Inhomogeneous Responses of Ionospheric Electron Density to the May 2024 Superstorm

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Outline

Motivation

- Superstorm: A rare event in 20 years
- Structural evolution of ionospheric perturbations?

GNSS Limb (RO, POD) Data and Sampling

- 20k not enough for spatiotemporal sampling of fast processes (e.g., E/F-region dynamo)
- Strong demands on sampling from science apps:
  - Temporal: < hourly
  - Spatial: < 5 deg

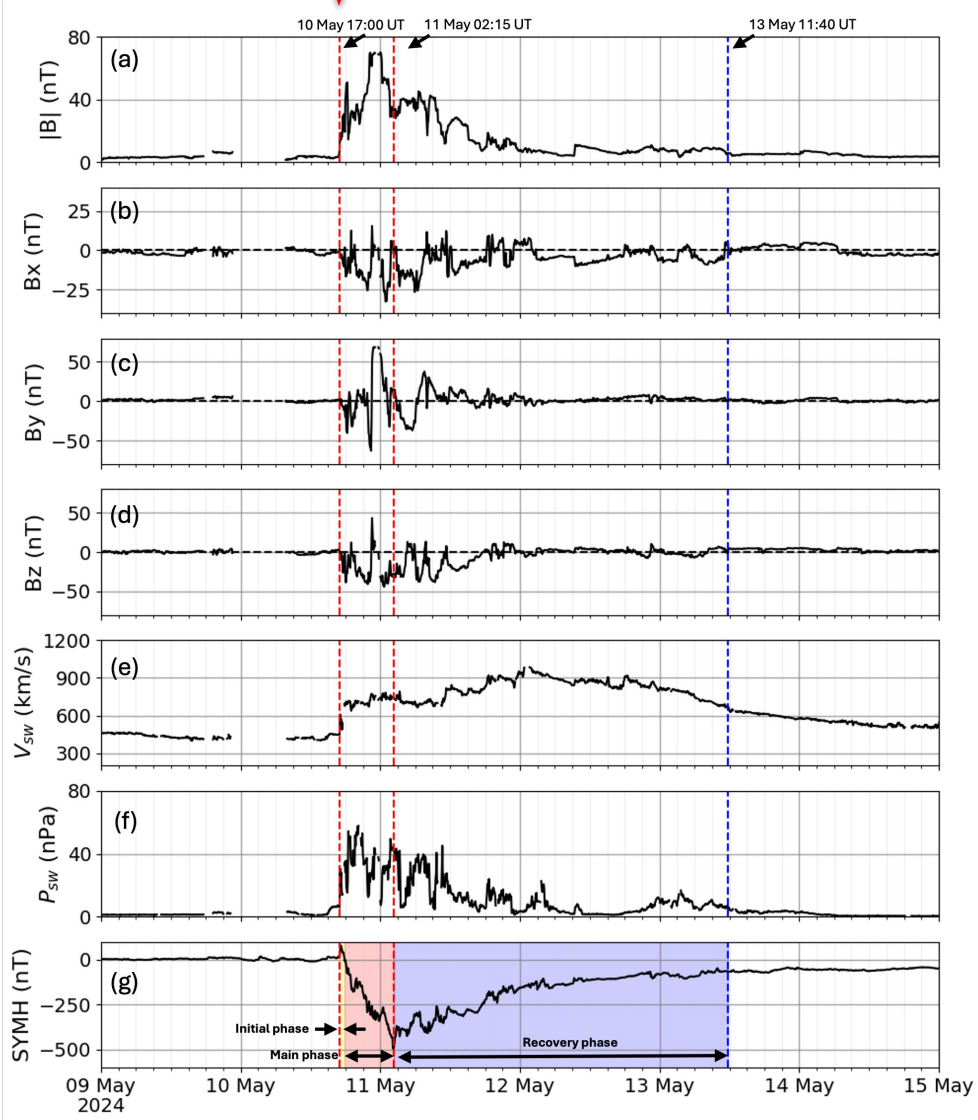
Storms Observations

- Polar region: Spire + FY3
- 2-hourly zonal mean for E-region (GNSS-RO)
- 4-hourly zonal mean for F-region (GNSS-POD)

SuperStorms with Dst ~ -400 nT

17 Z May 10

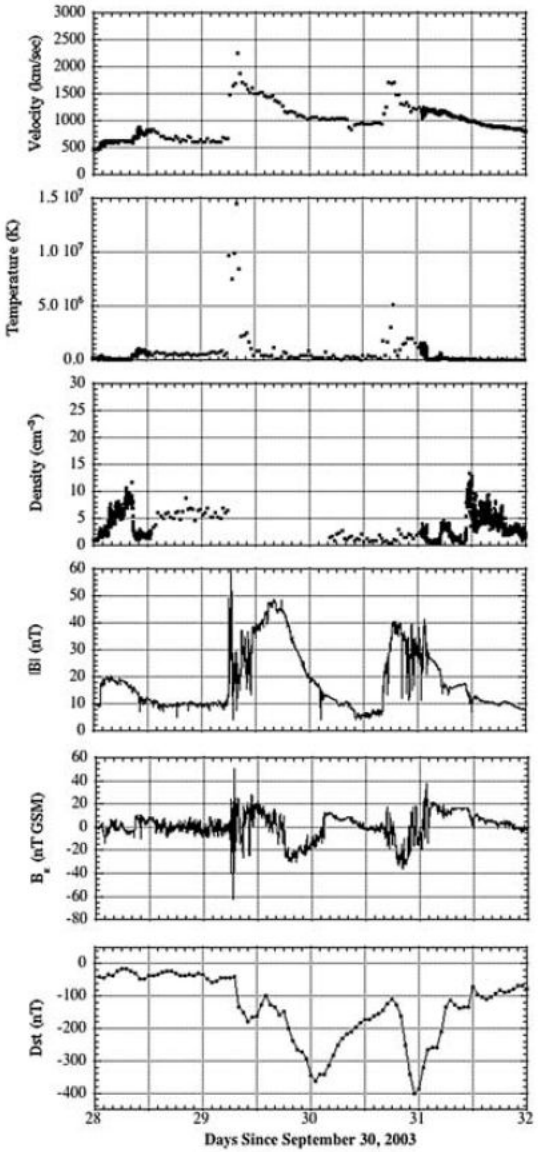
May 2024



Lee et al. (2024, in preparation)

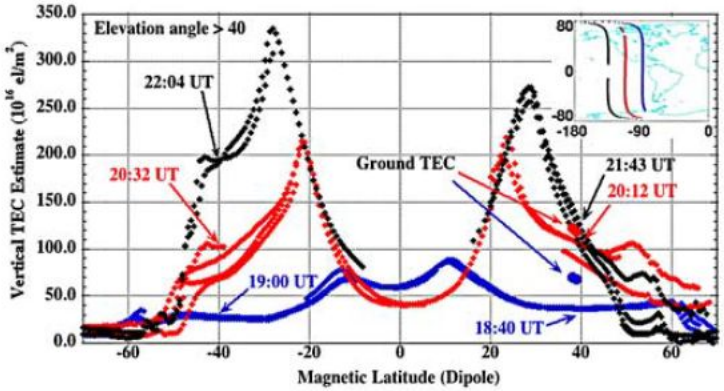
Sept 2003

CHAMP
SAC-C



Mannucci et al. (2005)

