Dynamic Responses of Ionosphere and SED Evolution during 2024 October Super Storm using GITM-SAMI3

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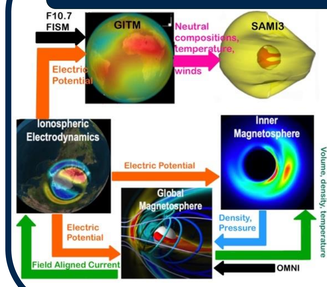
1. Introduction

- Mid-latitude ionosphere is subjected to various electromagnetic, chemical and transport responses under extreme geomagnetic conditions.
- SED (Storm-enhanced density) and plume are the manifestation of ionosphere-plasmasphere dynamics.
- Question remained: **How does SED evolve in space and time?**

2. Modeling



SWMF Geospace suite:

- GM (Global Magnetosphere): MHD model
- IM (Inner Magnetosphere): Rice Convection Model
- IE (Ionospheric Electrodynamics): Ridley Ionosphere Model
- Conductance model: **COMPASS**

GITM:

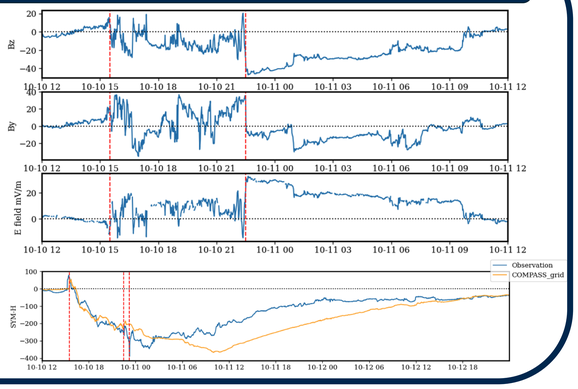
- High-latitude driver is IE output
- 2°×2° spatial resolution

SAMI3:

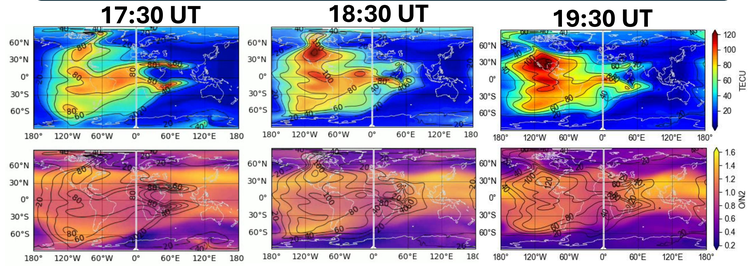
- One-way coupled with GITM via neutral

3. Storm Condition

- The 2nd strongest storm of solar cycle 25.
- Full-halo CME erupted on 10/8/2024 and SSC at ~10/10/15:15 UT.
- Sheath period: 15:15~22:30 UT.
- Minimum Dst index reached -390 nT at 23:15 UT.
- Magnetic Cloud period: Bz dropped to -45 nT



4.1 Results: Sheath



17:30 UT:

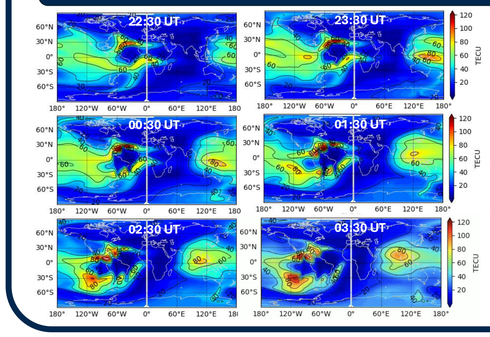
- After SSC, simulation shows roughly symmetric SED over the American continent, co-located with symmetric O/N2 enhancement.
- Negative By condition produces an eastward SED plume.

18:30 UT:

- Southern SED plume decays fast due to strong poleward wind driven by strong ion convection under pole-offset condition.
- Fluctuating By (±5 nT) produces a northward plume in NH.

