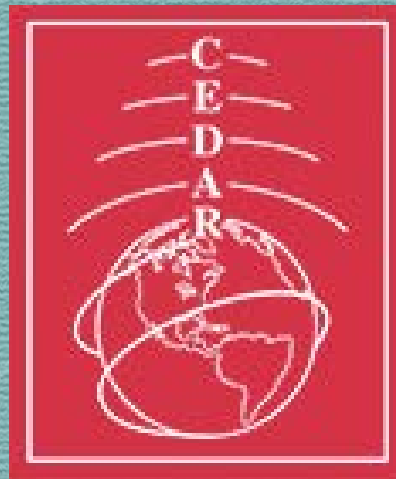




June 21-26, 2026

Des Moines, Iowa

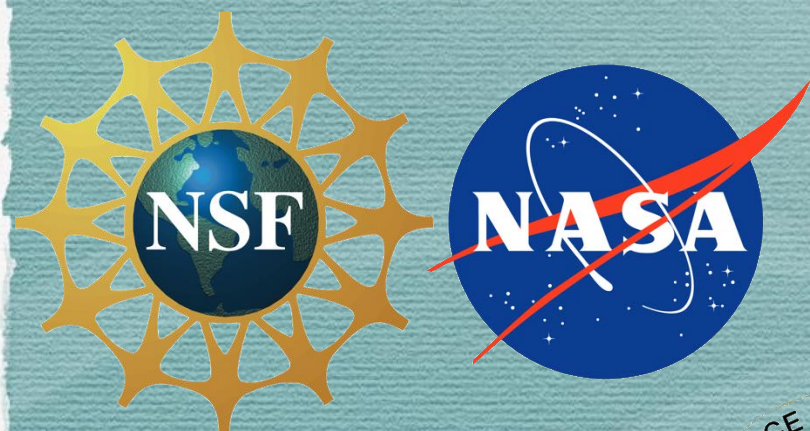
Monday 0840 | Jr. Ballroom

GNSS-Enabled Discoveries of Traveling Ionospheric Disturbances: New Insights into Multi-Source Coupling Within and Into Geospace

Shun-Rong Zhang

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Juha Vierinen, Nestor Aponte, Ercha Aa, Jing Liu, Sevag Derghazarian

MIT Haystack Observatory



Collaborators: Toshi Nishimura, Larry Lyons, Yue Deng, Juha Vierinen, Xian Lu, Hanli Liu,
Scott England, Wenbin Wang, Liying Qian, Jiuhou Lei, Changzhi Zhai, P.T. Jayachandran



GNSS Data is provided by the following organizations:

UNAVCO, Scripps Orbit and Permanent Array Center, Institut Geographique National, France, International GNSS Service, The Crustal Dynamics Data Information System (CDDIS), National Geodetic Survey, Instituto Brasileiro de Geografia e Estatística, RAMSAC CORS of Instituto Geográfico Nacional de la República Argentina, Arecibo Observatory, Low-Latitude Ionospheric Sensor Network (LISN), Topcon Positioning Systems, Inc., Canadian High Arctic Ionospheric Network (CHAIN), Centro di Ricerche Sismologiche, Système d'Observation du Niveau des Eaux Littorales (SONEL), RENAG : REseau NAtional GPS permanent, GeoNet - the official source of geological hazard information for New Zealand, GNSS Reference Networks, Finnish Meteorological Institute, and SWEPOS - Sweden, Chinese Meridian Project, and International Meridian Circle Program (IMCP).



1. Detecting TIDs

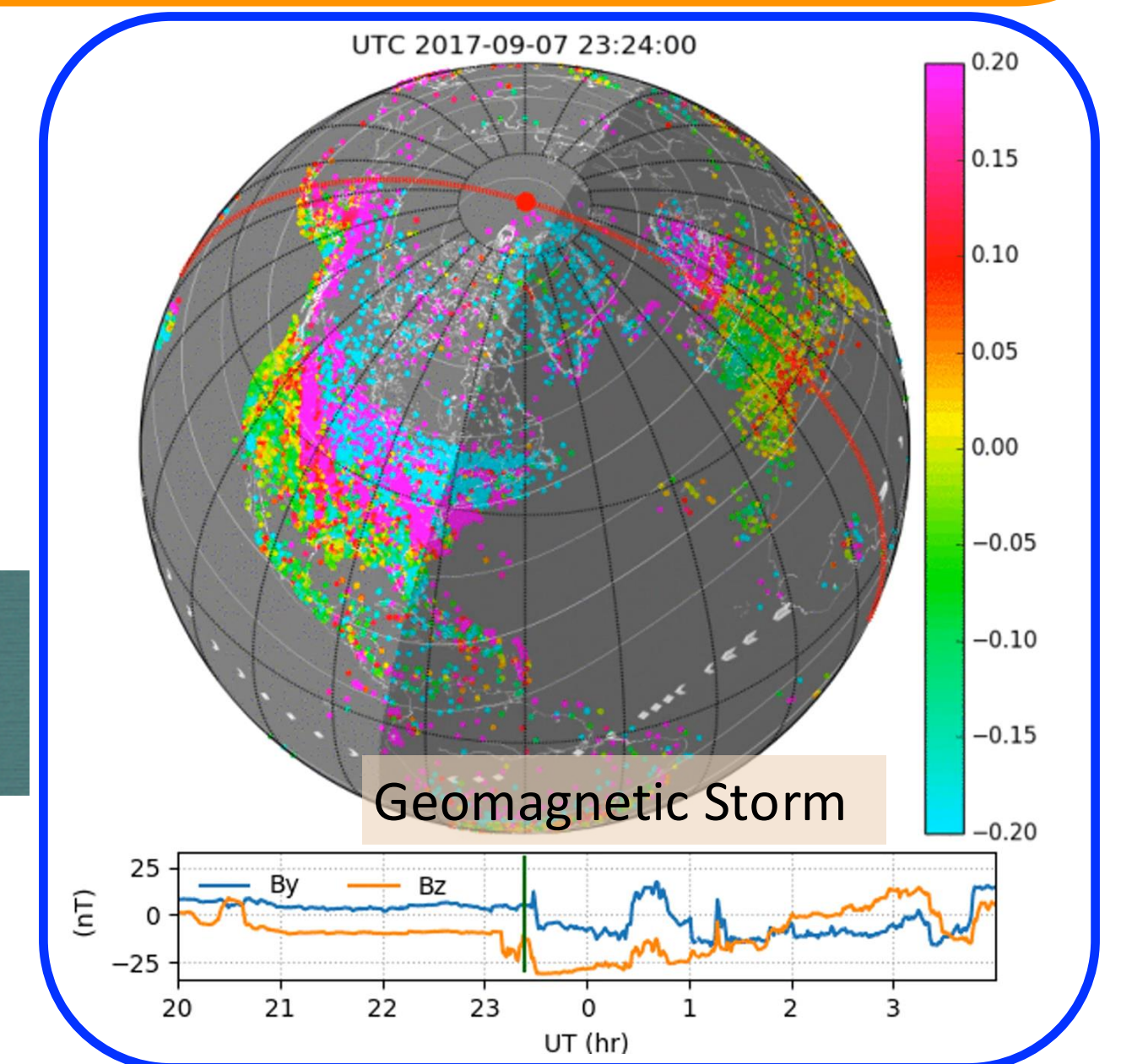
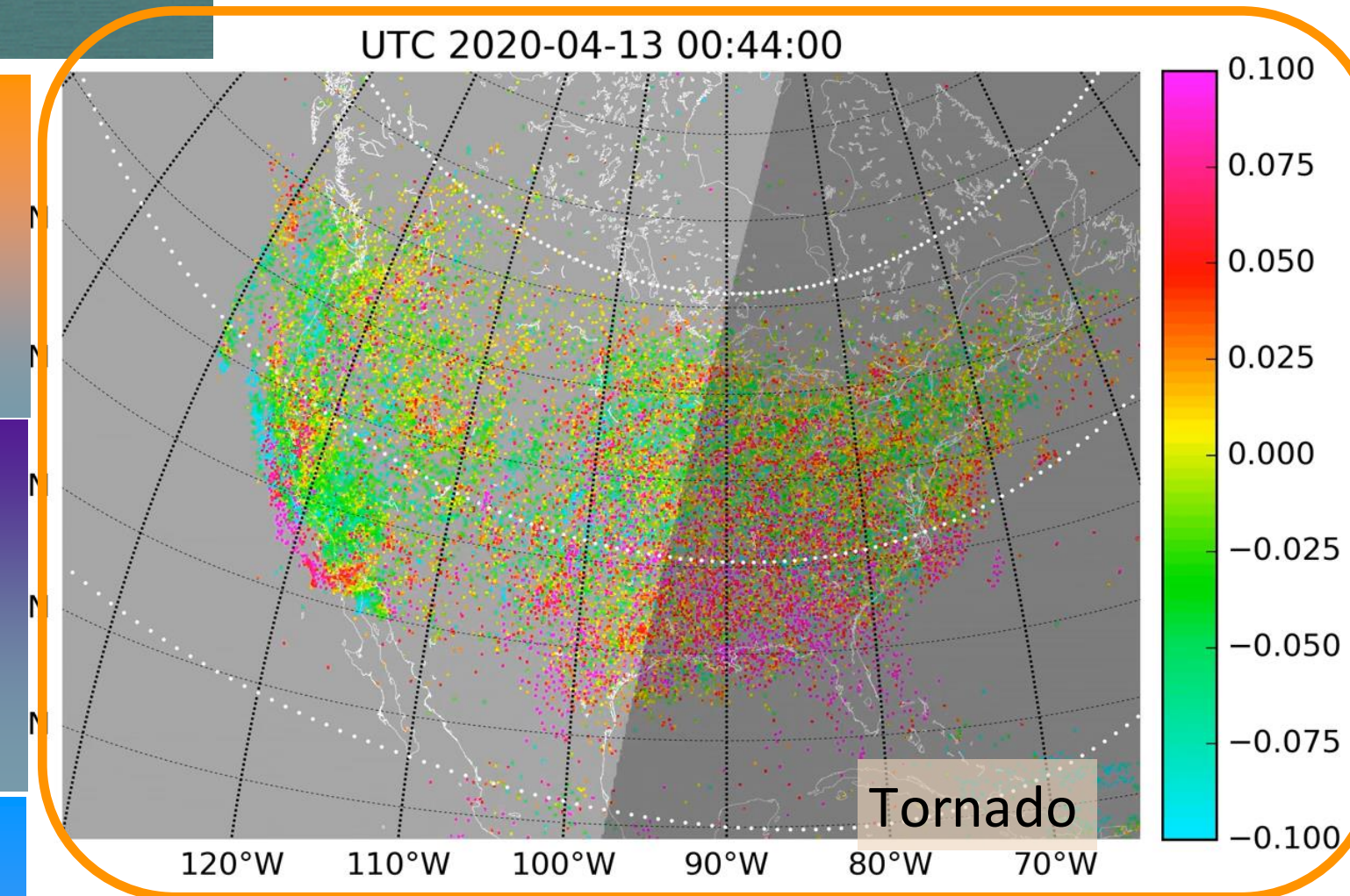
2. MSTIDs: Climatology, Trends, and GW Influences GWs or Ionospheric electric dynamics ?