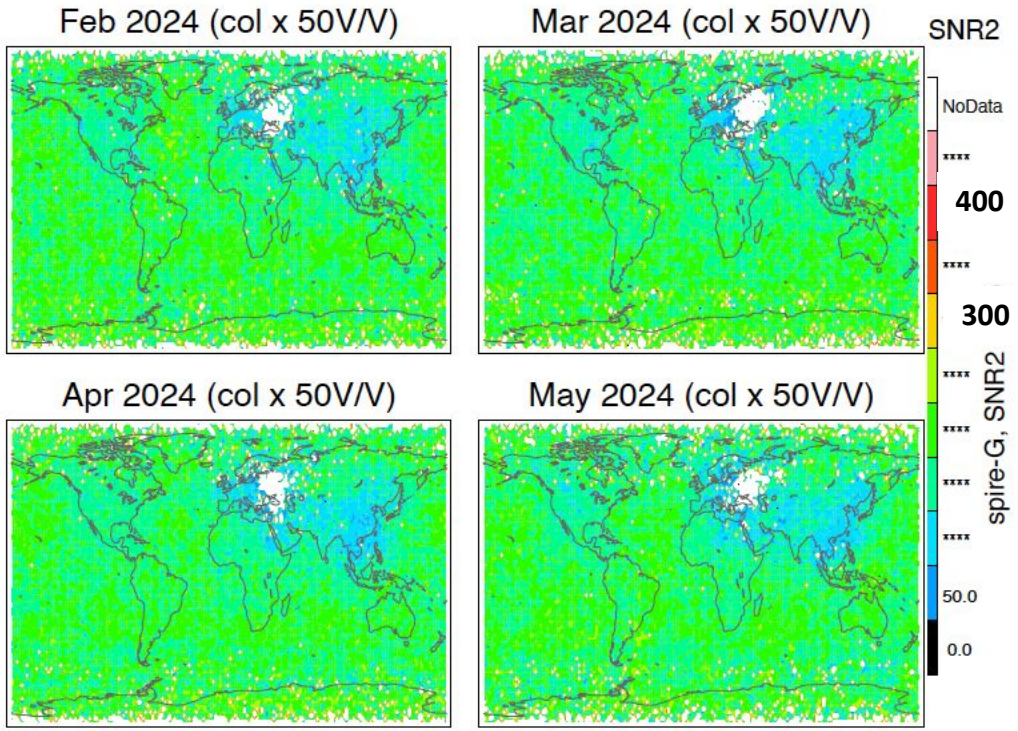
CSDA/CDAAC/ FengYun-3	# of Daily Profiles (May 2024)	
	E-region (V5)	F-region (V6p)
CSDA/Spire	7000	1800
COSMIC-2	6000	7200
FY3-D	450	350
FY3-E	900	950
FY3-F	1400	1200
FY3-G	1500	30
PlanetiQ	~1200	~1900
MetOp-B	~480	-
MetOp-C	~480	-
Kompsat-5	~230	-
TSX	~230	-
TDX	?	-
PAZ	?	-



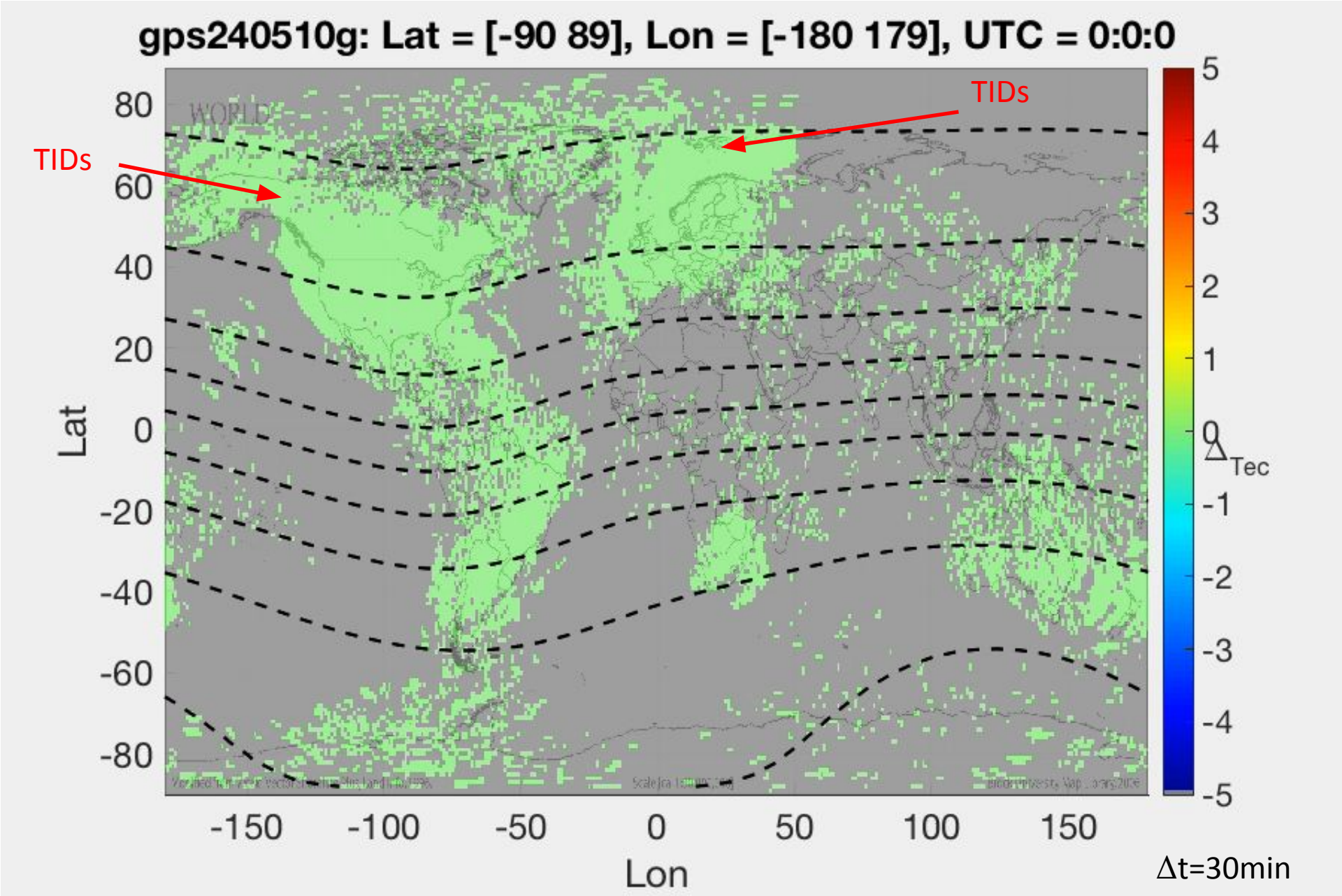
CHAMP
vTEC (z > 400km)

Mannucci et al. (2005)

CSDA/Spire GNSS-RO Sampling



Wu (2024, GPSWorld)

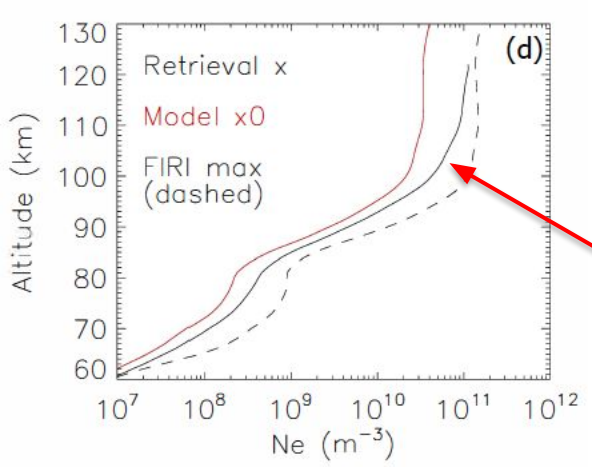


TIDs = Traveling ionospheric disturbances

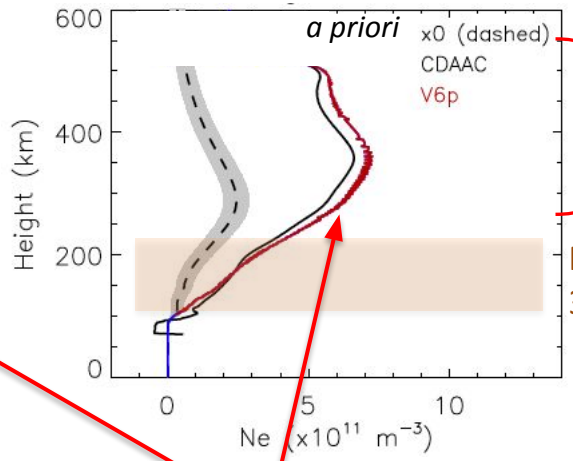
Swarnalingam et al. (2024, in preparation)

Electron Density N_e from GNSS Limb Sounding

D/E-Region (GNSS-RO Link)



F-Region (GNSS-POD Link)



