Simulating Polar Cap Ionosphere F-Region Peaks: Investigating Physical Drivers of Lifting

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Background

- Large electron density structures enter the Polar Ionosphere through large scale transport from mid-latitude sunlit plasma.
- The transported high density structures can be gain and lose density in transit to the polar cap through chemical processes, which are heavily modulated by the altitude of the plasma.[1]
- While this transport of mid-latitude plasma to polar regions is convectively dominated, large density struggles to survive intense geomagnetic activity due to enhanced thermospheric heating and increased chemical loss[2].
- We find the highest densities in the polar cap during moderate geomagnetic storms, creating a "goldilocks" region where plasma can convect easily without being destroyed by chemical processes

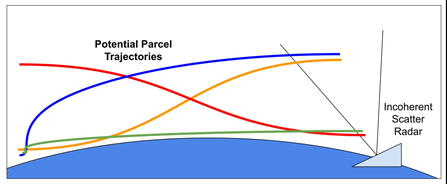

Figure 1. Variable flux tube histories in the Polar Cap.

Motivation

- These vertical plasma drifts likely have a significant effect on density, but are **very difficult to measure observationally**.
- Given the exponential increase in neutral density at lower altitudes, displacing plasma vertically will **greatly alter chemical loss** of density
- In a Lagrangian frame of reference moving with the parcel, changes in density within the parcel are governed by **only 3 terms**: production (all sources) chemical loss, and **"leaking"** ($n\nabla\cdot\vec{u}$).
- This "leaking" is due to the **compressibility of the plasma**, minor in the **ExB** direction, but significant **along magnetic field lines**

$$\frac{\partial n_{O^+}}{\partial t} + \nabla\cdot(n_{O^+}\vec{u}) = P_{O^+} - L_{O^+}$$

$$\frac{Dn_{O^+}}{Dt} = P_{O^+} - L_{O^+} - n\nabla\cdot\vec{u}$$

Goal: Quantify the terms that influence F-region plasma density in a TOI

Results

2 Hour Trajectories Starting From 19:15 UT

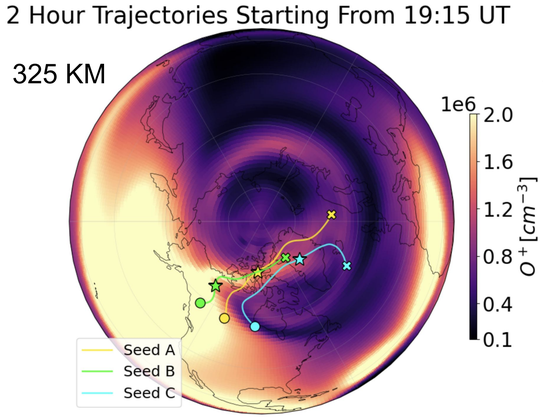

Figure 6. TIEGCM O+ Density slice at 325 km with all highlighted seed locations, the end of their back-trace, and the end of their forward-trace.

- **3 Parcels** were traced from varying stages of the TOI
- Their trajectories were traced forward and backward 2 hours one at:
  - Yellow: RISR-N
  - Cyan: Greenland
  - Green: Mid-latitude (NW Territory)

Legend
★ - Seed Point
X - End of Back-trace
o - End of Forward-trace

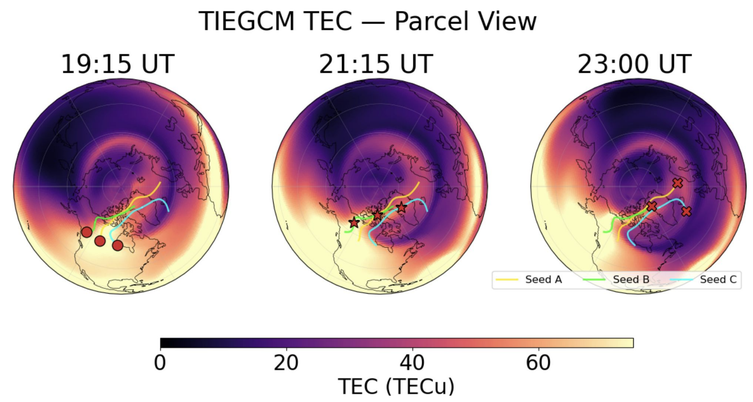

Figure 7. TIEGCM TEC with all highlighted parcel locations at each snapshot.

