Forecasting Equatorial F Region Instabilities using WAM-IPE

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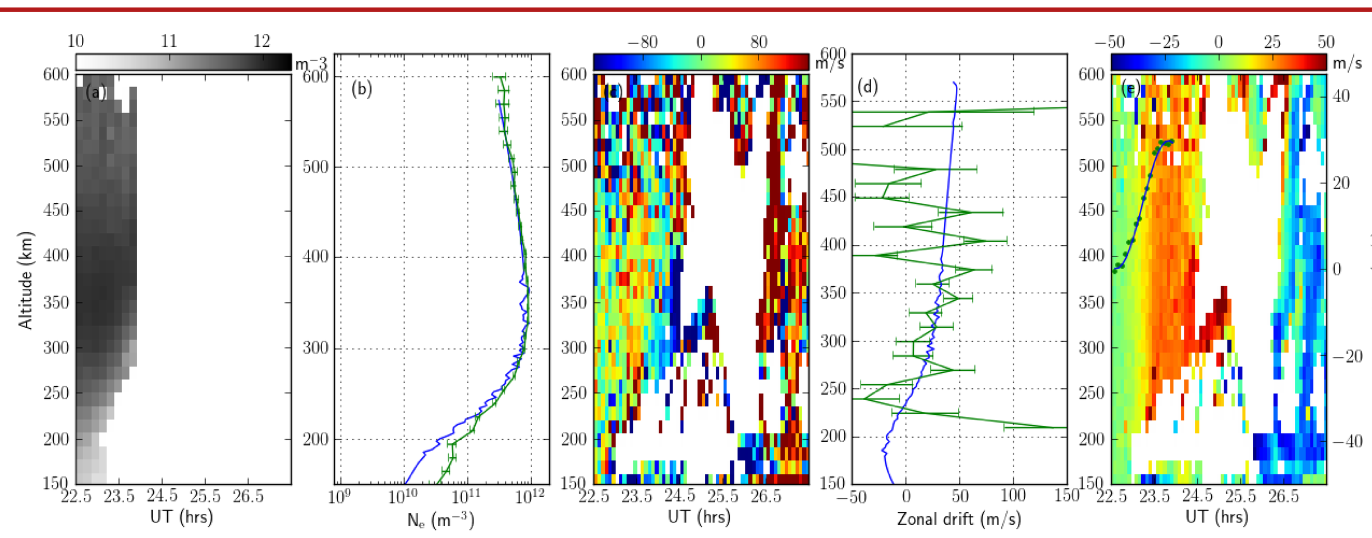
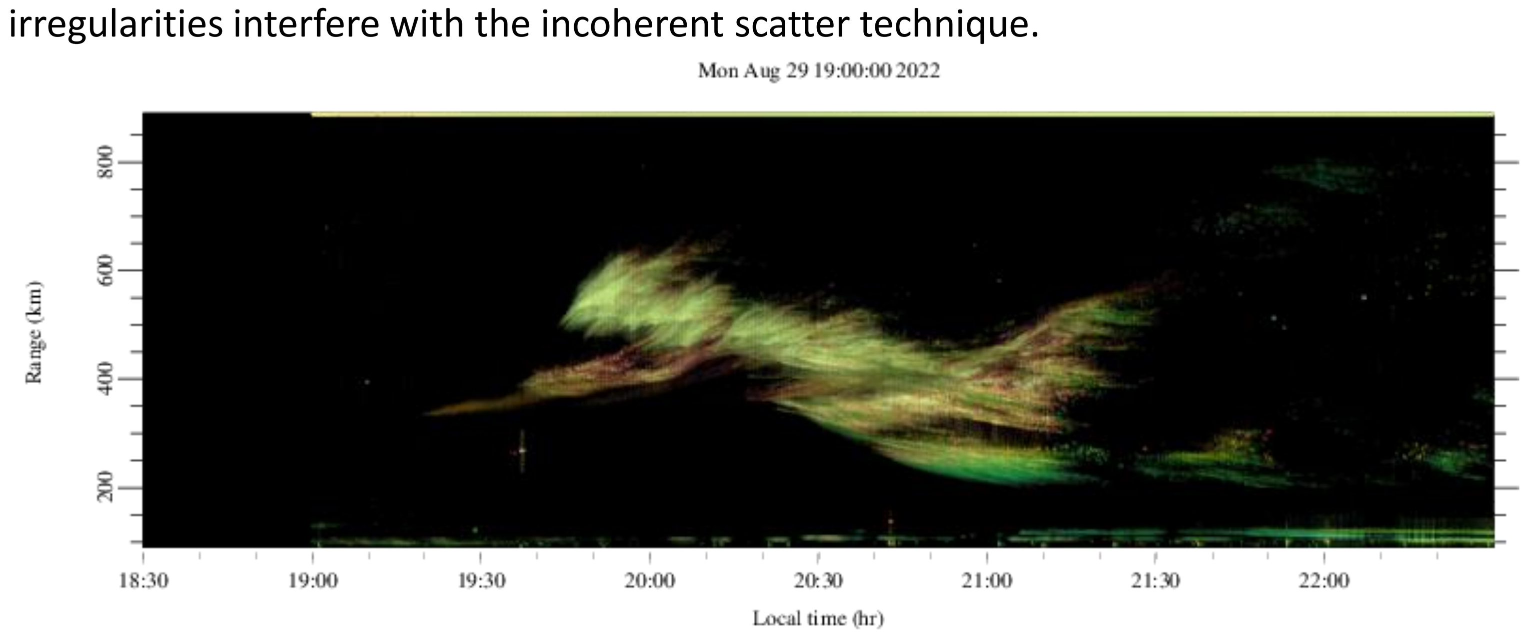
Abstract