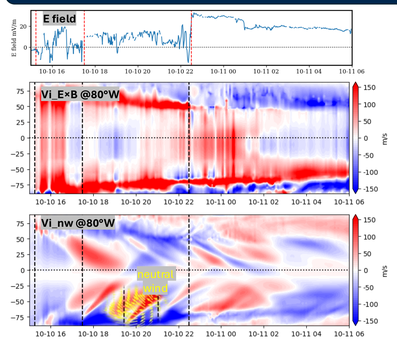
19:30 UT: Strong northern SED (>100 TECU) with westward SED plume.

4.2 Results: Magnetic Cloud



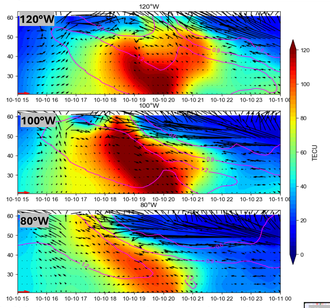
- During the MC period, ionosphere enters the negative phase due to reduced O/N2 at mid-high latitudes.
- Global TEC peak decreases from >100 to ~60 TECU.
- EPB locations and timing matched with GOLD observations

4.3 Results: Vertical Ion Drifts



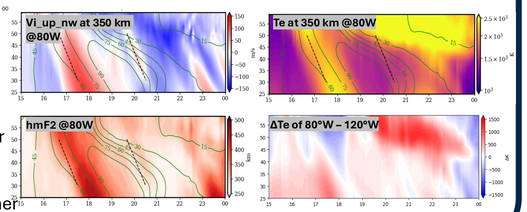
- Across the American sector mid latitude regions, upward E×B induced ion drift follows positive E field periods, reaching 50 m/s in the early sheath period and ~80 m/s during early MC.
- Intense high-latitude energy input initiates global-scale equatorward neutral wind (~900m/s wind front speed), which induced vertical ion drift reaching 120m/s.
- Equatorward neutral wind causes the second surge of southern upward ion drift and drives fast southern SED base decay.
- Wind crosses the equator at ~19 UT, which gives strong downward ion drift in the opposite hemisphere.

5. Results: North American SED Gradient



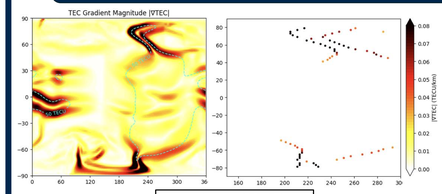
<u>During the sheath period, US continent experienced large SED growth and decay, forming sharp TEC gradient.</u>

- SED growth started immediately after the storm arrival.
- Sharper gradient formed at SED east boundary, aligned with O/N2 gradient and edge of strong westward convection flows.



- Initial equatorward wind played a major role in lifting the hmF2 to > 400km, then the across equator poleward wind suppressed it to 300km in the mid-latitude.
- The electron temperature Te is lower at the center of SED than the surrounding region.
- Te at the eastern edge of SED is higher than that at the west side.

6. Results: SED Gradient Evolution

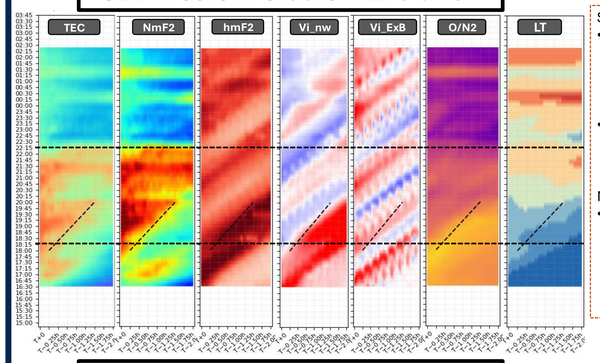


SED Edge Extraction:

1. Calculate the TEC gradient
2. Focus on the American sector (150°~300° lon, (±30°~±80° lat) with high TEC gradient (>0.03 TECU/km)
3. Select the east and west edge points of SED

- SED hmF2 in both hemisphere reach ~350 km; high-latitude plume reaches over 450 km.
- Traced backward, SED edges are 300 km hmF2 at –2 hrs.
- Majority of eastern edge parcels are transported northwestward from the east by convection. The western edge parcels travel less distances.
- In both hemisphere, SED eastern edge has higher NmF2 than the west edge.

