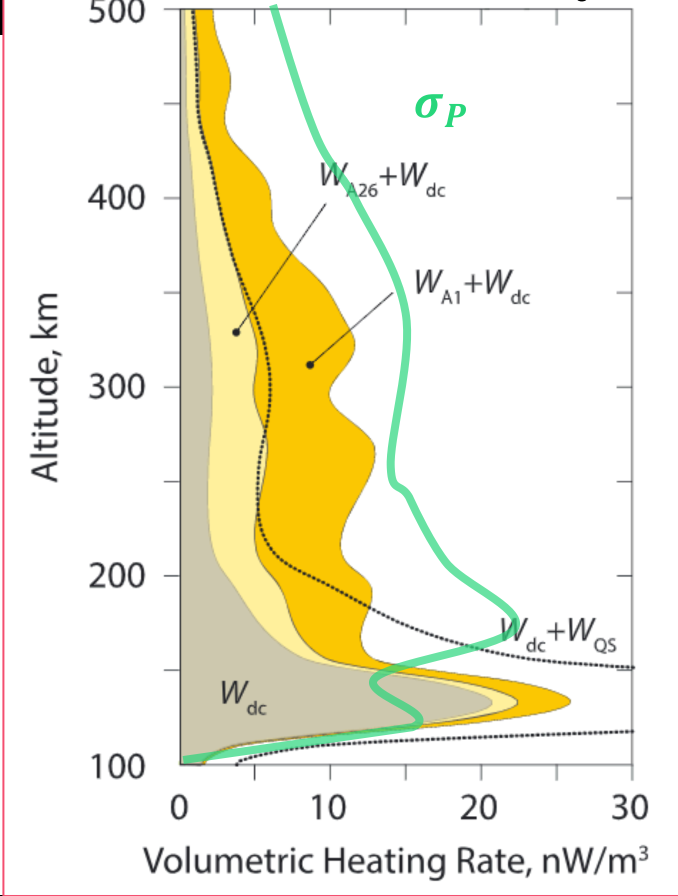
Observational and theoretical studies

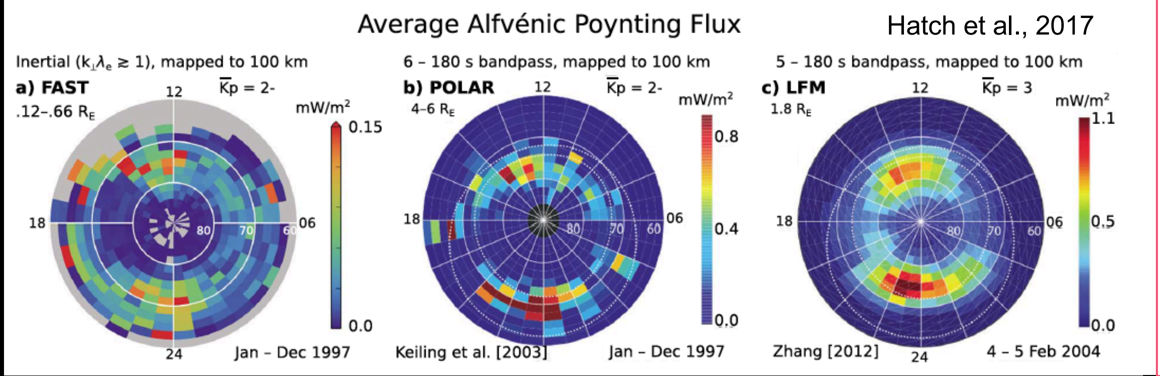
<u>Heating by Alfvén waves</u>

(depending on the frequency range and propagation mode): Verkhoglyadova et al., 2018; Lotko et al., 2018)



Brinkman et al., 2016





Hatch et al., 2017

Can we quantify the distinct effects of the meso-scale structures on the I-T system?

Questions:

- What is the importance of meso-scale structures on I-T energy budget?
- What are the characteristics of meso-scale energy deposition?
- What role do meso-scale structures play in M-I-T coupling?

Objectives:

→ Quantify dynamic IT driving using ISR measurements

→ Adapt a first-principles model (GITM) to dynamical driving

→ Quantify impacts on the regional I-T system

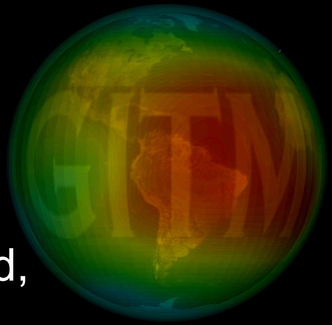
Outline for the Talk

Methodology:

- Global Ionosphere Thermosphere Model (GITM)
- Incoherent Scatter Radar Measurements
- Determination of the Electric Potentials

Introduction → Methodology → Results → Discussion → Future work

Methodology I: Model



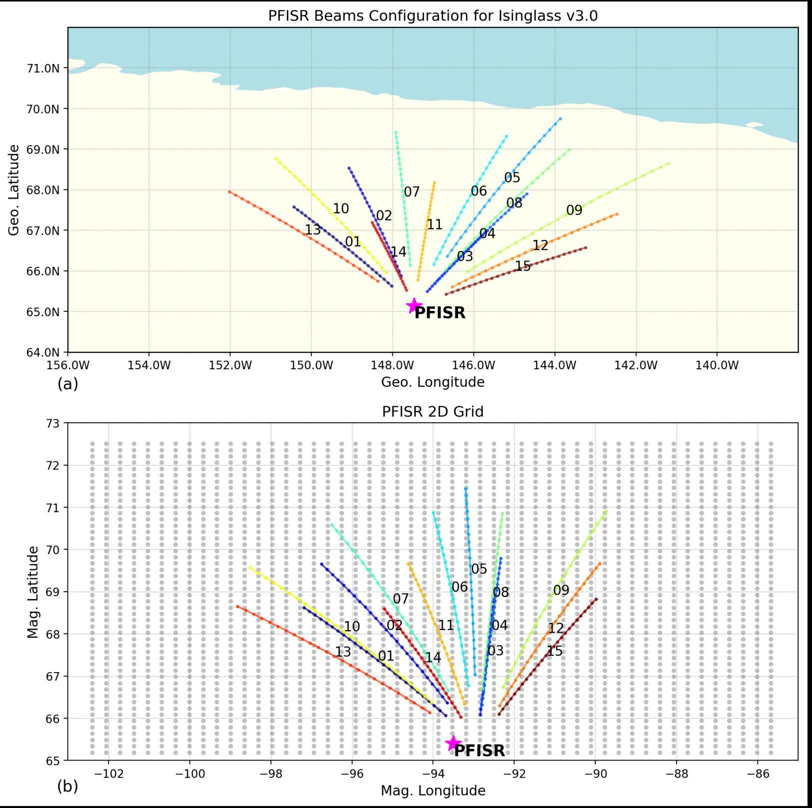
The University of Michigan Global Ionosphere-Thermosphere Model

- Solves Navier-Stokes equations on 3D, altitude based non-uniform grid, assuming non-hydrostatic solution
- Input: Solar wind plasma parameters, IMF vector measurements, F10.7
  - **Convection electric field models:** AMIE, Weimer, Heelis, RIM
  - **Particle precipitation models:** Newell, OvationPrime, OvationSME, RIM
- Heating: EUV, Joule and chemical heating
- Cooling: NO and O2 radiative cooling
- Species are:
  - Neutrals: O, O_2, N(2D), N(2P), N(4S), N_2, NO, H and He
  - Ions: O^+(4S), O^+(2D), O^+(2P), O^{+2}, N^+, N^{+2}, NO^+, H^+ and He^+
- Output: Plasma and neutral density, temperature, ion and electron velocity, neutral winds

Methodology II: Measurements

Poker Flat Incoherent Scatter Radar Observations

- Focusing on the interval between 0628 UT-0730 UT on 2 March 2017.
- PFISR aiding the ISINGLASS experiment with 15 beams operating [Lynch et al.]
- LOS velocity measurements were used to derive Electric fields on a 2D grid.
- Temporal resolution [66 seconds]
- Spatial resolution [0.05° in latitude and 0.3° in longitude, 100 km]
- Many short-lived structures during the period



Ionospheric Structuring: In Situ and Groundbased Low Altitude Studies (**ISINGLASS**) Experiment

PI: Kristina Lynch – Dartmouth College

Robert Clayton (Dartmouth), Matt Zettergren (ERAU), Meghan Burleigh (ERAU-UMich), Mark Conde (UAF), Guy Grubbs (GSFC), Don Hampton (UAF), David Hysell (Cornell), Marc Lessard (UNH), Robert Michell (UMD), Ashton Reimer (SRI), T. Maximillian Roberts (Dartmouth-JPL), Marilia Samara (GSFC), Roger Varney (SRI)

Aim: Sampling multiple locations simultaneously in the auroral ionosphere to take gradient measurements of plasma parameters.

Clayton et al., 2019a, 2019b, JGR

Credits: NASA/Terry Zaperach

Methodology III: Combining the model and measurements

Calculating the Electric Potentials

Requirements:

1. Unconstrained problem
2. Should preserve the Efield features in both coordinates (potential is a scalar quantity)
3. Should yield to low errors with Central Differencing (GITM)
4. Should convert the measurements from non-uniform to uniform grid
5. Should be computationally affordable

Relationship between electric potentials and electric fields:

$$\nabla\Phi = \boldsymbol{E_x} + \boldsymbol{E_y}$$

$$\nabla\Phi = \boldsymbol{e_x}\frac{\boldsymbol{\partial\Phi}}{\boldsymbol{\partial x}} + \boldsymbol{e_y}\frac{\boldsymbol{\partial\Phi}}{\boldsymbol{\partial y}}$$

Integration in magnetic coordinates:

$$\phi_x = \int_{x_1}^{x_2} E_x\,dx \qquad \phi_y = \int_{y_1}^{y_2} E_y\,dy$$

Forward Euler method in integration leads to best results.