3. Ionospheric waves induced by Tonga volcanic eruption Lamb waves or/and GWs ?

4. Toward building a global picture of storm-time TIDs Transpolar TIDs: GWs or patches ?

5. New Applications: Using dTEC to detect Penetration Electric Field (PEF)

6. Summary



A-H equation is simplified for high frequency radio ($f \gg f_p, f \gg \nu_e, \omega = 2\pi f \gg \omega_B$)

$$n = (1 - f_p^2/f^2)^{1/2} \approx 1 - f_p^2/(2f^2) = 1 - 40.3N/f^2$$

refractive index

$$v_p = \omega/k = c/n = c(1 - 40.30N/f^2)^{-1} \approx c(1 + 40.30N/f^2)$$

phase velocity

$$v_g = \partial\omega/\partial k = c/[\partial(nf)/\partial f] = c(1 + 40.30N/f^2)^{-1} \approx c(1 - 40.30N/f^2)$$

group velocity

$$\tau_{g|p} = \int_s ds/v_{g|p} = 1/c \int_s (1 \pm 40.30N/f^2) ds = \tau_0 \pm 40.30/(cf^2) \int_s N ds$$

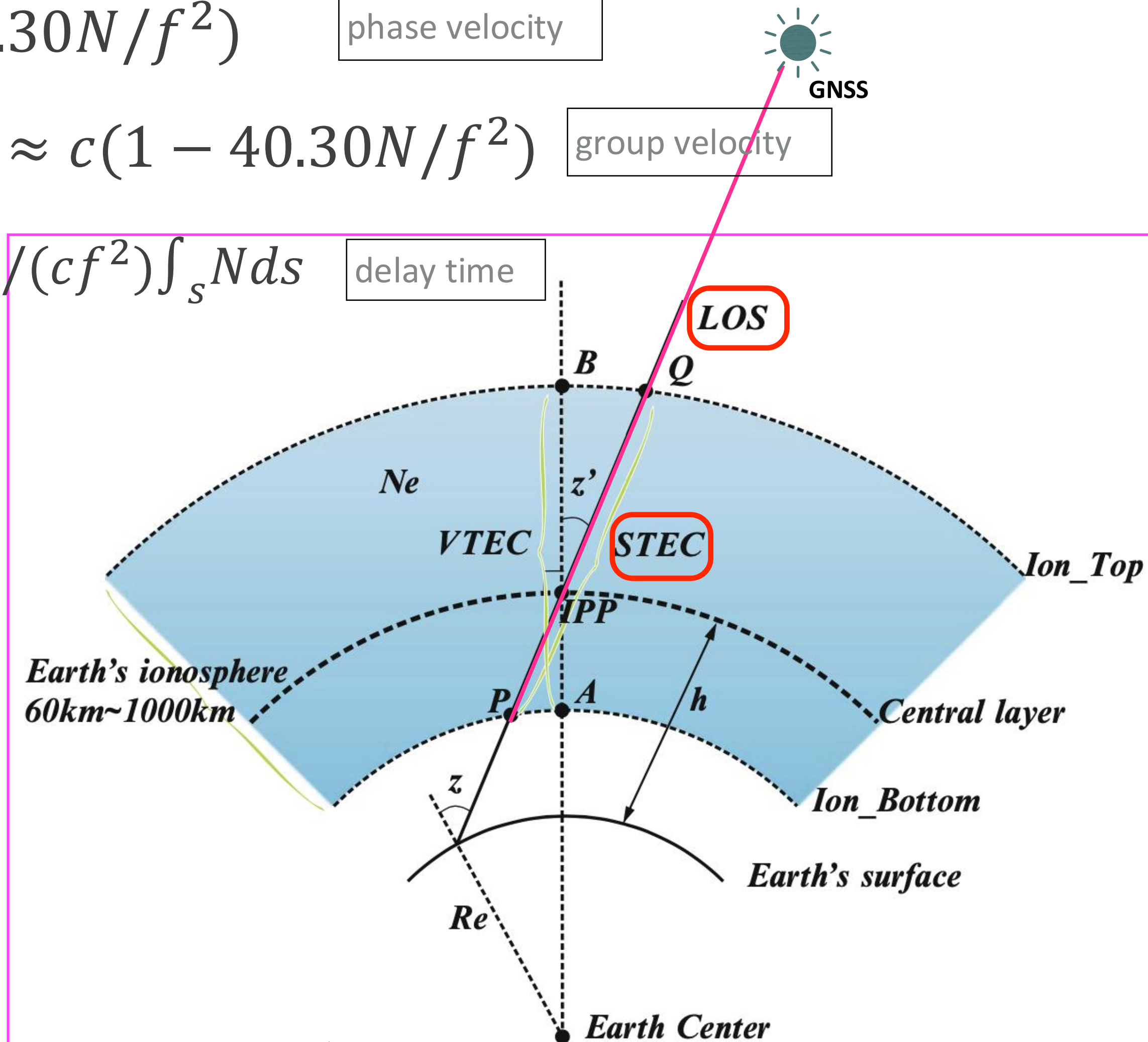
delay time

$$\text{TEC (los)} = \int_s N ds$$

$$\delta\tau_{g1} - \delta\tau_{g2} = \frac{40.30}{c} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \text{TEC}$$

$$\delta\tau_{p2} - \delta\tau_{p1} = \frac{40.30}{c} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \text{TEC}$$

Errors: bias: DCB; Multipaths

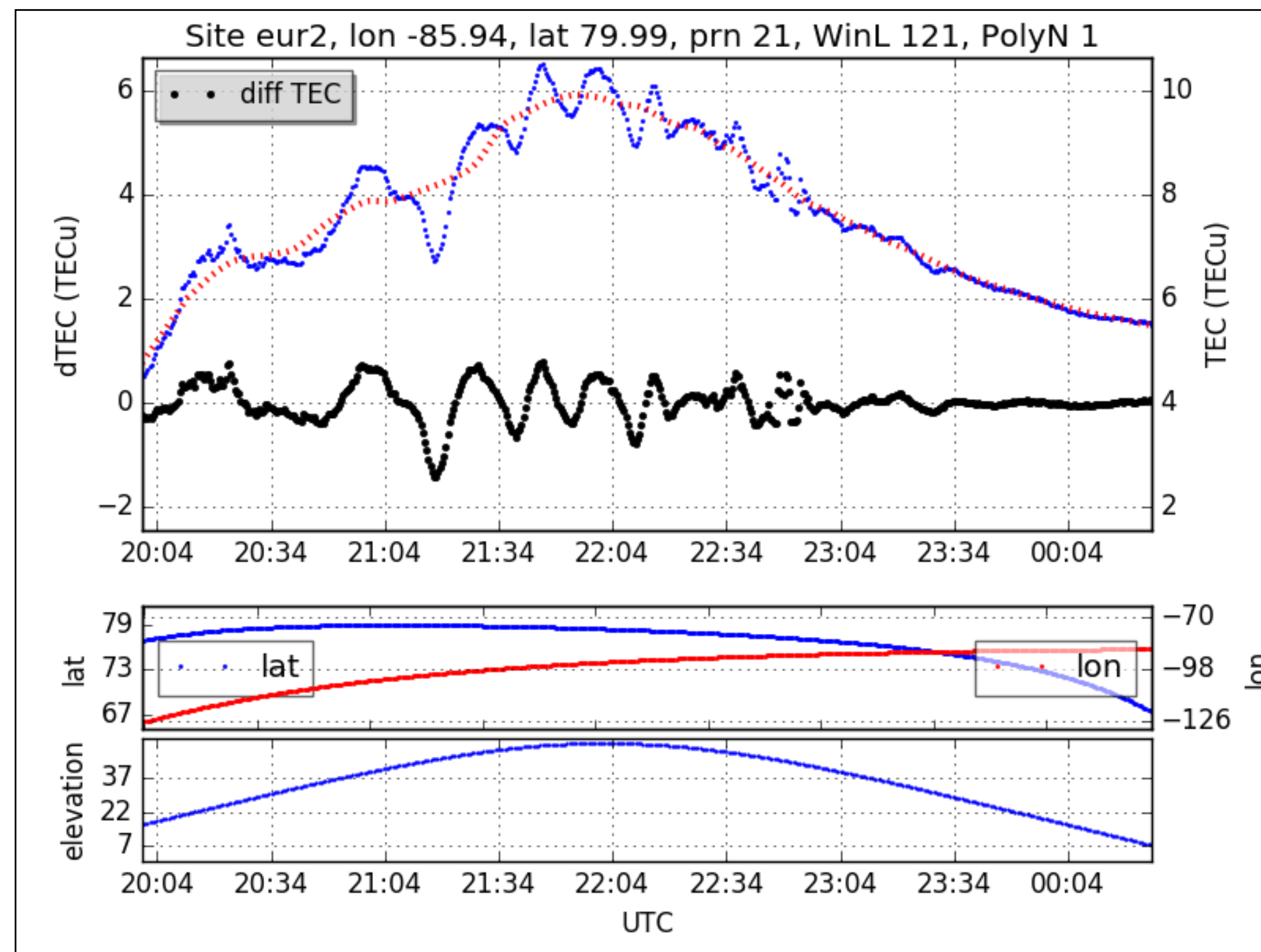


S. Jing et al. (2014)

Savitzky-Golay low-pass filter to provide background TEC variations that will be de-trended: similar to running averaging with sliding windows.

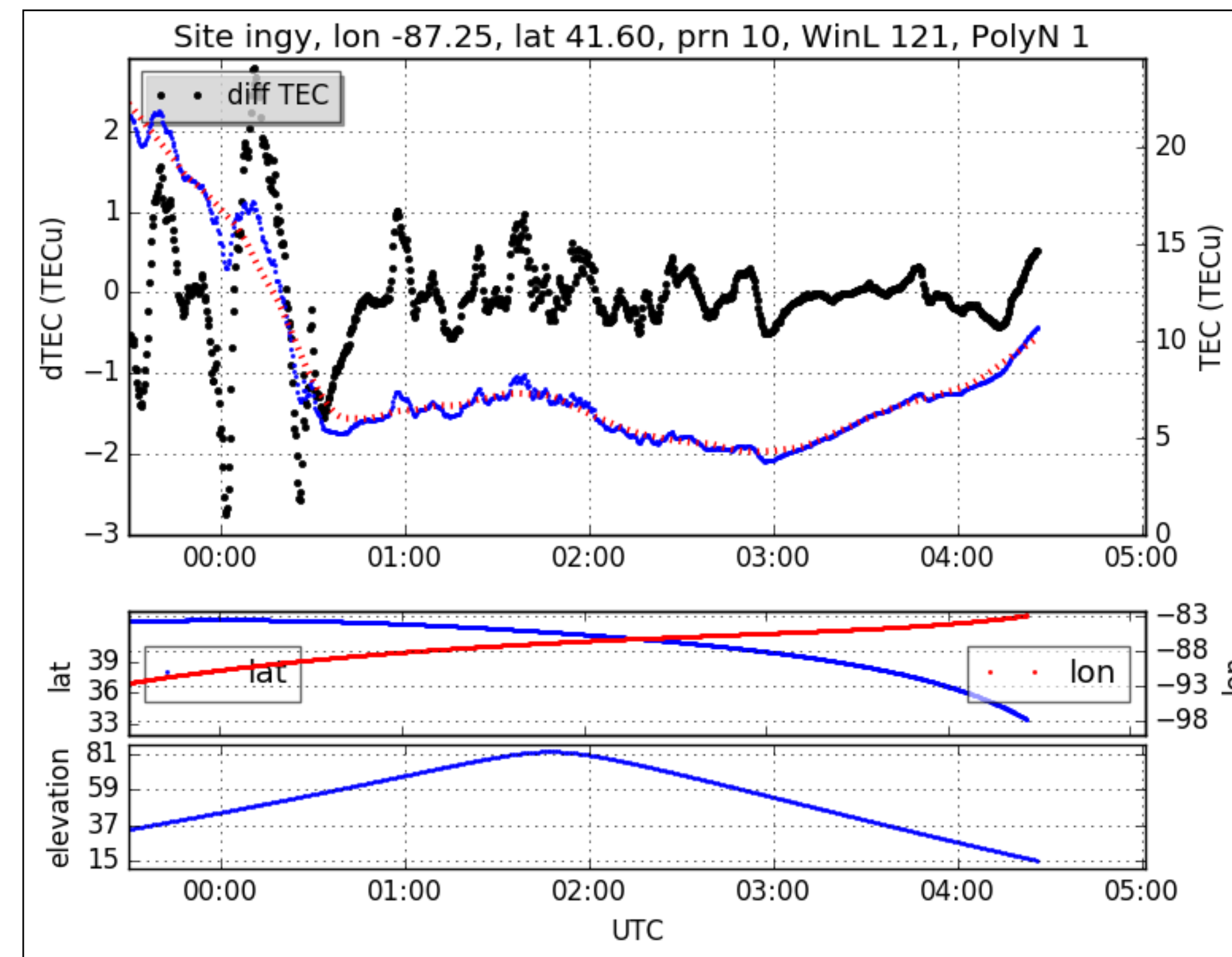
$$\text{TEC} = B \text{ (lp-filter)} + d\text{TEC}$$