A regional simulation is used to forecast ionospheric irregularities in the equatorial F-region. The simulation is first initialized and forced using measurements from Jicamarca Radio Observatory during multiple campaign events during August and September of 2021 and 2022. Next, initialization and forcing is performed using parameters from the Whole Atmosphere Model – Ionosphere, Plasmasphere, Electrodynamics (WAM-IPE) model. A key source of error was found when background electric fields provided by WAM-IPE were introduced to the simulation. Observed and simulated prereversal enhancement (PRE) of vertical plasma drifts differ. These disagreements prompt a necessary discussion and investigation into the F-region dynamo theory used by WAM-IPE and the production of PRE.

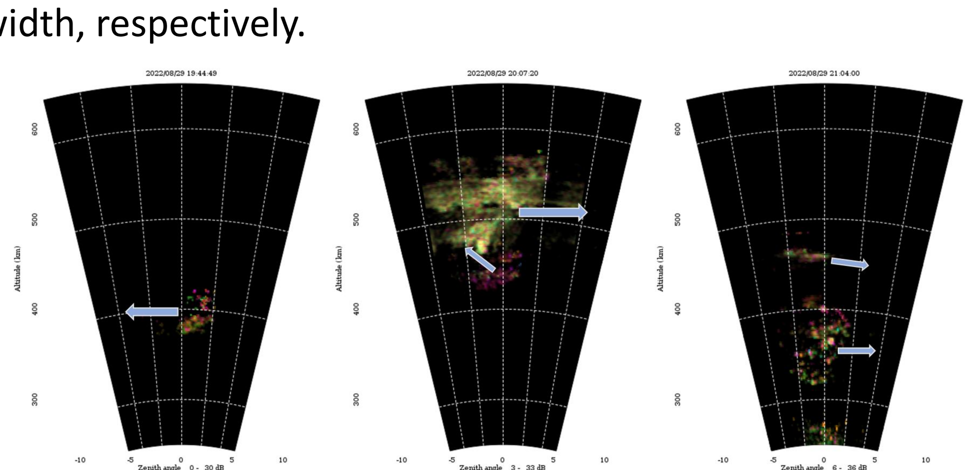
Radar Data



Jicamarca Radio Observatory (JRO) utilizes coherent scatter radar (CSR) and incoherent scatter radar (ISR) to monitor ionospheric conditions. An example of ISR data is shown above for the night of Aug. 29-30, 2022. From left to right the data shown is (a) electron number density, (b) electron number density profile at 2300 UTC, (c) zonal plasma drift velocities, (d) zonal plasma drift velocity profile at 2300 UTC, and (e) vertical plasma drift velocities. Green curves are ISR data while blue curves are empirical model results (SAMI2/HWM14). Plotted against the right axis on the far-right panel is vertically-averaged vertical plasma drifts fit to a sinusoidal function. Blank patches in ISR data are where irregularities interfere with the incoherent scatter technique.