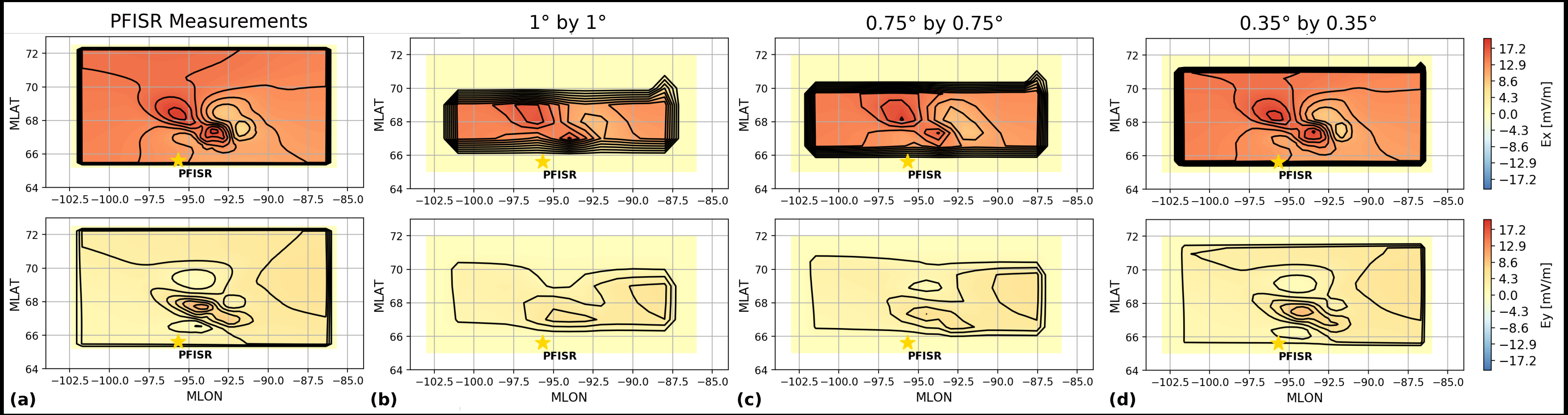
Forward Euler:

$$\phi_{x_{i,j}} = \phi_{x_{i-1,j}} + E_{x_{i,j}}dx$$

$$\phi_{y_{i,j}} = \phi_{y_{i,j-1}} + E_{y_{i,j}}dy$$

Methodology III: Combining the model and measurements

Downsampling the data resolution

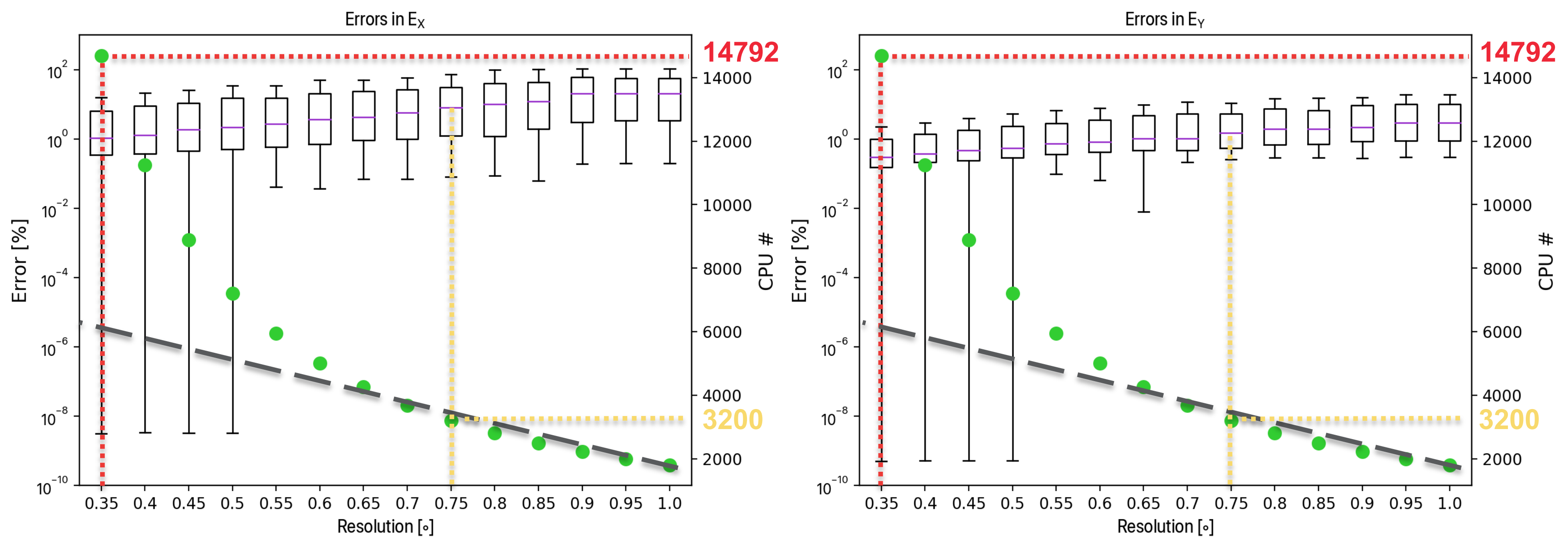


As the grid size decreases, more features are captured.

But how does the computational cost change?

Methodology III: Combining the model and measurements

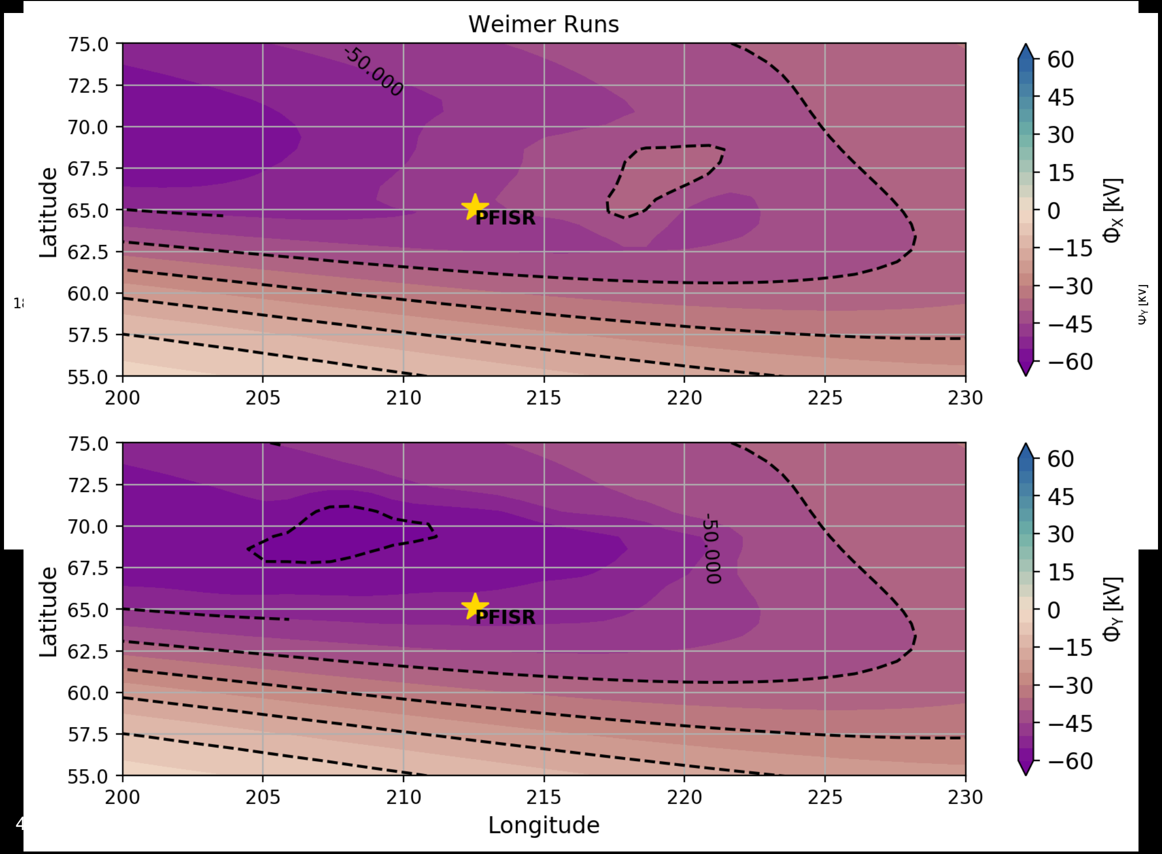
Determining the grid resolution



- Computational cost increases exponentially.
- Grid resolution was chosen as 0.75°.

Methodology III: Combining the model and measurements

Bringing together the large-scale and the meso-scale potentials



- Gaussian filter → Smoothing the boundaries
- Nearest Neighbor Interpolation → Transforming to GEO grid

<u>Requirements:</u>

- ✓ Constrained the problem with Weimer potentials
- ✓ Two potentials to preserve the features in X and Y
- ✓ ~%1 error
- ✓ Uniform grid
- ✓ Computationally affordable

Outline for the Talk

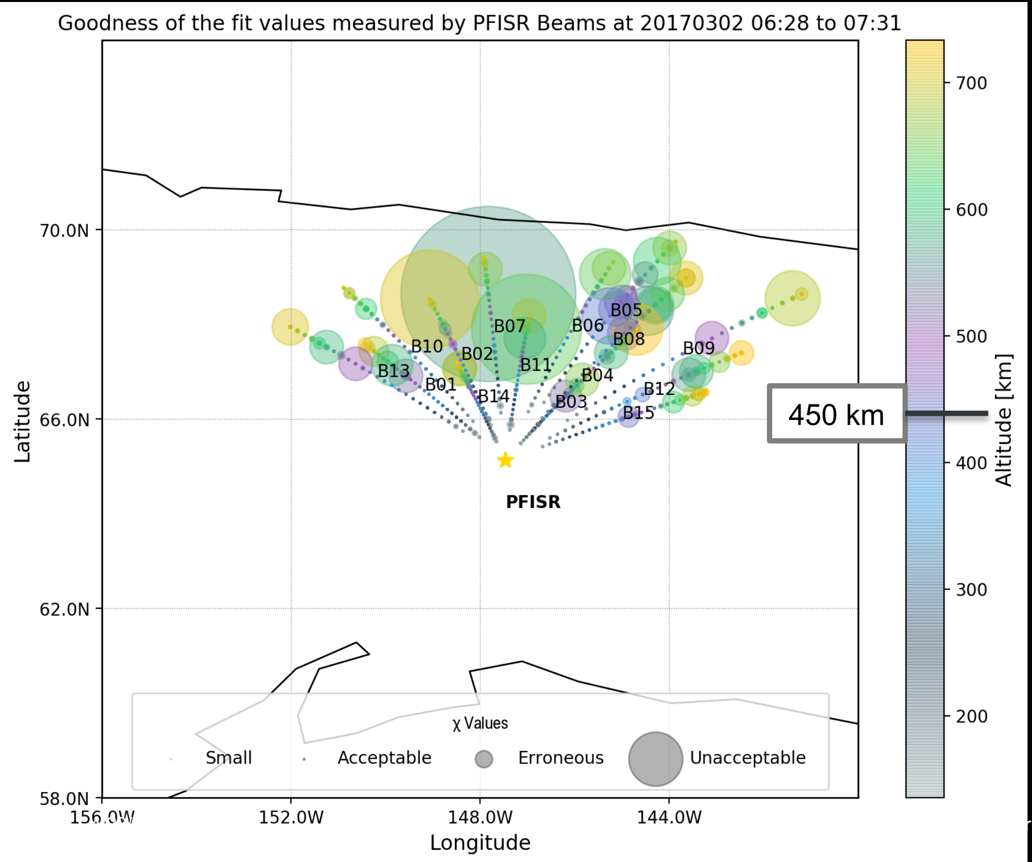
Results:

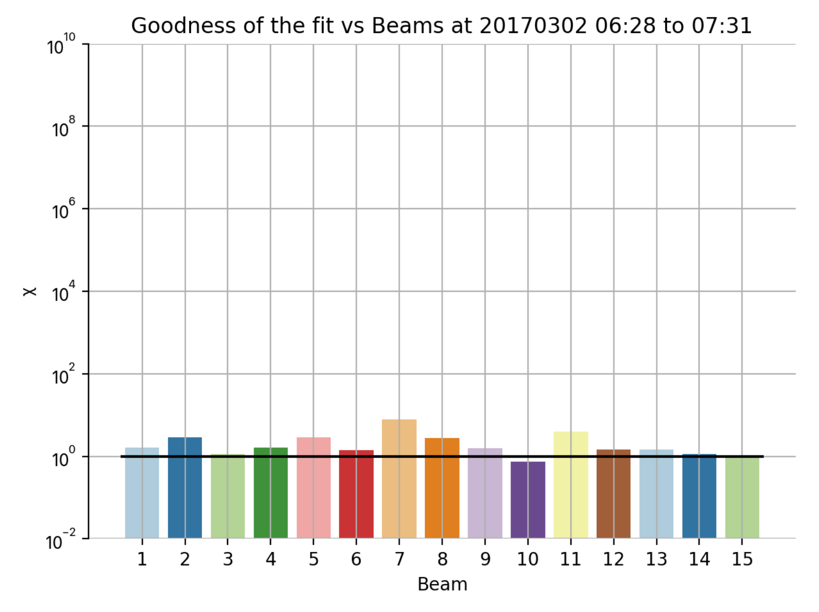
- Measurement errors
- Validation of the model results
- Sources of Meso-Scale Drivers
- Effects of Meso-Scale Drivers

Introduction → Methodology → Results → Discussion → Future work

Results I: Validation

Understanding the constraints of data



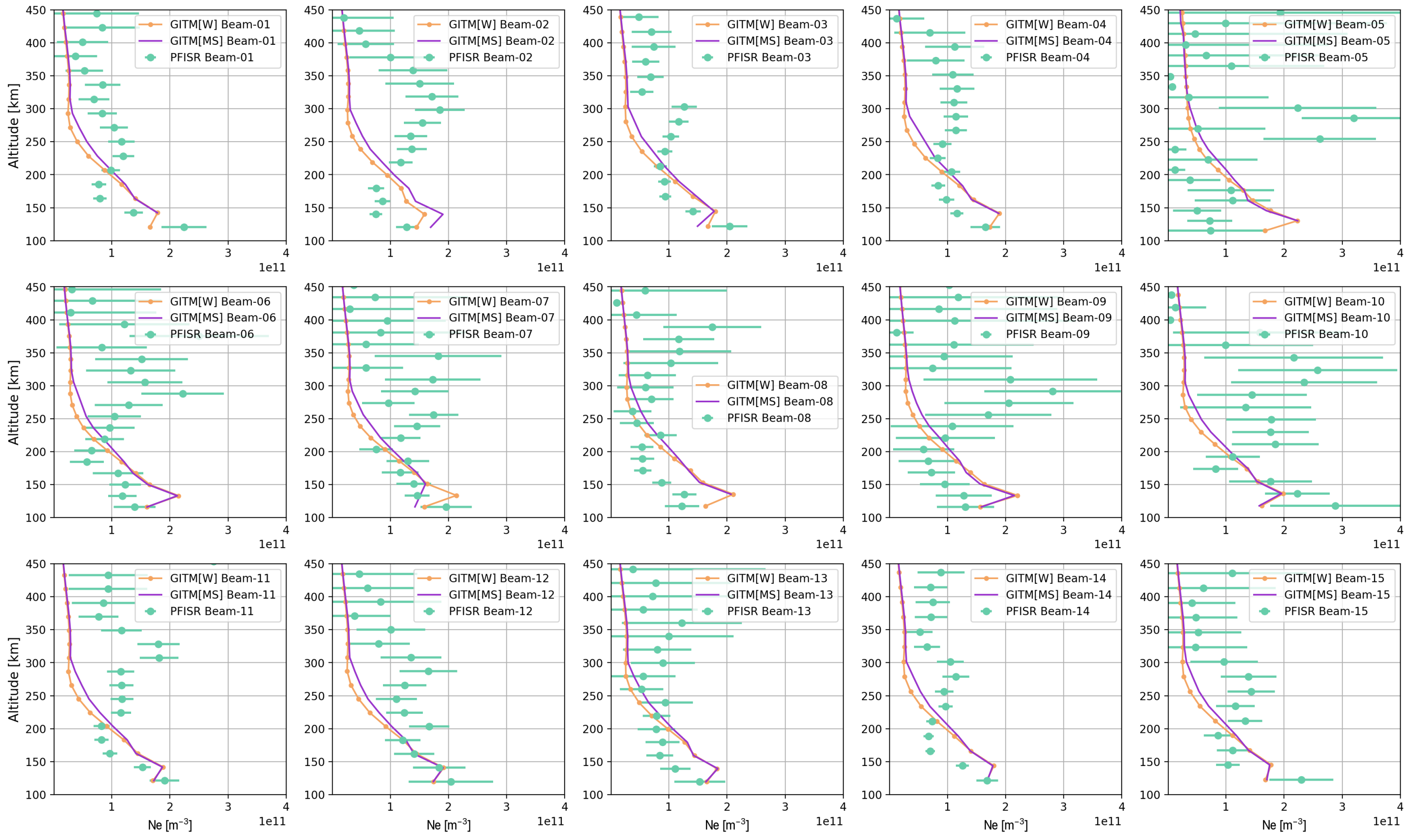


- Certain measurements are more reliable
- Errors guide validation efforts

CEDAR Session on "Reconciling observations and models of high-latitude IT processes" at 20 June 2019, Thursday am.

Results I: Validation

Electron Density along the Beams at 0630 UT



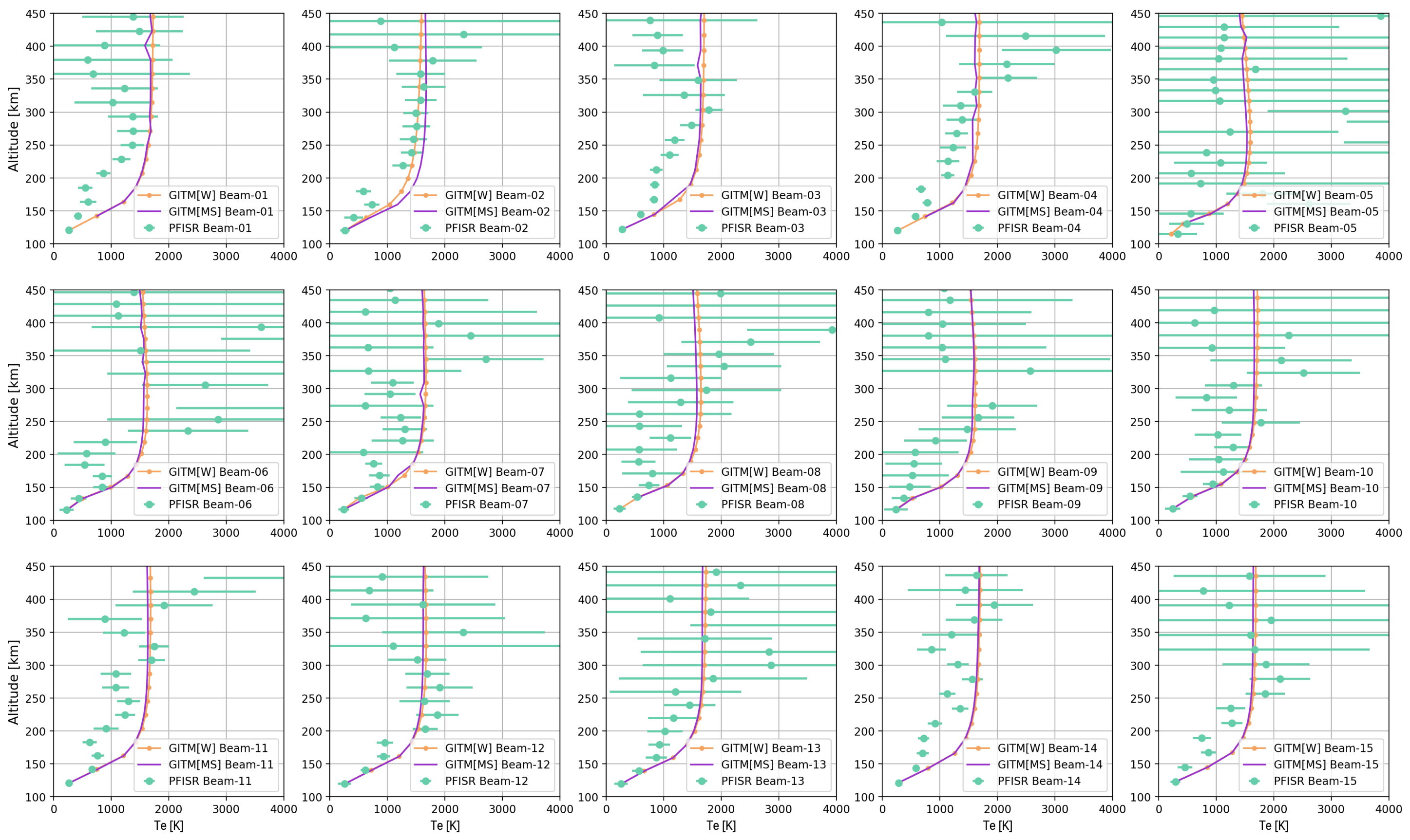
o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements

