Observation of irregularities with scales from 3 meters to 100s of kilometers during the May 2024 Superstorm

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Background

Extreme geomagnetic storms can dramatically perturb the high latitude ionosphere resulting in increased plasma convection, turbulence and instabilities. This can lead to the generation of electron density irregularities with scale lengths ranging from a few meters up to several hundreds of kilometers that are capable of affecting radio signals in the megahertz to gigahertz range. Since the modern society is heavily dependent on technologies and services that uses radio waves such as communication, positioning, and navigation, the presence of irregularities with different scale sizes can disrupt the operation of such services during extreme space weather events.

Significance

- A storm of such extreme intensity, in terms of Kp or Dst index, last occurred in 2003 making it one of the strongest storms of the 21st century [1,2].
- The superstorm provided a unique opportunity to study the irregularity evolution and decay across different scales simultaneously using instruments/network such as Ionospheric Continuous-wave E-region Bistatic Experimental Auroral Radar (ICEBEAR) and Canadian High Arctic Ionospheric Network (CHAIN) that were not operational in 2003.

Irregularities with a wide spectrum of scale sizes

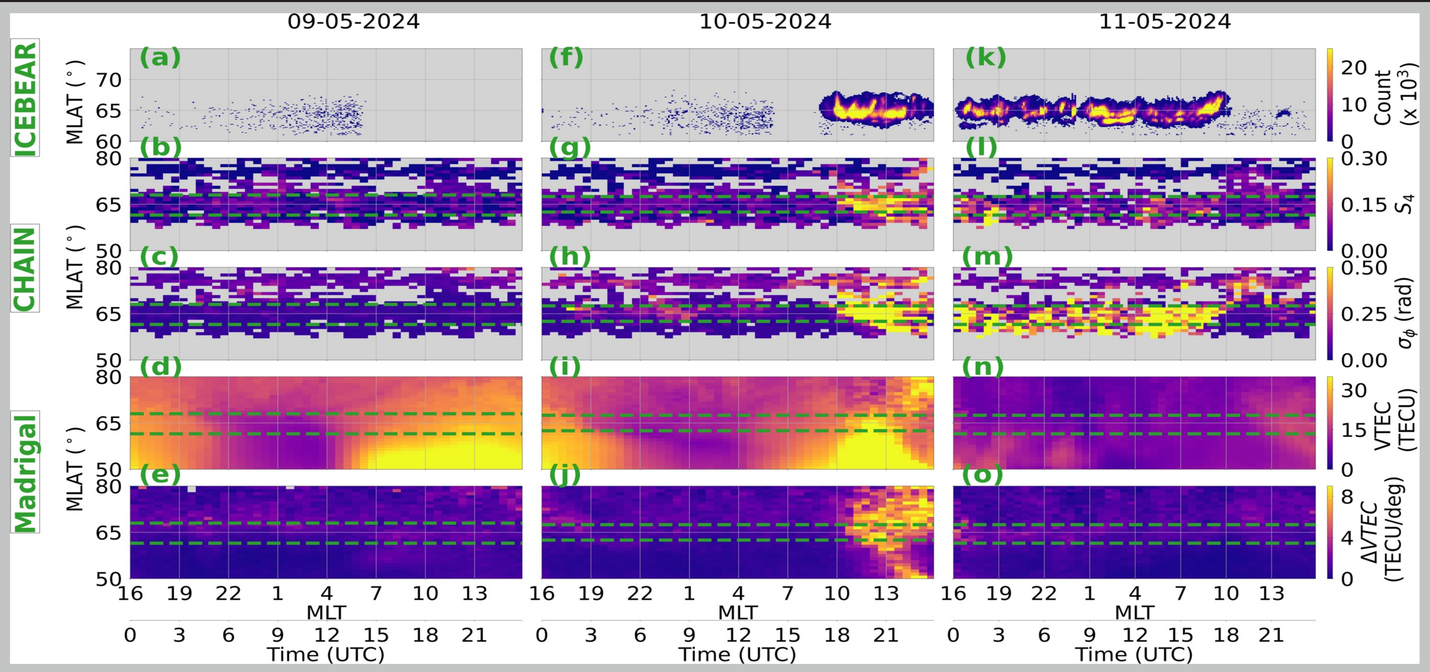

Fig 1: (a, f, k): E-region backscatter observed by ICEBEAR, (b, g, l): S_4 index, (c, h, m): σ_ϕ index, (d, i, n): VTEC, and (e, j, o): gradient in VTEC. Horizontal green lines in all panels, except the top three, indicate the MLAT regions corresponding to ICEBEAR's field-of-view (FOV).