Assume Spherical Symmetry

Prone to 3D inhomogeneity

Optimal Estimation Inversion: $\mathbf{y} = \mathbf{y_0} + \mathbf{K} \cdot (\mathbf{x} - \mathbf{x_0}) + \boldsymbol{\varepsilon}_y$ $\quad \hat{\mathbf{x}} = \left[\mathbf{S_a^{-1}} + \mathbf{K}^T\mathbf{S_y^{-1}}\mathbf{K}\right]^{-1}\left[\mathbf{S_a^{-1}}\mathbf{a} + \mathbf{K}^T\mathbf{S_y^{-1}}\mathbf{y}\right]$

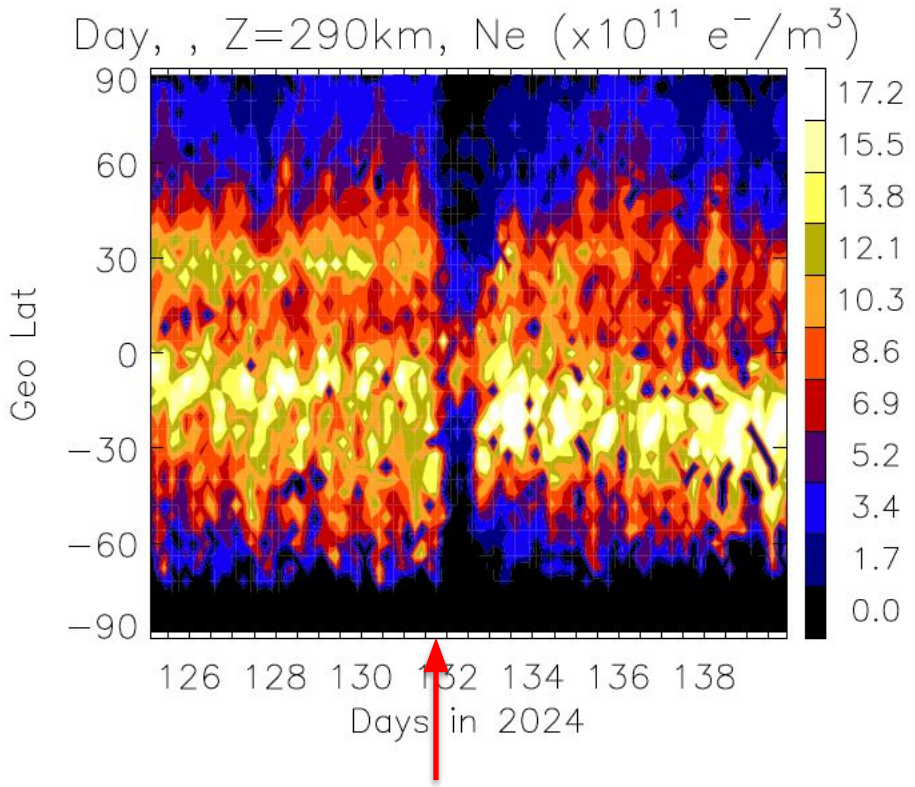
Wu et al. (2022, v4 algorithm)
(D/E-region Ne, vTEC, new v5)
Shaver et al. (2023, Ne vs ionosonde)
Salinas et al. (2024, empirical model)
Salinas et al. (IROWG-10 poster)

Wu et al. (2023, v6p algorithm)
Swarnalingam et al. (2023, NmF2, hmF2)
Swarnalingam et al. (2024, in review)
(Comparisons with IRI, NeQuick2)

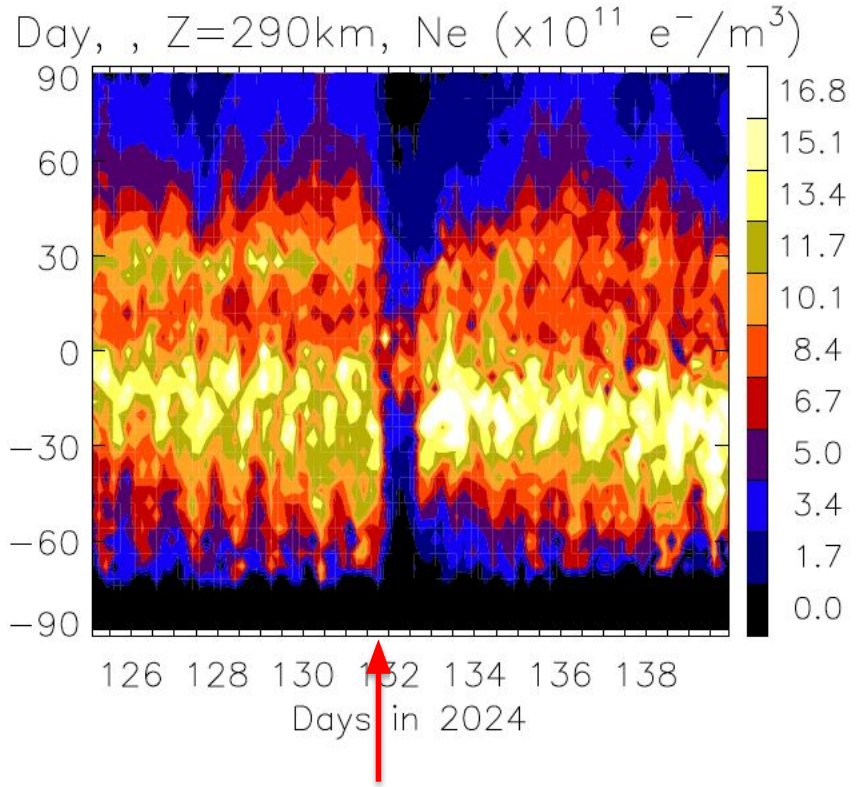
Daytime 4-Hourly F-Region Ne

- Spire + FY3 sampling helps
- Large polar and tropical depletion in F-region
- Stronger and earlier in the NH than in the SH
- Reduced Ne in the NH subtropics during the recovery
- Enhanced Ne in the SH subtropics during the recovery