Polar region

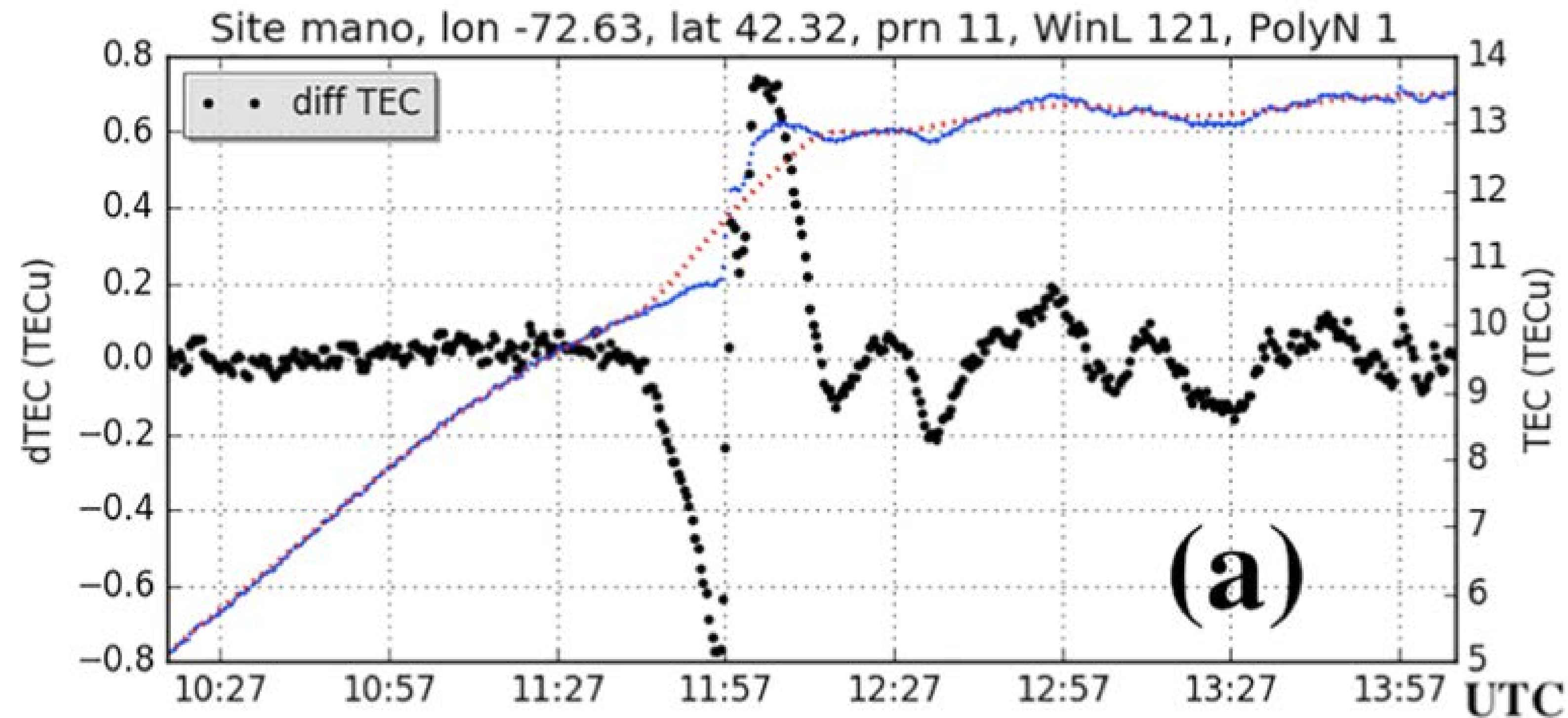


$$\begin{aligned} \mathbf{aTEC} &= |d\text{TEC}| \text{ (dTEC intensity)} \\ \mathbf{aTEC} &\sim d\text{TEC (std)} \text{ [Gaussian Distribution]} \\ \mathbf{pTEC} &= \mathbf{aTEC}/\text{TEC} \text{ (dTEC relative intensity)} \end{aligned}$$

Midlatitude main trough region

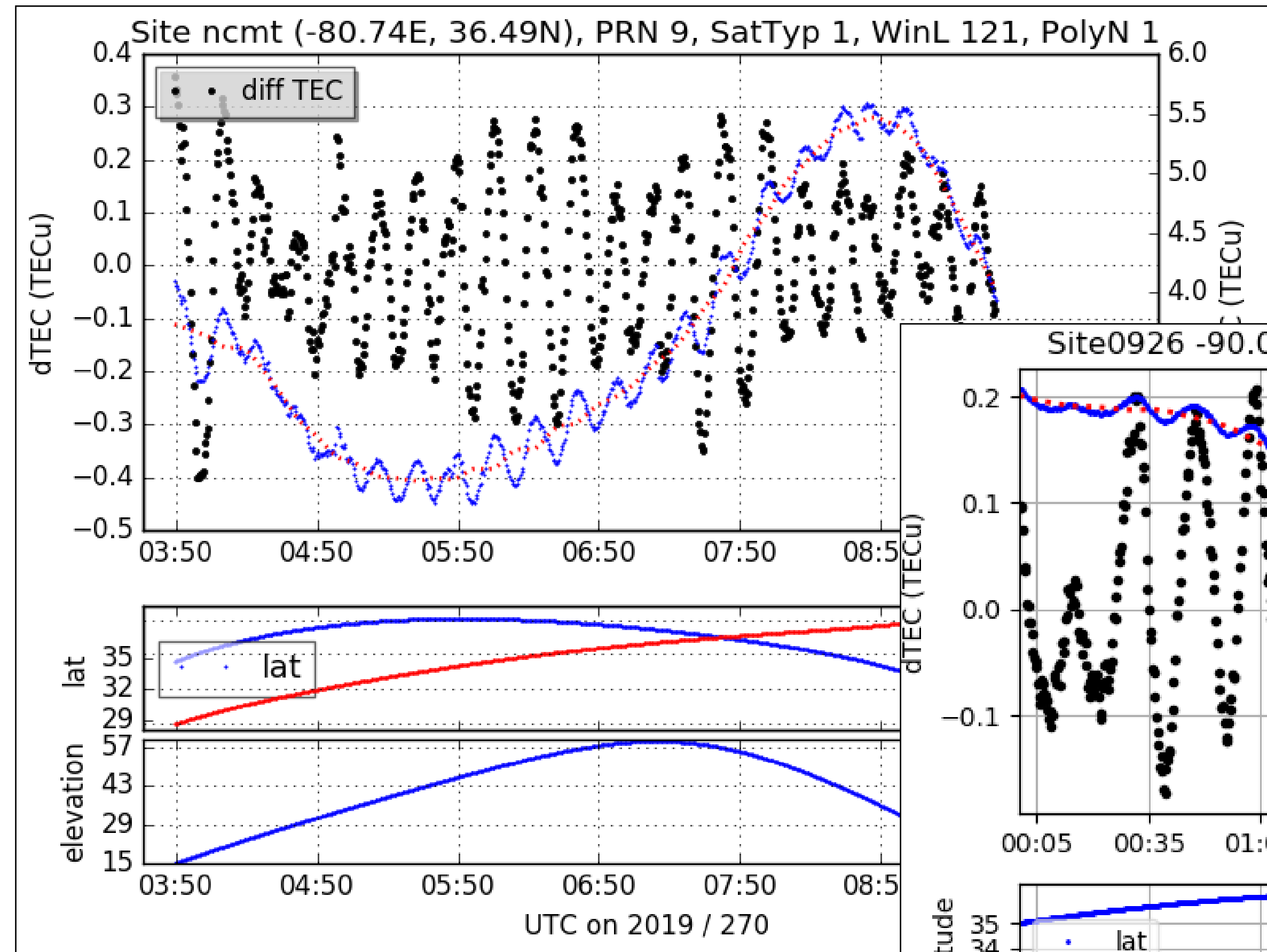


Sept 6, 2017: X9.3

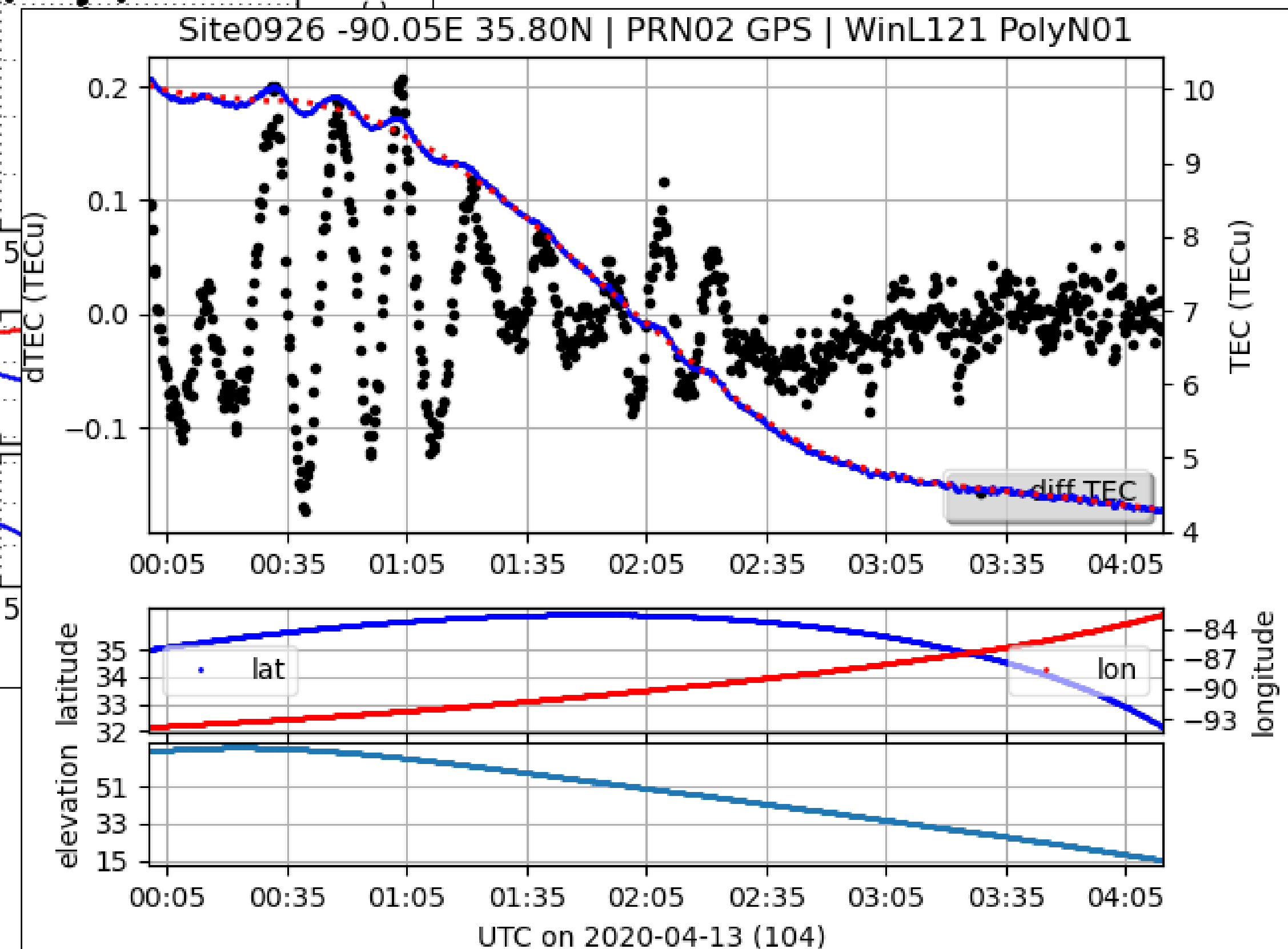


Zhang, S.-R., Coster, A. J., Erickson, P. J., Goncharenko, L. P., Rideout, W., & Vierinen, J. (2019). Traveling Ionospheric Disturbances and Ionospheric Perturbations Associated With Solar Flares in September 2017. *Journal of Geophysical Research: Space Physics*, 60(8), 895. <http://doi.org/10.1029/2019JA026585>

Hurricane Lorenzo Category 4 at 00 UTC 2019-09-27



2020 Easter Tornado



Period	% Amplitude retained after	
	30-min detrending	60-min detrending
15	100	100
30	100	100
45	59	121
60	36	100
90	17	59
120	10	36
180	5	17

A 30-minute running-average subtraction is a high-pass filter, but it does not create a sharp cutoff at 30 minutes.