CSR data provides better visualization of irregularities in the F region. The range-time-intensity (RTI) plot shown above for the night of Aug. 29-30, 2022 (same night as ISR above) exhibits a strong spread-F event with irregularities penetrating over 600 km. Brightness, hue, and saturation of pixels represent signal-to-noise ratio, Doppler shift, and spectral width, respectively.



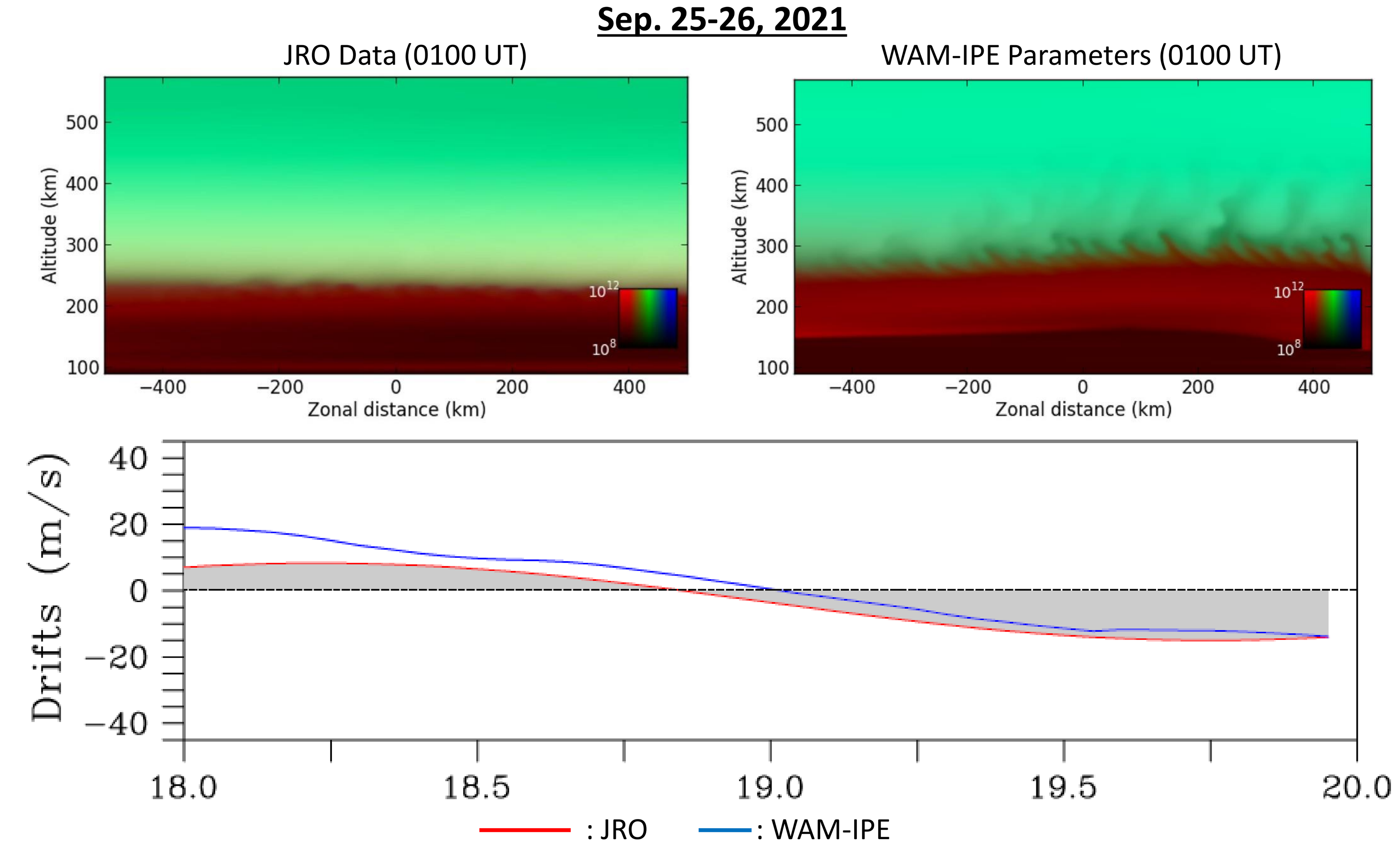
Frames of azimuthal windows of CSR provide a visualization of the dynamics of irregularities throughout the night. Scan the QR code above to view a video of these windows for the night of Aug. 29-30, 2022 (same night as ISR and CSR above).