- Across all trajectories, we see a **net decrease in density** coinciding with a **decrease in altitude** from start to finish
- When decomposing the sources of density production, we see **leakage** on the same order as chemical loss and production, but is much more dynamic
- Leakage (n div u) contributions are **near zero in the midlatitudes**, but during the mesoscale transport of the TOI this term becomes **important**

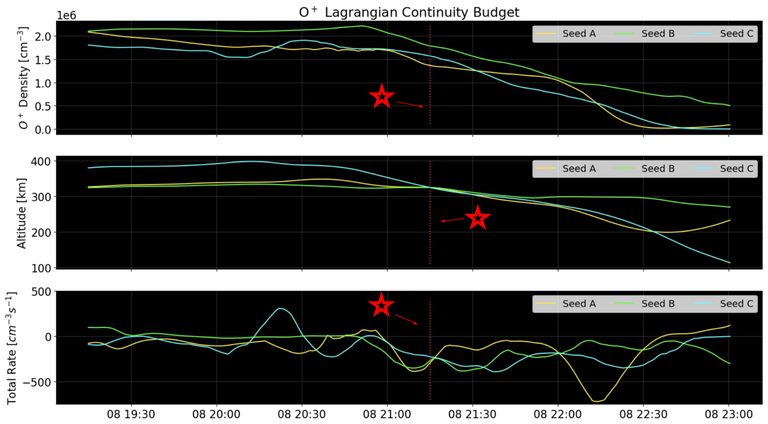

Figure 8. Parcel densities, altitudes, and net production throughout trajectory. Dotted red line denotes starting point for both forward and backward traces.

- Starts sunlit, then in the nightside polar cap div u dominates
- Chemical Loss dominates loss in sunlit polar cap
- In the nightside polar cap we see a spike in losses due to transport

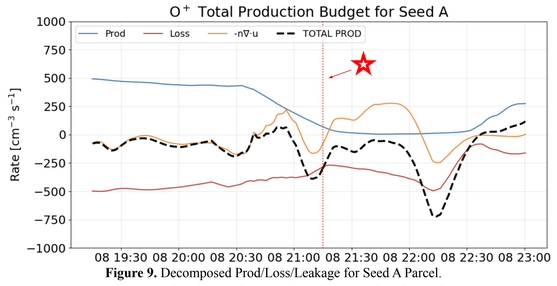

Figure 9. Decomposed Prod/Loss/Leakage for Seed A Parcel.

- Chemical Loss is dominant loss process
- Starts sunlit, then production is dominated by leakage/loss of density
- Leakage is much more dynamic than the chemical loss and production terms

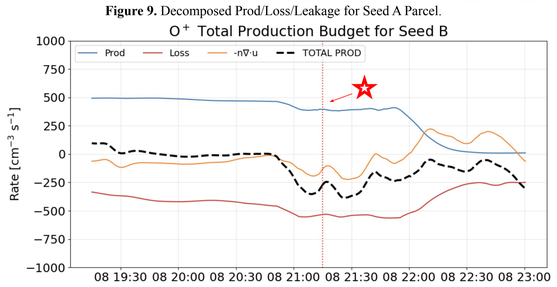

Figure 10. Decomposed Prod/Loss/Leakage for Seed B Parcel.

- Parcel exits the 2-cell convection
- Production spikes due to auroral precipitation in the auroral oval
- Chemical Loss is the dominant loss process as the parcel enters midlatitudes

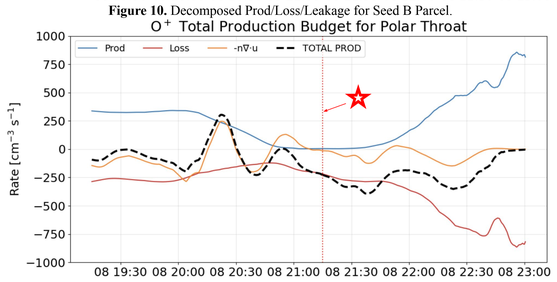

Figure 11. Decomposed Prod/Loss/Leakage for Seed C Parcel.

Methods

- We have developed a Lagrangian parcel tracer for the Thermosphere-Ionosphere- Electrodynamics Global Convection Model (TIEGCM)
  - Model Setup: TIEGCM with 1.25° horizontal resolution, 0.25 scale height vertical resolution, and Weimer convection pattern empirical model
- To follow parcels of high-density plasma through their Lagrangian trajectory, we numerically integrate through the velocity field of TIEGCM

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i(\mathbf{x}, t)$$

$$\mathbf{v}_i = \mathbf{v}_{E\times B} + v_{\parallel}\hat{\mathbf{b}} \qquad \mathbf{v}_{E\times B} = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

- The time-evolving velocity field is rebuilt from the ExB and parallel velocity calculated from TIEGCM, which combines ambipolar and neutral wind velocity contributions
- Use Continuity eq. to recreate density changes along the trace

$$\frac{\partial n_{O^+}}{\partial t} + \nabla\cdot(n_{O^+}\vec{u}) = P_{O^+} - L_{O^+}$$

$$\frac{Dn_{O^+}}{Dt} = P_{O^+} - L_{O^+} - n\nabla\cdot\vec{u}$$

$$-n\nabla\cdot\vec{u}_i = -\nabla\cdot(n_i\vec{u}_i) + \vec{u}_i\cdot\nabla n$$

- We calculate the $-n\nabla\cdot\vec{u}$ term by taking precomputed $\nabla\cdot(n_i\vec{u}_i)$ from TIEGCM, calculating ∇n manually, and combining both
- With this we can take measurements in the frame of the convecting plasma, quantify the sources and sinks of density in the polar cap, and locate source regions for polar cap density structures

