Storm-time ionospheric electric fields and their effects during the Sept. 7-10, 2017 geomagnetic storm

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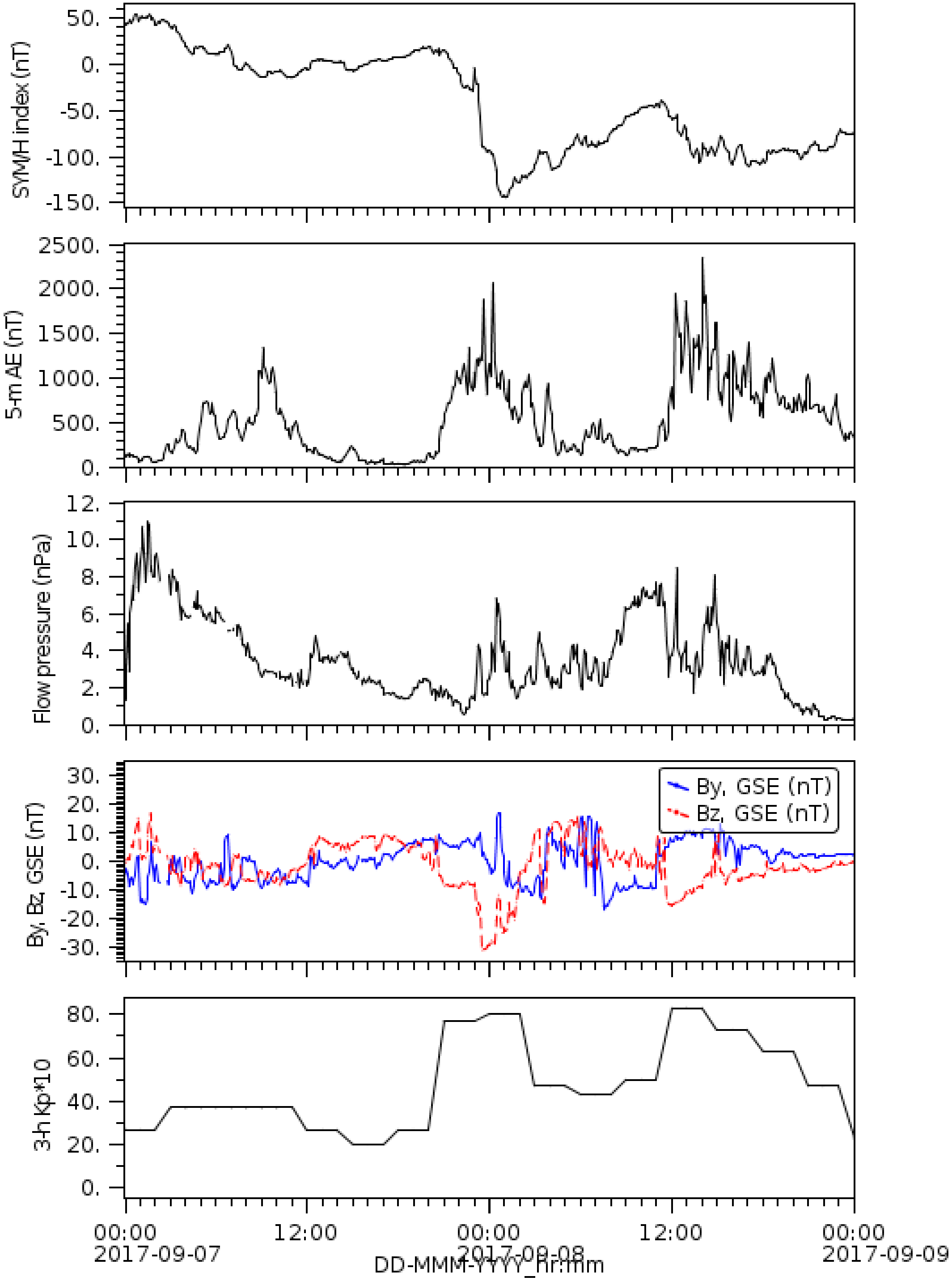
Motivation

- Examine self-consistent ionospheric electrodynamics with a focus on prompt penetration E-fields
- Run numerical simulations trying to predict global distribution of prompt penetration E-fields in the context of magnetosphere-ionosphere coupling
- Compare simulations with data (Jicamarca ISR, etc) to identify areas of agreement and disagreement
- Use simulations to examine electrodynamics when irregularities are observed
- Ultimately to improve modeling and predictive capability of plasma instabilities, and large-scale ionospheric response to storms.