- Largest errors along Beams 5, 6, 7, 9 and 10
- Electron density enhancement between 175-300 km

jpl.nasa.gov

Results I: Validation

Electron Temperature along the Beams at 0630 UT

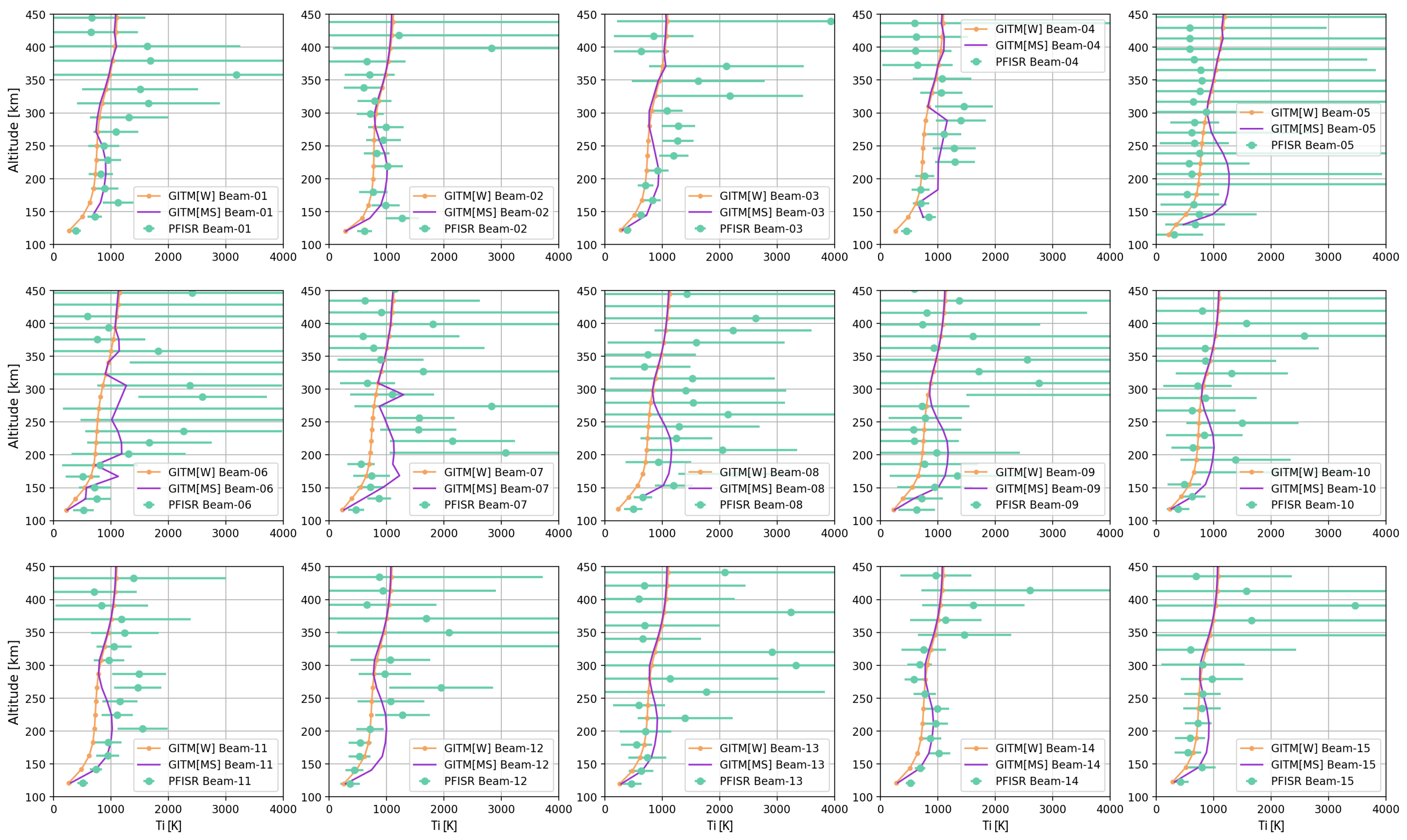


- Largest errors along Beams 5, 6, 7, 8, 9, 10, 12, 13 and 15
- Small electron temperature drop above 200 km.

Results I: Validation

Ion Temperature along the Beams at 0630 UT

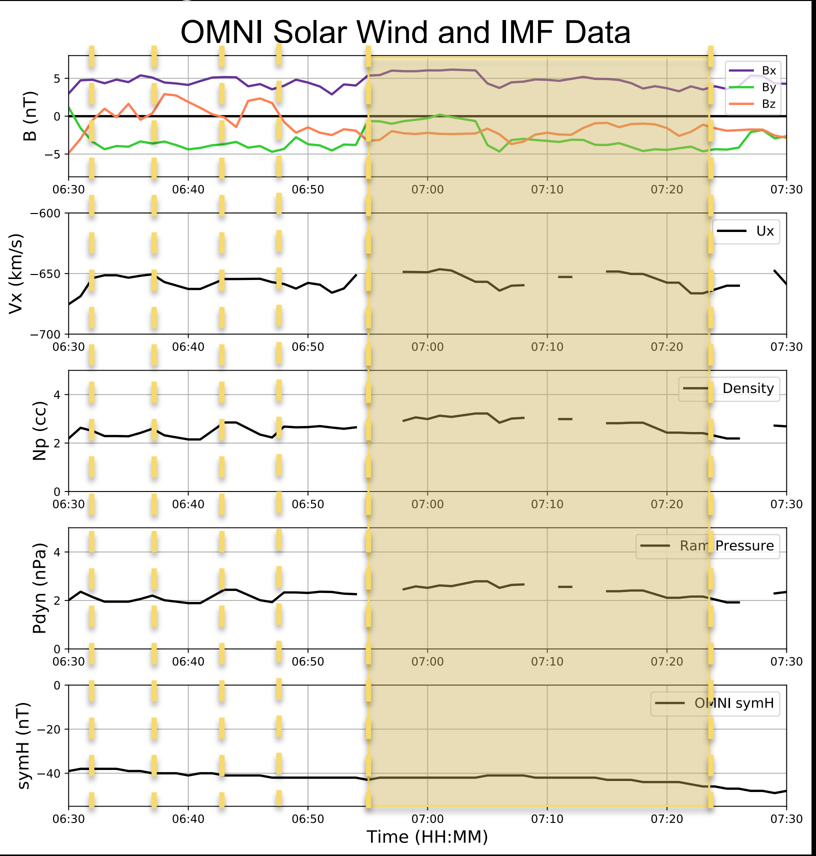
- Weimer simulations
- PFISR+Weimer simulations
- PFISR measurements



- Largest errors along Beams 5, 6, 7, 9 and 10
- Significant ion temperature enhancement between 120-300 km.

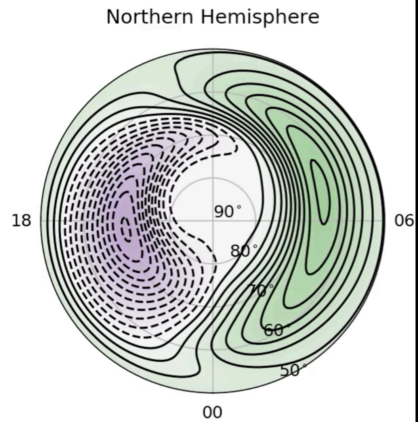
Results II: Sources of Meso-Scale Drivers

The large-scale drivers



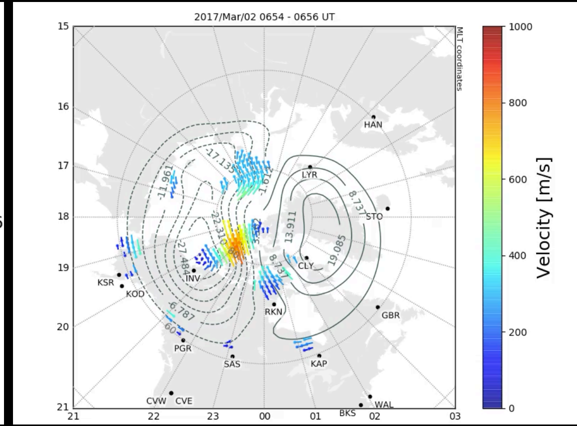
- Multiple IMF B_Z reversals
- High-speed solar wind
- Recovery phase

Weimer Potentials:



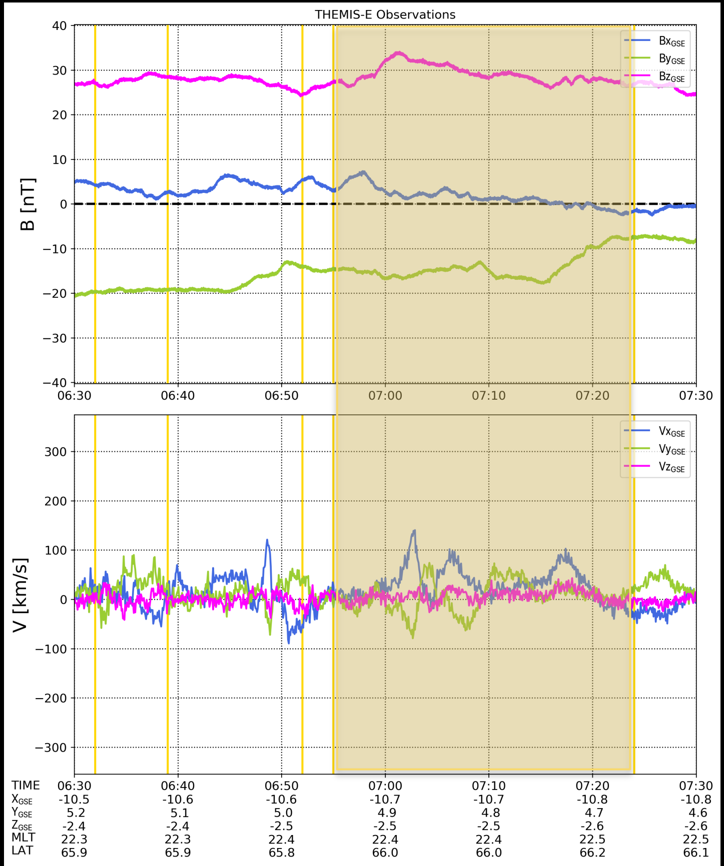
No significant response

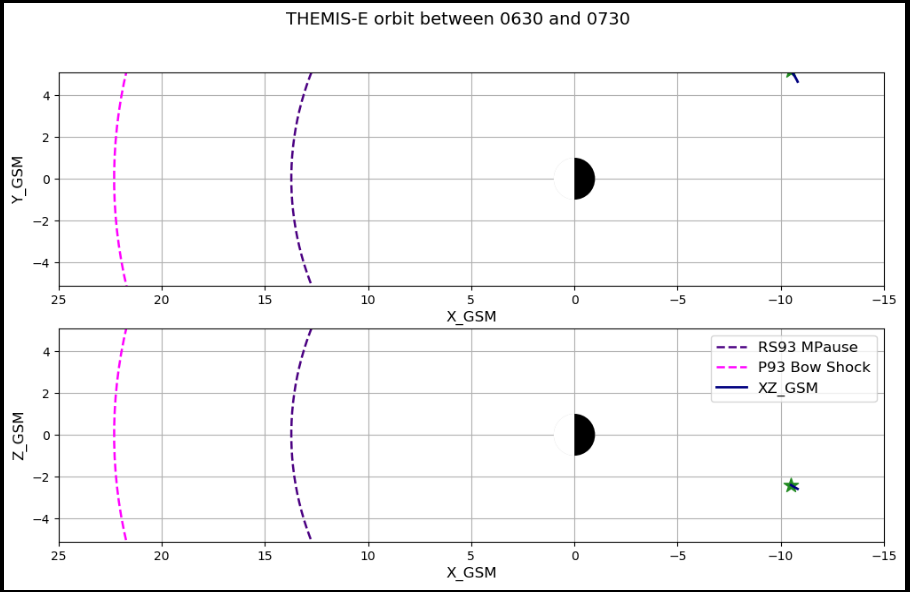
SuperDARN Potentials:



Flow enhancements

Results II: Sources of Meso-Scale Drivers

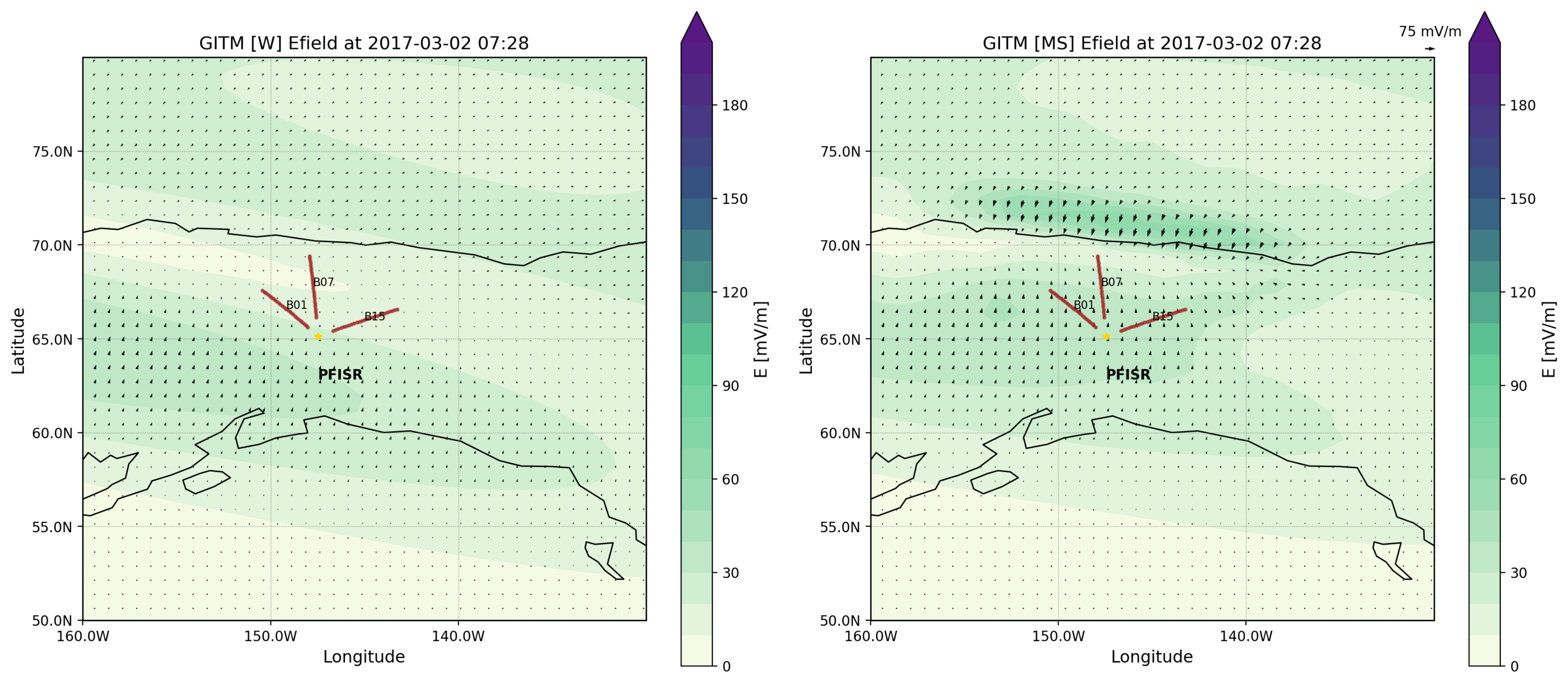




Themis-E recorded Earthward flow enhancements and slight B_Z reversals indicating possible magnetotail activity.

Results II: Sources of Meso-Scale Drivers

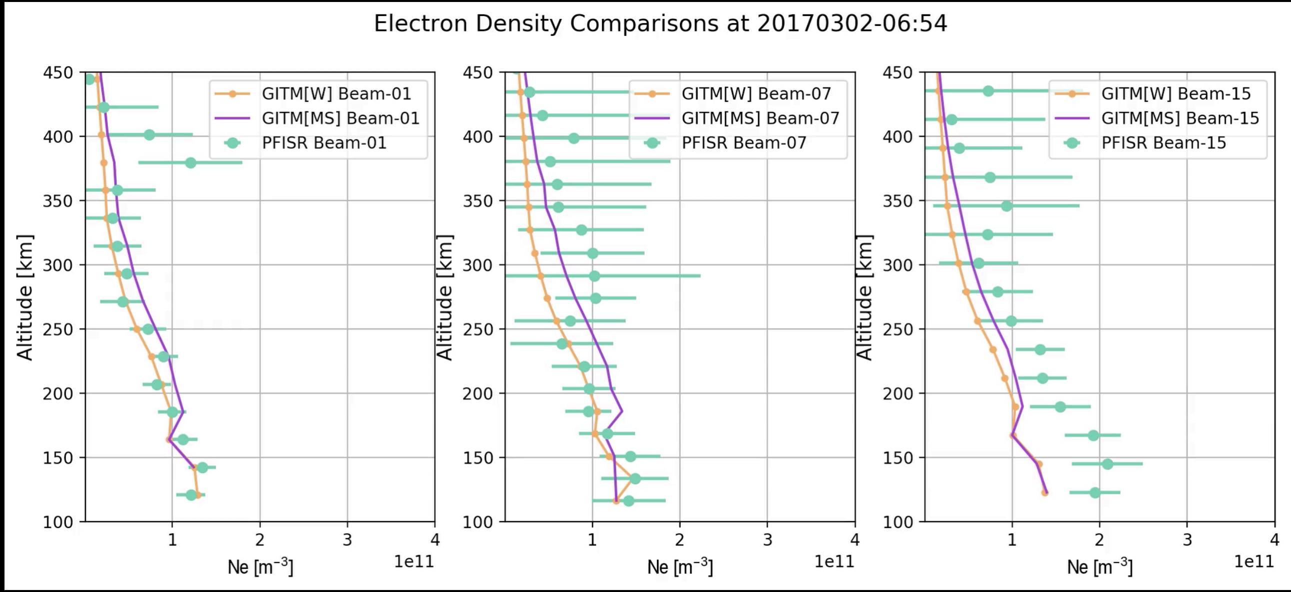
Measured vs Modeled Electric Fields between 0655-0725 UT



Results III: Effects of Meso-Scale Drivers

o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements

Electron density variation between 0655-0725 UT

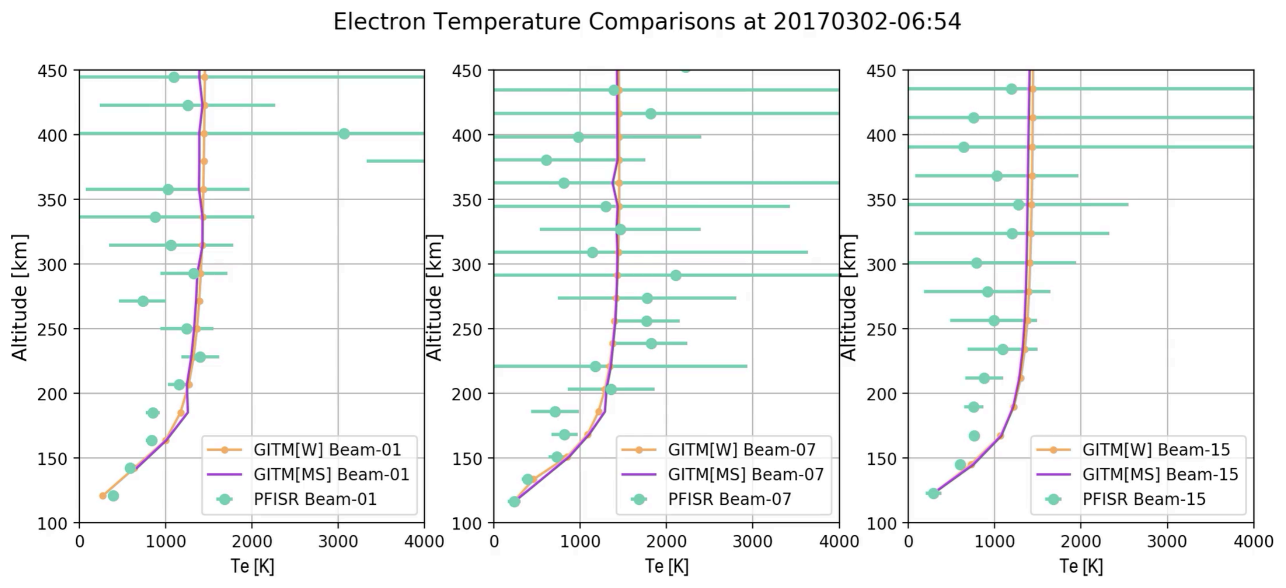


- Overall electron density increases compared to Weimer driven model.
- Measured enhancements around 150 km not captured well.
- Vertical profiles of measured electron densities are very dynamic.
- Meso-scale particle precipitation is not included.

