Effects of E region nonlinear instabilities in the generation of a strong SAID channel

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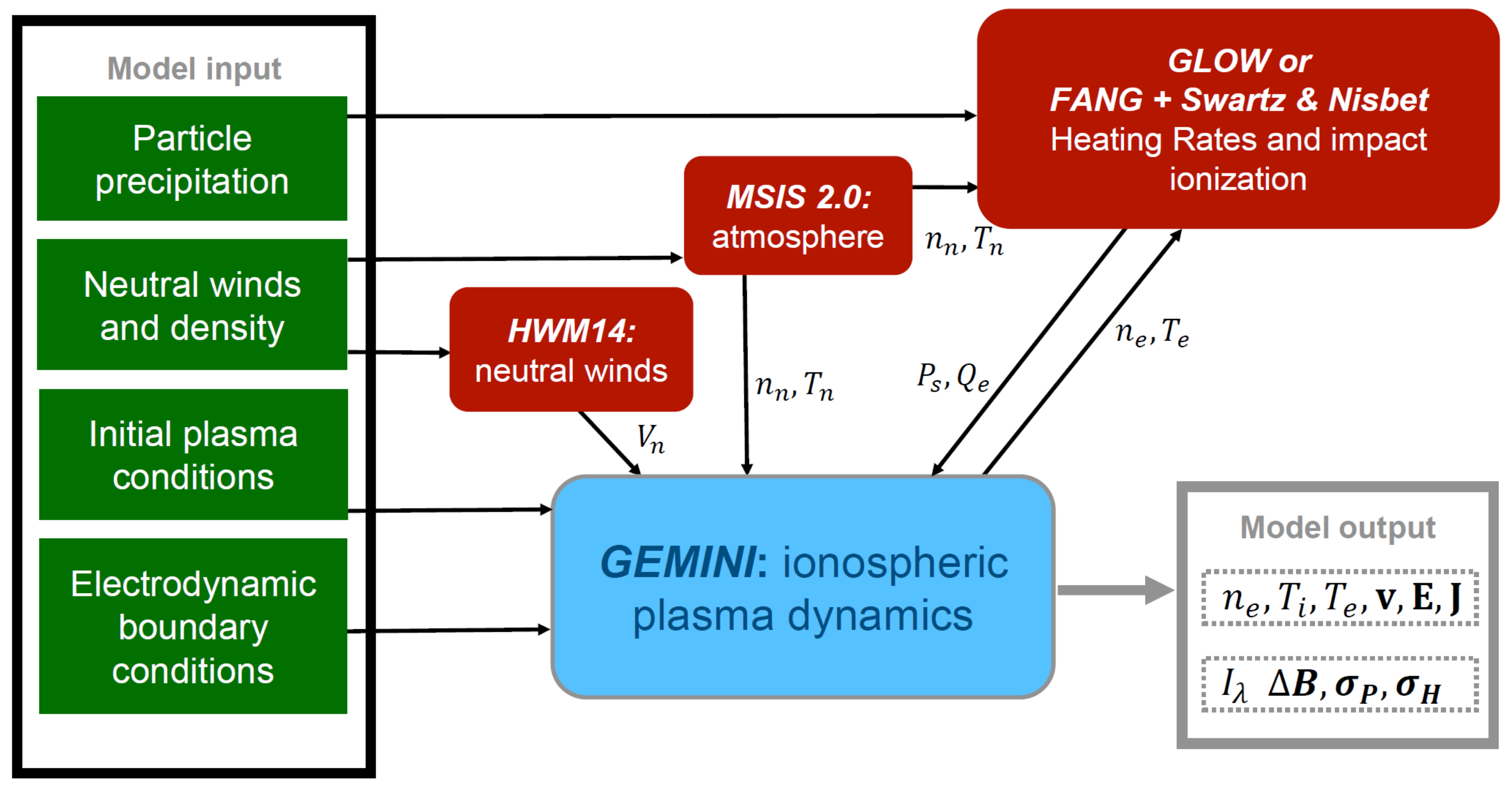
ABSTRACT