For a centered moving average of width T, the low-pass gain for a sinusoid of period P is

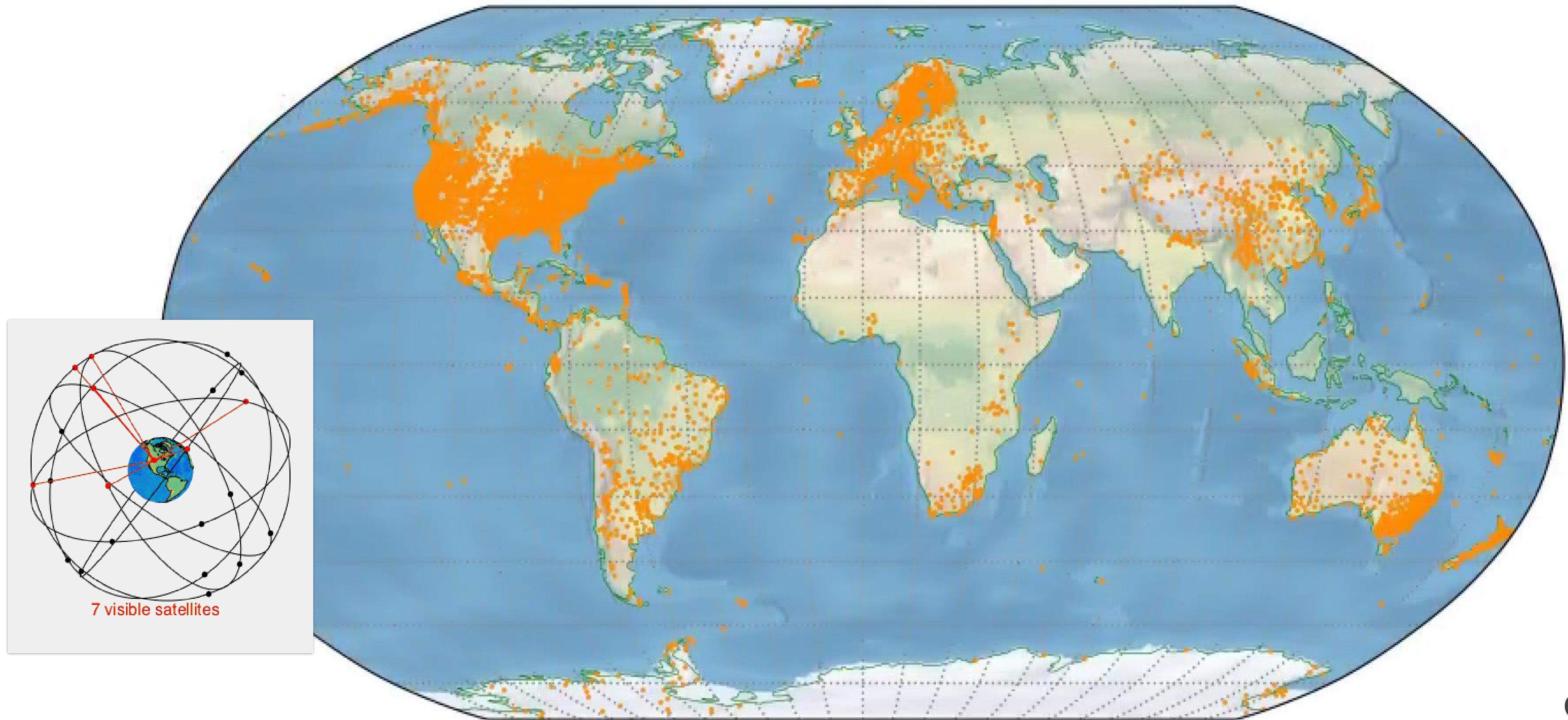
$$H_{LP} = \frac{\sin(\pi T / P)}{\pi T / P}.$$

After subtraction, the residual gain is

$$H_{HP} = 1 - H_{LP} = 1 - \frac{\sin(\pi T / P)}{\pi T / P}.$$

A long window detrending can preserve the long-period of waves but could potentially be contaminated by large storm-time density gradients such as SED and EIA crests

GNSS sites on 09 Sep 2017



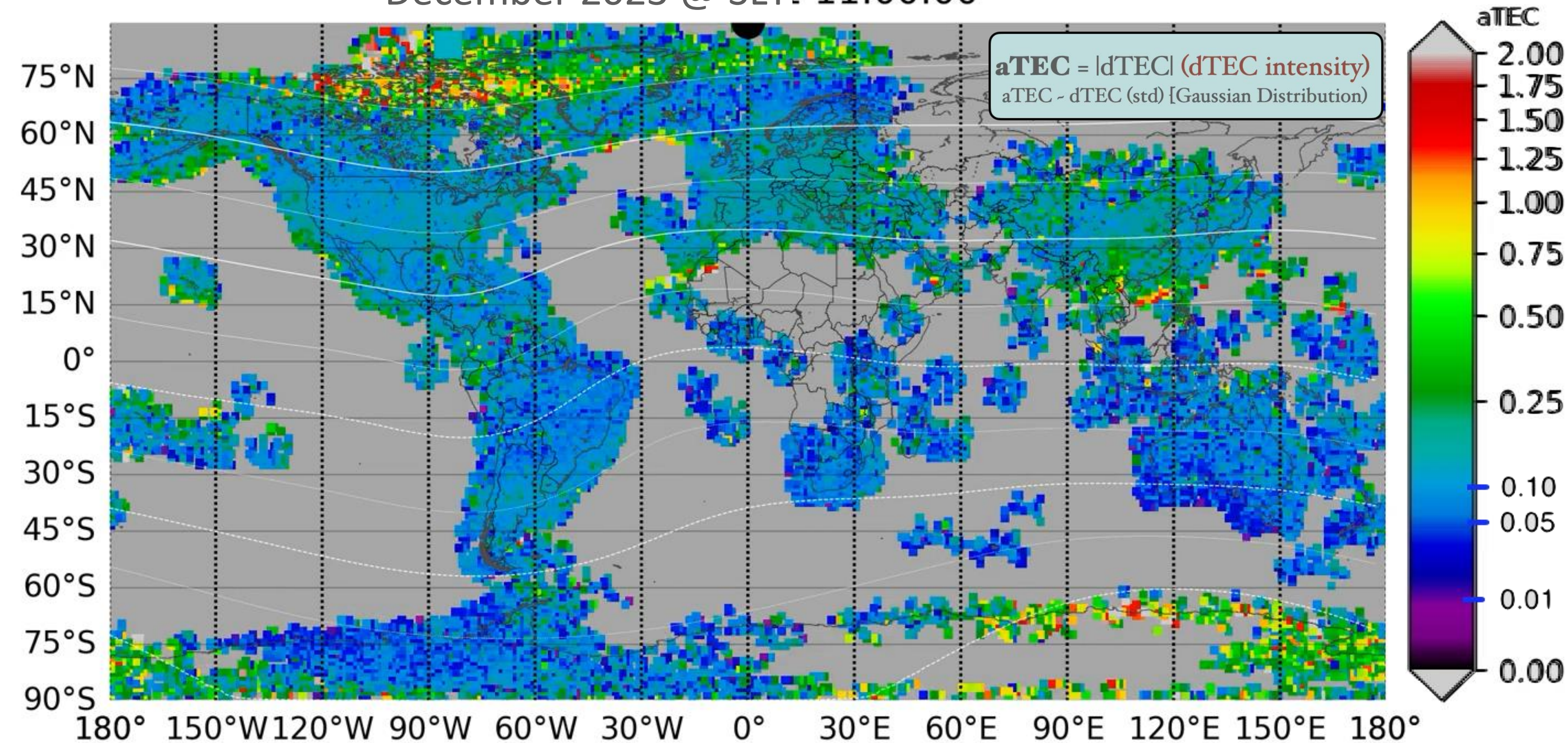
7 visible satellites

The spatial resolution of the IPP distribution is 12–18 times higher than that of the receiver network.

GPS
GLONASS
BeiDou

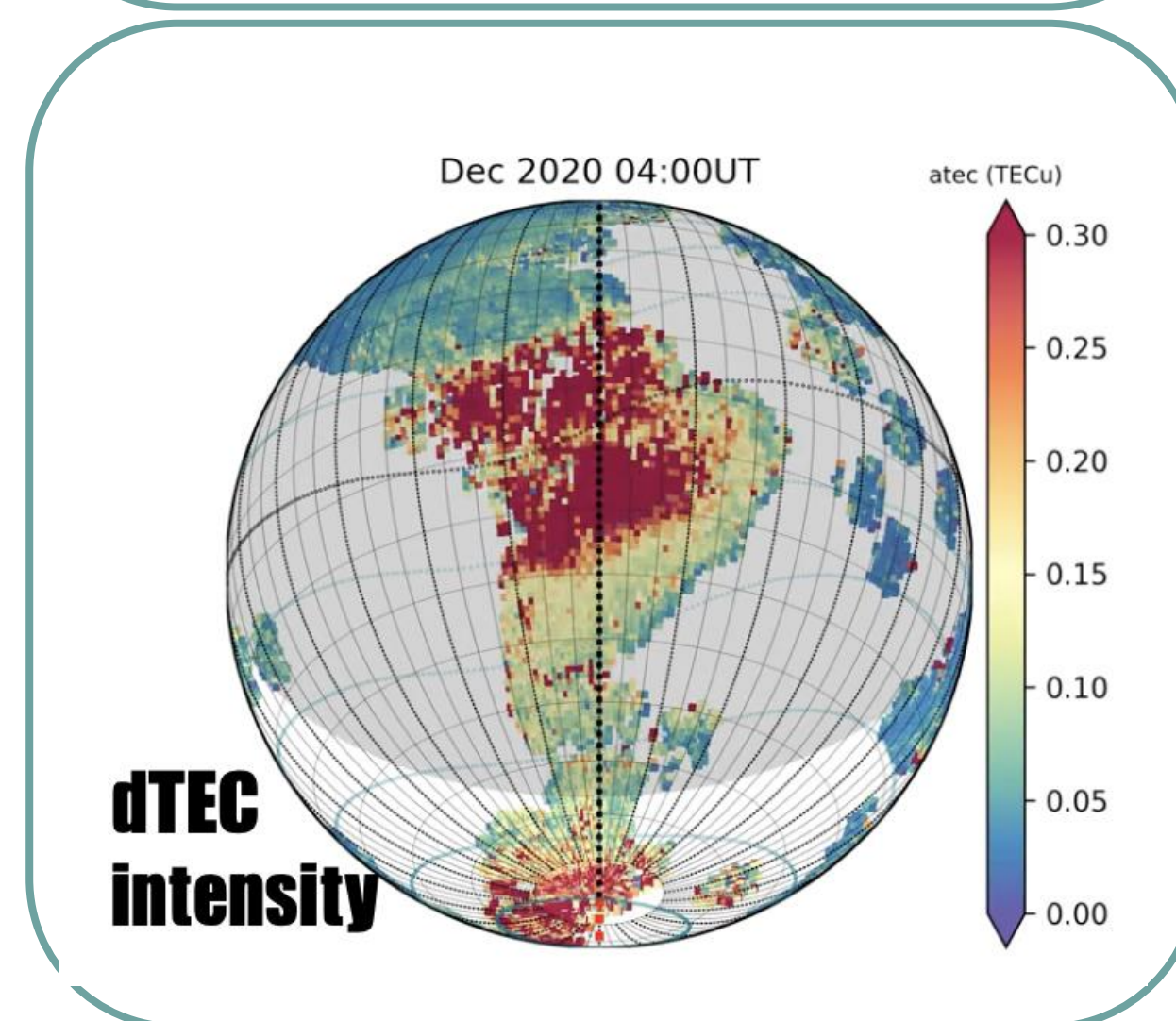
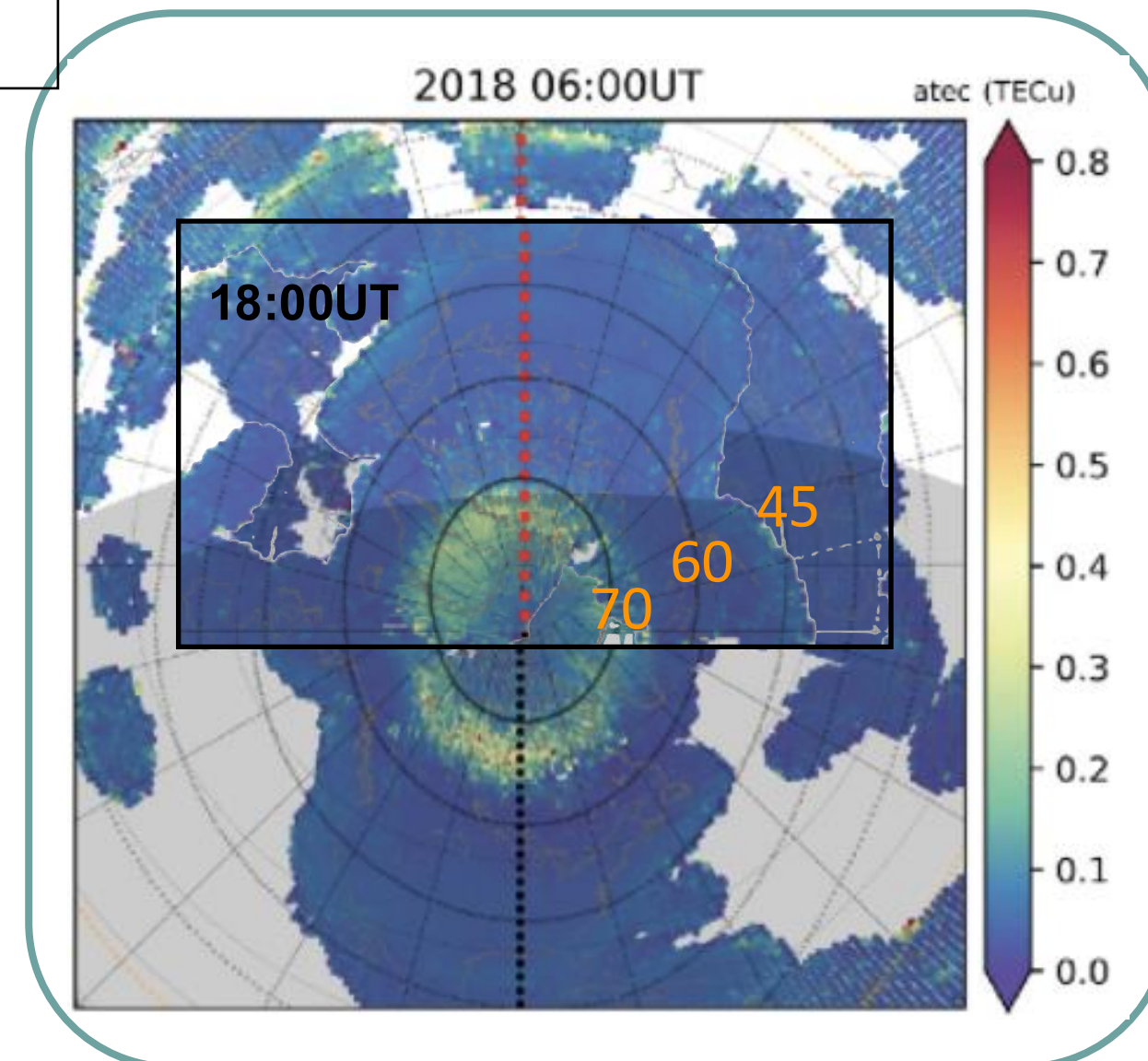
Global Map of Mesoscale Irregularities: Monthly Average Amplitudes: December