Regional Simulation

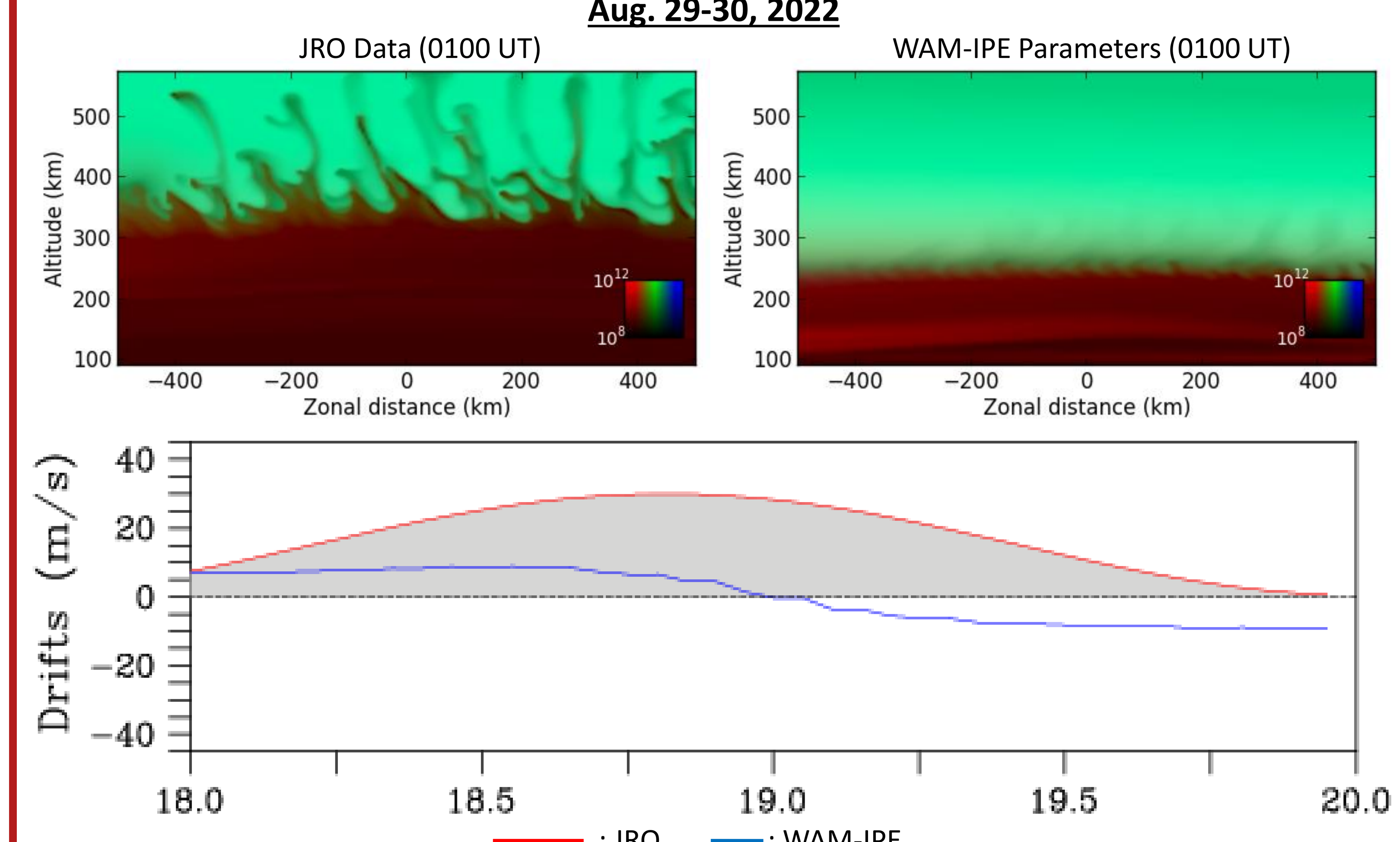
The regional simulation is described in detail by Hysell et al. (2014) and has two primary components. The first of these is a linear potential solver to enforce the quasineutrality condition: $\nabla \cdot \boldsymbol{J} = 0$. A preconditioned biconjugate gradient method is used to solve the elliptic PDE for potential.