Ionospheric flow channels play a vital role in shaping the dynamics and structure of the ionosphere. These channels are characterized by localized and swift plasma flows, which have a profound impact on the distribution of ionospheric plasma, energy and momentum transport, as well as the interaction between the ionosphere, magnetosphere, and atmosphere. Consequently, these channels can greatly influence the behavior of the ionosphere, affecting the propagation of radio waves and the distribution of ionospheric plasma. Among these flow channels, a specific type called subauroral ion drift (SAID) flow channels occurs in the subauroral region, situated between the auroral and midlatitude regions of the ionosphere. These channels are narrow, latitudinal pathways characterized by fast westward flows, appearing during magnetically disturbed periods. Recent research has indicated that SAID channels are closely related to the formation and behavior of the Strong Thermal Emission Velocity Enhancement (STEVE) aurora. STEVE is a unique type of aurora that was initially discovered by citizen scientists and stands apart from the classic auroral oval. It manifests as a narrow ribbon of light at lower latitudes, often accompanied by a distinctive pattern of green vertical stripes resembling a "picket fence." Due to its remarkable appearance and unusual behavior, STEVE has garnered significant attention from both scientists and the public. This study employs the GEMINI3D model to simulate an extreme SAID event using a three-dimensional grid, building upon previous observations of the STEVE phenomenon. The E region is of particular importance in this investigation, as the effects of non-linear instabilities. These instabilities can significantly influence conductance, temperature, and the ambient electric field, subsequently impacting the flow channel. To address this, we have updated the GEMINI3D model to incorporate the macroscopic effects of the Farley-Buneman instability.

SAID, STEVE and GEMINI3D

Recent studies have suggested that **SAID channels are associated with the formation and behavior of the Strong Thermal Emission Velocity Enhancement (STEVE) aurora**. STEVE is a new type of aurora that has been discovered, initially by citizen scientists (MacDonald et al., 2018) that is distinct from the classic auroral oval and is characterized by a **narrow ribbon of light that often accompanied by a `picket fence' of green vertical stripes**. The flow channel associated with STEVE shows velocities larger than **5km/s** and higher than **10.000K** electron temperature at LEO altitudes, which would make it an extreme version of an SAID flow channel. Measuring STEVE presents a challenge due to its lack of a fixed location. Fortunately, **GEMINI3D** (Zettergren and Semeter, 2012) can solve this issue by incorporating inputs from empirical models and allowing for a grid size that can be adjusted to cover a smaller geographical area than global models.

- Fluid-electromagnetic ionospheric model that solves a **5-moment fluid equation**
- Separate species tracked using consistent chemistry and impact ionization calculations.
- **Requires inputs**: Boundary electromagnetic fields, Particle precipitation, Neutral atmospheric specification
- **Massively parallel**, BUT can be run on a laptop
- **Open source**: https://github.com/gemini3d/


Model input
Particle precipitation
Neutral winds and density
Initial plasma conditions
Electrodynamic boundary conditions
MSIS 2.0: atmosphere
HWM14: neutral winds
GLOW or FANG + Swartz & Nisbet Heating Rates and impact ionization
GEMINI: ionospheric plasma dynamics
Model output
$n_e, T_i, T_e, \mathbf{v}, \mathbf{E}, \mathbf{J}$
$I_\lambda\ \ \Delta\mathbf{B}, \boldsymbol{\sigma_P}, \boldsymbol{\sigma_H}$

SIMULATION SET UP AND OBJECTIVES

- **Initial target:** model the details of a **SAID flow channel**
- Eventually: generate an **"extreme"** version of a SAID that resembles **STEVE**
- We include the Farley-Buneman Instability (FBI) turbulent effects in order to better simulate the E region
- To realistically **constrain STEVE**, we rely on the (relatively limited) available satellite measurements (Nishimura et al. 2020). This can be seen in the figure to the right.

