Ionospheric variability over Jicamarca during the recent extreme space weather event (10-12 October 2024)

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Abstract

This study analyzes measurements from the Jicamarca Radio Observatory (JRO; 11.9° S, 76.8° W, magnetic dip 1° N) during the 10–12 October 2024 space weather event of Solar Cycle 25. We used JRO incoherent scatter radar (ISR) to examine equatorial ionospheric electrodynamics and spread-F irregularities, ionosonde data for virtual height (h'F) and equatorial spread F, ACE satellite measurements for solar wind parameters, and SuperMAG ground magnetometers for geomagnetic variations. Additionally, Swarm satellite and GPS-derived total electron content (TEC) data were used to characterize electron density and irregularity evolution. During the storm's main phase, a strong eastward prompt-penetration electric field produced over one hour of enhanced E×B vertical plasma drift, equatorial electrojet (EEJ) strength, and F-layer virtual height. This intensified the equatorial ionization anomaly (EIA) and expanded its latitudinal extent. In the pre-reversal enhancement period, combined electric fields drove vertical drifts up to 98 m/s, promoting plasma bubble formation that rose to ~950–1500 km above Jicamarca, as observed by ISR. Concurrent rate change of TEC index (ROTI) and Swarm observations recorded the expansion of ionospheric irregularities to higher latitudes.

1. Introduction

- During the geomagnetic storm time, the electric field in the equatorial ionosphere could be primarily affected by following processes:

1. Prompt penetration electric fields (PPEFs)

- PPEFs originate from enhanced magnetospheric convection, and polarization electric fields associated with the ring current.

- **Undershielding Condition:**
  When IMFBz in the Southward direction>> dawn to dusk convection electric field intensified, or R1 field-aligned currents intensified
  Polarity: dayside eastward and westward at nightside

- **Overshielding condition:**
  When IMF Bz in northward >> dawn to dusk convection electric field reduces, or R2 field-aligned currents intensified;
  Polarity: dayside westward and eastward at night

2. Disturbance Dynamo Electric Fields (DDEFs)

- The ionospheric DDEFs, due to global thermospheric wind circulation associated with Joule heating at high latitudes (Arise **3–6 hours after storm onset**).

- Exhibit **opposite polarity** to PPEFs: **westward by day, eastward at night**, leading to **long-lasting ionospheric perturbations**.

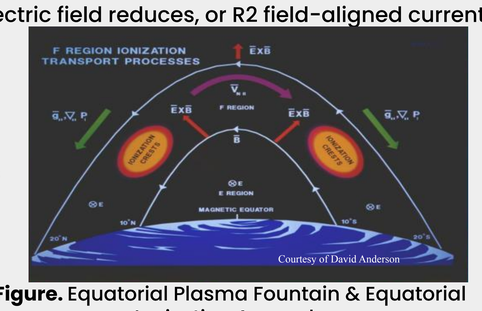


Figure. Equatorial Plasma Fountain & Equatorial Ionization Anomaly

2. Observations and Results

- **Interplanetary and Geomagnetic Conditions for October 10–12, 2024**

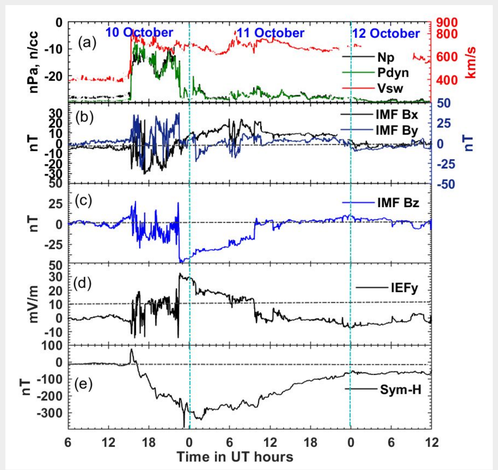
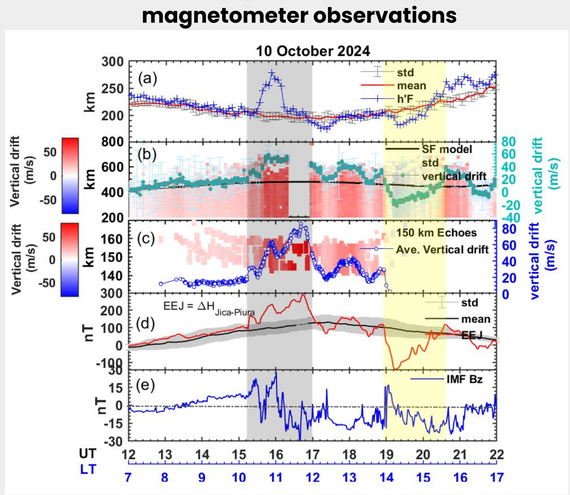