Spire only



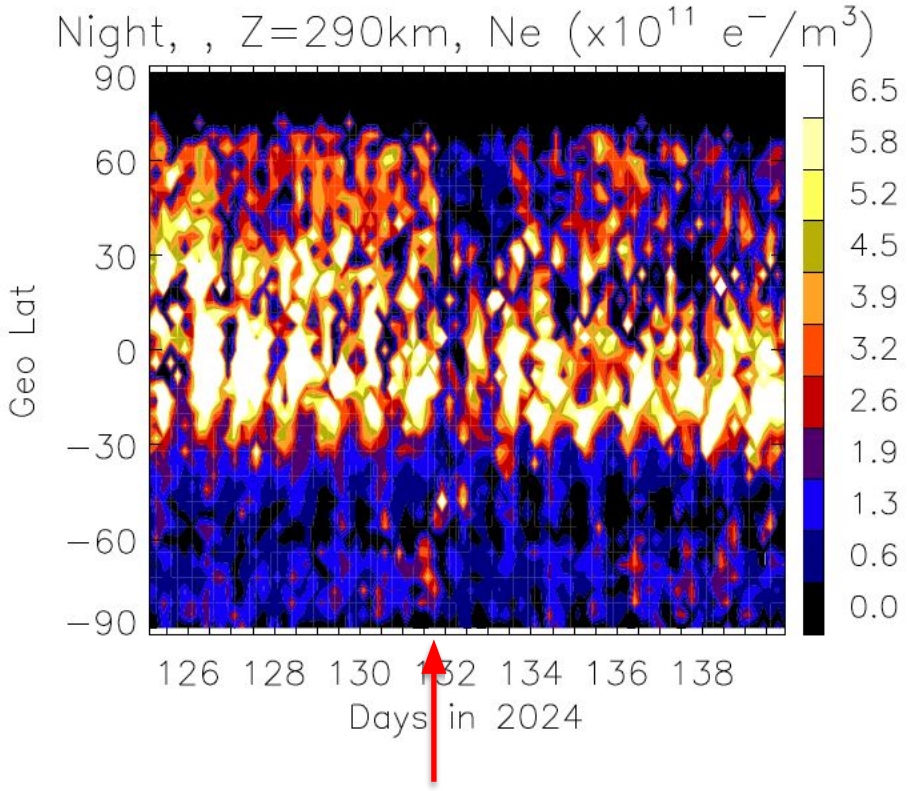
Spire + FY3



Nighttime 4-Hourly F-Region Ne

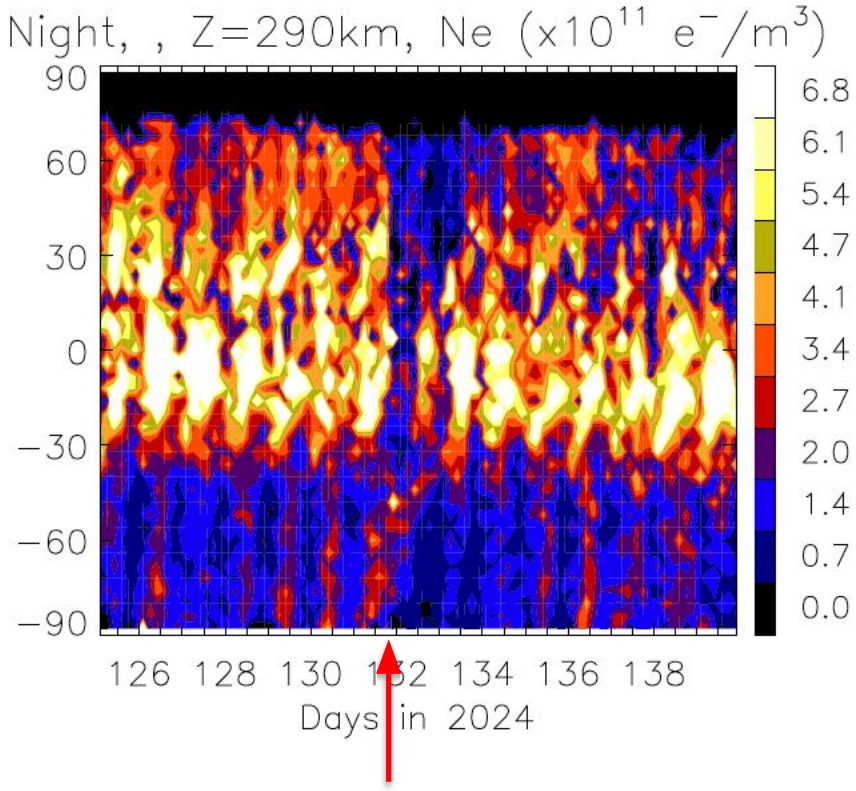
- Spire + FY3 sampling helps
- Significant polar and tropical depletion
- Reduced Ne in the NH subtropics during the recovery

Spire only



17 Z May 10 (Day 131)

Spire + FY3

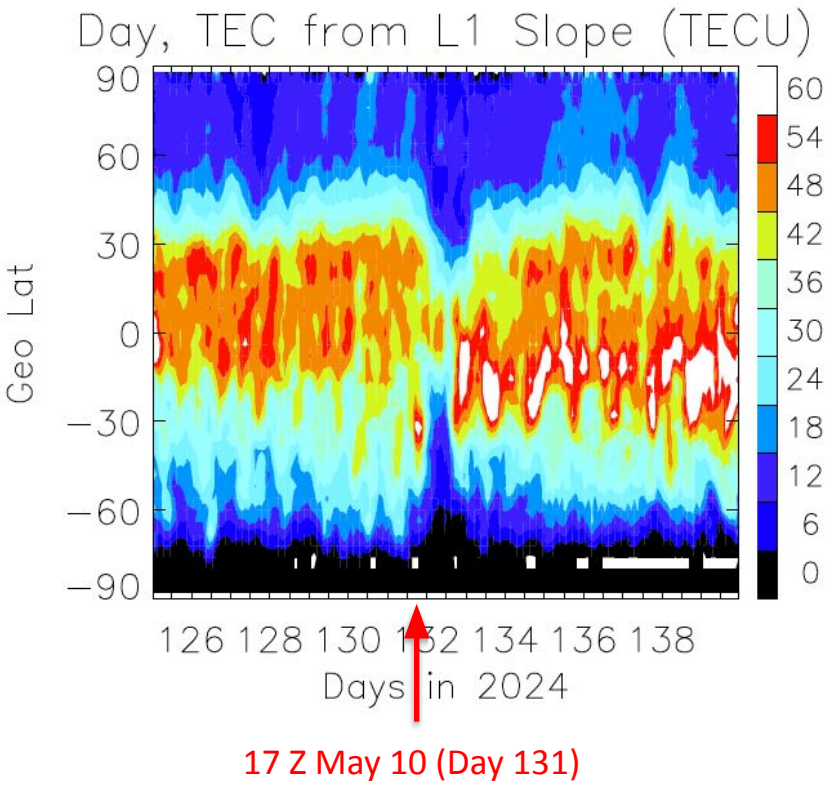


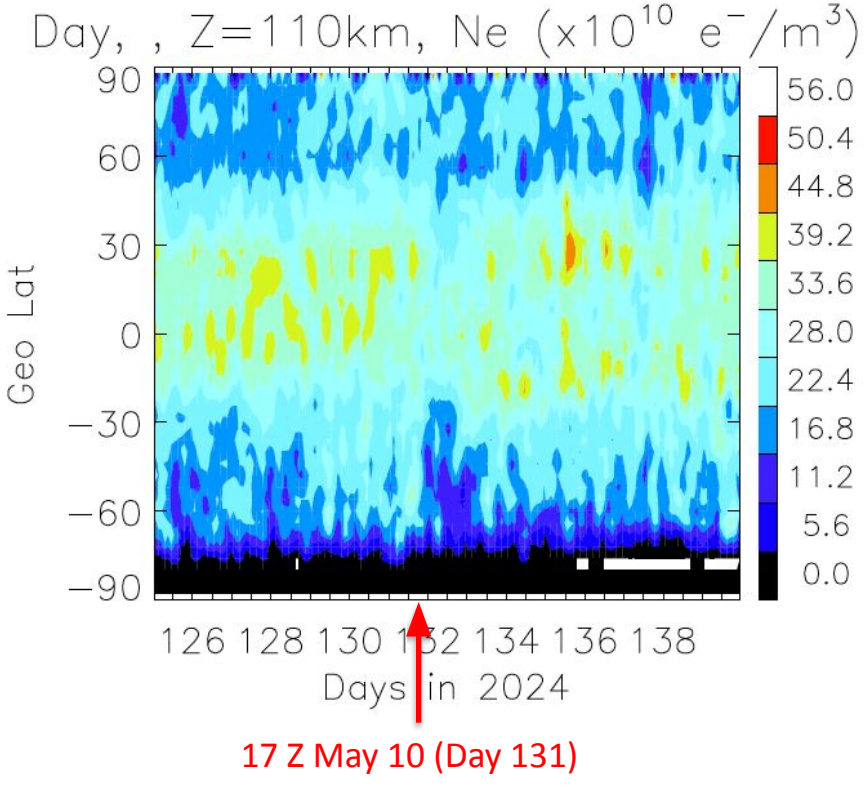
17 Z May 10 (Day 131)

Daytime 2-Hourly (Spire + FY3) E-Region Ne

- Consistent polar depletion between RO vTEC and F-region Ne
- Unlike F-region, stronger E-region depletion in the SH
- Small E-region changes during the recovery