September 2017 Geomagnetic Storm

- The storm began at 23 UT on 9/6/2017.
- The main phase of the storm began at ~22 UT on 9/7/2017 when a large CME arrived as shown below.
- Low-latitude ionosphere was observed to have severe ionospheric disturbances, including spread-F, biteouts, etc.



Datasets

- **World-wide GNSS Receiver Network**: These receivers can be used to measure the line-integrated electron between the satellite and the receiver (**TEC**). The GNSS network >2,000 receivers. We use the Madrigal database of TEC values binned into 5-minute bins on a 1° by 1° grid.
- **Floating Potential Meter Unit aboard the International Space Station**: The FPMU measures ion density and electron temperature at 400km altitude, with 1-second resolution when the instrument is activated. ISS is in an unusual mid-inclination orbit shown above (~ 51° 92-minute orbital period). Over the course of a day, ISS covers all longitudes, but only crosses the equator in two narrow bands in local-time which shift each day.
- **Jicamarca Incoherent Scatter Radar**: The main radar at Jicamarca Radio Observatory is a VHF radar operating on 50 MHz. When running in ISR mode, Jicamarca measures electron density, electron and ion temperature, and drift velocities.

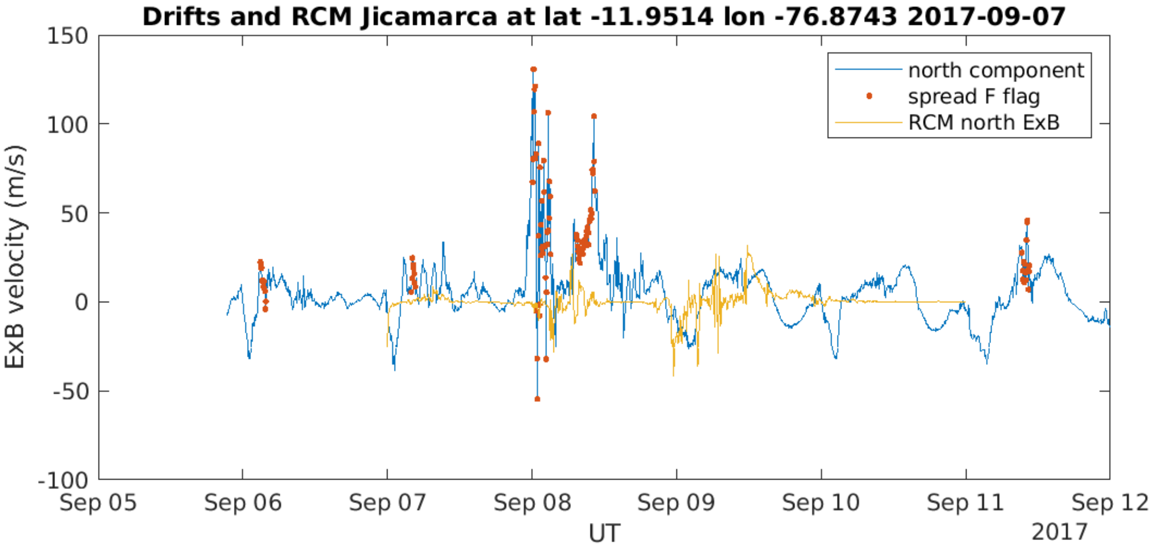
Coupled Magnetosphere-Ionosphere model

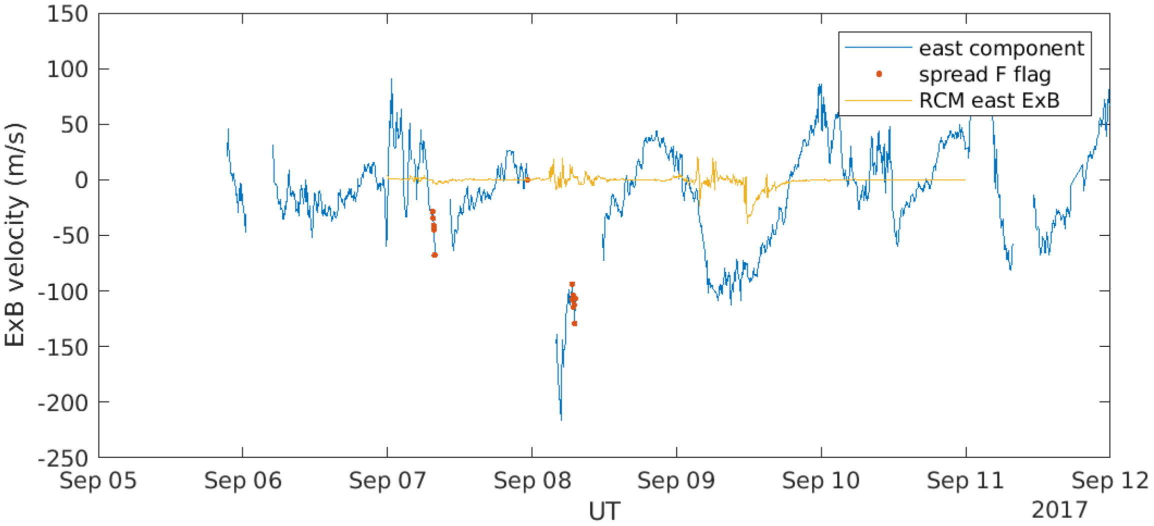
- Inner Magnetosphere: Rice Convection Model (RCM), evolves Vlasov equations of inner magnetospheric plasma and provides field-aligned currents and auroral precipitation
- Ionosphere: NRL ionospheric code SAMI3 or empirical IRI
- The coupling of RCM and SAMI3 is through the solution of the potential equation:

$$\nabla\cdot\left(-(\hat{\Sigma}_{EUV}+\hat{\Sigma}_{AURORA})\cdot\nabla\Phi\right)=J_{||}\sin I$$

  - SAMI3 or IRI provides conductance tensor to RCM
  - RCM solves the potential equation for ionospheric potential
  - RCM provides potential (or E) to SAMI3
  - SAMI3 and RCM use E to transport the plasma with °t = 2 sec
- Neutral wind dynamo contribution is fixed at quiet-time levels
- RCM is driven (convection in the polar cap, magnetospheric magnetic field) by time series of solar wind and IMF (high-res./5-min OMNI). Some inputs are parameterized by geomagnetic indices.
- This study uses RCM with IRI.