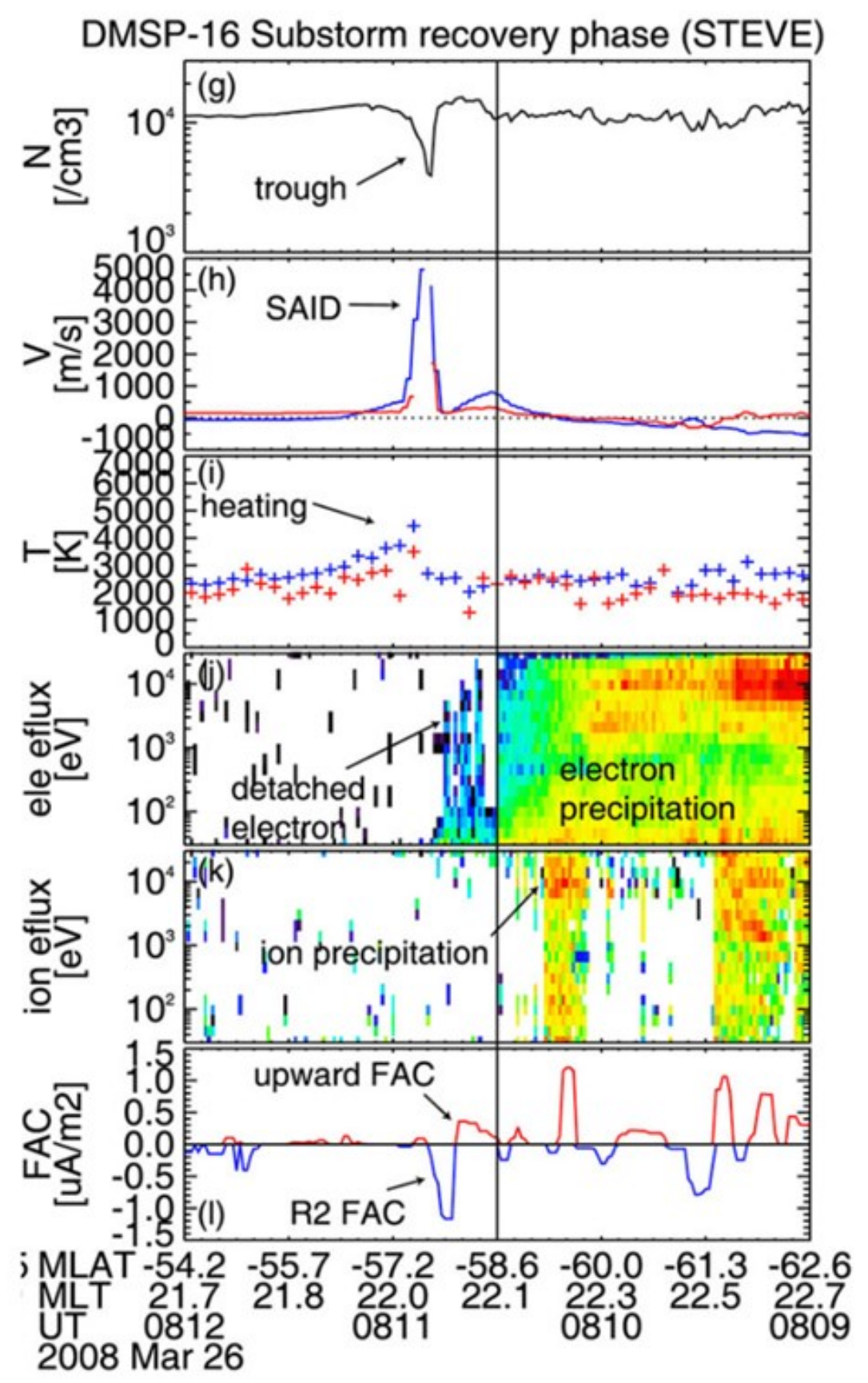
  Currents: 1.0 μA/m2 downward and upward

  Velocity: up to 5Km/s

  Particle precipitation: almost no particle precipitation
- **Caveats:** use low resolution, for now, to save resources until we have a better idea of what we need to examine in detail.

Gemini Inputs:

- Simulation is run for 60 minutes with 15 seconds output intervals
- J target of 0.8 μA/m2, ramp up to max value for 15 minutes
- Background precipitation: 0.014 mW/m2
- Total energy flux and 1keV characteristic energy



ELECTRON ABNORMAL HEATING AND NON LINEAR CURRENTS EFFECTS

Electron Abnormal Heating (EAH) can be estimated by adding a extra heating term to the electron energy equation as presented by **Dimant & Milikh (2003).** In this case **Q_e^{tot}** represents the total heating due to electrons.