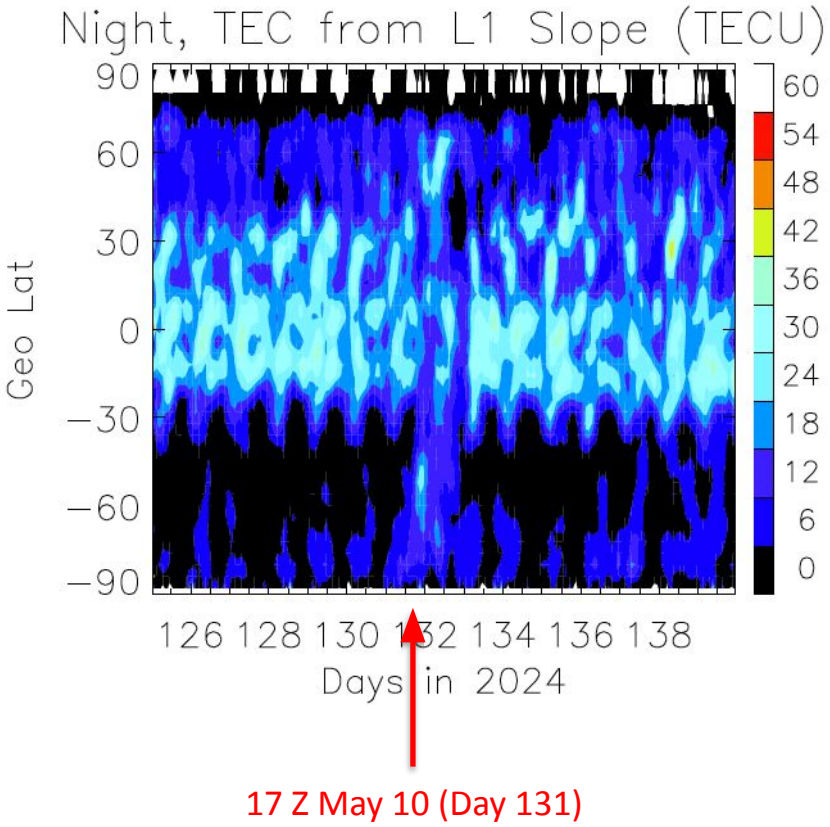
Uncalibrated vTEC from RO (20-50km)

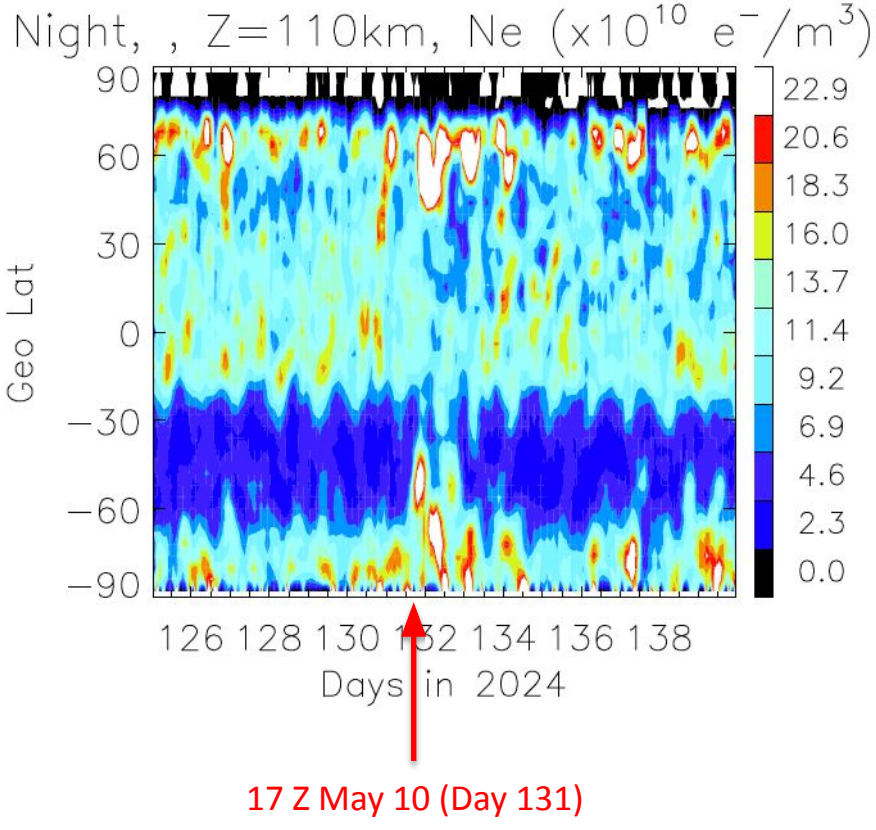




Nighttime 2-Hourly E-Region Ne

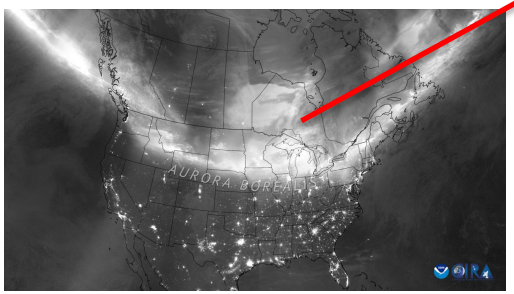
- Weak enhancement in RO vTEC
- Unlike F-region, significant nighttime E-region enhancements
  - Associated with auroral electron precipitation
- Small E-region changes during the recovery



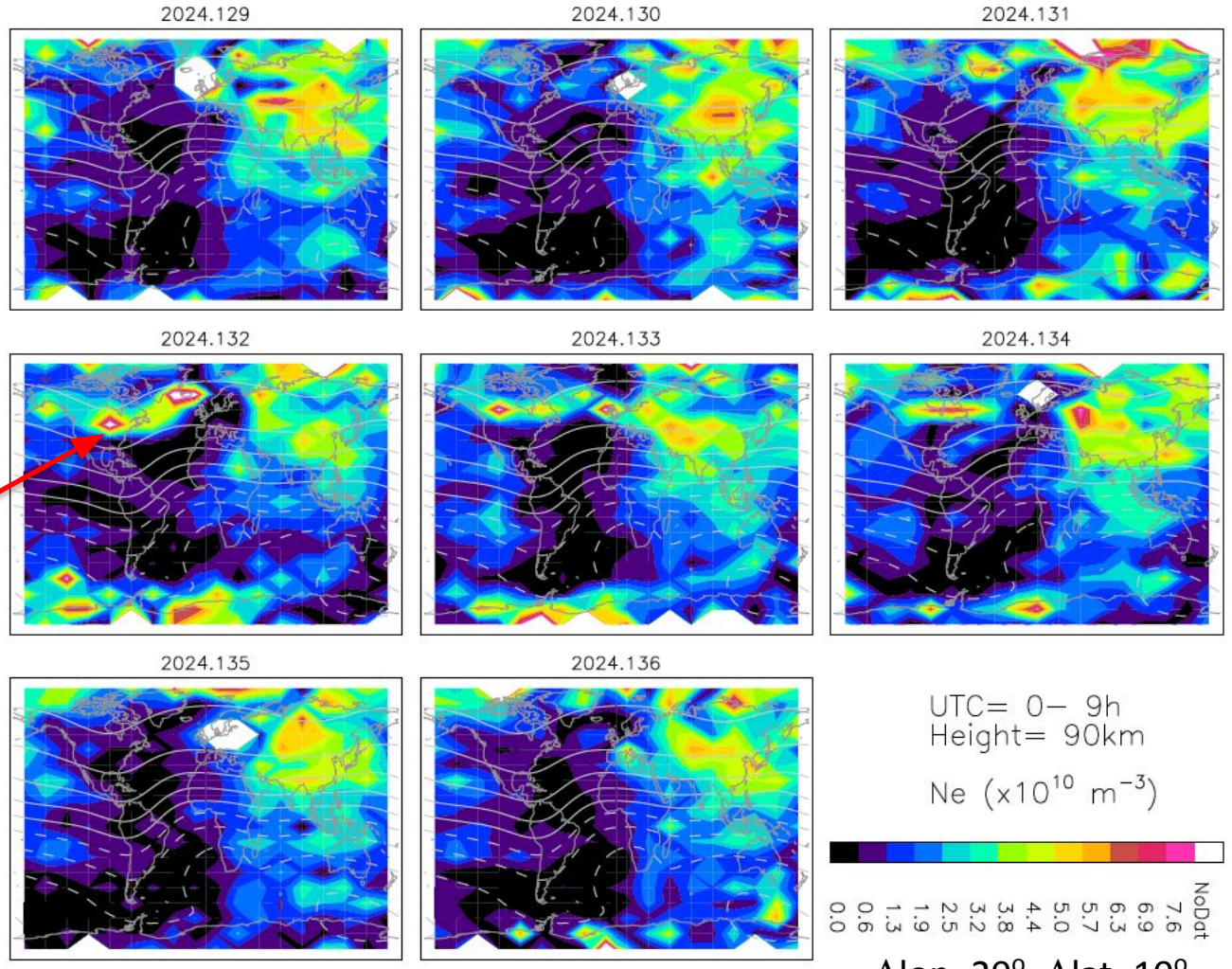


9-Hourly UTC (00Z-09Z) Daily E-Region Ne Maps at 90 km (Spire + FY3 + COSMIC2)