Low latitude response to the Storm



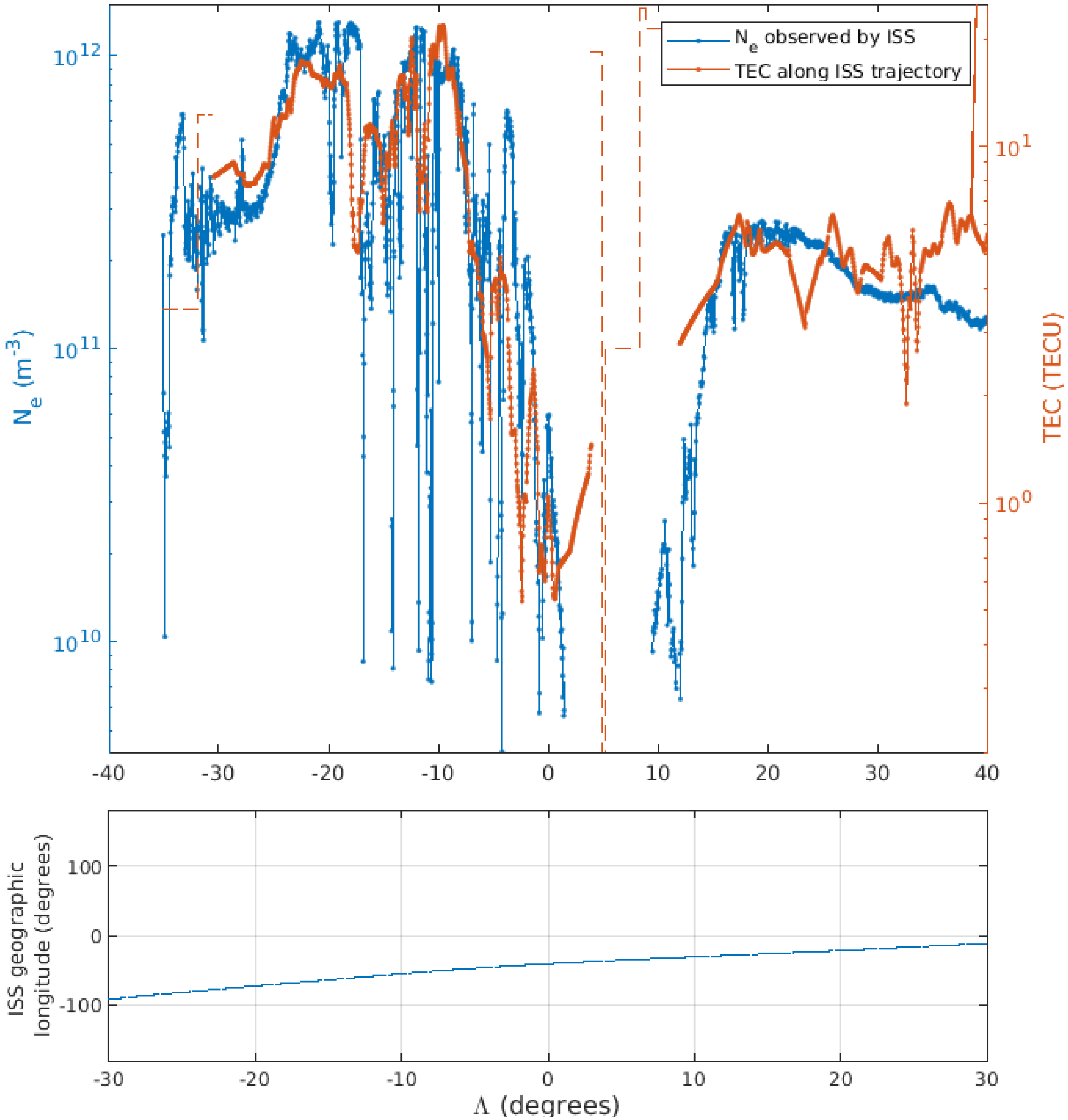


- Overall, the northward drift component from the RCM results reacts to the activity similarly to the drifts observed at Jicamarca.
- RCM does not show the dramatic increases in northward drift during the main phase of the storm

Depletions from Equatorial Plasma Bubbles

- Low density plasma bubbles form at the terminator
    - Large scale structure (tens of km)
- Thought to be due to the generalized Rayleigh-Taylor instability
- Highly dependent on the electric field environment

9/8/2017 2:27UT



Generalized Rayleigh-Taylor Instability

- Occurs in the equatorial region ionosphere because of the electric field configuration
  - Increased electric field causes the F layer to rise in response to ExB drift
  - This causes a steep density gradient to develop, setting up the generalized RT instability.
- Geomagnetic storms can strengthen the electric fields