Results III: Effects of Meso-Scale Drivers

Electron temperature variation between 0655-0725 UT

- o Weimer simulations
- o PFISR+Weimer simulations
- o PFISR measurements

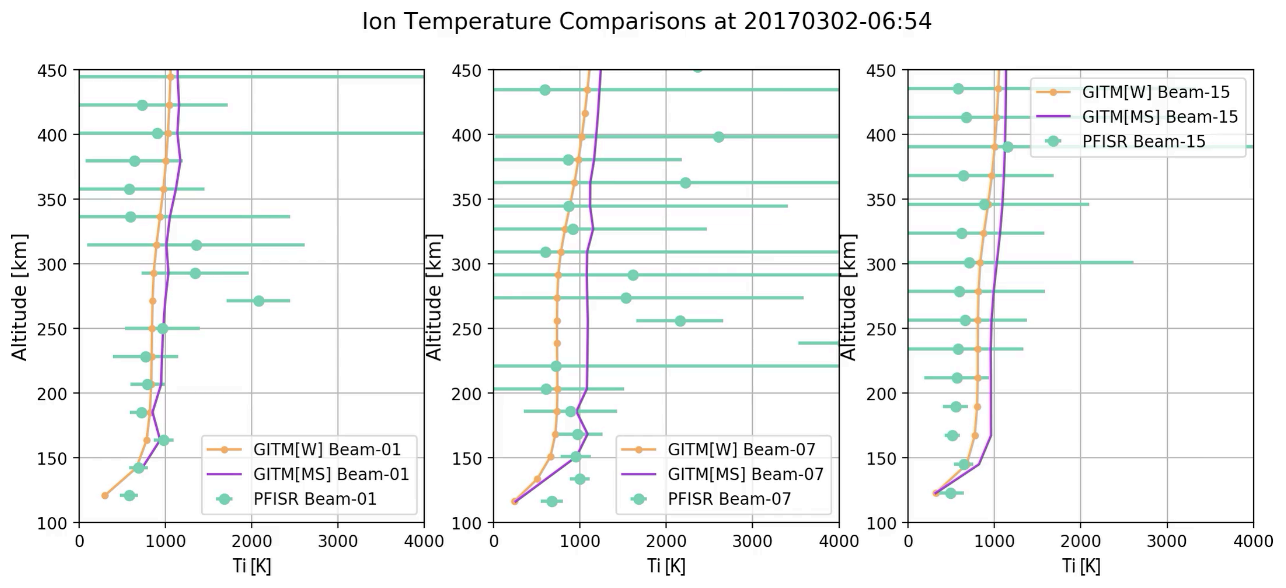


- Electron temperature is lower in the MS driven GITM simulations.
- Not enough cooling in electron temperature.
- No electron flux or energy input in meso-scale was included in the model.

Results III: Effects of Meso-Scale Drivers

o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements

Ion temperature variation between 0655-0725 UT



- Ion temperature is more sensitive to Efield variability than electron temperature and density.
- More wave-like structures appear in the vertical profiles of ion temperature.
- Ion cooling mechanisms need improvement.
- Electron precipitation can lead to drops in ion temperature.

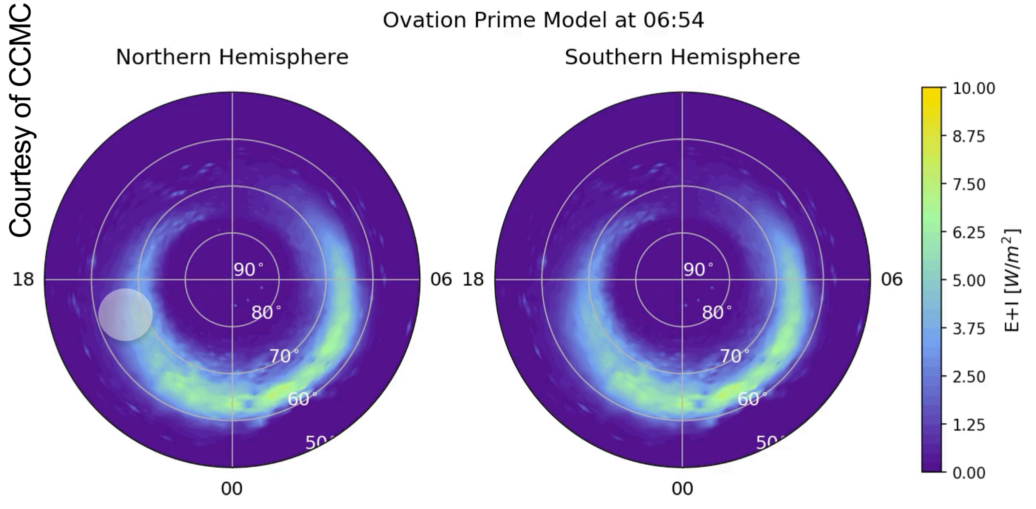
Outline for the Talk

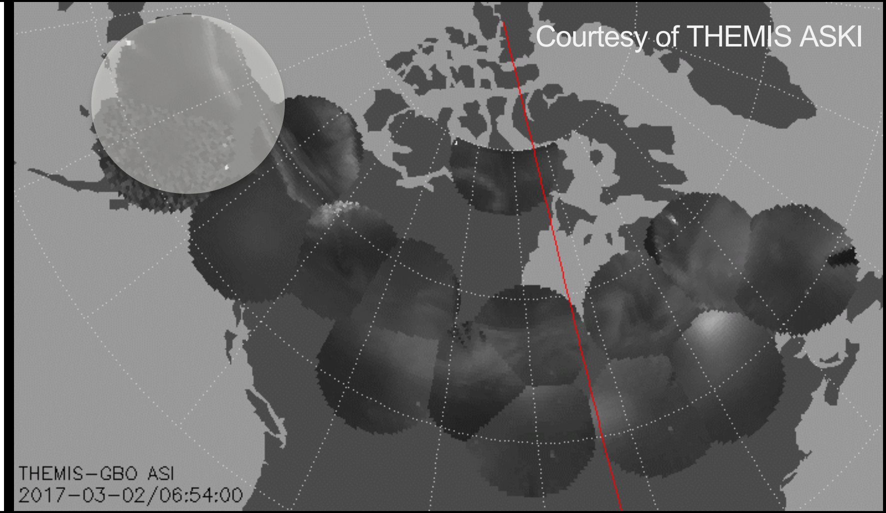
Discussion:

- Role of particle precipitation
- Global effects of the meso-scale variability
- Summary of results

Introduction → Methodology → Results → Discussion → Future work

Discussion I: Role of particle precipitation



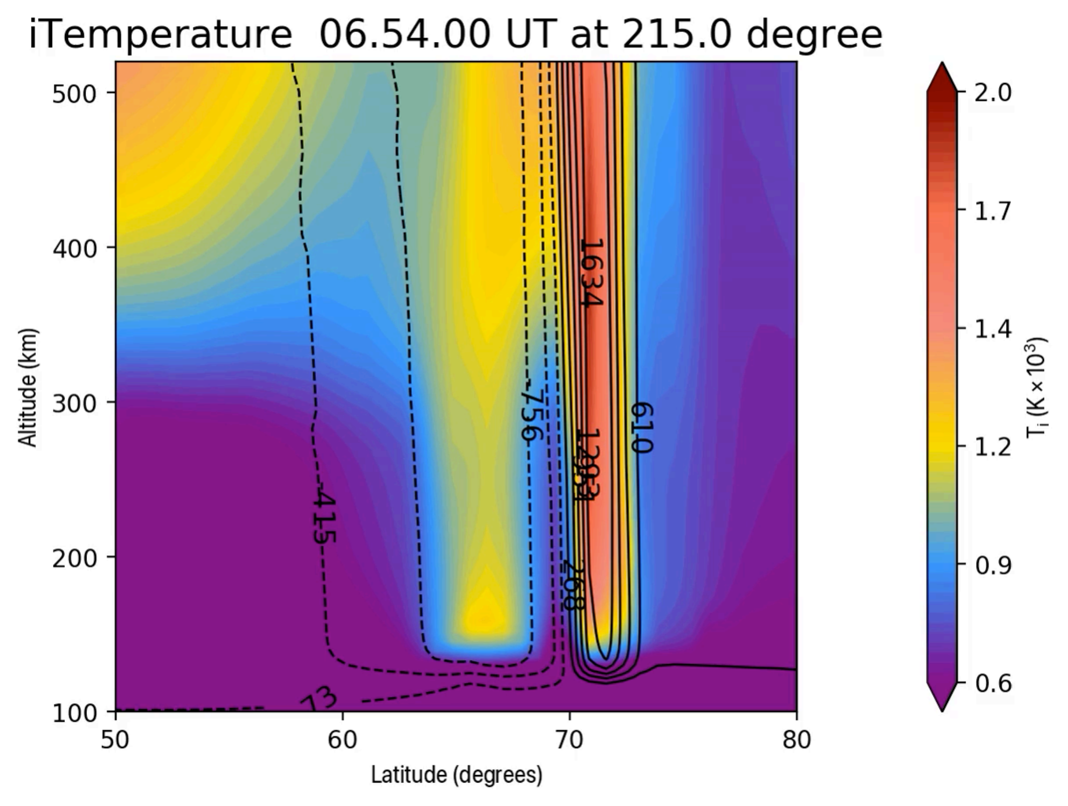


- Constant auroral arc over Alaska during the period
- Multiple impulsive brightening over Alaska, 1 W/m^2 in Venetia ASKI data*
- No significant change in OvationPrime

*courtesy of Guy Grubbs and Matt Zettergren

Discussion II: Global effects of the meso-scale variability

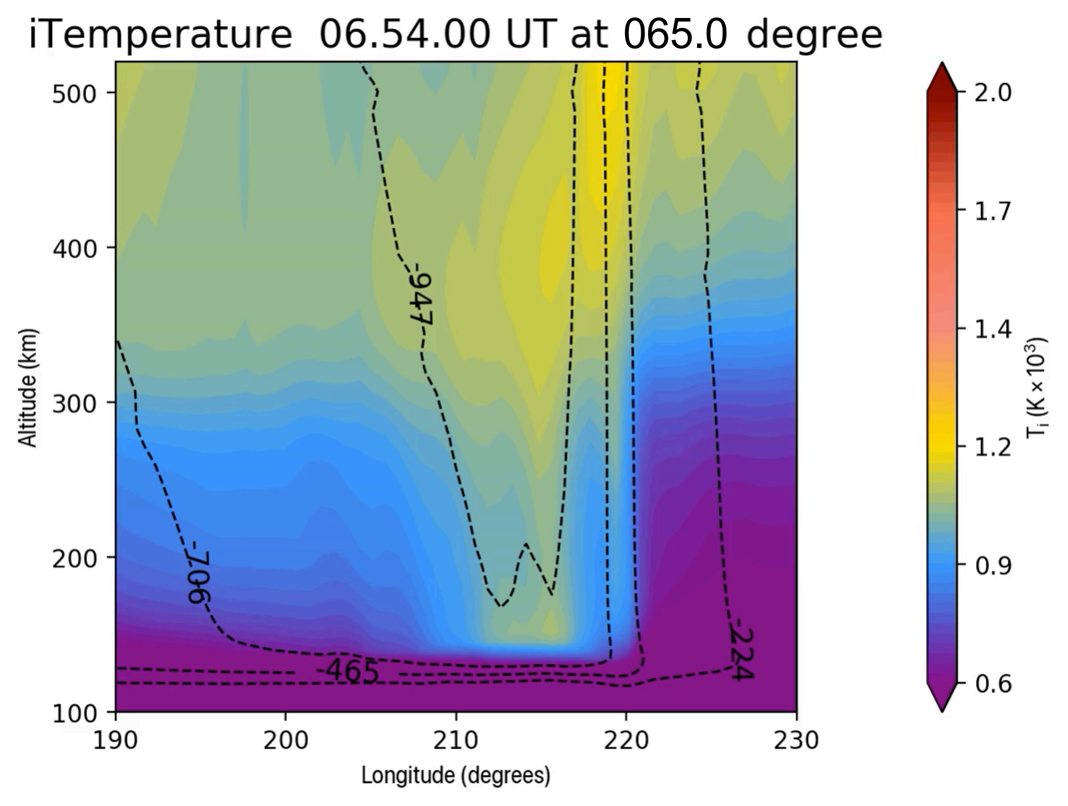
Meridional extent of ion temperature variation



- Two heating channels form, southward (westward convection) and northward (eastward convection) of 70°.
- Highest enhancements are around 175 km and above 400 km.
- Up to 1000 K enhancement.
- Latitudinally limited, with short-lived (1 minute) effects over 16° (~1800km).