Aurora Borealis
over the U.S.
from VIIRS DNB mosaic

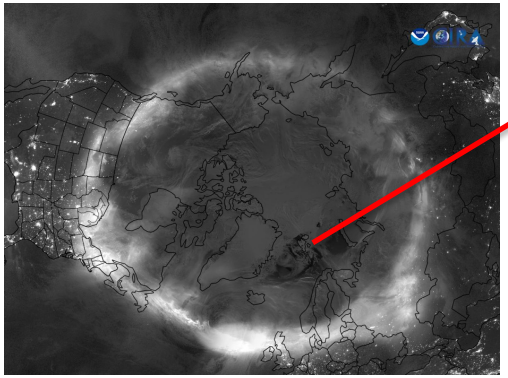


Courtesy of:
CSU/CIRA & NOAA

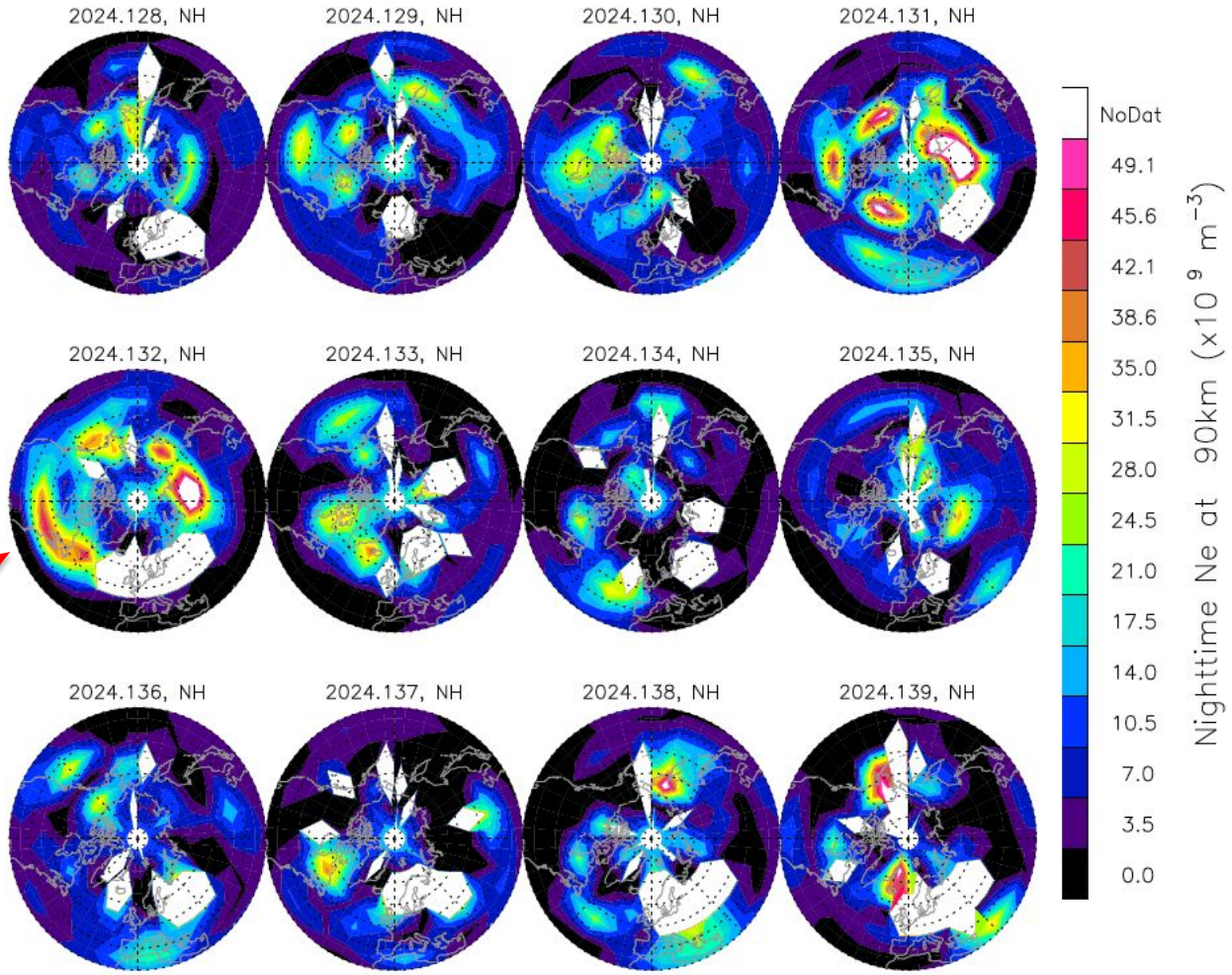


Nighttime Polar E-Region Ne Maps at 90 km (Spire + FY3 + COSMIC2)

Aurora Borealis
over the U.S.
from VIIRS DNB mosaic



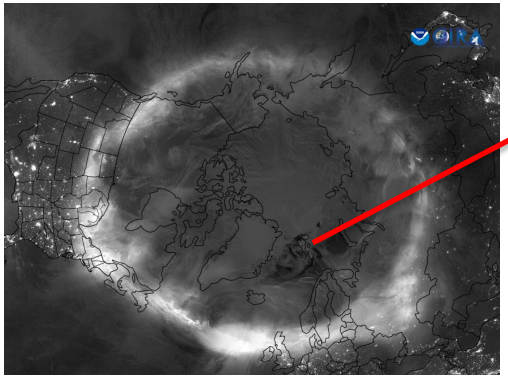
Courtesy of:
CSU/CIRA & NOAA



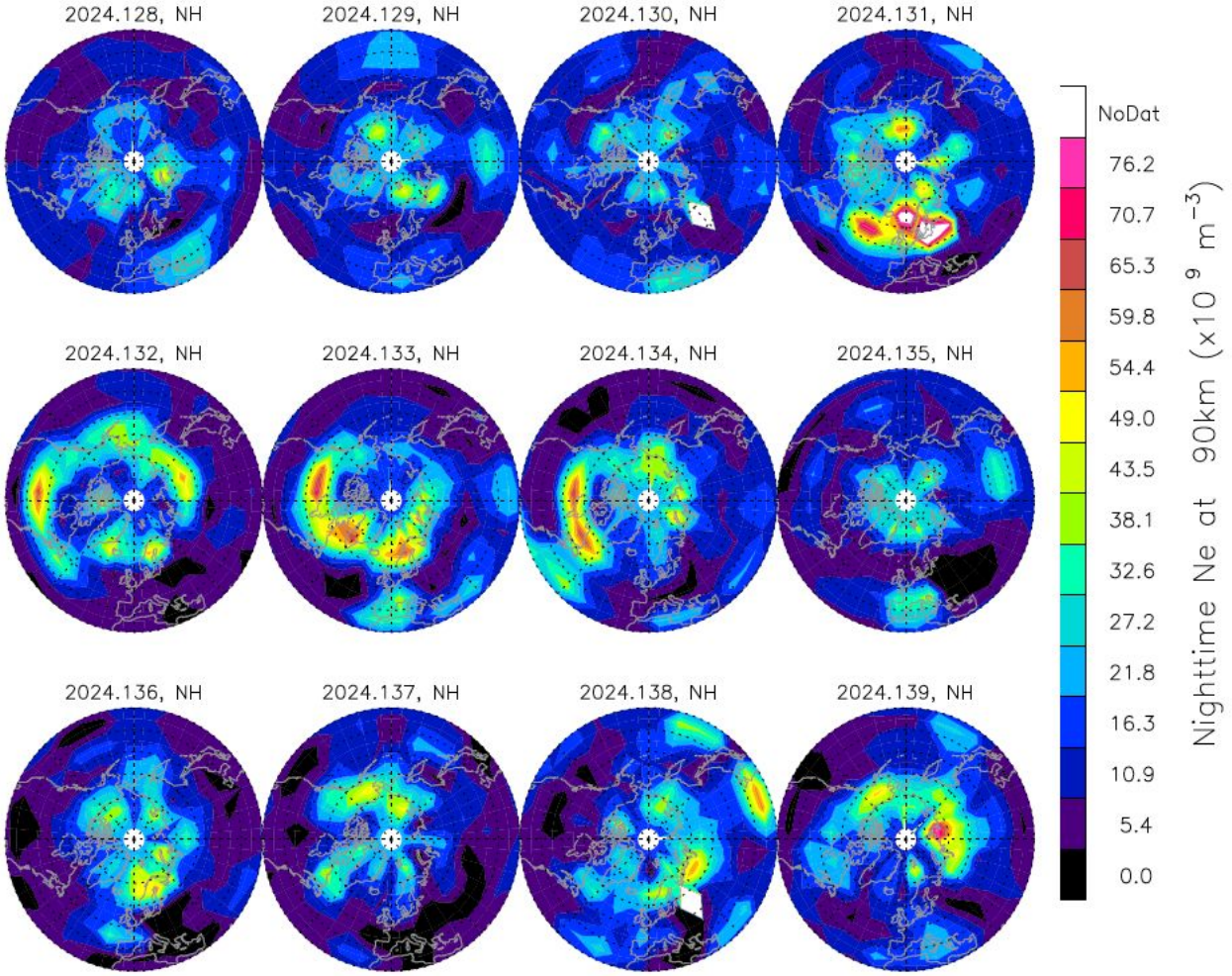
- Insufficient nighttime polar coverage from Spire + FY3