SED Western Gradient Evolution



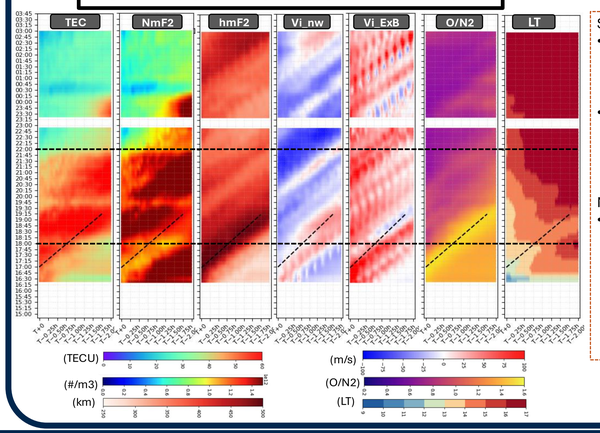
Sheath growth:

- at 18 UT, western gradient parcels traveled from pre-noon with initial low density experienced strong upward Vi_nw to 500km.
- Only after historic strong uplift and O/N2 enhancement, NmF2 increases at 300km of EUV heating altitude.

MC decay:

- at 2230 UT, western edge -2hrs tracing parcels experience downward Vi_nw and Vi_ExB, and parcels traveled within noon local time with lower density due to negative O/N2 phase.

SED Eastern Gradient Evolution



Sheath growth:

- Eastern edge NmF2 increase comes from prior strong upward Vi_ExB and prior higher density from post-noon.
- Equatorward wind also pushes O/N2 enhancement, such that western parcels experience O/N2 gradient change is more prominent

MC decay:

- The prior eastern edge parcels from local dusk had very high density. As they staying within local dusk, negative O/N2 phase and overall downward vertical Vi decrease NmF2 a lot to the current time cadence T-0.

7. Summary & Conclusions

During the Sheath:

- Initial hemispheric symmetric SED is contributed by O/N2 enhancement under UT effect.
- Southern SED plume decayed faster due to equatorward neutral wind and expanded southern convection pattern by pole-offset.
- The global neutral wind surge led to ~120m/s induced ion upward drift, while suppressed the SED hmF2 in the late sheath period.
- Plume directions are sensitive to By condition, eastward in the beginning of the sheath and then long-lasting westward during the rest of the sheath.

During the magnetic cloud:

- The SED and plume were much weaker due to reduced thermosphere O/N2 ratio in the mid and high latitude region.

Pronounced northern American SED TEC/density gradients:

- SED east boundary moved in the southwest direction, aligned with sharp gradient of the O/N2. Poleward of this boundary, erosion of SED and its plume is due to enhanced frictional heating and rapid loss.
- Electron temperature is lower at the center of SED and shows an east-west asymmetry, higher on the eastern side (80°W) than on the western side (120°W).

The evolutions of SED eastern and western gradient edges have vast differences:

- Eastern NmF2 is greater than the western side at T-0.
- In the growth period, western edge NmF2 increase is more contributed by the previous upward Vi_nw; eastern edge is vice versa with existing high density transporting from the local dusk.
- In the MC decay period, western edge has sudden NmF2 decrease due to prior downward Vi_nw and Vi_ExB with prior lower density from noon. Eastern edge NmF2 decreases less due to prior upward Vi_ExB.