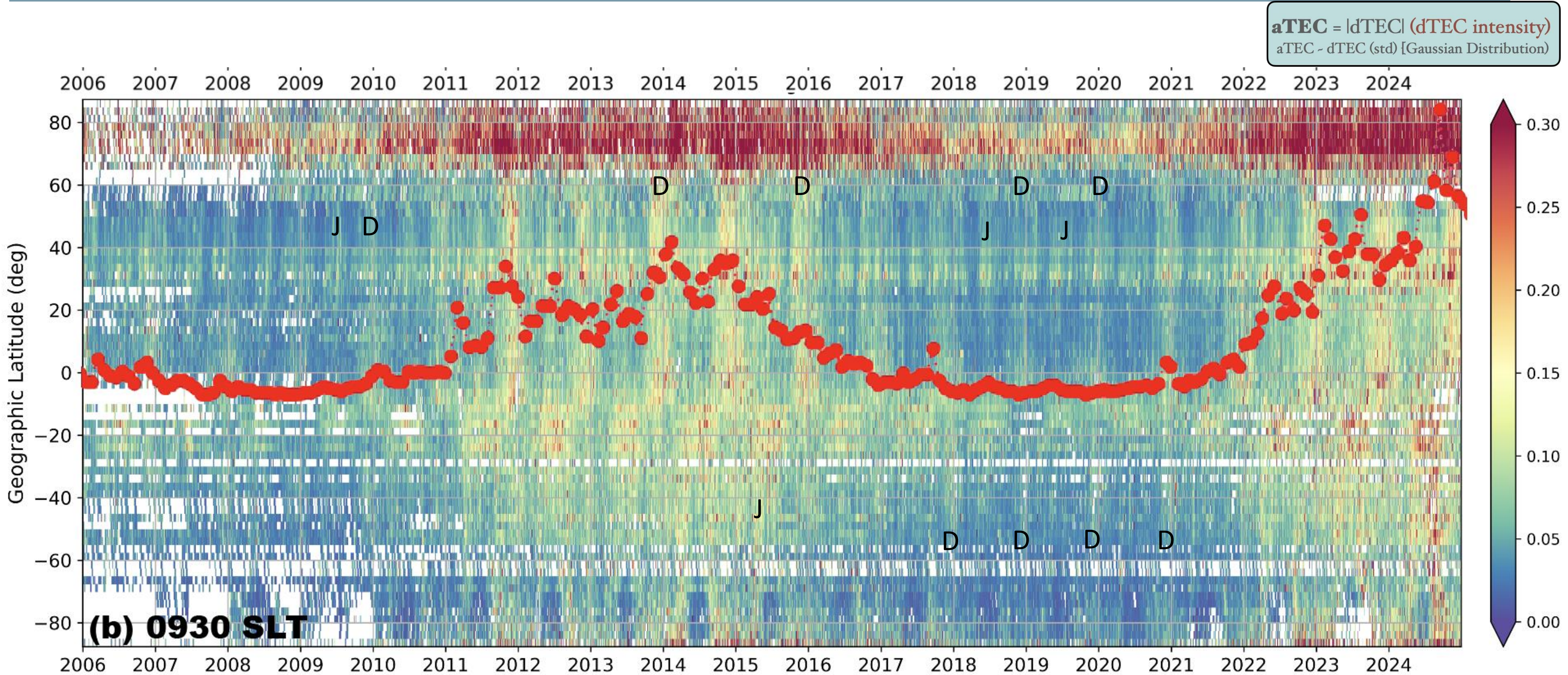
December 2023 @ SLT 11:00:00



Three Characteristic Zones

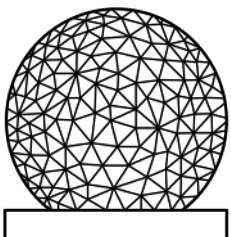
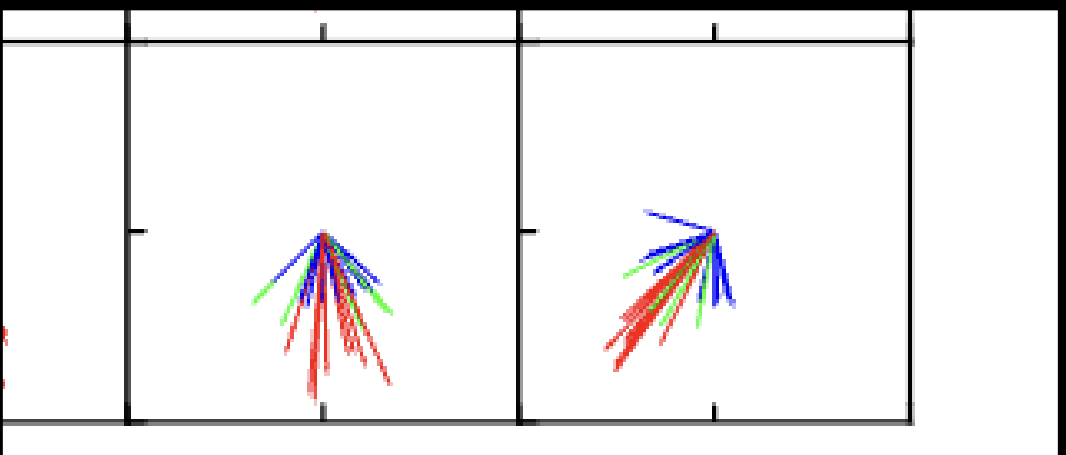
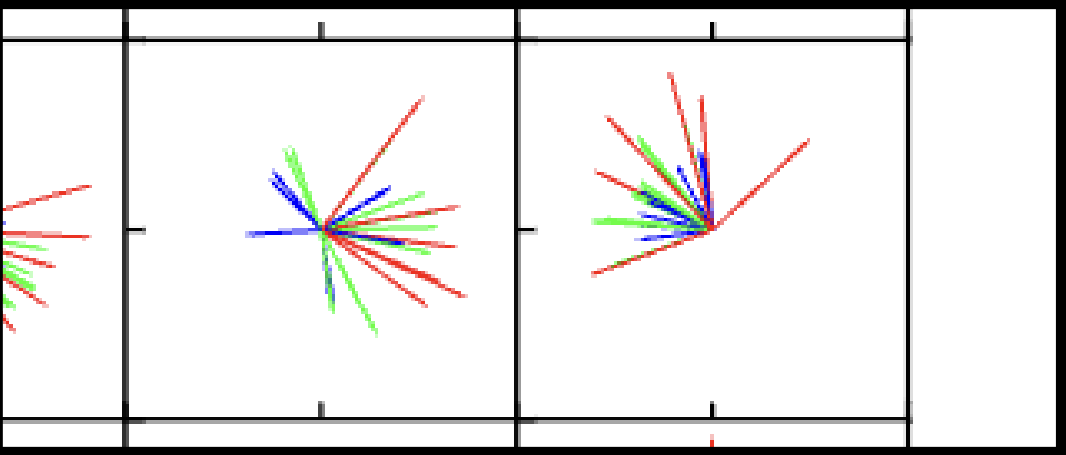
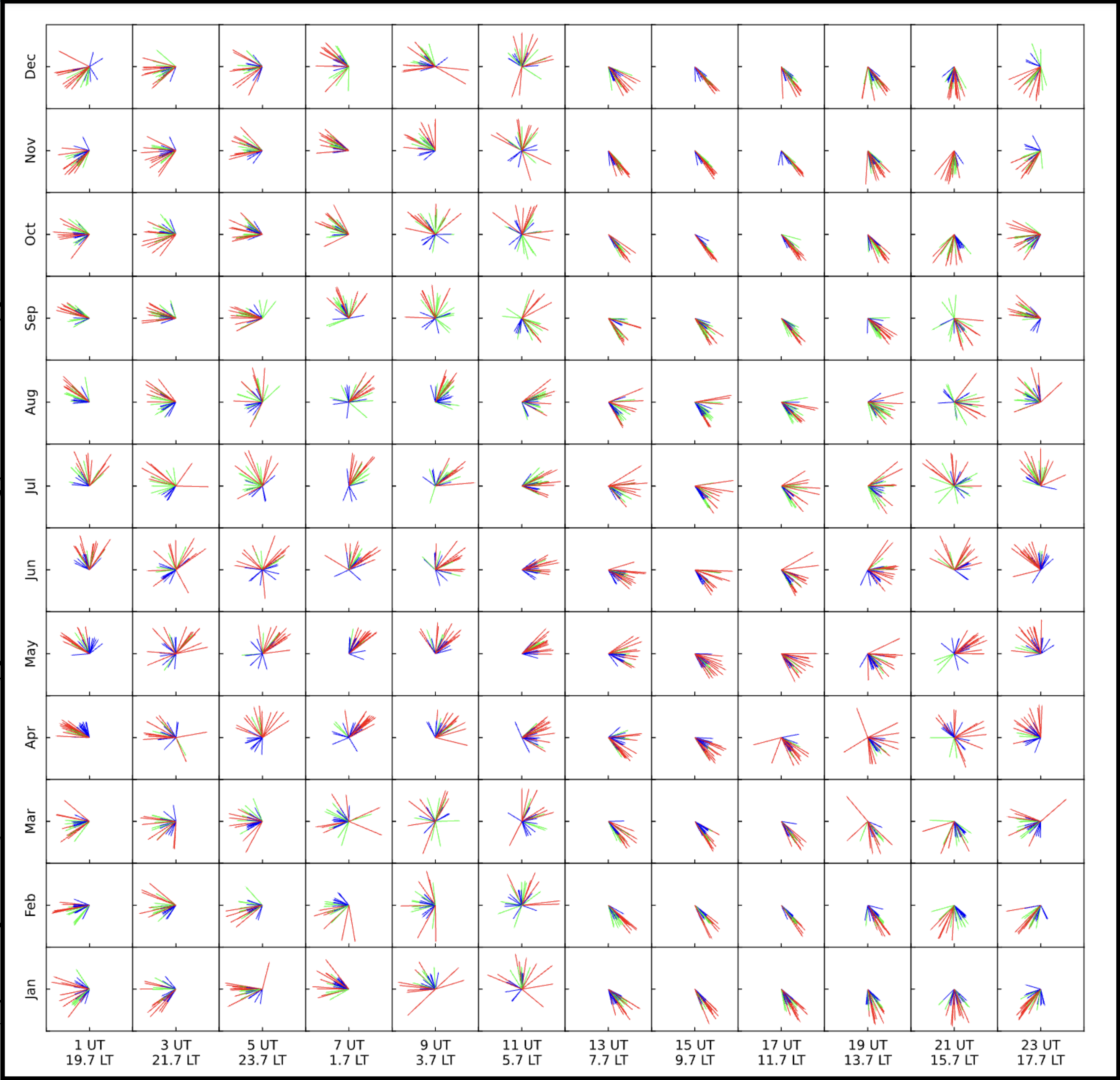
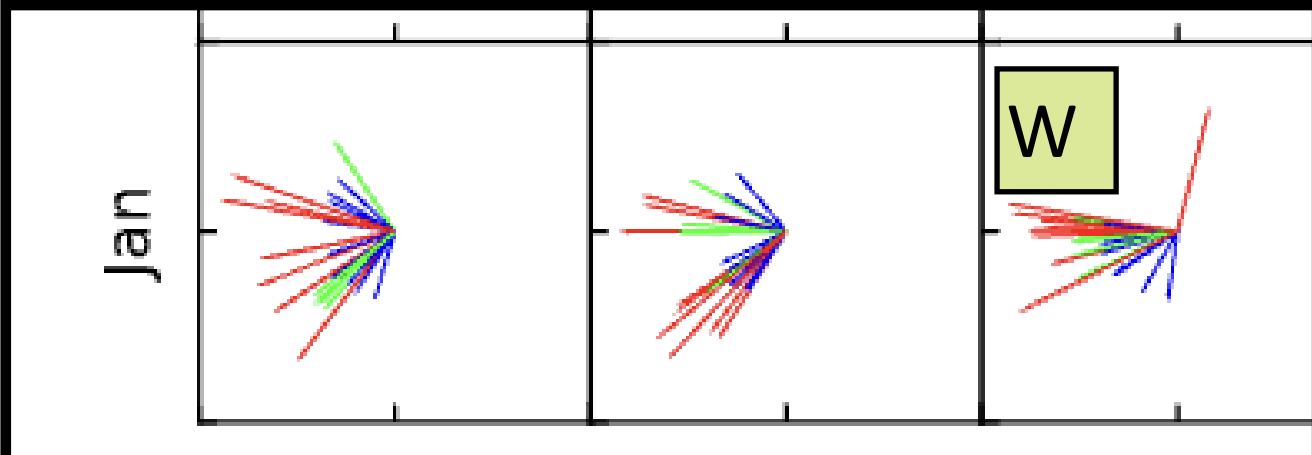
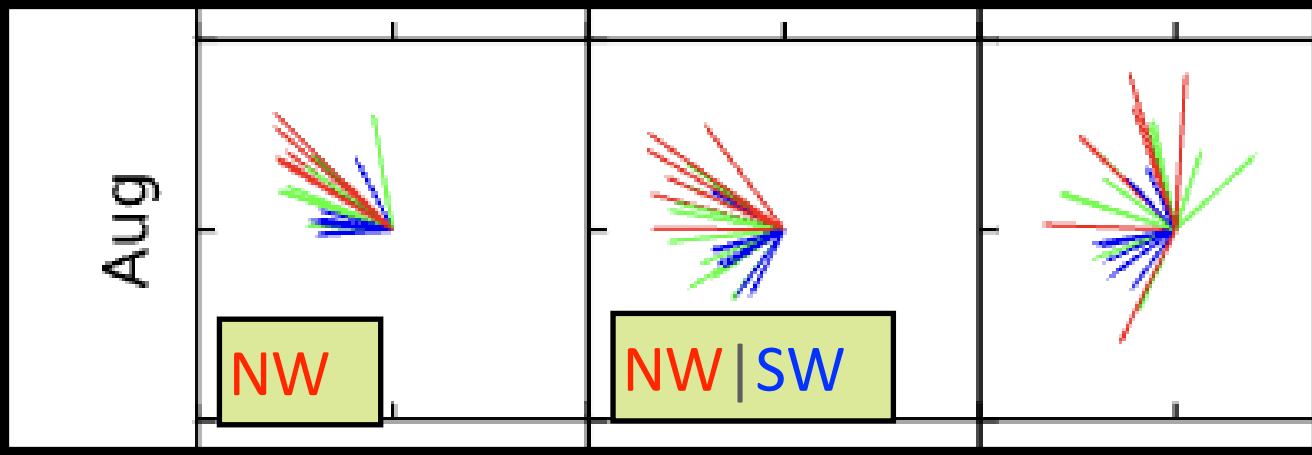
High latitudes | Mid- and low latitudes | Equatorial latitudes