$$Q_e^{tot} = \frac{m_e \nu_e n_0 E_0^2}{B_0^2} + \frac{m_i \nu_i n_o \kappa_i^2 \left(E_0 - E_{Thr}^{min}\right)^2}{\left(1+\kappa_i^2\right) B_0^2} \left[\frac{E_0}{E_{Thr}^{min}} \left(1+\psi_\perp\right) - 1\right]$$

$$E_{Thr}^{min} = \left(1+\psi_\perp\right) B_0 \left[\left(\frac{1+\kappa_1^2}{1-\kappa_1^2}\right) \left(\frac{k_B (T_e + T_i)}{m_i}\right)\right]^{1/2}$$

$$\psi_\perp = \frac{\nu_e \nu_i}{\Omega_e \Omega_i} = \frac{m_e m_i \nu_e \nu_i}{e^2 B^2}, \qquad \kappa_i = \frac{\Omega_i}{\nu_i} = \frac{eB}{m_i \nu_i}$$

A loss term is also applied to the electron energy losses due to the fact that under strong electric field the electron distribution function becomes substantially non-Maxwellian with effective "bite-out".

Conductivity changes due to non linear currents (NLC) can be estimated by adding a extra conductivity term as presented by **Dimant & Oppenheim (2011)**.

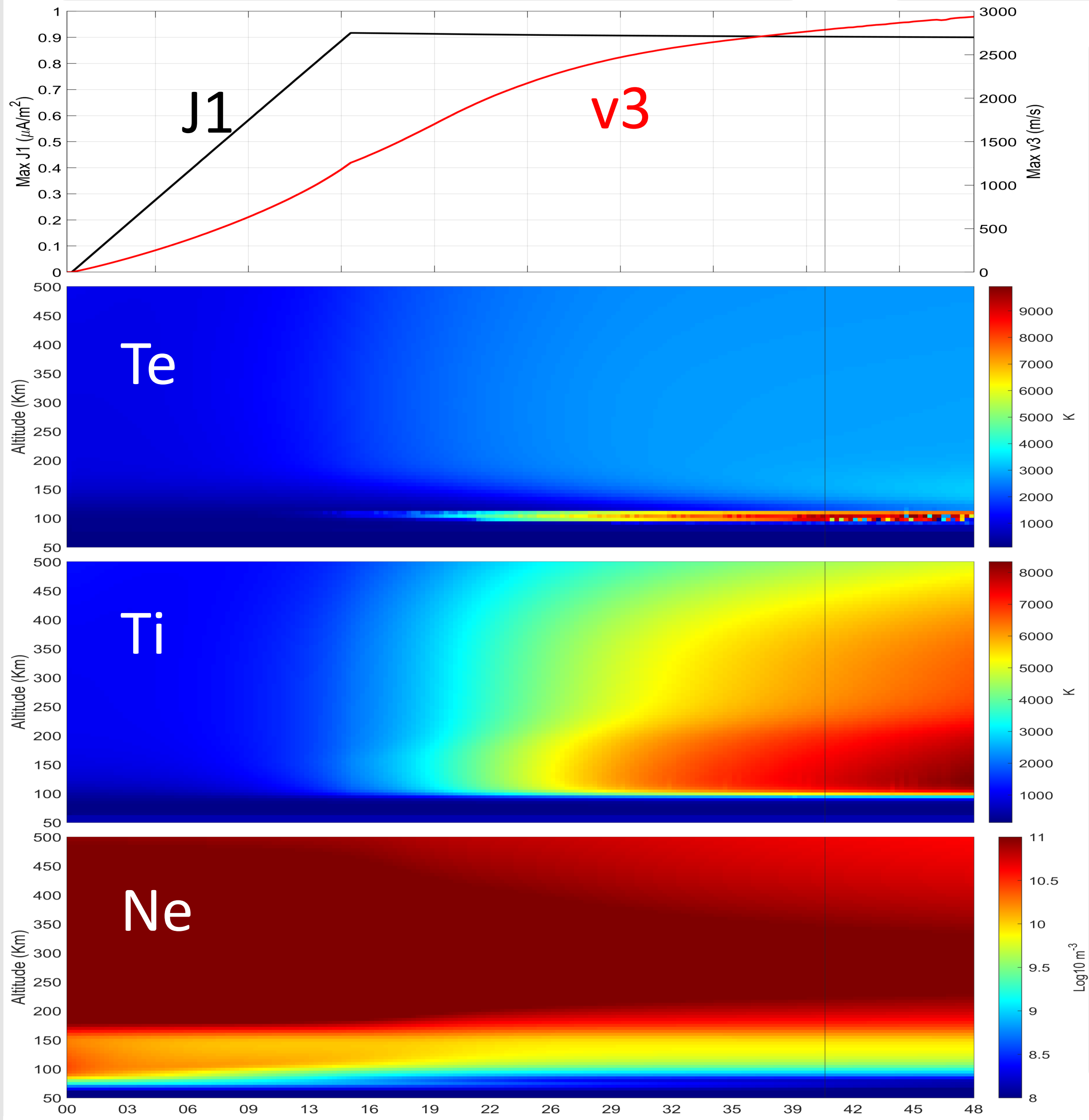
$$\sigma_P^{tot} = \sigma_P^{||} + \sigma_P^{NL} \quad \sigma_H^{tot} = \sigma_H^{||} + \sigma_H^{NL}$$