Discussion II: Global effects of the meso-scale variability

Zonal extent of ion temperature variation



- Heating mostly due to westward convection flows,
- Highest enhancements are centered around 150 km and 300 km.
- Longitudinal extent 10° (~935 km) but not limited.
- Shows short-lived enhancements (1 minute).
- Wave-like structures along the vertical profile.

Discussion III: Summary of Results

- What is the importance of meso-scale structures on I-T energy budget?
  - Up to %40 enhancement in electron density
  - Up to %100 enhancement in ion temperature
- What are the characteristics of meso-scale energy deposition?
  - Mostly in the F_2 region
  - Short-lived (1-2 minutes) based on the driver
  - Wave like structures in vertical temperature profiles
- What role do meso-scale structures play in M-I-T coupling?
  - Geomagnetic activity: Prolonged IMF B_Z period
  - Earthward flow enhancements in magnetotail
  - B_X reversals in magnetotail
  - Impulsive aurora

Outline for the Talk

Future work:

- Including particle precipitation
- Improving model capabilities
- Quantifying uncertainties in the model
- More event studies with different drivers

Introduction → Methodology → Results → Discussion → Future work

Thank you.

Acknowledgements

- This work is funded by the NASA ROSES 2016 Heliophysics LWS Science (NRA NNH16ZDA001N) Program.
- GITM is developed and supported by Prof. Aaron Ridley at University of Michigan.
- Simulations were done on NASA High-End Computing Program through the NASA Advanced Supercomputing Division at Ames Research Center, and Stampede Supercomputer at Texas Advanced Computing Center at University of Texas at Austin.
- We acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb (or CDAWeb or ftp) service, and OMNI data.
- We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission. Specifically: C. W. Carlson and J. P. McFadden for use of ESA data; K. H. Glassmeier, U. Auster and W. Baumjohann for the use of FGM data provided under the lead of the Technical University of Braunschweig and with financial support through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302.
- We acknowldge the use of the VT SuperDARN Web site (vt.superdarn.org) for access to radar data and data products. SuperDARN is a collection of radars funded by national scientific funding agencies of Australia, Canada, China, France, Italy, Japan, Norway, South Africa, United Kingdom and the United States of America.
- Simulation results have been provided by the Community Coordinated Modeling Center at Goddard Space Flight Center through their public Runs on Request system (http://ccmc.gsfc.nasa.gov). The Weimer Model was developed by Daniel R. Weimer at Virginia Tech. The Ovation Prime Model was developed by Patrick Newell at JHU/APL.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

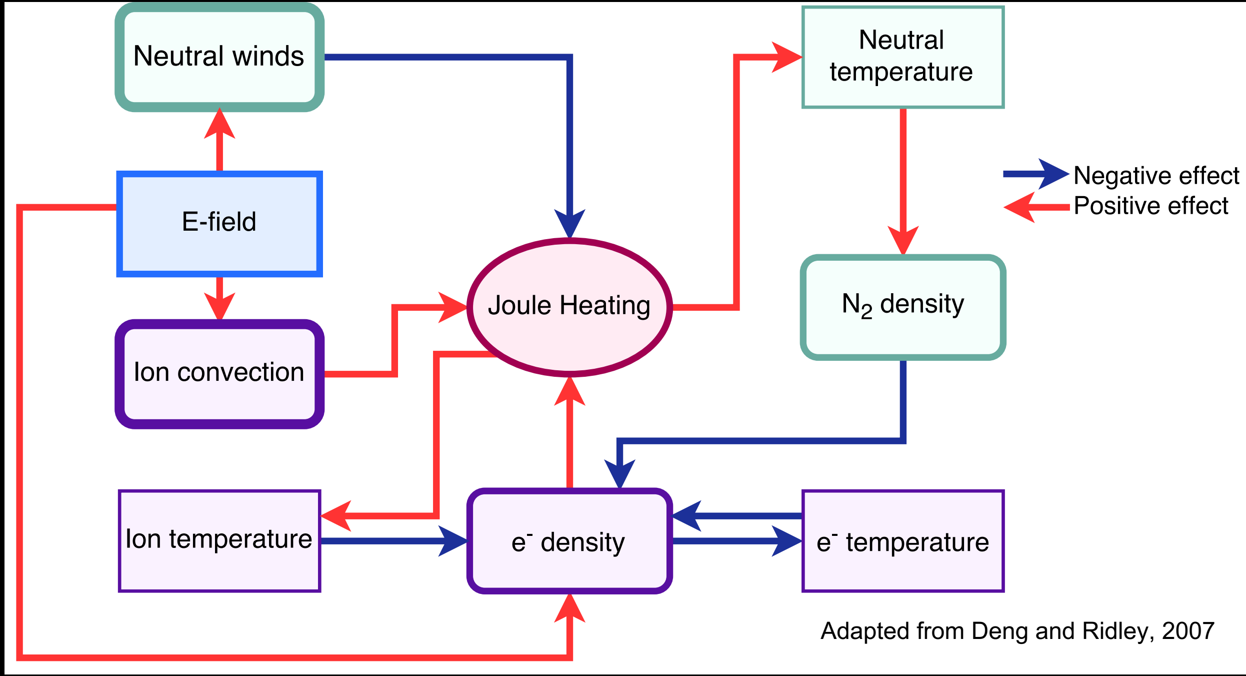
BACK-UP SLIDES

Introduction I: The energy deposition from the Magnetosphere to the I-T system

Electromagnetic energy transfer rate : $J.E = J.(E + U \times B) + U.(J \times B)$

Joule heating: $J.(E + U \times B)$

Work done on neutrals by ion drag force: $U.(J \times B)$



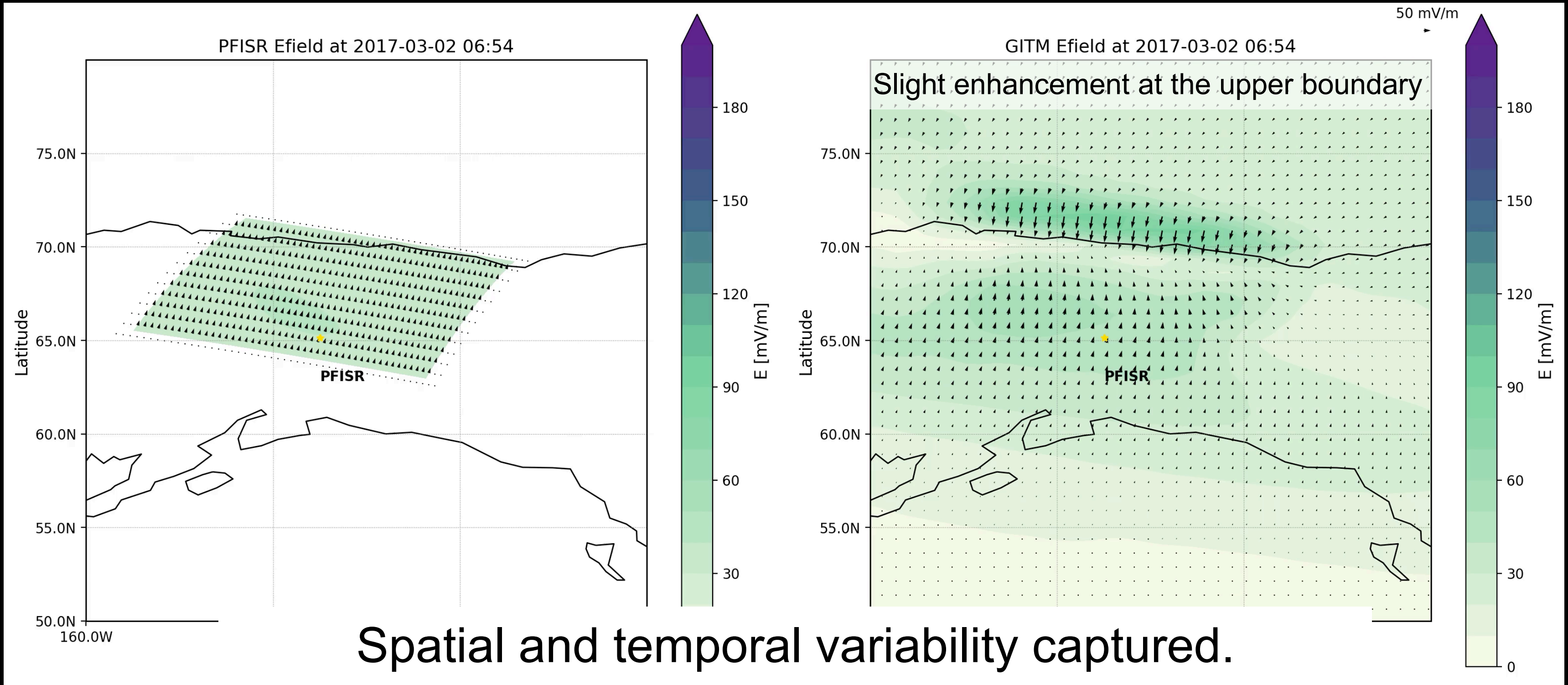
Adapted from Deng and Ridley, 2007

E-field variability affects the Joule heating through:

- Ion convection patterns
- Neutral winds
- Electron density profiles
- Secondary processes