Daytime Polar E-Region Ne Maps at 90 km (Spire + FY3 + COSMIC2)

Aurora Borealis
over the U.S.
from VIIRS DNB mosaic



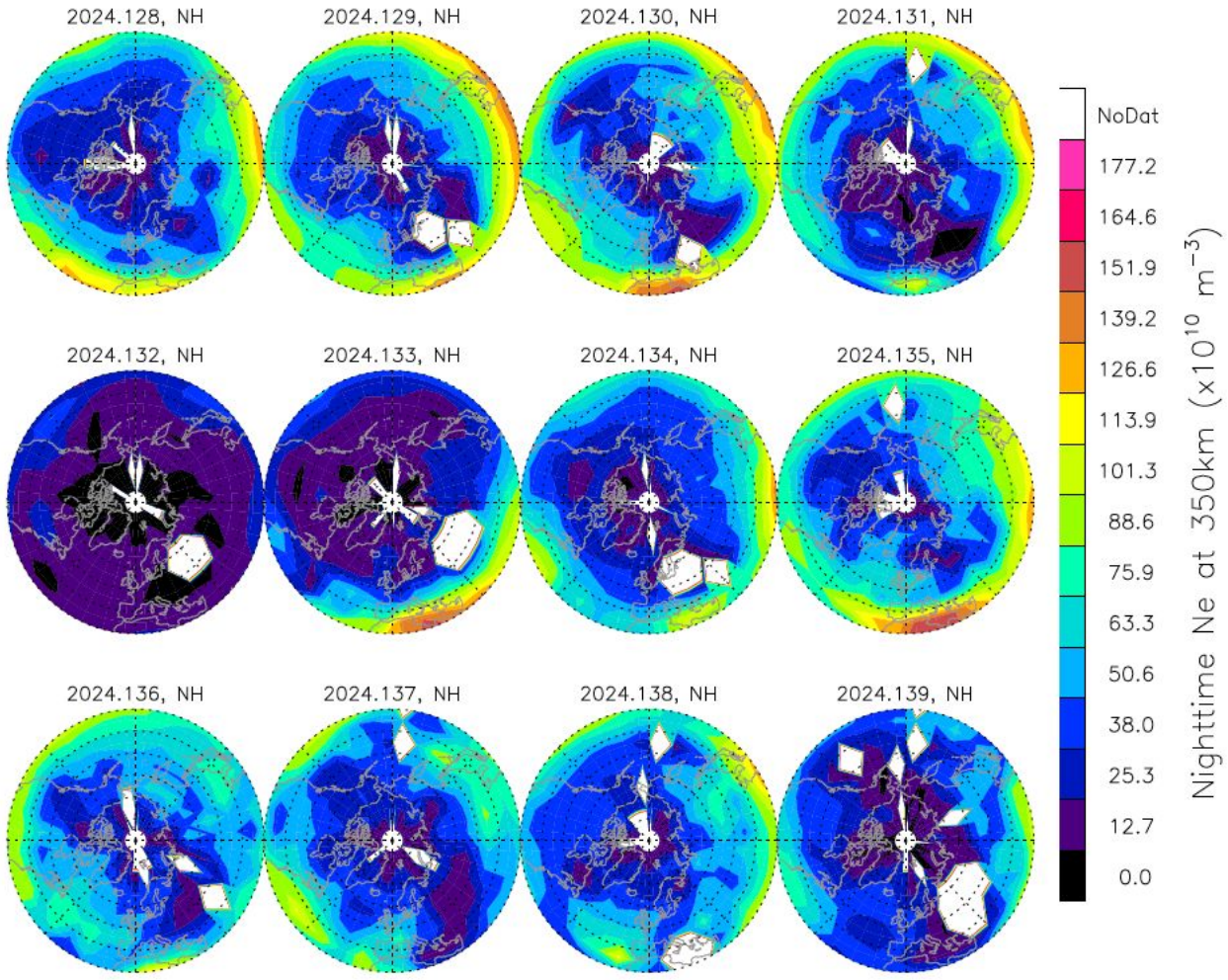
Courtesy of:
CSU/CIRA & NOAA



- Better daytime polar coverage from Spire + FY3

Daytime Polar F-Region Ne Maps at 350 km (Spire + FY3 + COSMIC2)

- Polar daytime Ne was depleted in the F-region shortly after the storm hits.
- Recovery took ~2 days.
- Russia-Ukraine war has a significant impact on sampling.



Summary

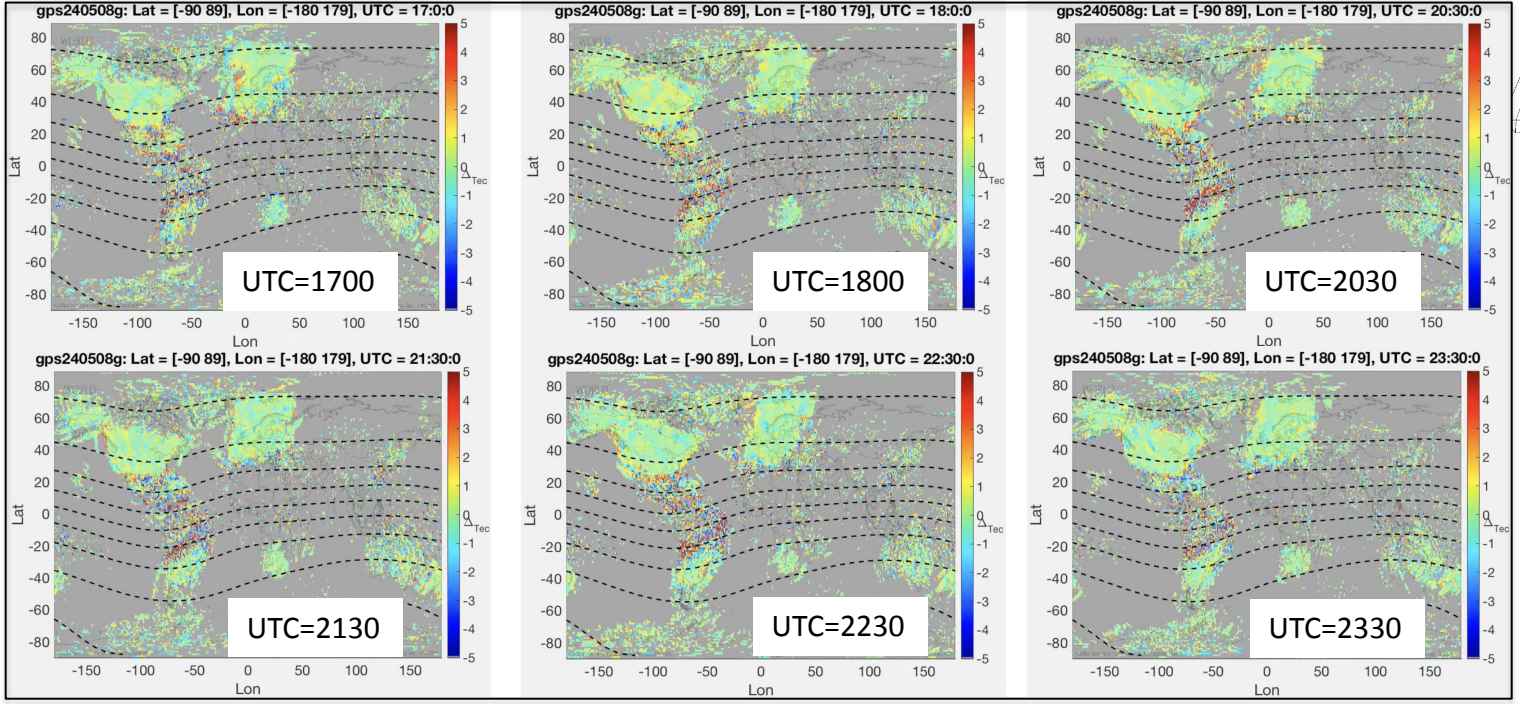
- GNSS-RO and GNSS-POD soundings provided unprecedented observations of the May 10 superstorm impacts on the global E- and F-region ionosphere.
- Hemispheric differences are evident in F-region responses:
  - Stronger and earlier NH Ne reduction
  - Enhanced Ne in the SH subtropics during the recovery
- E-region nighttime Ne enhancement extended to mid-latitudes, consistent with worldwide auroral reports.
- The 20k of daily GNSS-RO samples remain insufficient for observating rapid global ionospheric disturbances.