$$\frac{\sigma_P^{NL}}{\sigma_P^{||}} = \left(\frac{1+\kappa_1^2}{1-\kappa_1^2}\right) \left(\frac{E_0}{E_{Thr}^{min}} - 1\right) \left(1 - \frac{E_{Thr}^{min}}{E_0}\right)$$

$$\frac{\sigma_H^{NL}}{\sigma_H^{||}} = -\left(1+\psi_\perp\right) \left(\frac{2\kappa_1}{1-\kappa_1^2}\right) \left(\frac{E_0}{E_{Thr}^{min}} - 1\right) \left(1 - \frac{E_{Thr}^{min}}{E_0}\right)$$

It once again depends strongly on the minimum electric field for the Farley-Buneman instability to trigger.

The hall term borrows resemblance and can be seen in equation 23b of **Dimant & Oppenheim (2011).** The hall term actually decreases but is not enough to make it zero.



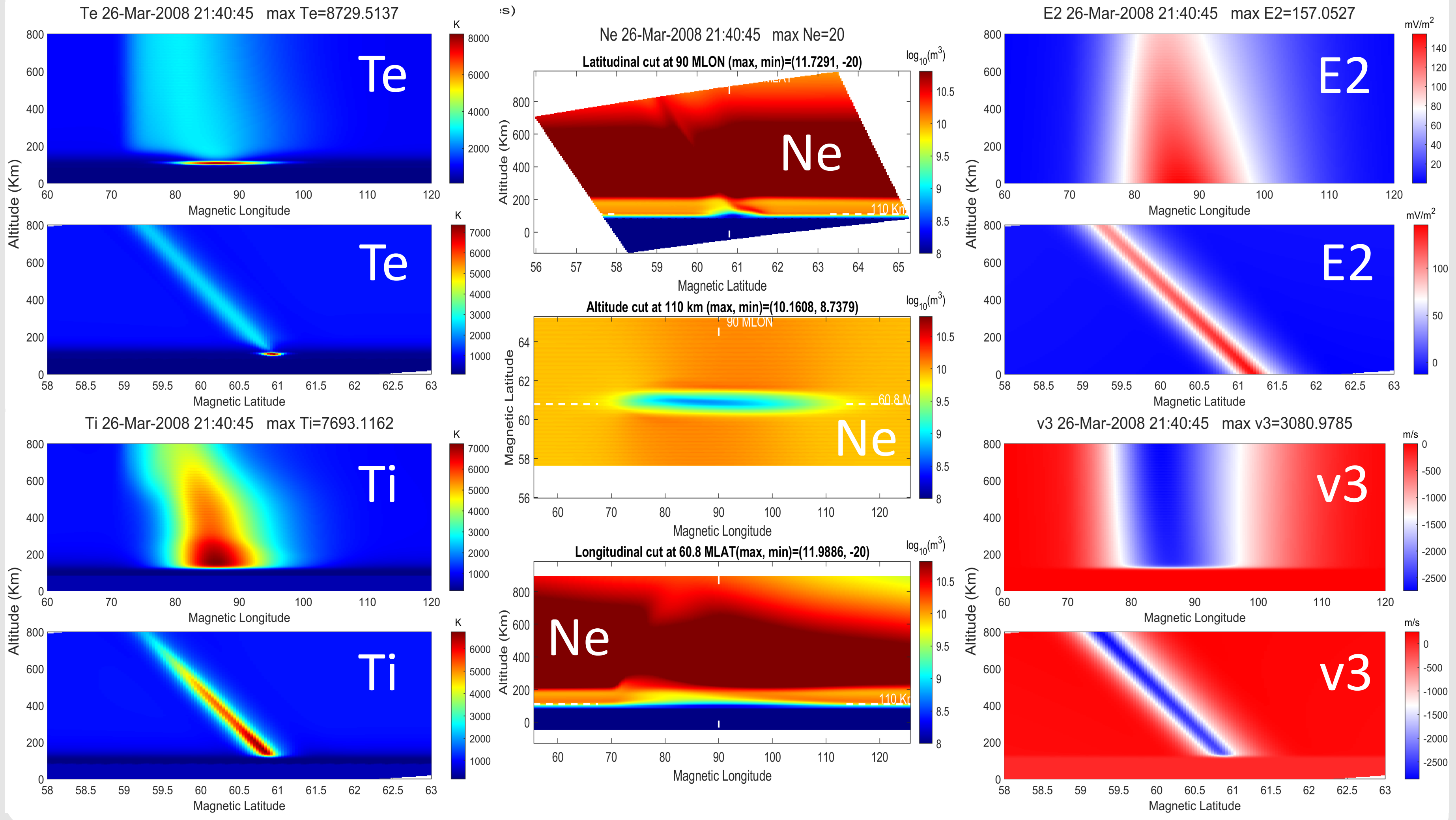
Ne: The density depletion caused by the current density is visible. The increase in conductivity due to NLC causes the density to not deplete as much if turbulent effects where not considered, still reaching about 100-300 particles/cm^3