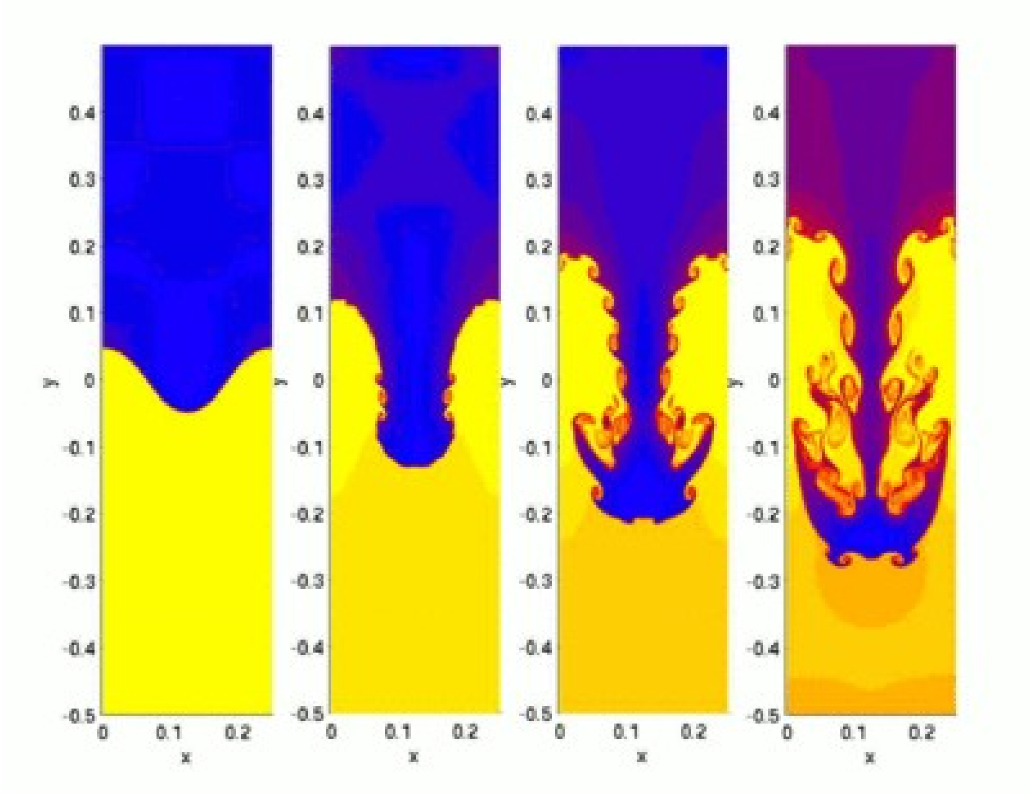


Image from Shengtai Li and Hui Li at LANL

Generalized Rayleigh-Taylor Instability

Stages of RT

1. Linear growth of the perturbation
2. Bubbles and mushroom-shaped spikes begin to form
3. Bubbles and spikes begin to merge, non-linear behavior dominates
4. Turbulent mixing