Results II: Sources of Meso-Scale Drivers

Measured vs Modeled Electric Fields between 0655-0725 UT



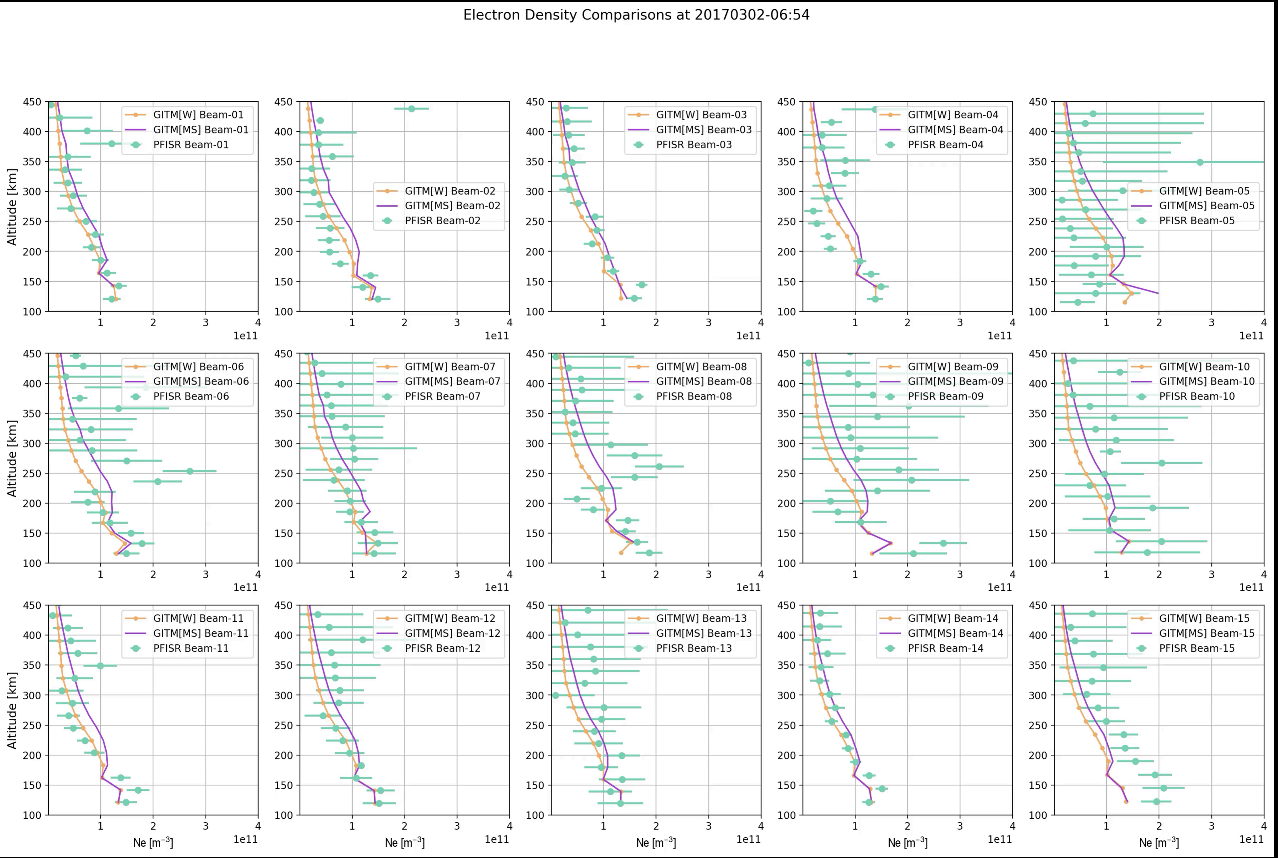
Spatial and temporal variability captured.

Efield is directed northwards unlike Weimer fields.

Results III: Effects of Meso-Scale Drivers

Electron density variation between 0655-0725 UT

- o Weimer simulations
- o PFISR+Weimer simulations
- o PFISR measurements



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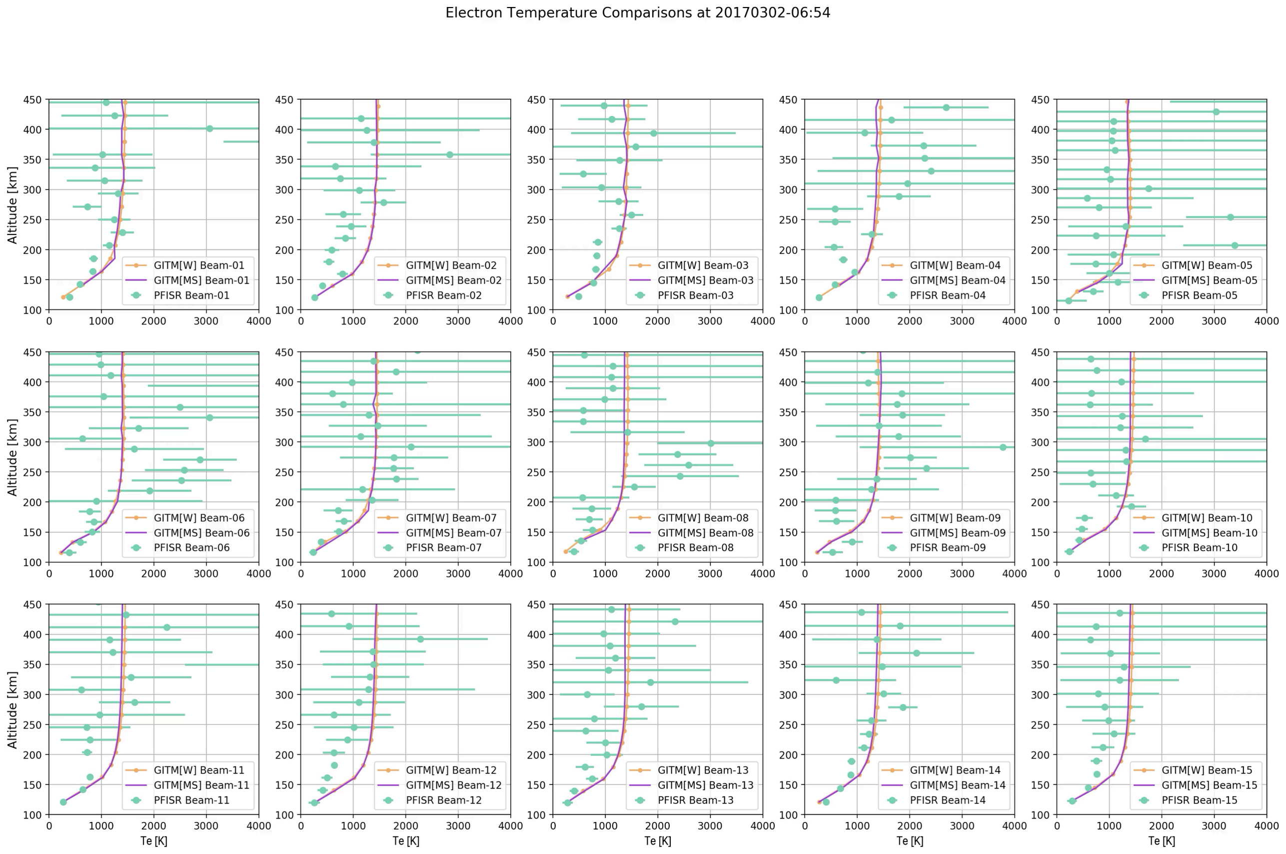
Results III: Effects of Meso-Scale Drivers

Electron temperature variation between 0655-0725 UT

o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements

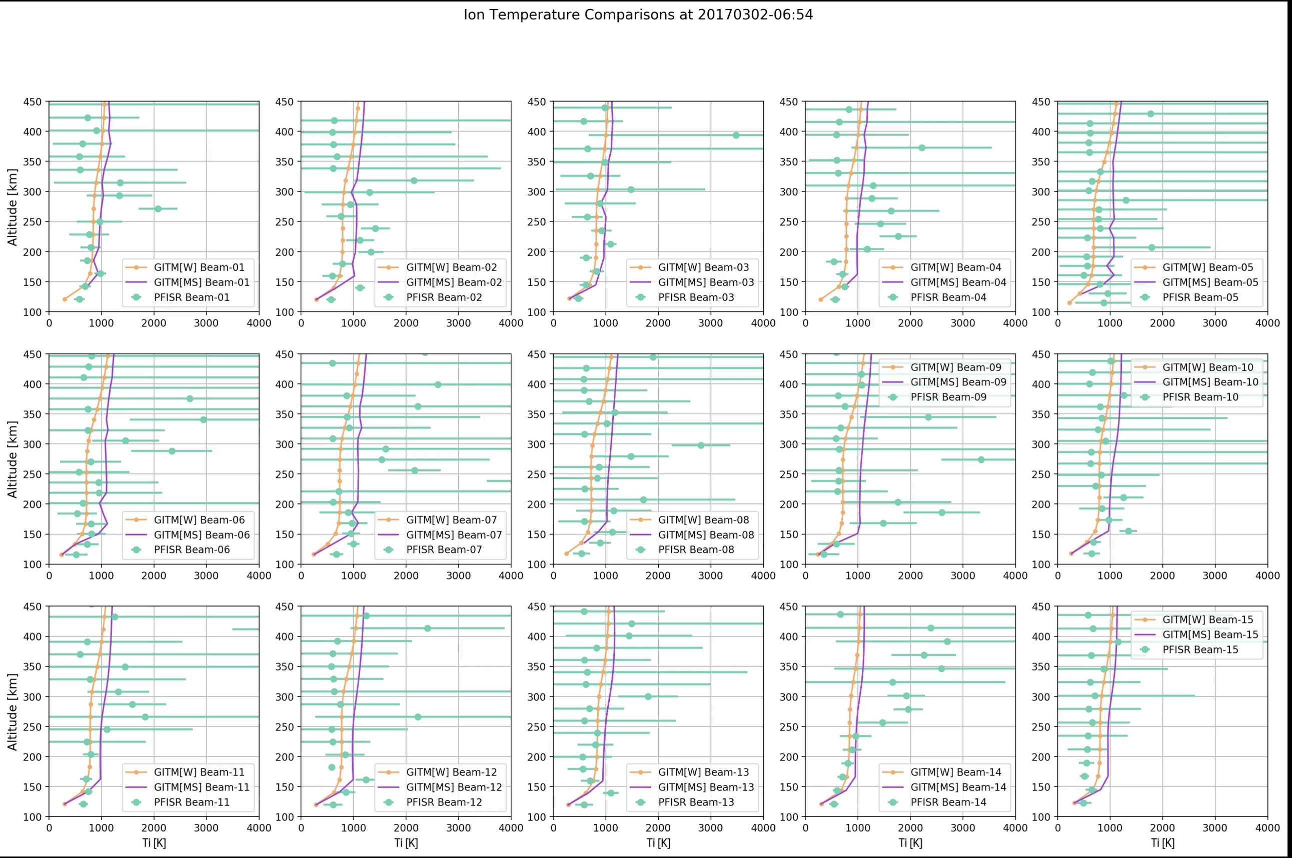


- Electron temperature is lower in the MS driven GITM simulations.
- Not enough cooling in electron temperature.
- No electron flux or energy input in meso-scale was included in the model.

Results III: Effects of Meso-Scale Drivers

Ion temperature variation between 0655-0725 UT

o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements



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- Ion cooling mechanisms need improvement.
- Electron precipitation can lead to drops in ion temperature.