Mid-latitude Sporadic-E Structuring due to Convective Instability in the Thermosphere

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OBJECTIVES:

- Investigate QP echoes from sporadic-*E* layer observed in the upper mid-latitudes and its possible connection to Ekman-type convective instabilities.
- Determine a causal link between observations of unique sporadic-*E* structuring and turning shear in the lower thermosphere.

BACKGROUND:

The Ithaca radar was first used by Hysell and Larsen (2021) for QP echoes captured in 2020, linking Kelvin-Helmholtz (KH) convective instabilities to backscatter observed in 2020.[1] The study focused primarily on planar wind shear and KH instability as a causal link to some of the observed structuring in sporadic-E.

While KH instabilities are commonly evident in the mesosphere-lower thermosphere (MLT) region, Larsen et al. (2004) and Hurd et al. (2009) have both suggested the connection between neutral winds in the MLT region to analogous structures in the atmospheric boundary layer, which is known to exhibit many instabilities including Ekman-type spiral flows.[2,3] Follow-up studies revealed a possible link between echoes and another type of convective instability, Ekman-type instabilities.

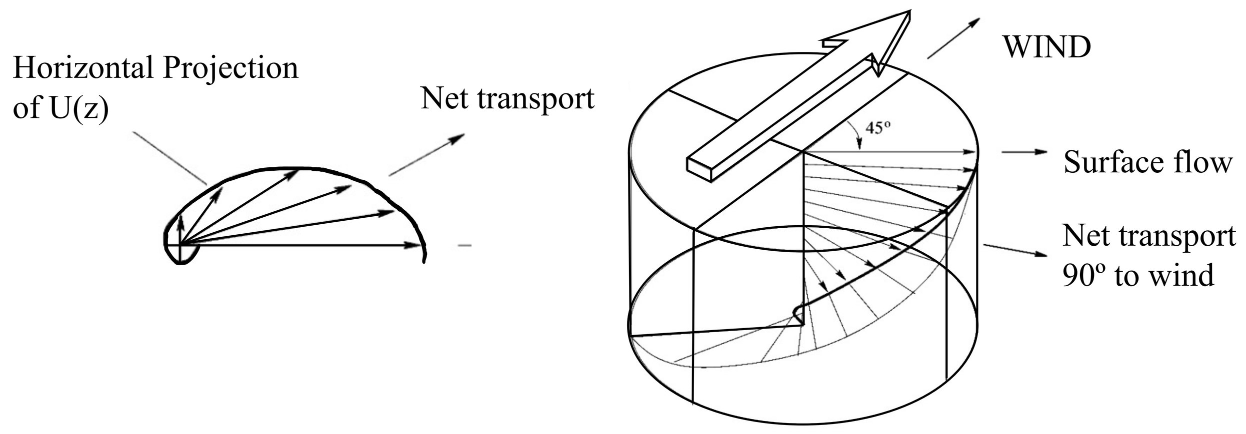

Figure 1: Schematic of Ekman spiral, illustrating geostrophic flow. Diagram from Allen and Bridges (2003).[4]

The stability of Ekman-type flows was investigated by Lilly (1966), who determined observations of a parallel wave type for Re greater than 55 and a cross-flow wave type for Re greater than 110.[5] Further, Dubos et al. (2007) observed the emergence of secondary instabilities for Re greater than 300.[6]