MSTID propagation direction

Directions of these line represent azimuth angles of MSTIDs propagation directions, whose lengths / colors represent the magnitude of the solar flux

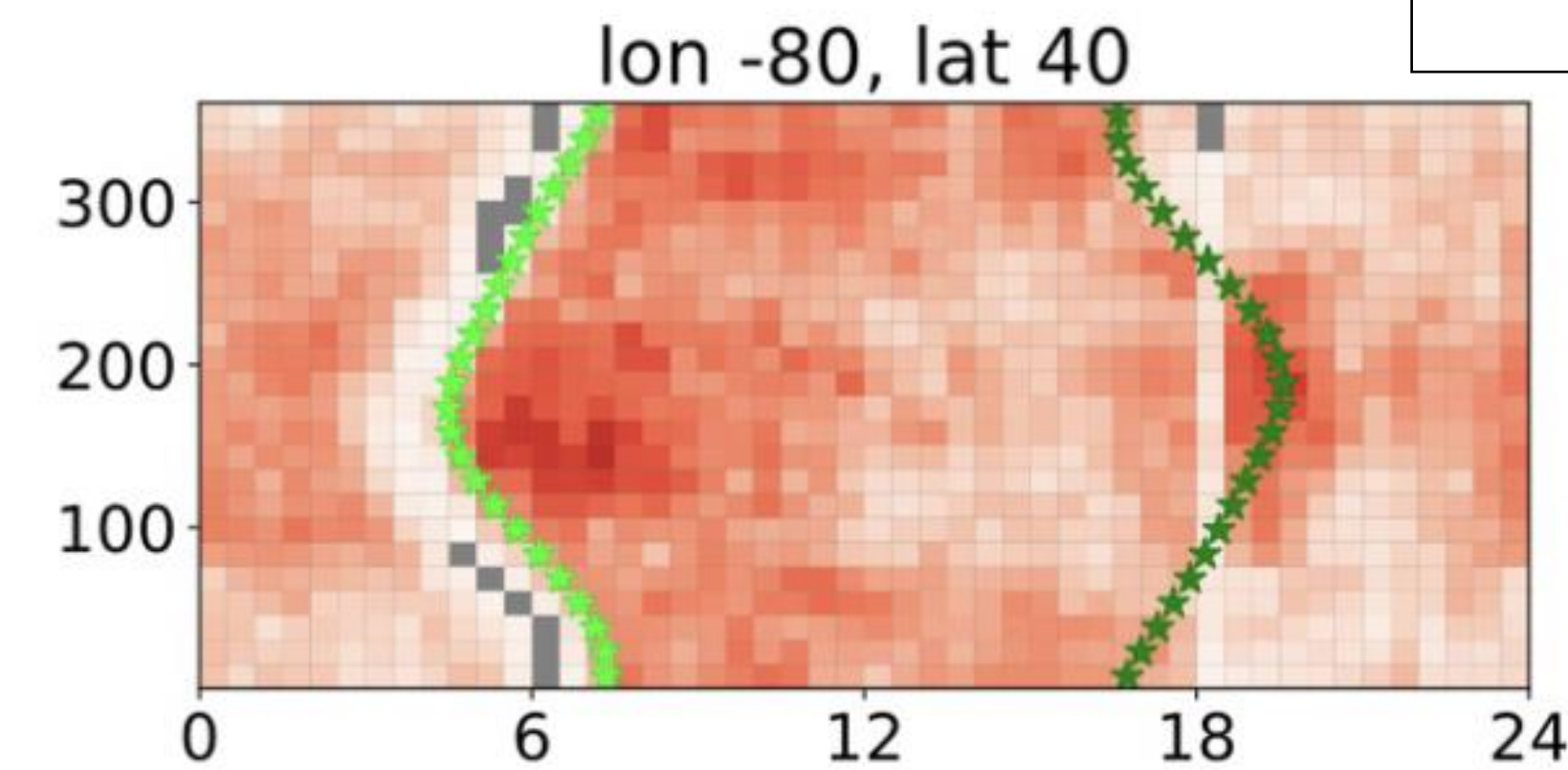


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Liu, J., Zhang, S.
Continental US U