Te: Large increase at the E region reaching up to 9000K, as expected due to the addition of turbulent effects. Along the current path the temperature reaches about 3000K to 4000K. Higher temperatures cause the FBI model to oscillate.

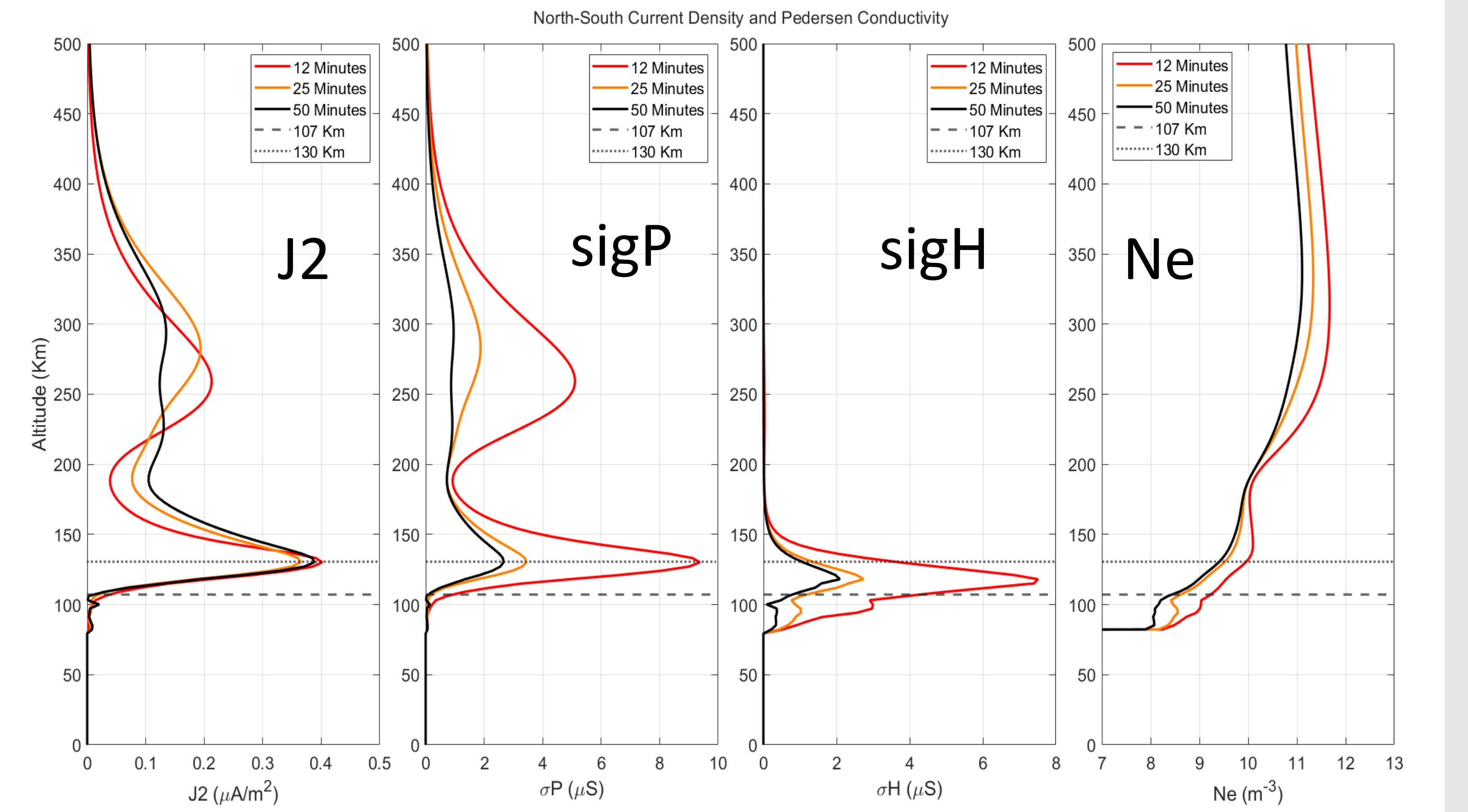
Ti: Negligible increase in the E region, with very high temperatures in the current path reaching up to 8000K. Always trailing Te, which agrees with the measurements