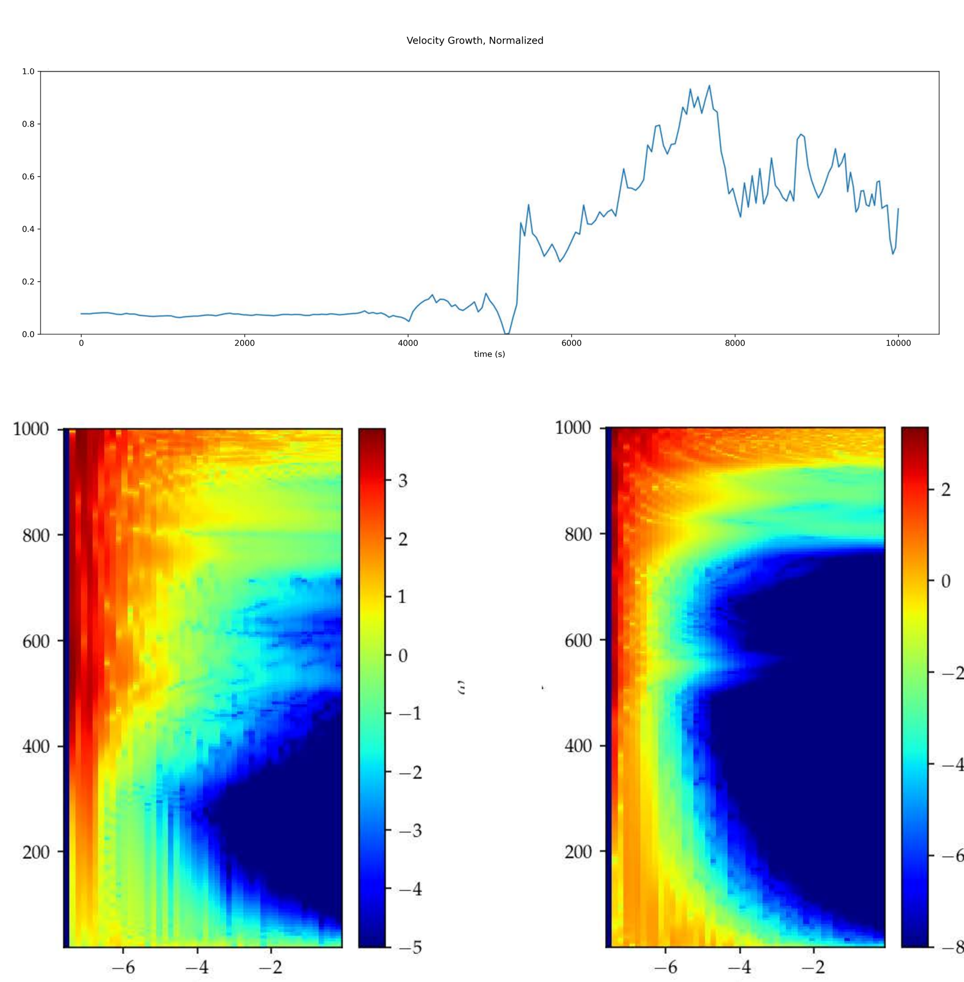

Figure 2: Stability analyses of Ekman through (a) average velocity growth of the vertical component of velocity of an Ekman-type instability (b-c) horizontal wavenumber analyses.

Recently, Chkhetani and Shalimov (2013) have proposed a causal link between Ekman-type instabilities and frontal structures in sporadic-*E* instability.[7] Bui et al. (2023) recently analyzed a connection between Ekman-type instabilities and QP echoes observed in the Cornell radar near Ithaca, NY.[8]

CORNELL RADAR & OBSERVATIONS:

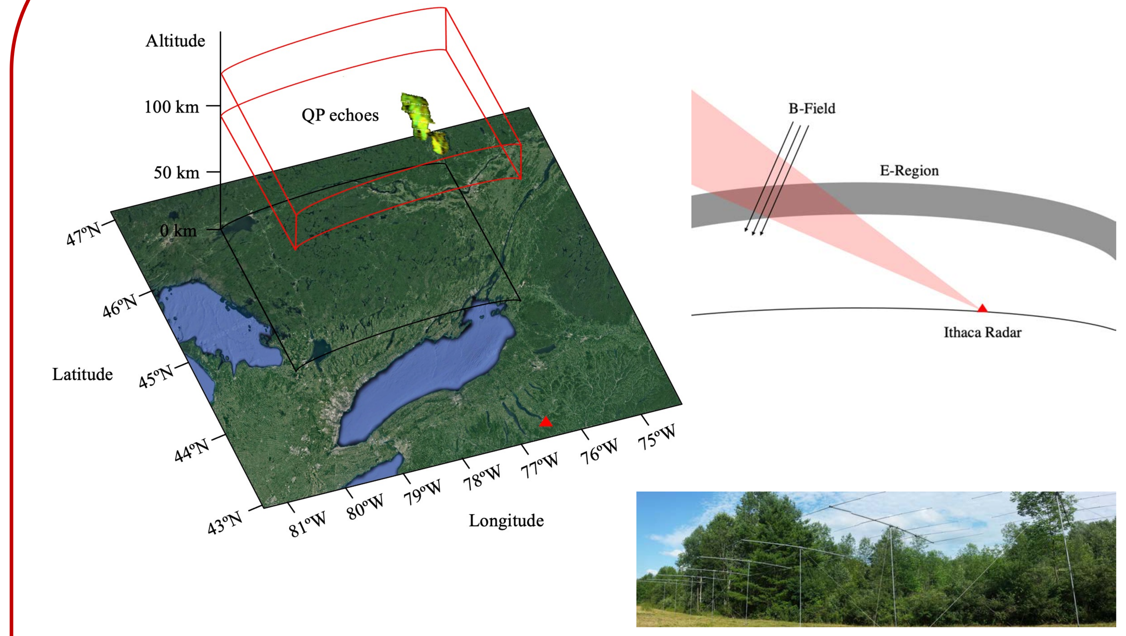

Figure 3: Schematic of Cornell radar near Ithaca, NY [9]

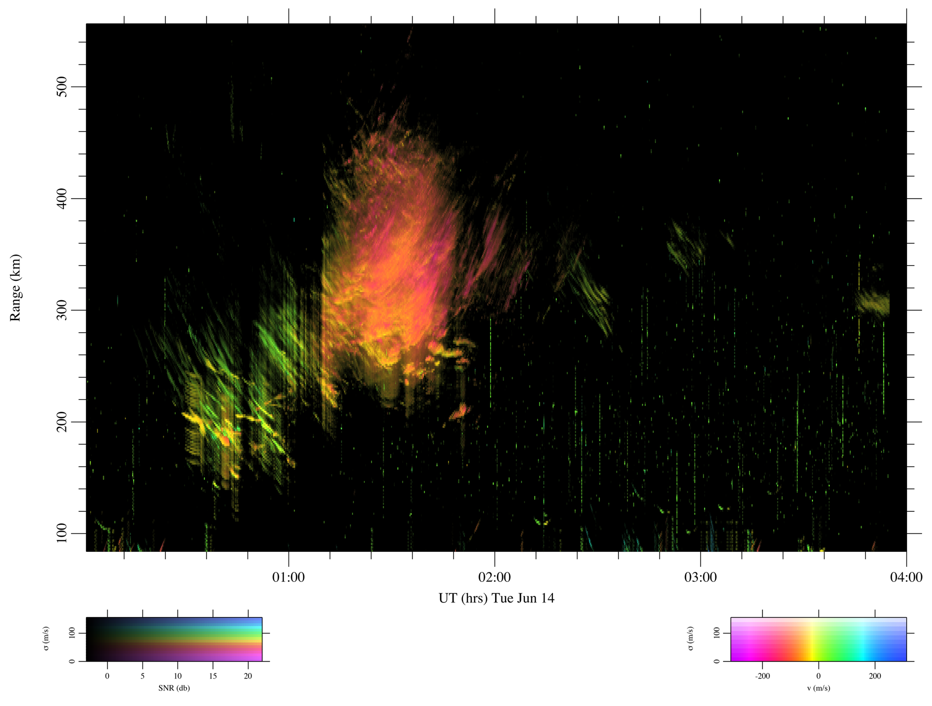

Figure 4: RTI plot on Jun. 14, 2022.