$$\nabla \cdot (\boldsymbol{\sigma} \cdot \nabla \phi) = \nabla \cdot \left[\boldsymbol{\sigma} \cdot (\boldsymbol{E}_0 + \boldsymbol{u} \times \boldsymbol{B}) + \sum_s q_s \boldsymbol{D}_s \cdot \nabla n_s + \Xi \cdot \boldsymbol{g} \right]$$

The second component is a finite-volume code that advances the number density of four ion species (NO^+, O_2^+, O^+, H^+) and electrons forward in time. Simulation results are verified with CSR data.

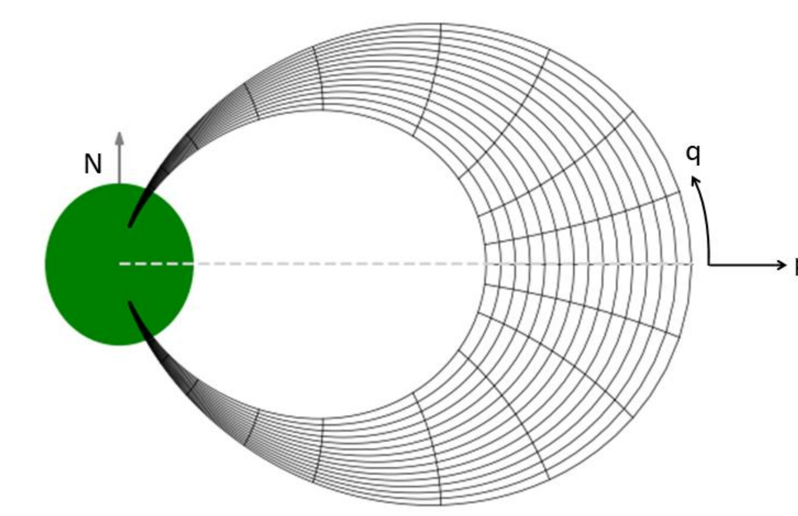


Shown above is a simulation result in which the introduction of WAM-IPE background zonal electric fields generated artificial irregularities. The top two plots show number density of atomic oxygen (green), molecular ions (red), and hydrogen ions (blue). The left plot shows results when driven with JRO data alongside empirical and physics-based models. The right plot shows results when the simulation is driven with WAM-IPE parameters. The bottom plot shows vertical plasma drifts plotted against local time produced by JRO (WAM-IPE) in red (blue).



Another set of results is shown above in which WAM-IPE failed to produce irregularities that were present (see CSR imagery). Notice in the first results the artificial PRE generated by WAM-IPE and the lack of a PRE produced by WAM-IPE in the second set of results. Accurately reproducing the PRE is crucial to forecasting spread F events.

