Thermospheric Wind Dynamics in High Latitude Regions: Case Study

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1. Introduction:

1.1: Motivation:

The high-latitude thermosphere is highly dynamic. During geomagnetic storms, ion-neutral collisions, along with other accelerations, transport momentum to neutral particles and drive global winds; therefore, studying wind dynamics is crucial for understanding space weather impacts.

1.2: Thermospheric Wind Accelerations:

$$\frac{\partial \mathbf{U}_n}{\partial t} = \underbrace{-\frac{1}{\rho}\nabla P}_{(1)} + \underbrace{\nu_{ni}(\mathbf{V}_i - \mathbf{U}_n)}_{(2)} - \underbrace{2\mathbf{\Omega} \times \mathbf{U}_n}_{(3)} + \underbrace{\frac{1}{\rho}\nabla(\eta\nabla\mathbf{U}_n)}_{(4)} - \underbrace{(\mathbf{U}_n \cdot \nabla)\mathbf{U}_n}_{(5)} + \mathbf{g}$$

1. Pressure Gradient: Wind-driven from high- to low-pressure regions.
2. Ion Drag: Momentum exchange via collisions.
3. Coriolis: Deflects wind due to Earth's rotation.
4. Viscosity: Smooths wind shear between layers.
5. Advection: Transports momentum by the bulk motion.

1.3: Background:

Thermospheric wind accelerations vary with altitude and across the polar cap, auroral oval, and sub-auroral regions across geomagnetic storm phases.

1.4: Research Gap:

Most studies overlook the full vertical and temporal evolution of the accelerations, often focusing on a single region or altitude.

Objective: Understand thermospheric wind dynamics in high-latitude regions during geomagnetic storm.

Science Question:

How do the thermospheric acceleration terms compare in their contributions to wind dynamics across different regions, altitudes, and storm phases ?

2. Methodology:

Particle Precipitation

Feature Tracking of Aurora Model
(Input: AE index)

Electric Potential

Weimer Model
(Input: IMF , Solar wind conditions)

GLOBAL IONOSPHERE THERMOSPHERE MODEL (GITM)
Storm: March 17, 2013
Resolution: 0.5° latitude by 2.0° longitude.

- **Output:** 3D neutral and ion parameters at 15-minute intervals.
- **Altitude Focus:** 100–450 km
- **Momentum Evaluated At:** Four locations across three regions — polar cap (82.5°N, 62.3°W), auroral oval (65°N, 147.5°W; 70°N, 18.9°E), and sub-auroral (50°N, 87.6°W)

Takeaway Message: Viscosity is dominant above 300 km across all storm phases and regions.

3. Results

3.1: Geophysical Conditions of March 17, 2013:

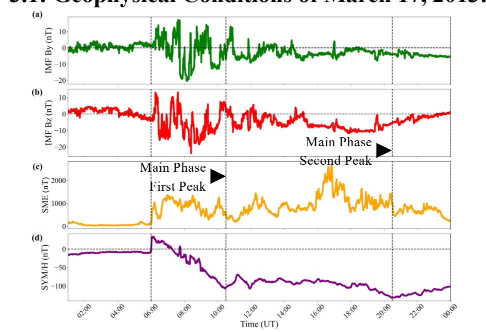

Figure 1: Solar wind and geomagnetic indices during the March 17, 2013, storm. Panels (a) and (b) show IMF By and Bz, respectively; panel (c) the auroral electrojet index SME; and panel (d) the ring current index SYM/H. Vertical dashed lines indicate the storm onset at 06:00 UT, the first peak at 10:30 UT, the second peak at 20:30 UT, and the recovery phase at 00:00 UT on March 18.

3.3: Role of Viscosity:

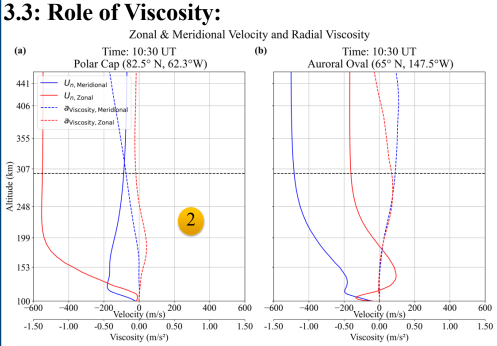

Figure 3: Altitude profiles of zonal and meridional wind velocities (solid lines) and corresponding radial viscous accelerations (dashed lines), at 10:30 UT for (a) the polar cap (82.5° N, 62.3° W) and (b) the auroral oval (65° N, 147.5° W). A horizontal black dashed line marks 300 km

$$\left|\frac{dU_n}{dz}\right|_{z\geq 300\,\text{km}} \ll \left|\frac{1}{\rho}\right|_{z\geq 300\,\text{km}}$$

Key Findings: :

2 Viscosity arises as a response to vertical gradients in horizontal wind, transferring momentum vertically.

3 Inverse mass density drives large magnitude of the viscosity in high altitudes.

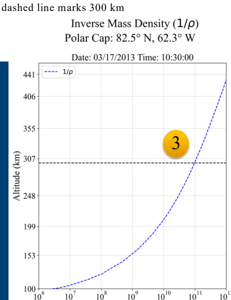

Figure 4: Inverse mass density as a function of altitude over the Polar Cap (82.5°N, 62.3°W), on March 17, 2013, at 10:30 UT.