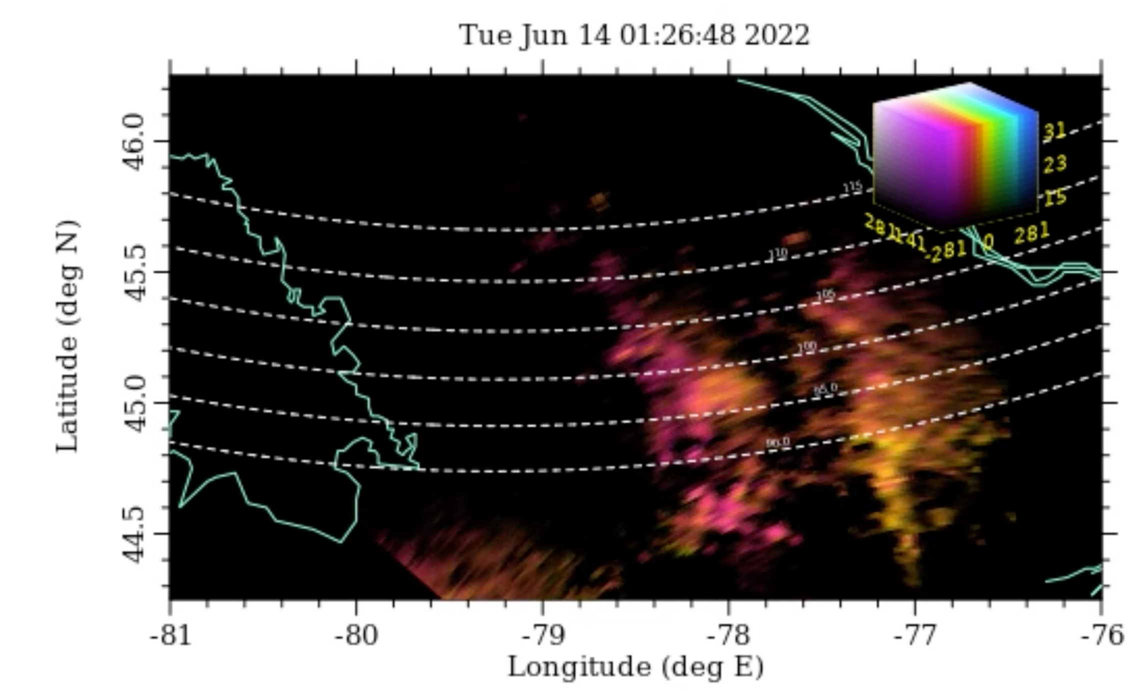

Figure 5: Radar images representative of coherent backscatter, corresponding to Fig. 4. [9]

SIMULATING EKMAN-TYPE INSTABILITIES

The following equation set models Ekman-type flow in the neutral thermosphere, where a boundary condition is imposed for a non-slip condition of zero flow at the boundary of $z = 0$.[4]

$$\nabla \cdot \bar{u} = 0 \qquad (1)$$

$$\frac{\partial \bar{u}}{\partial t} + (\bar{u} \cdot \nabla)\bar{u} = -\frac{1}{\rho}\nabla p - 2\Omega\hat{k}\times\bar{u} + \nu\nabla^2\bar{u} \qquad (2)$$

$$\frac{\partial S}{\partial t} + \bar{u} \cdot \nabla S = D\nabla^2 S \qquad (3)$$

The system above was solved using the Dedalus spectral solver.[10] The simulation showed the expected wave-types derived from stability analyses. We first observe a viscous, travelling type wave evident by parallel flow, which is followed by an inviscid, cross-flow type wave. Finally, the simulation ends with secondary wave breaking.