Field-Line Integrated Dynamo

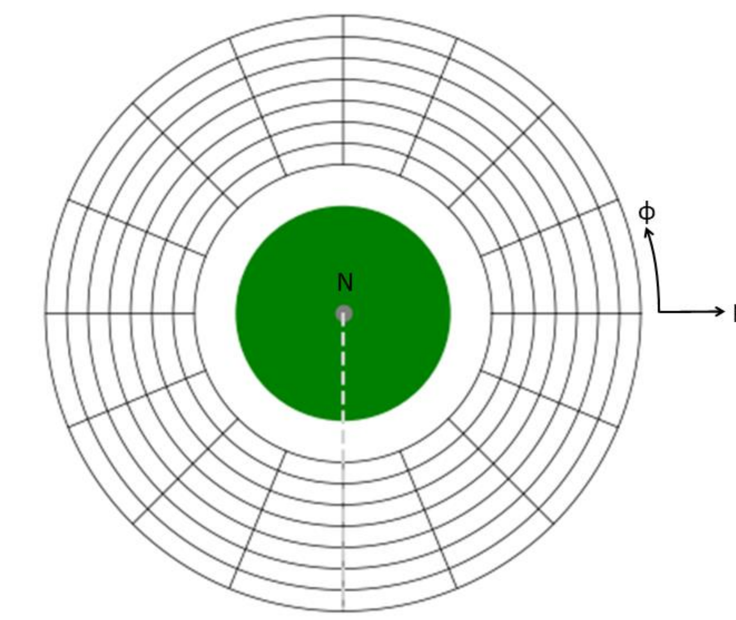


Reproducing background electric fields from WAM-IPE allows for investigation into the reproduction of the PRE. Using a field-line integrated method, the problem collapses to a 2-dimensional one.

Using a dipole coordinate system, shown to the left, the current density is given by:

$$\boldsymbol{J} = \sigma_P(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}) + \sigma_H \boldsymbol{b} \times (\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B})$$

$$\begin{cases} J_p = \sigma_P(E_p + u_\phi B) - \sigma_H(E_\phi - u_p B) \\ J_\phi = \sigma_P(E_\phi - u_p B) + \sigma_H(E_p + u_\phi B) \end{cases}$$



Integrating current densities along magnetic field line produces integrated current densities:

$$\boldsymbol{K} = \int_{q_S}^{q_N} \boldsymbol{J}\, dq = K_p \hat{\boldsymbol{p}} + K_\phi \hat{\boldsymbol{\phi}}$$

A divergence-free current is then assumed in the 2-dimensional problem.

$$\nabla \cdot \boldsymbol{K} = \frac{1}{p}\left[\frac{\partial [pK_p]}{\partial p} + \frac{\partial K_\phi}{\partial \phi}\right] = 0$$

Substituting integrated current density values and using an electrostatic potential ($\boldsymbol{E} = -\nabla\Phi$) generates a second order PDE in Φ. Zonal electric fields generated by WAM-IPE data contribute to the vertical plasma drifts.

$$v_p = \frac{E_\phi}{B} = -\frac{1}{B h_\phi}\frac{\partial \Phi}{\partial \phi}$$

Using compositions, winds, and temperatures from WAM-IPE, the vertical plasma drifts can be reproduced and compared to those measured with ISR. Tuning WAM-IPE data to produce matching vertical plasma drifts will hopefully provide insight into how WAM-IPE is generating equatorial electrodynamics and specifically the PRE.

Conclusions/Future Work

- The background zonal electric fields determined by WAM-IPE unreliably produce ionospheric conditions to predict ESF events. Specifically, night-to-night variability and reproduction of the PRE is necessary for ESF forecasts.
- Reproduction of background zonal electric fields from WAM-IPE data will provide insight into what dynamics are being missed or improperly reproduced.
- Dipole magnetic field is currently being used to reproduce electric fields, but an IGRF field may be implemented in the future.
- A new regional simulation will be produced in the future to provide "real-time" forecasts of F region irregularities.

References

Hysell, D. L., R. Jafari, M. A. Milla, and J. W. Meriwether (2014), Data-driven numerical simulations of equatorial spread *F* in the Peruvian sector, *J. Geophys. Res. Space Physics*, *119*, 3815–3827, https://doi:10.1002/2014JA019889

Hysell, D. L., Fang, T. W., & Fuller-Rowell, T. J. (2022). Modeling equatorial *F*-region ionospheric instability using a regional ionospheric irregularity model and WAM-IPE. *Journal of Geophysical Research: Space Physics*, *127*, e2022JA030513. https://doi.org/10.1029/2022JA030513

Richmond, A. D. (1995). Ionospheric Electrodynamics Using Magnetic Apex Coordinates. *Journal of Geomagnetism and Geoelectricity*, *47*(2), 191–212. https://doi.org/10.5636/jgg.47.191

Richmond, A. D., Fang, T.-W., & Maute, A. (2015). Electrodynamics of the equatorial evening ionosphere: 1. Importance of winds in different regions. *Journal of Geophysical Research: Space Physics*, *120*(3), 2118–2132. https://doi.org/10.1002/2014JA020934