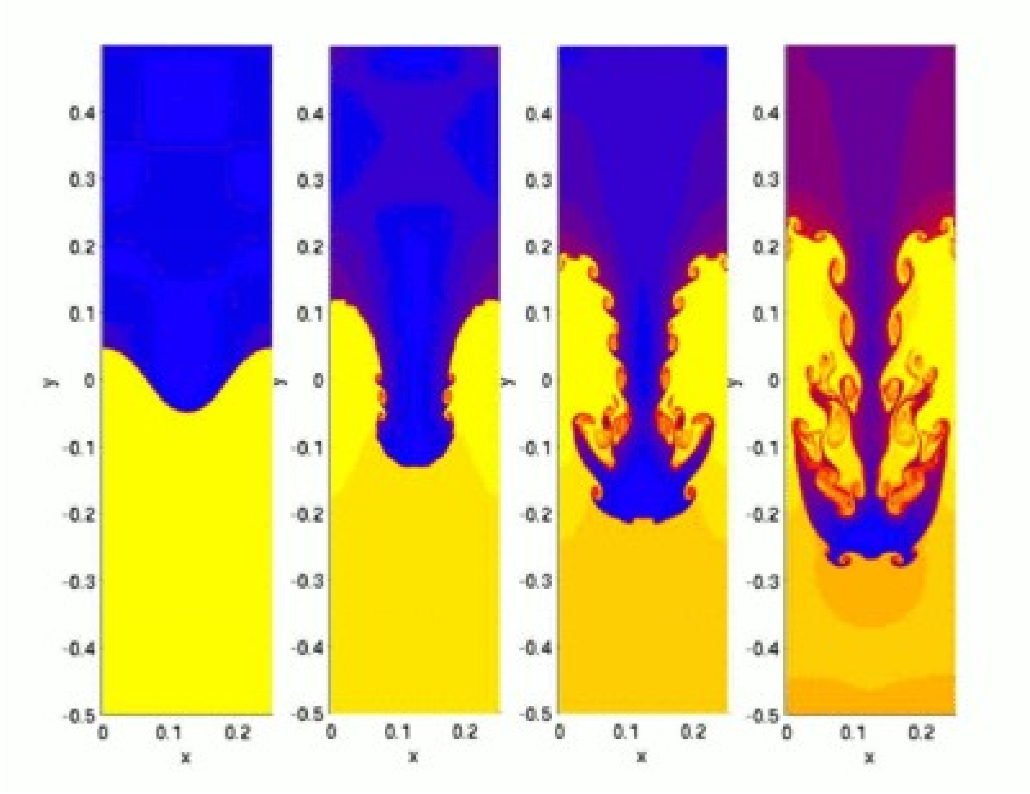


Image from Shengtai Li and Hui Li at LANL

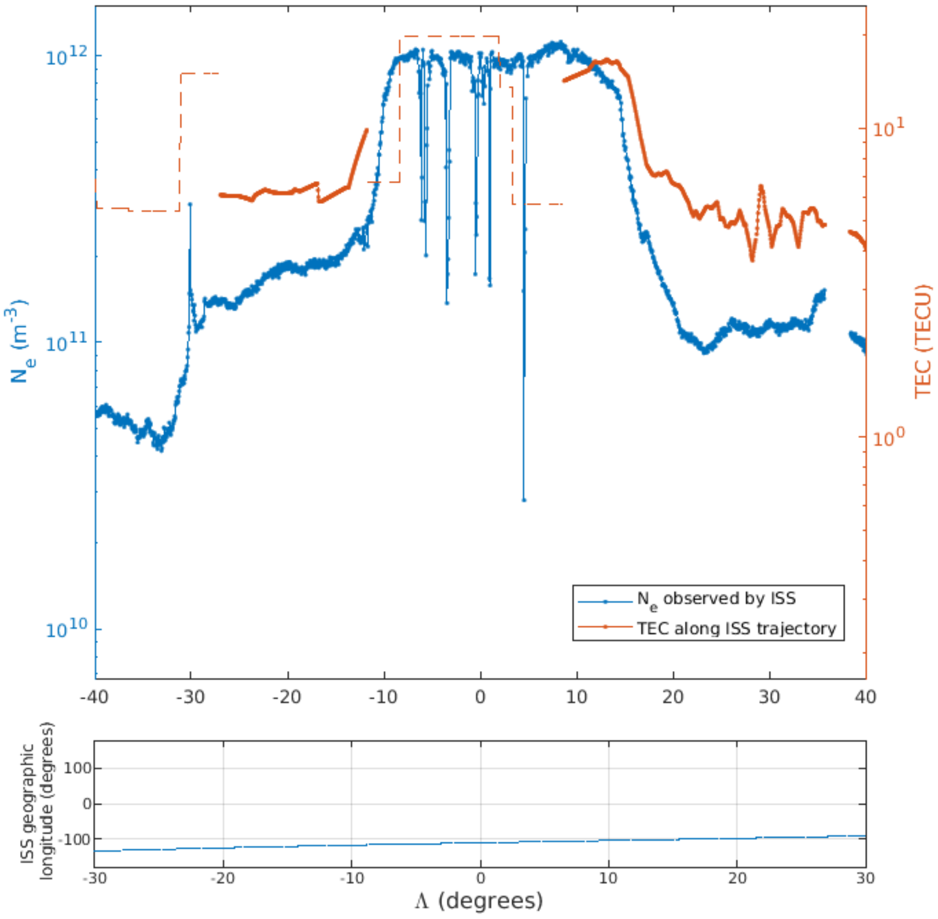
R-T Growth Rates in the Ionosphere

$$\gamma_{RT} = \frac{\tilde{\Sigma}^F_{P,0}}{\tilde{\Sigma}^E_{P,0} + \tilde{\Sigma}^F_{P,0}} \left(V_p - U^P_L - \frac{g_e}{\nu^F_{eff}} \right) K^F - R_T \qquad K = \frac{1}{R_E L^3 N_0} \frac{\partial}{\partial L} \left(L^3 N_0 \right) \qquad g_e = g_0 / L^2$$