3.2: Acceleration Terms Across Time, Altitudes, and Regions:

1 Key Finding: Viscosity dominates above 300 km. Below that, advection is the primary driver in the polar cap, while pressure gradient forces dominate in the auroral oval.

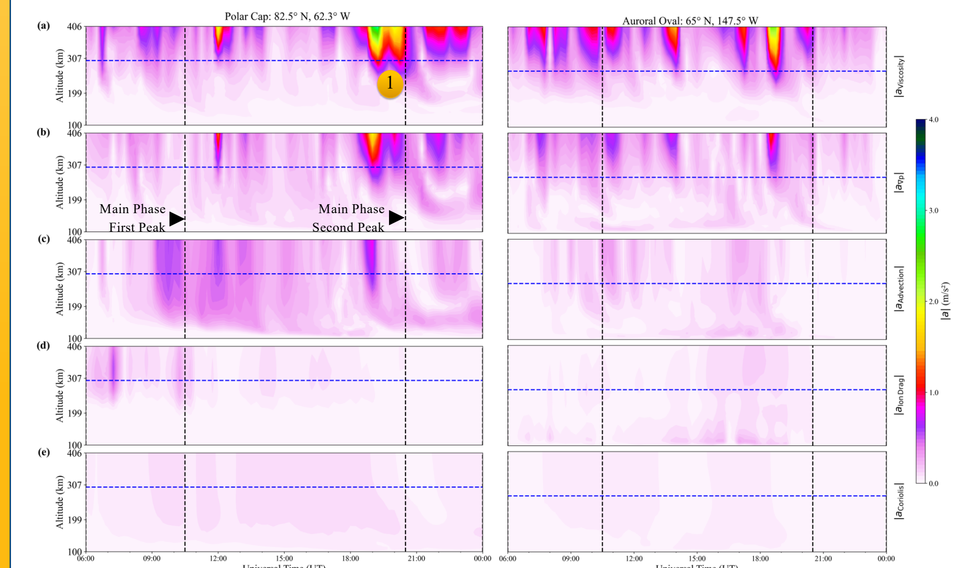

Figure 2: Momentum accelerations from 06:00 UT on March 17 to 00:00 UT on March 18, 2013, at two locations: **(left)** the Polar Cap (82.5°N, 62.3°W) and **(right)** the Auroral Oval (65°N, 147.5°W). Each panel shows: (a) viscosity, (b) pressure gradient, (c) advection, (d) ion drag, and (e) Coriolis acceleration (all in m/s²). The altitude range spans 100–450 km. Dashed vertical lines mark the two SYM-H main phase peaks at 10:30 and 20:30 UT, while the horizontal dashed line highlights the 300 km altitude.

Conclusion:

The results provide critical insight into the complex influence of geomagnetic storms on thermospheric wind dynamics.

1 Viscosity consistently dominates at 300 km and above across all regions and storm phases.

2 & 3 This dominance is primarily driven by the sharp decrease in mass density—with altitude—by nearly six orders of magnitude.

Future Work:

Extend current study to include multiple locations:

- Test if observed acceleration patterns are consistent across different locations within each region.
- Generalize findings across storm phases and altitudes.

Limitation:

GITM currently accounts only for vertical gradients of horizontal winds (vertical shear), neglecting horizontal gradients of vertical winds (horizontal shear), limiting its representation of wind dynamics.

References:

Aruliah (1991), Tech. Rep., Burns (1995), JGR: Space Physics, Chand (2024), JGR: Space Physics, Deng (2006), JGR: Space Physics, Dhadly (2017), JGR: Space Physics, Dhadly (2017), JGR: Space Physics, Dungey (1961), Tech. Rep., Ferdousi (2019), JGR: Space Physics, Fuller-Rowell (1994), JGR: Space Physics, Fuller-Rowell (1987), JGR: Space Physics, Killeen (1991), Tech. Rep., Killeen (1984), JGR: Space Physics, Kwak (2007a), JGR: Space Physics, Kwak (2007b), JGR: Space Physics, Mayr (1978), JGR: Space Physics, McCormac (1987), JGR: Space Physics, Niciejewski (1992), Tech. Rep., Ridley (2006), JASTP, Rishbeth (1972), Tech. Rep., Schunk (2009), Cambridge Univ. Press, Smith (1995), Tech. Rep., Straus (1978), Rev. Geophysics, Thayer (1995), JGR: Space Physics, Thayer (1991), GRL, Wang (2008), JGR: Space Physics, Weimer (1996), GRL, Wu (2021), Space Weather