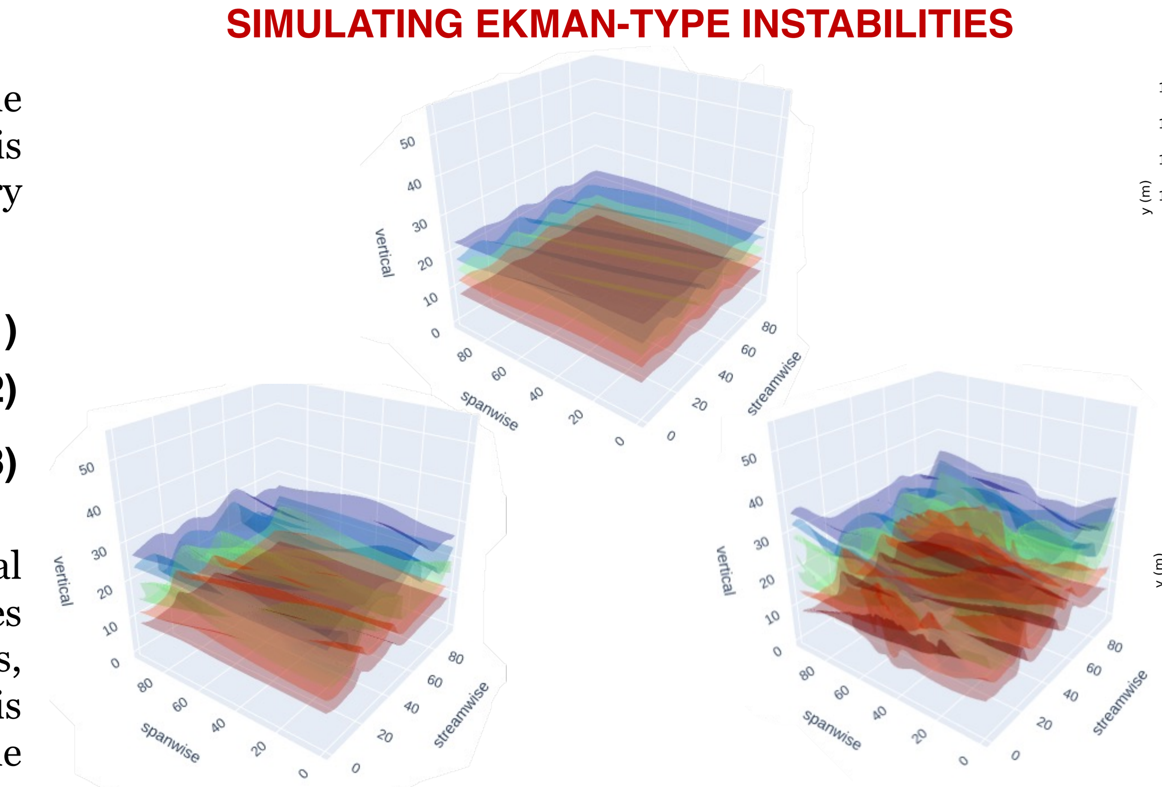

Figure 6: 3D simulation of Ekman-type flow capturing parallel flow type, cross-flow type, and secondary wave structuring.[8,10]