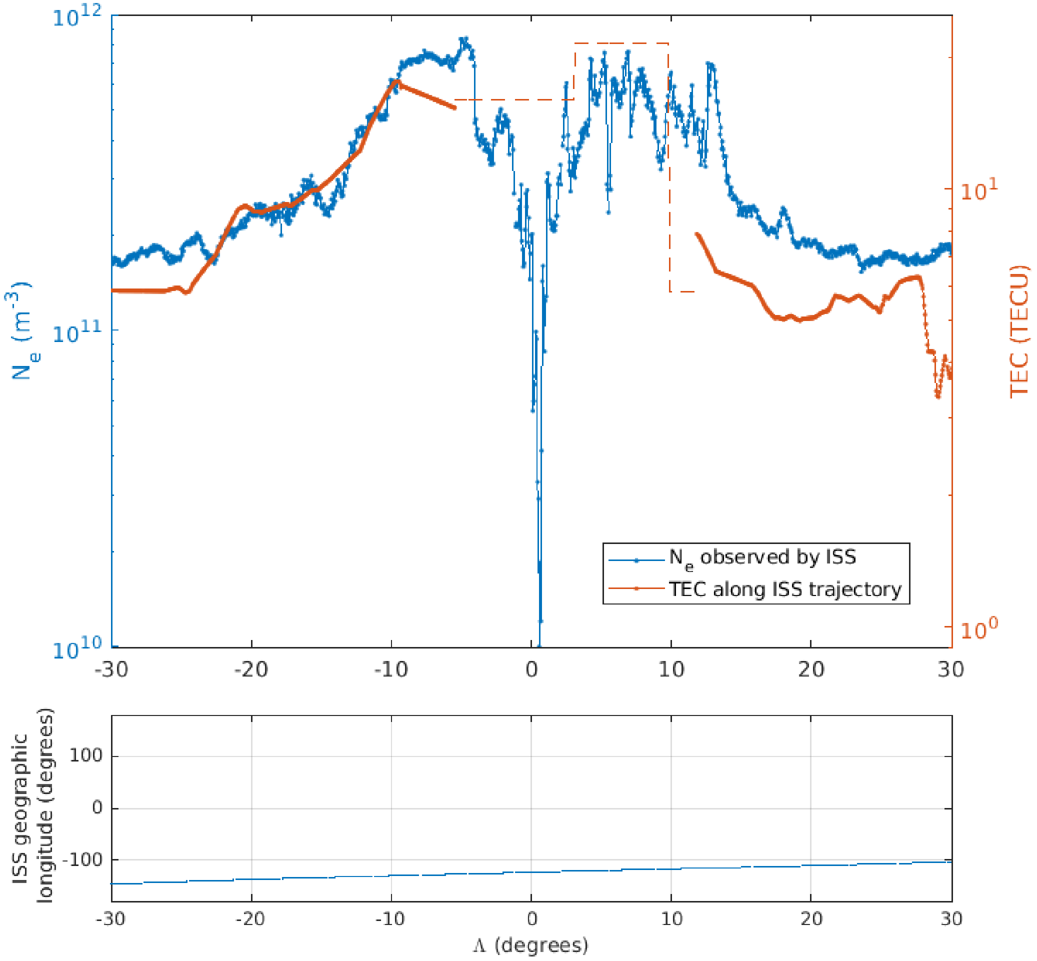
(Sultan, 1996)

- Linear growth rates can be found analytically
- Assumes the E layer is horizontally uniform in density
- $\tilde{\Sigma}^E_{P,0}$ is the pedersen conductance in the E region
- $\tilde{\Sigma}^F_{P,0}$ is the pedersen conductance in the F region
- V_P is the flux tube integrated plasma velocity perpendicular to B, dependent on the **zonal electric field**
- R_T is the flux tube integrated recombination rate
- N_0 is the initial density
- L is the L-shell
- ν_{eff} is the effective collision frequency in the F region
- U^L_P is the neutral wind
- R_E is the earth's radius