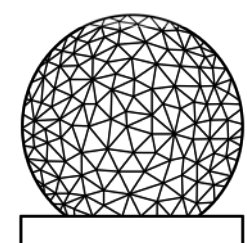
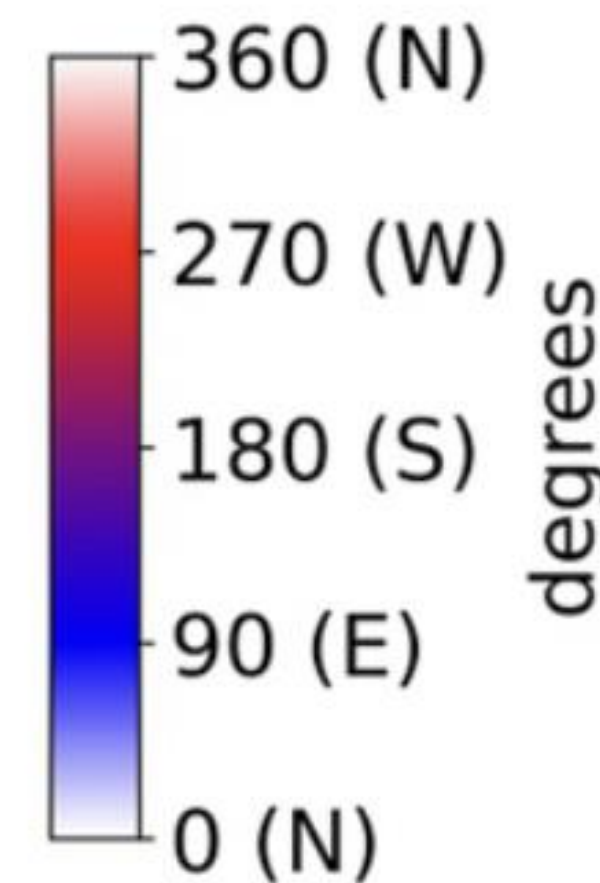
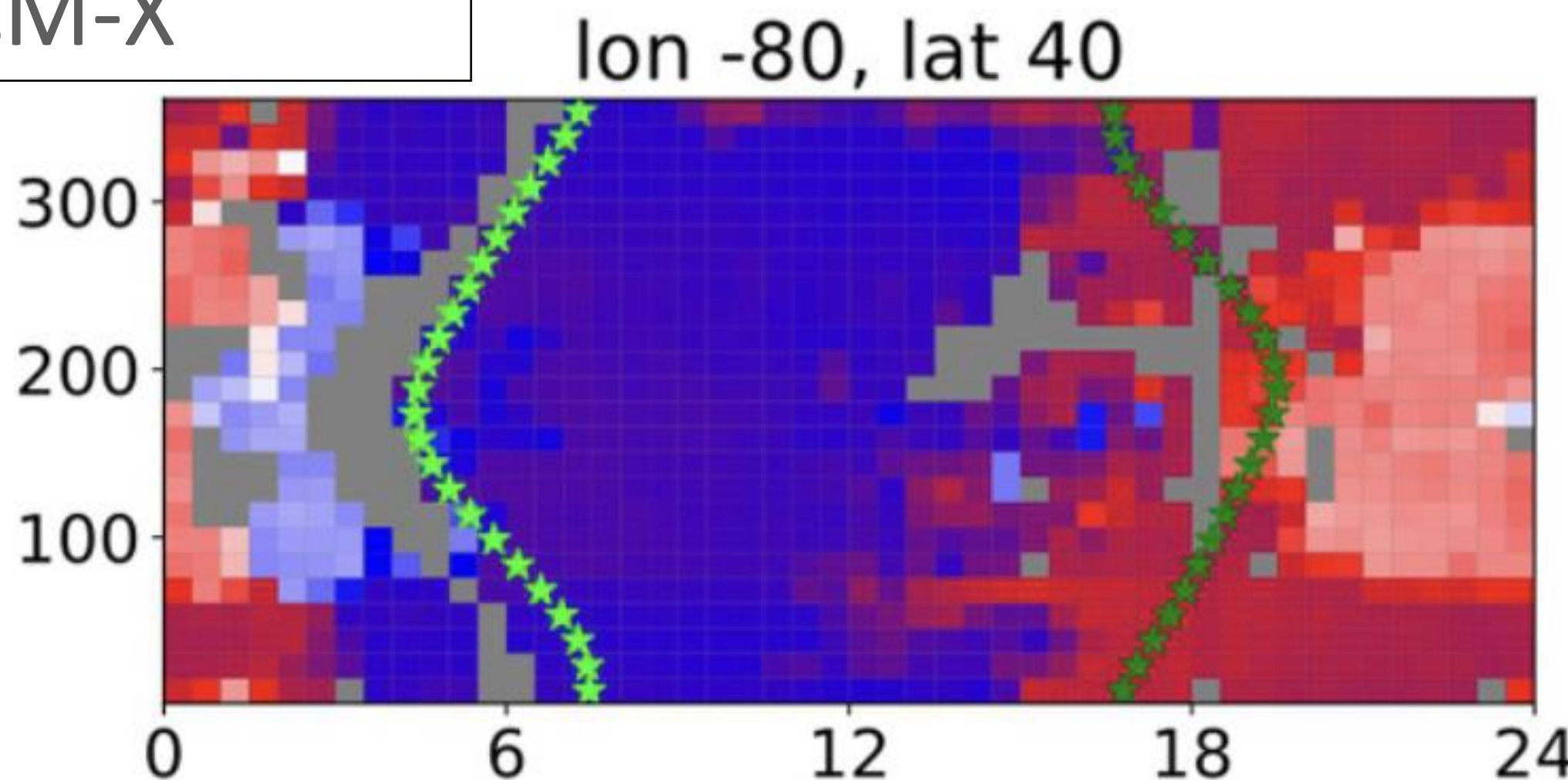
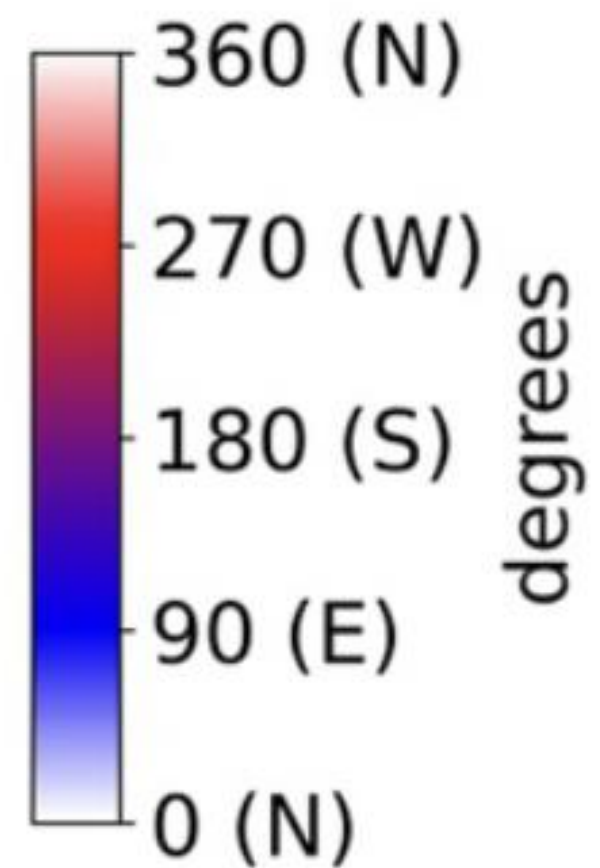
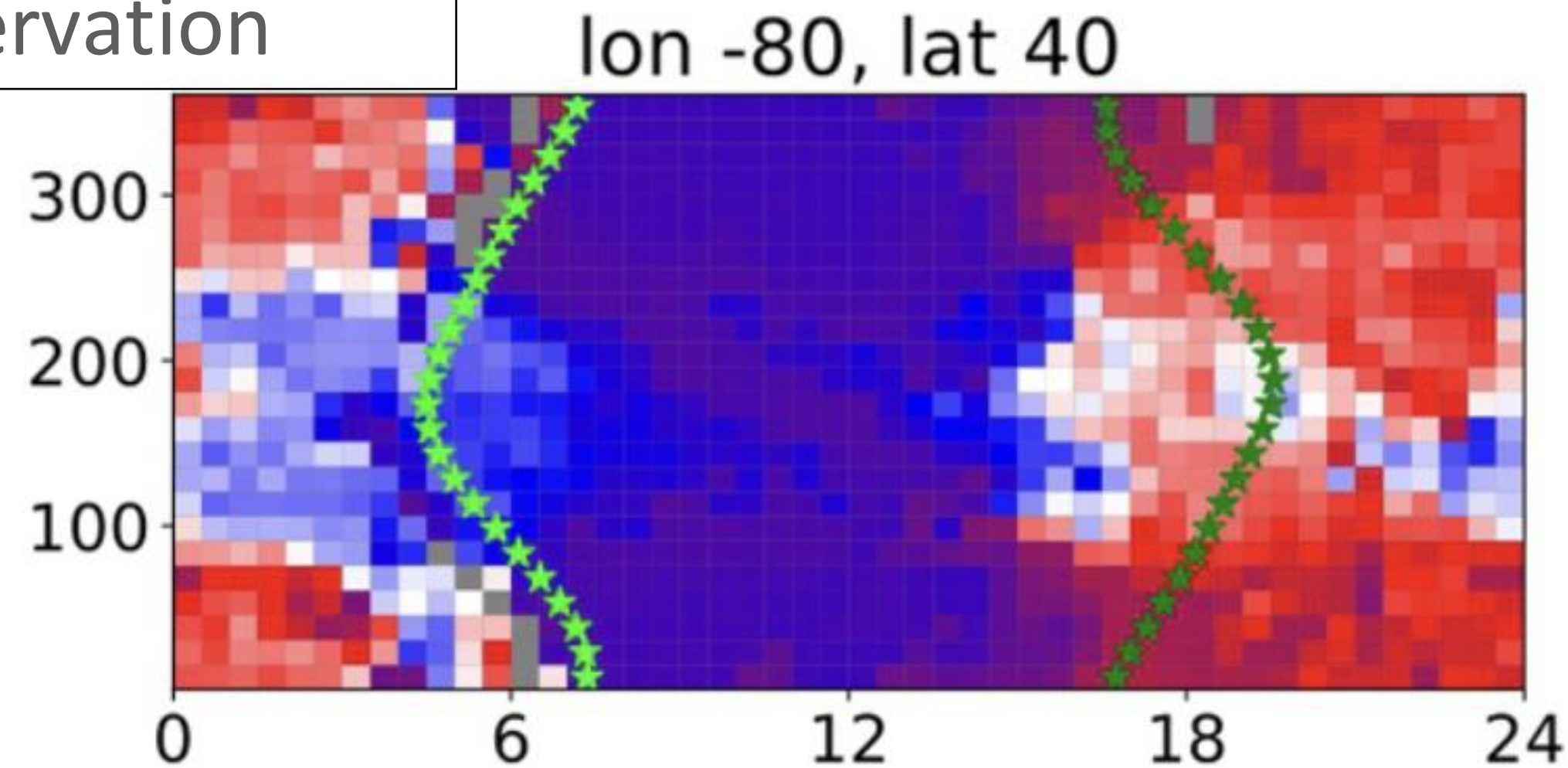
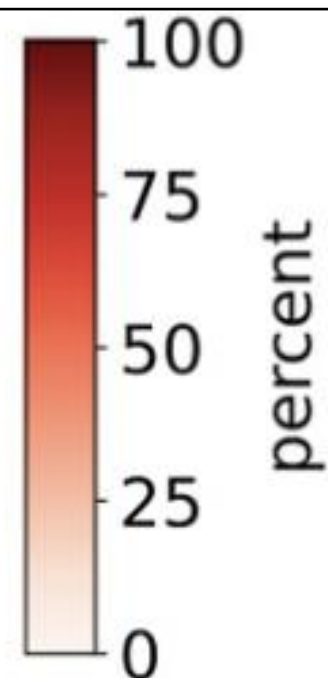
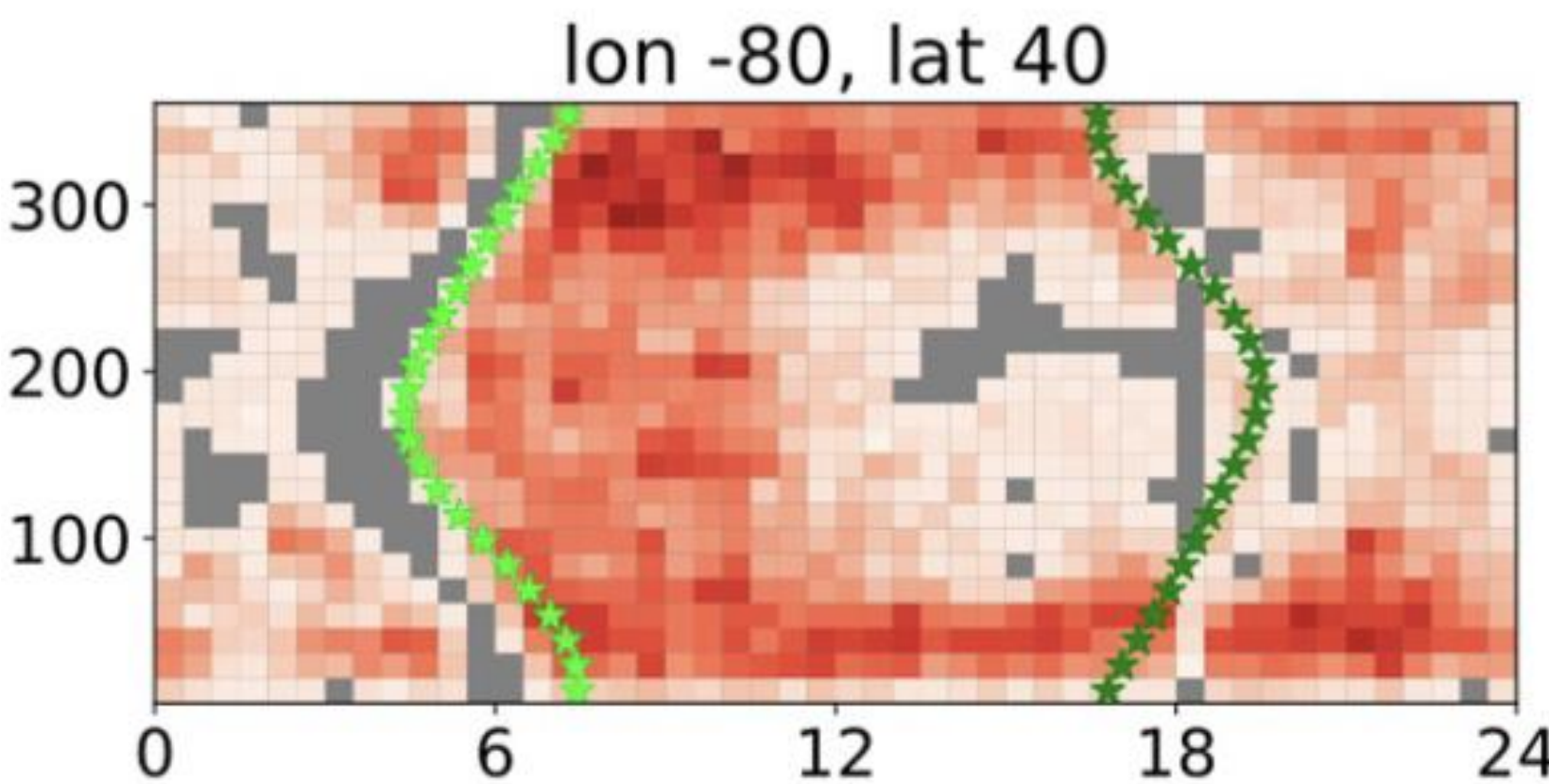
ospheric Disturbances Over
<https://doi.org/10.1029/2025ja034134>