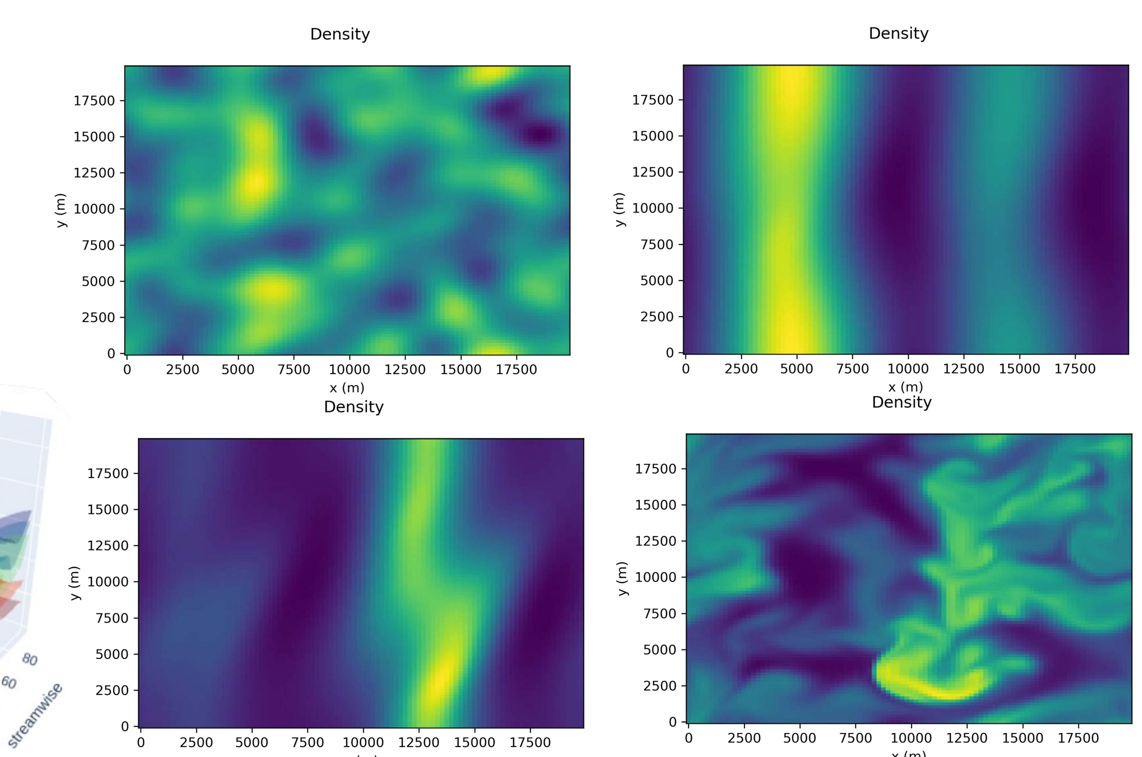

Figure 7: Turbulent Ekman-type flow at the midpoint of z throughout 10,000 seconds, revealing various wave types.[10]

SIMULATING SPORADIC-E

The following equations, derived from extended magnetohydrodynamic (MHD) equations, were used to simulate a sporadic-E layer which could be driven by neutral wind shear.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}_i) = 0 \qquad (1)$$

$$\frac{D(\rho \bar{u})}{Dt} = -\nabla p + \bar{J}\times\bar{B} + \rho\nu_i(\bar{u}_n - \bar{u}_i) \qquad (2)$$

$$\nabla\times\bar{B} = \mu_0\bar{J} \qquad (3)$$

$$\nabla\times\bar{E} = -\frac{\partial \bar{B}}{\partial t} \qquad (4)$$

$$\bar{E} + \bar{v}\times\bar{B} - \frac{1}{n_e e}\bar{J}\times\bar{B} + \frac{1}{n_e e}\nabla(n_e\kappa T) - \frac{m_e\nu_e}{q}(\bar{u}_n - \bar{u}_e) = \eta\bar{J} \qquad (5)$$

Similarly to the Ekman simulation, equations were solved using the Dedalus spectral solver.[10] To model irregularities caused by Ekman-type convective instabilities, neutral wind values solved by the Ekman simulation were fed into the plasma simulation as parameters.