Figure: (a) proton density (Np), solar wind dynamic pressure (Pdyn), and solar wind velocity (Vsw); (b) IMF Bx and IMF By; (c) IMF Bz; (d) IEFy; and (e) Sym-H

- **Ionosonde, Jicamarca ISR, and magnetometer observations**



Figures : (a) Virtual height (h'F),(b) ISR measured F-region vertical plasma drift; (c) Vertical plasma drift from 150 km echoes; (d) EEJ; and (e) IMF Bz.

2.1 Observations and Results

- **Madrigal GPS Total Electron Content**

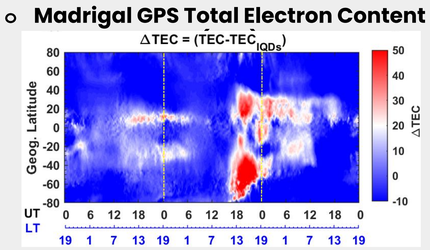


Figure. ΔTEC over approximately -77°E ± 10°E longitudes

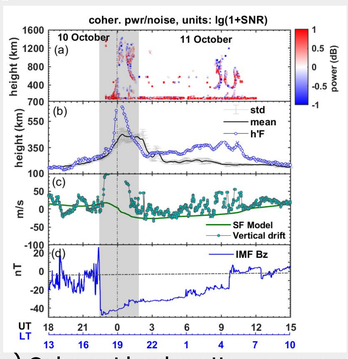


Figure. (a) Coherent backscatter power associated with equatorial spread F (ESF); (b) h'F; (c) ISR measured F-region vertical plasma drift; and (d) IMF Bz.

- **Swarm satellite and GPS TEC observations**

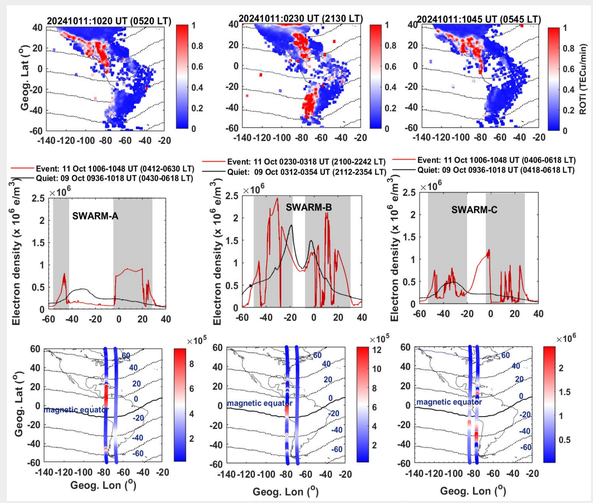


Figure: Rate of change of TEC index (top panel), electron density (middle panel), and Swarm satellite passes along with corresponding electron density measurements (bottom panel).

3. Summary and Conclusion

- During the daytime, a strong eastward penetration electric field caused a simultaneous increase (approximately 1.5 hours) in the EEJ, E×B vertical plasma drift (at 150 km echoes), F region vertical plasma drift and the virtual height of the F layer, with enhancements of approximately 290 nT, 85 m/s, 60 m/s, and 280 km, respectively.
- The persistent E × B drift enhancement extended the EIA to higher latitudes and was observed in the southern hemisphere (25°/18°–70°/57° S Geog/Geom).
- During the pre-reversal enhancement (PRE), the combined penetration and background eastward electric fields produced a pronounced uplift of the equatorial ionosphere, resulting in off-scale VIPIR ionograms and ESF echoes in JULIA MP measurements at altitudes of approximately 950–1,500 km.
- Simultaneous observations from ISR, the VIPIR ionosonde, the GPS ROTI index, and Swarm satellite measurements revealed the presence of ionospheric plasma irregularities during the post-midnight and early morning hours.
- EPBs (equatorial plasma bubbles) were observed between 17°/13°–50°/38° S and 0°/16°–32°/42° N Geog/Geom latitude at 0230 UT (2130 LT).

Acknowledgments

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