v3: East-west flows reach a max speed of 3 Km/s. Not enough velocity for a SAID/STEVE event as we should get 5 Km/s. The inclusion of NLC does not affect as much due to the closure current being at higher altitudes than the FBI effects

TeRatio: Large increase (25 times larger) at the E region compared to a simulation that does not include turbulent effects.



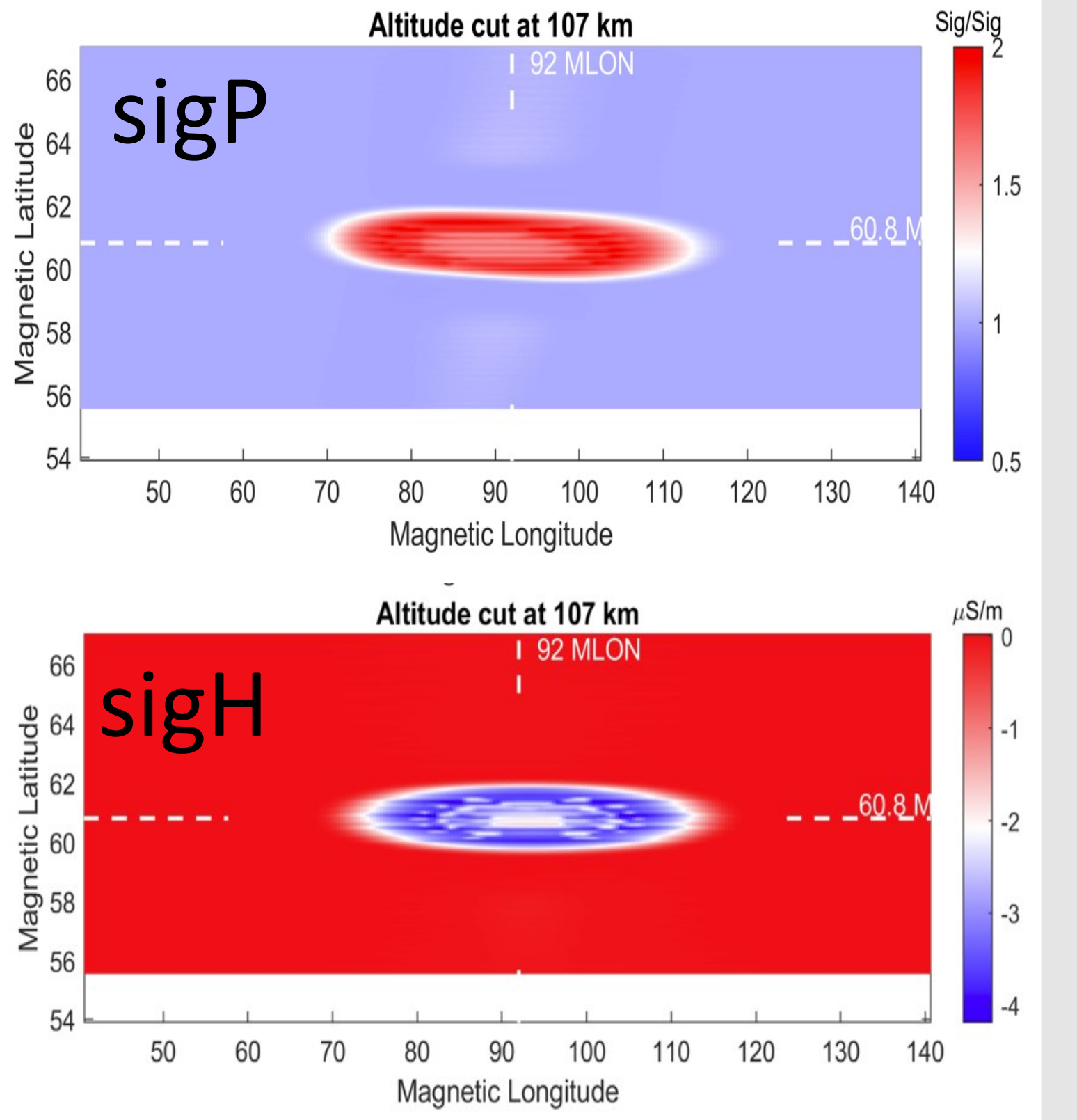
CONDUCTIVITY RESULTS AND CHALLENGES



Pedersen: The figure on the right shows the ratio of the Pedersen conductivity in a simulation that includes turbulent effects over one that does not. It shows **an increase** and even on the same level (100% more or less) that is predicted by **Dimant & Oppenheim (2011).**

Effects on the Electric Field: We originally expected this to **reduce the value of the electric field**, and in turn the flow channel velocity since an increase in conductivity under the same current would result on that. **This did not happen** since the altitude at which we are affecting the Pedersen conductivity (107) is below the Pedersen closure current region (130 km). The figure on the bottom shows how most of the current closes at a higher altitude.

Pedersen comparison: The time evolution of the Pedersen conductivity at 130 km does follow what was expected, with a large decrease from a maximum value of 35 μS on a non disturbed state to as low as 3 μS by the end of the run.



There are **many challenges** with trying to simulate an extreme SAID. Constrain values for STEVE are not well define, with "larger than…" being typically used. The model itself has its own structures that limits an arbitrary input, becoming extremely sensitive to **initial conditions, currents, and heat flux in and out of the grid box**. Other elements must also be defined, such as: **shape of the current density** (maximum gradient, positions, separation of peaks, etc.), **precipitation effects** (both shape and magnitude), **heat flux effects**, and others.