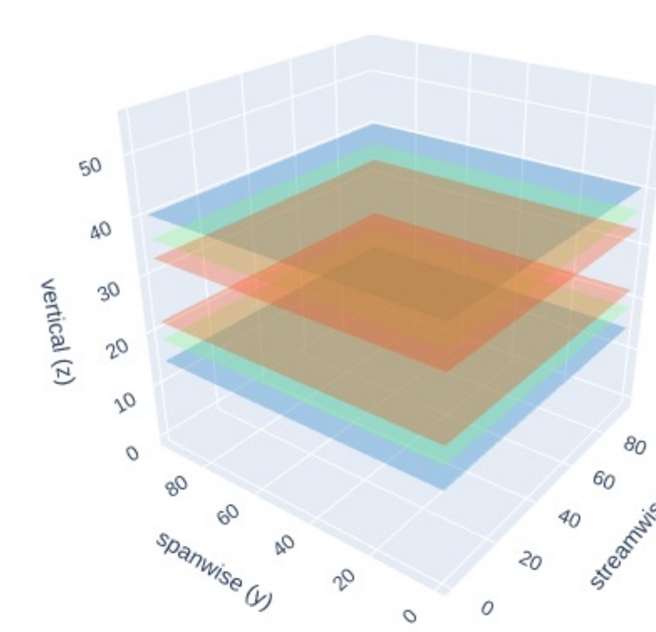

Figure 8: Simulated sporadic-E layer at initial iterations.[10]

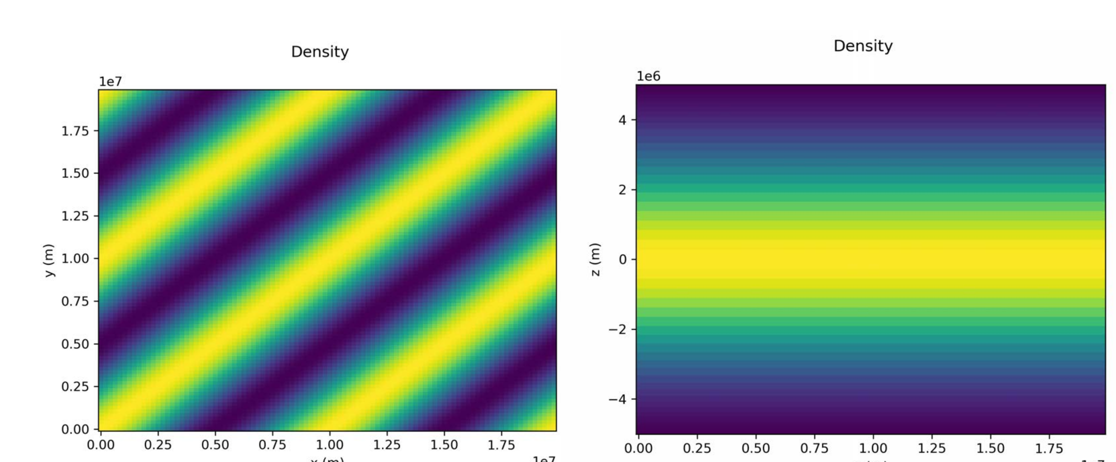

Figure 7: Simulated sporadic-E layer at the midpoint of z.[10] Plasma appears to be field-aligned and plasma layer appears to be well-defined along the vertical.

CONCLUSION:

We propose that sporadic-*E* structures observed by the Ithaca radar may correspond to mixing in the MLT region, particularly Ekman-type spiral flows, based on similar characteristics (turbulent length scales and time scales). We are now working to model sporadic-E irregularities through extended MHD equations.

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Future direction:

- Simulations involving neutral wind shear as well as feedback between both plasma and neutral particles
- Analyses of simulated convective instabilities and comparison with data
- Continued observations using the Cornell radar in Ithaca, NY and comparisons to external data

DATA AVAILABILITY & ACKNOWLEGEMENTS:

- Data discussed in this paper can be accessed through the Cornell eCommons repository through https://doi.org/10.7298/8sxf-b977.2
- Numerical simulations were generated using Dedalus, an open-source spectral solver available at https://dedalus-project.org [10]
- This work was supported by NSF awards AGS-2011304 to Cornell University and AGS-2012994 to Clemson University.
- To watch the movies & simulations in action, scan this QR code or go to: https://linktr.ee/michellexbui

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[9] Radar images & movies https://landau.geo.cornell.edu/zeman.html
[10] Dedalus Project: https://dedalus-project.readthedocs.io/en/latest/