Examples of Depletions during the September 2017 Storm



9/9/2017 06:23 UT

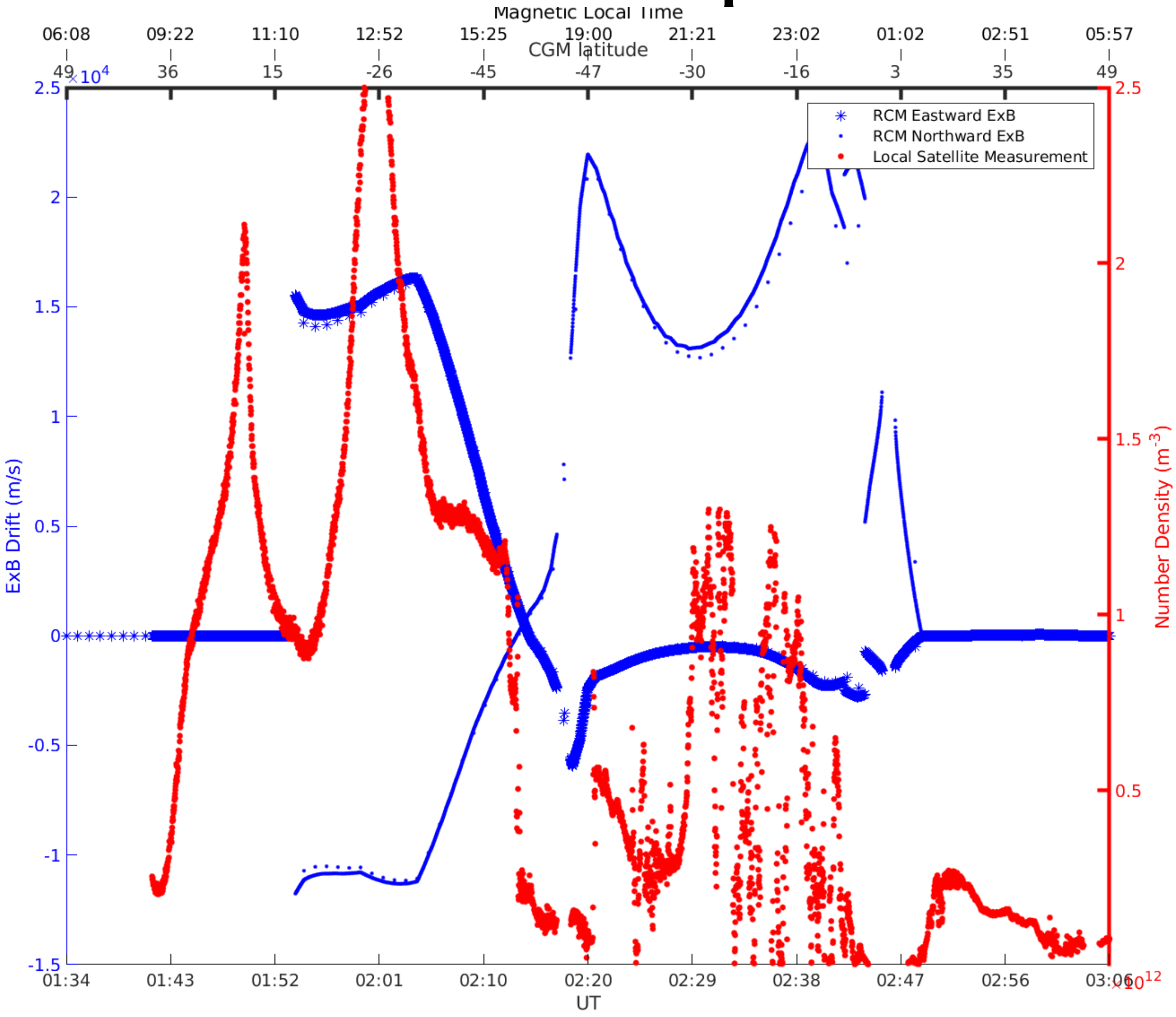


9/7/2017 08:08 UT

Depletions during the September 2017 Storm

- In total, ISS FPMU observed **13 spread-F type irregularities** during the storm.
- Using computational modeling, we can examine the effects of PPEFs by looking at the simulated electric field along the satellite's trajectory.

Electric Field Environment around a Depletion



- During the main phase of the storm, the FPMU aboard ISS observed a major depletion.
- At the same time, RCM shows a huge increase in the northward component of the ExB drift (approximately vertical at low latitude).

Summary

- Simulated with RCM penetration electric fields at the equator in general agree with ISR data, except for large sharp increases that are not reproduced (not clear why).
- Electric field simulations can provide context for depletions measured by satellite.