The inclusion of **turbulent effects** brings the model to extreme points where **stability becomes a problem**. The model for FBI heating and conductivity changes was not built with these extreme settings in mind, and thus oscillates when a high enough state is reach. Current model issues also limit the value of the E region density, not allowing us to generate a stable simulation with extremely low density in the closure current region. Currently the simulation runs with a 0 derivative for heat flux in and out of the grid box, **so heat flux is not being pushed in or out of the simulation**, other works (Liang et al. 2021) **have included specific heat flows inside the current density** structure to generate the desire high electron temperature.

Conclusion and future work

It is possible to simulate an SAID channel utilizing GEMINI3D. The inclusion of **turbulent effects due to Farley-Buneman** instability helps us breach the gap between simulations and measurements of extreme SAID/STEVE by accurately considering their effects in the E region. **There are discrepancies between simulation and measurements**, such as a channel velocity that does not exceed 3 km/s and a temperature at 800km that is not as high as measured by DMSP. The temperature issue could be fixed by increasing the current, though this also generated a problem with the model and its stability. **There are several things that must be improved** in future work, such as:

- There is a need for an **increase in the certainty or uncertainty** of the input information for the simulation.
- **The role of precipitation or heat flux** from the top of the simulation has not been studied. Other models include heat flux inside the current density to achieve the high temperatures measured at 800km. Background precipitation sets the value of E region density, which is in turn sets how low the conductivity gets.
- What dynamical information can be derived from sequences of images, and can these be used to test hypotheses about sources of STEVE structure?