Acknowledgments

- UCAR COSMIC Data Analysis and Archive Center (CDAAC) for C2 L1B data
- NASA's Commercial Smallsat Data Acquisition (CSDA) and NOAA's Commercial Data Program (CDP) for Spire L1B data
- China Meteorological Administration (CMA) National Satellite Meteorological Center (NSMC) for FY3 L1B data
- Support from NASA's Living With a Star (LWS) program

Backup Slides

May 8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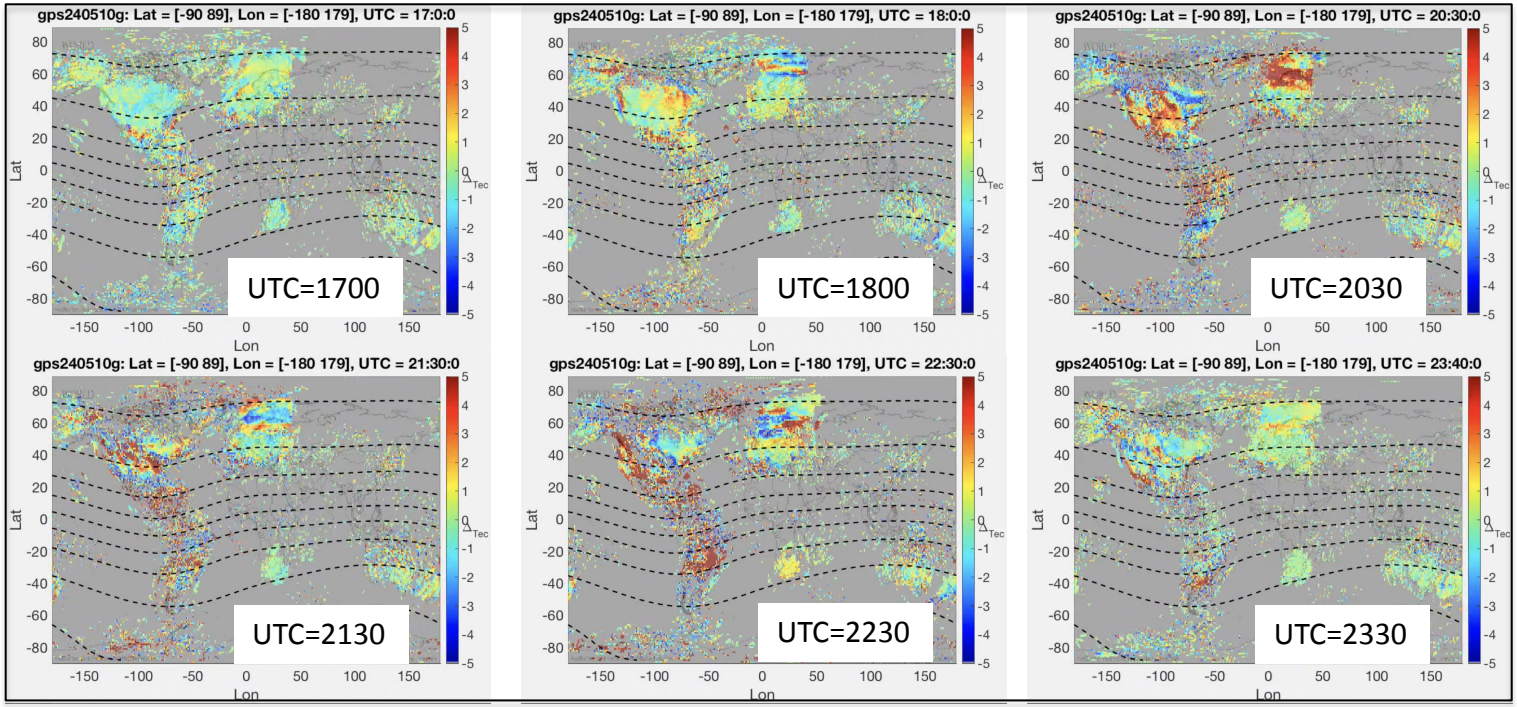
May 10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Lat
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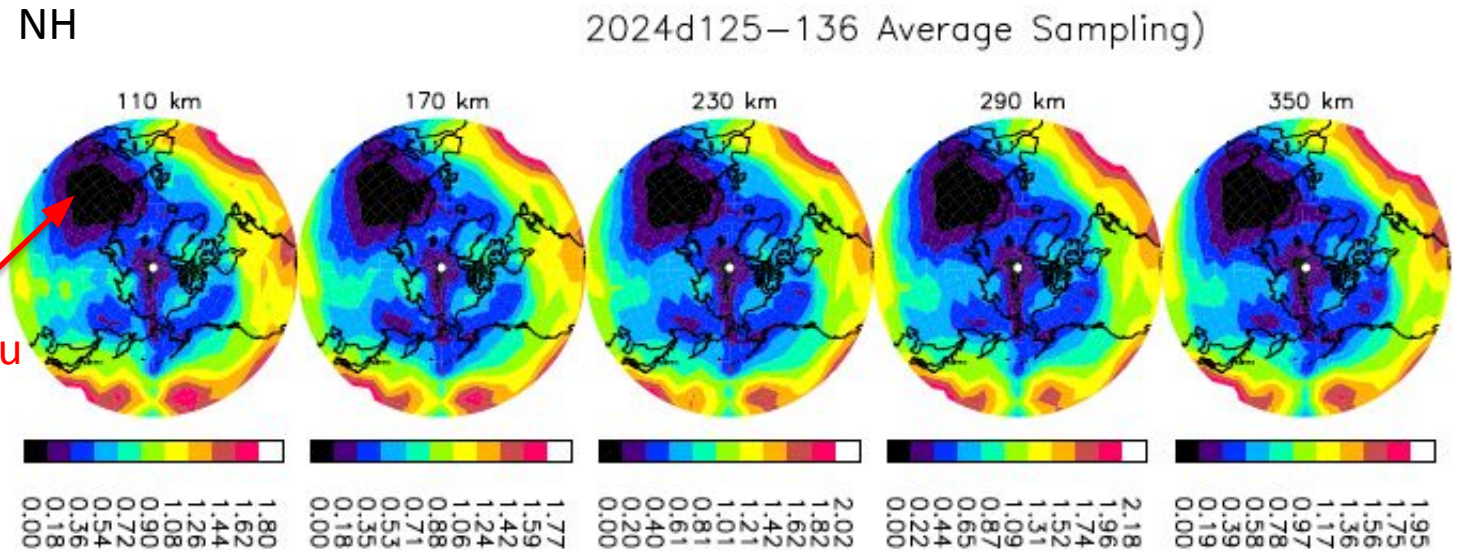
Sampling Density Maps

NH



Missing Data in Ukraine-Russia

SH