- **Summary:** Explosion in irregularity occurrence with scales from 3m to several hundreds of kilometers after 17:00 UT on 10 May following the onset of the storm.
- Fresnel scales were most intense during the initial hours of the storm's main expansion phase.
- On the other hand, 3m and kilometer-scale structures persisted for approximately 24 hours.

* Figures adapted from [3]

Global plasma dynamics: 10 May 2024

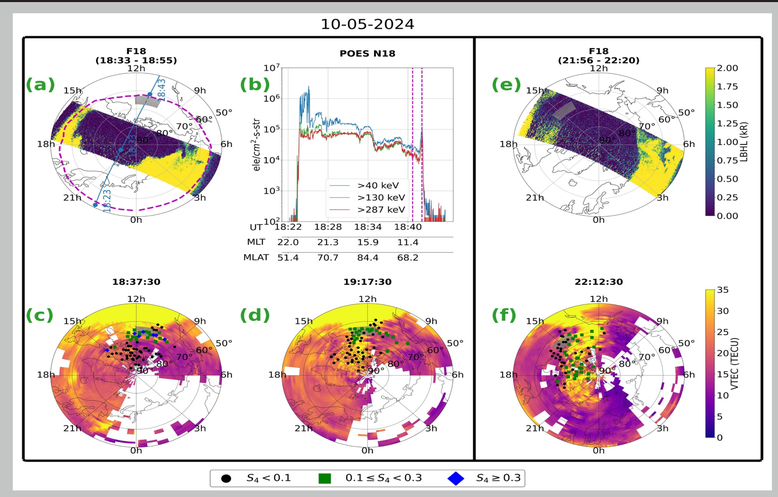

Fig 2: (a, e): SSUSI radiance data with the POES N18 trajectory shown as a blue line and equatorward auroral boundary as a magenta curve. (b): Electron precipitation data from POES N18. (c,d,f): Global TEC maps with S_4 overplotted. ICEBEAR's FOV is shown as gray stripes in the maps.

- **Summary:** Auroral oval encompassing ICEBEAR's FOV at the dayside - see panel (a).
- Strong Tongue of Ionisation (TOI)/patch activity during periods of energetic precipitation at the dayside during the storm's expansion phase (panels a-d).
- Enhanced scintillation around ICEBEAR's FOV but absent poleward of the radar (panels c-d).

Global plasma dynamics: 11 May 2024

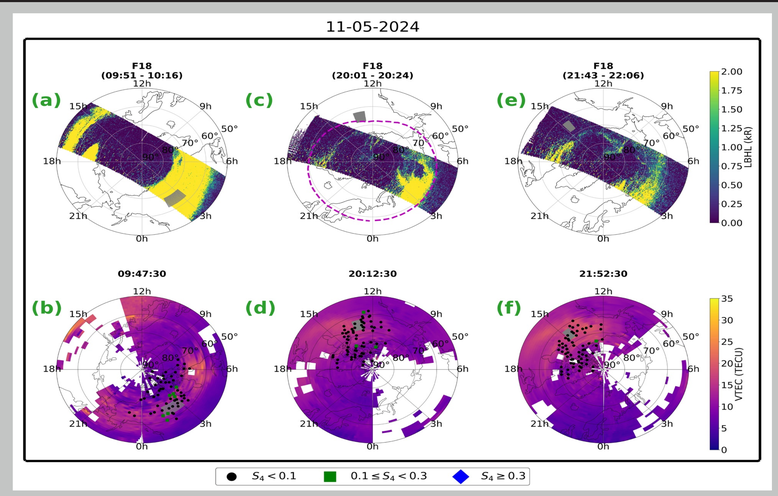

Fig 3: SSUSI radiance data and TEC maps in a similar format as Figure 2 but for 11 May.

- **Summary:** Enhanced auroral activity around ICEBEAR's FOV in the morning sector on 11 May 2024 though amplitude scintillation was absent - lack of high density structures such as patches.
- Contracted auroral oval that lacked both precipitation and TOI/patch activity at the dayside of 11 May.

References:

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[2] Elvidge, S., Themens, D. R. (2025). The probability of the may 2024 geomagnetic superstorm, Space Weather
[3] Madhanakumar, M. et al. (2025). Co-existence of irregularities across different scales observed with ICEBEAR and GNSS during the May 2024 Superstorm, Submitted to Space Weather

Acknowledgement: This research is part of the CASCADE project funded by the Research Council of Norway grant 326039. UiT the Arctic University of Norway's contribution to the EISCAT 3D project funded by RCN through research infrastructure grant 245683 is acknowledged. We acknowledge the use of data from ICEBEAR, CHAIN, Madrigal, DMSP SUSSI and NOAA.