Storm of Interest

November 7-9th 2024, moderate CME Storm (~ -120 nT SYM-H), solar max

- **Madrigal GPS TEC** observes >75 TECU in the Polar Cap
- **RISR-N** Observations are **>2e12 m^{-3}**
- The TOI wags in and out of the FOV of RISR-N
- Very clear example of one Tongue of Ionization (TOI) in the polar cap resolved by GPS TEC

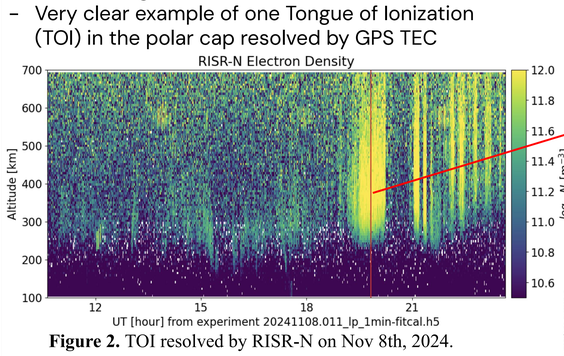

Figure 2. TOI resolved by RISR-N on Nov 8th, 2024.

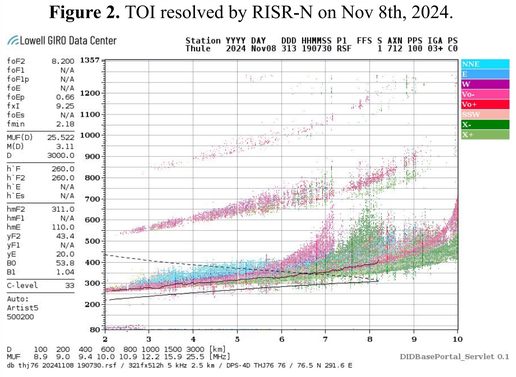

Figure 3. TOI resolved by Thule Ionosonde on Nov 8th, 2024.

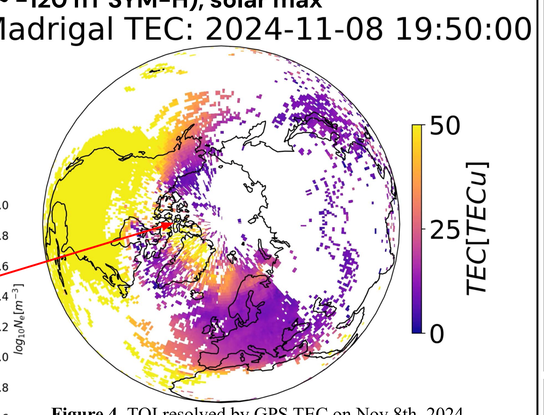

Figure 4. TOI resolved by GPS TEC on Nov 8th, 2024.

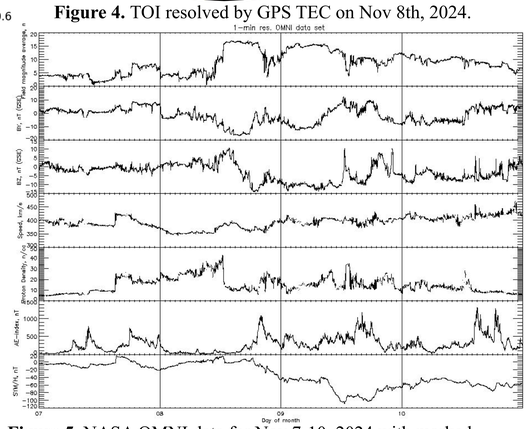

Figure 5. NASA OMNI data for Nov 7-10, 2024 with marked start time for backtrace seeds.

Conclusions

- **Density fluctuations** throughout the lifespan of a **Tongue of Ionization (TOI)** are **not** explained by only **chemical loss** and **production**
- Convection of plasma to **polar regions** is a **non-equilibrium state** influenced heavily by the **divergence** of plasma **along magnetic field lines**
- TOIs can survive at high altitudes for long periods (>2 hours), indicating a balance between vertical velocity components

Future Work

- Investigate the origin of TOI density **before** it is lifted to high altitudes and into the polar cap
- Further characterize the importance of plasma **"leakage"** during geomagnetic storms and across various regions of the ionosphere.

References

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2. Themens, D. R., Elvidge, S., McCaffrey, A., Jayachandran, P. T., Coster, A., Varney, R. H., et al. (2024). The high latitude ionospheric response to the major May 2024 geomagnetic storm: A synoptic view. Geophysical Research Letters, 51, e2024GL111677. https://doi.org/10.1029/2024GL111677

Acknowledgements

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