GNSS Observation



Clearly, GWs can explain generally MSTID climatology at midlatitudes (although not very well at night)

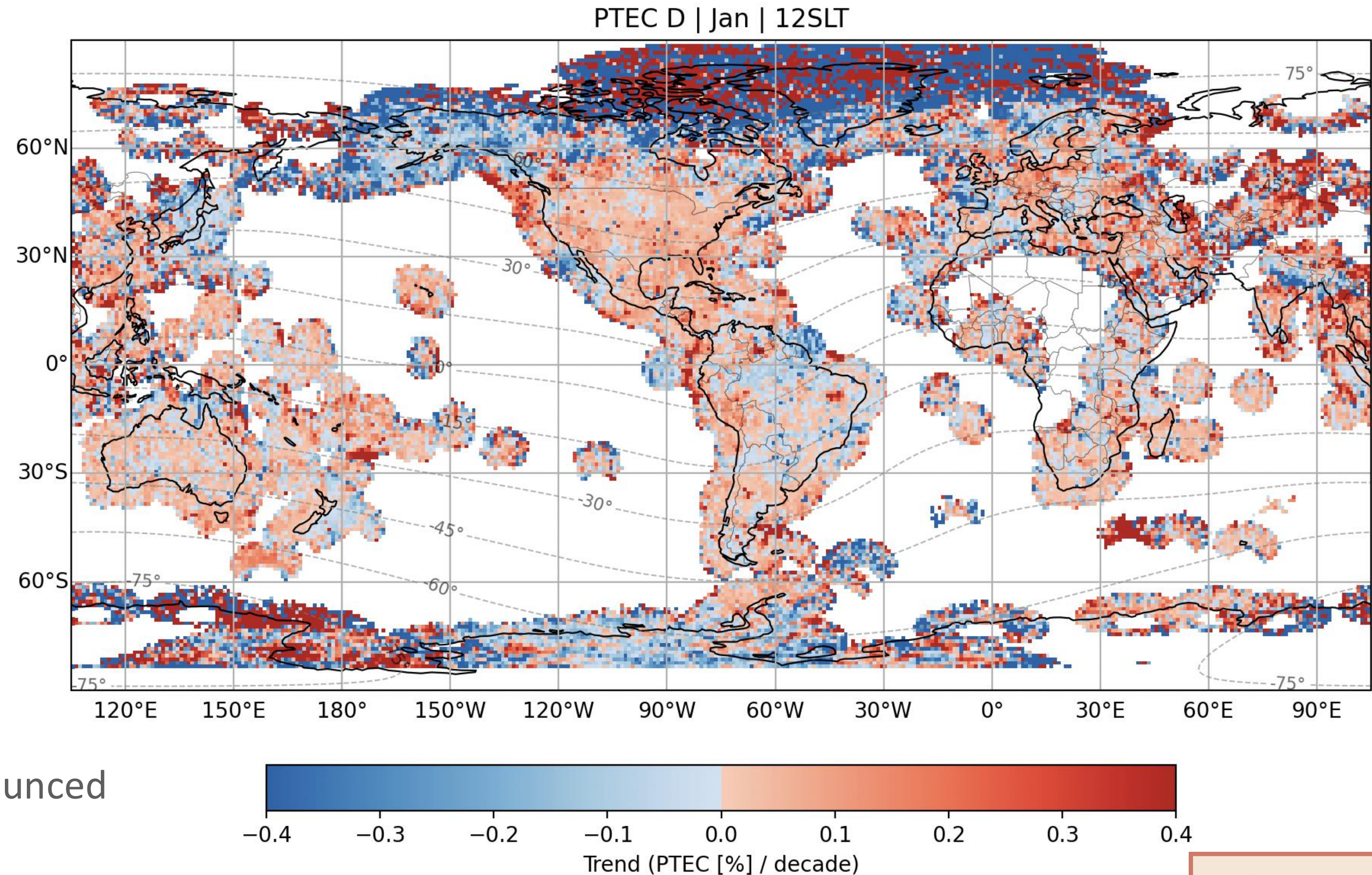
WACCM-X



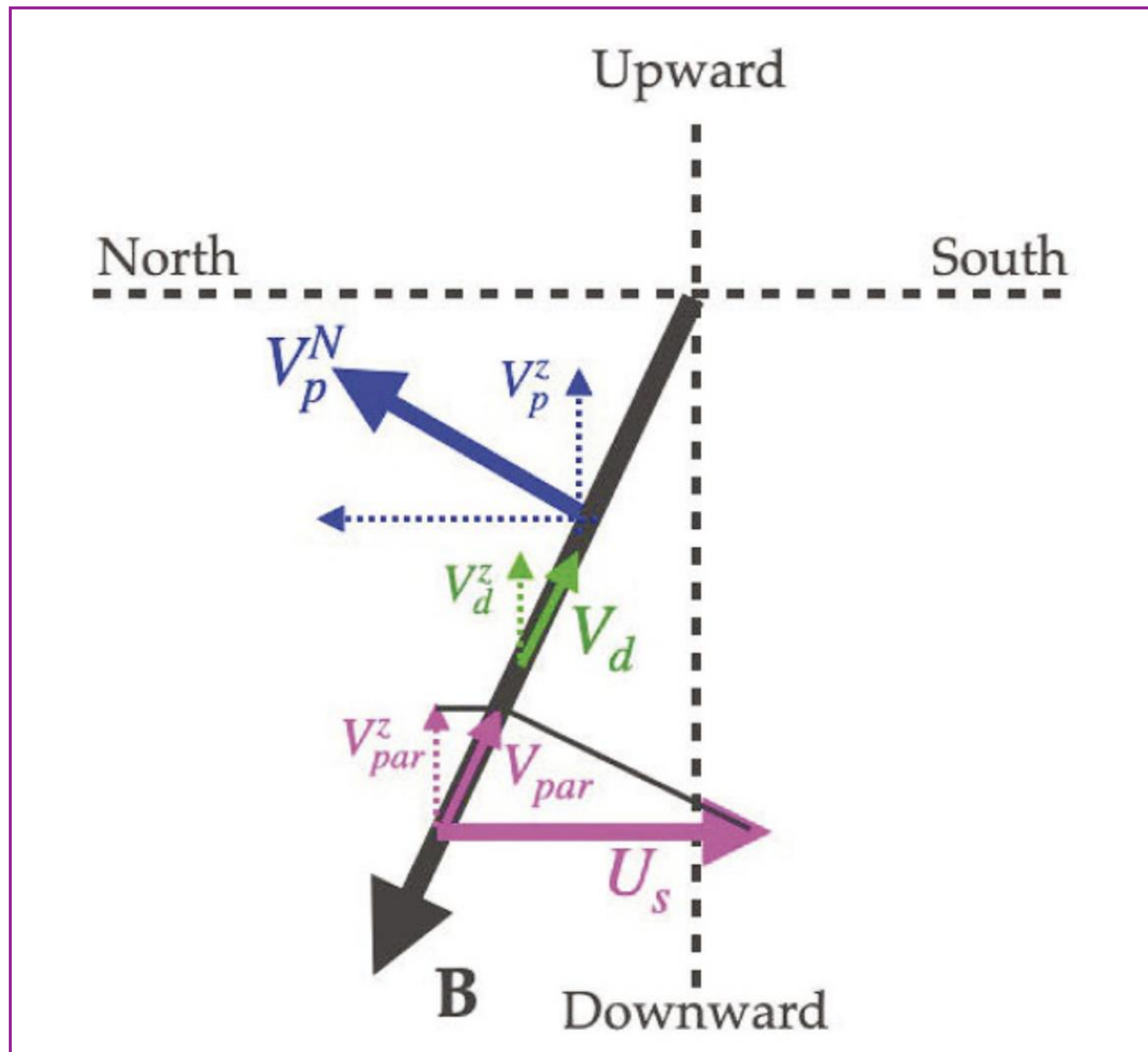
Analysis of GNSS dTEC over 2004-2024 to detect GW trends in the upper atmosphere and potential association with climate change forcing

Pronounced intensification of TID/GW amplitudes in the last 20 years

QBO modulation is pronounced

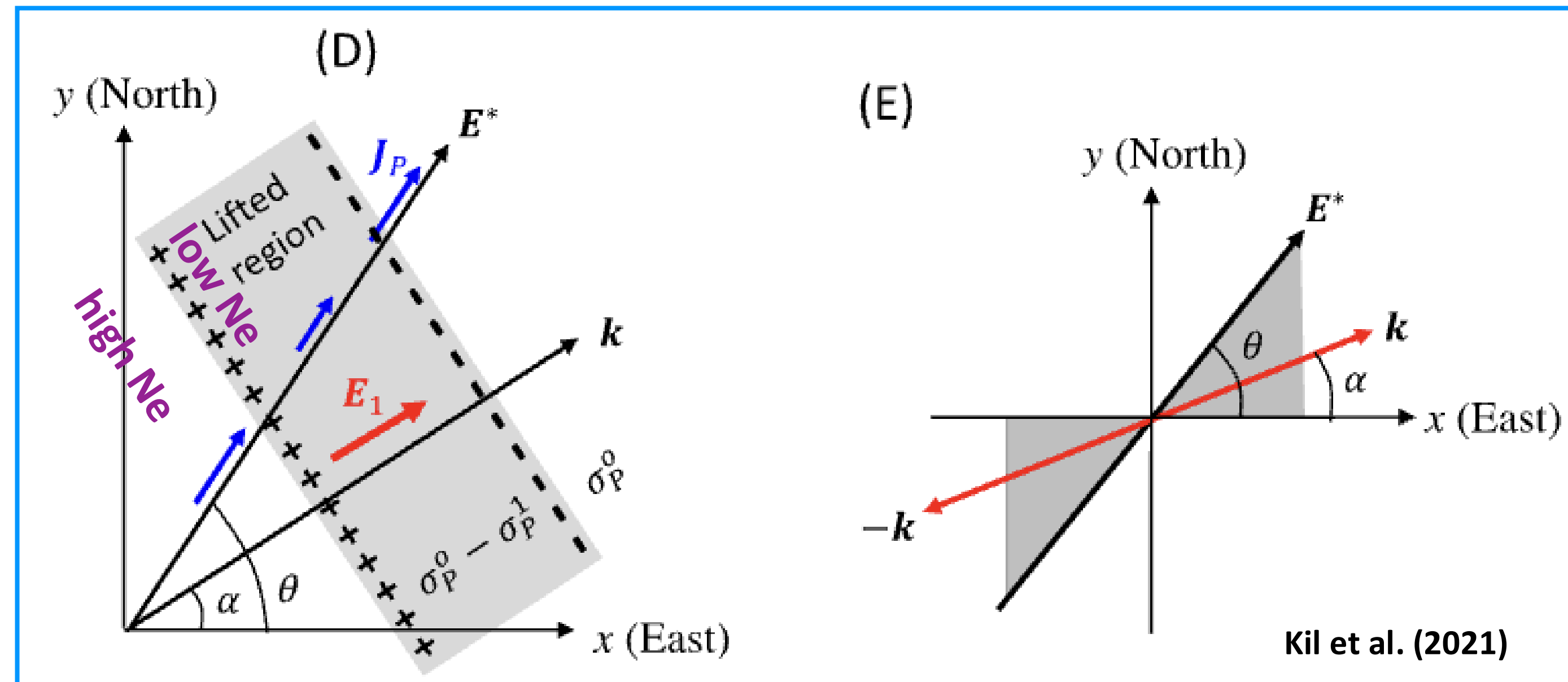


Meridional Winds



Zhang et al. (2021)

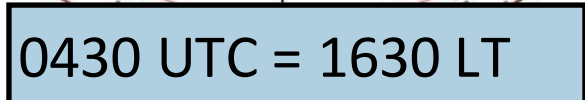
Perkins Instability



$$\gamma = \frac{E^*}{BH_n} \cos I \sin(\theta - \alpha) \sin \alpha = \frac{g \sin^2 I \sin(\theta - \alpha)}{\langle \nu \rangle H \cos \theta}$$

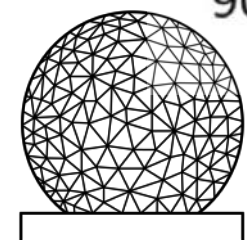
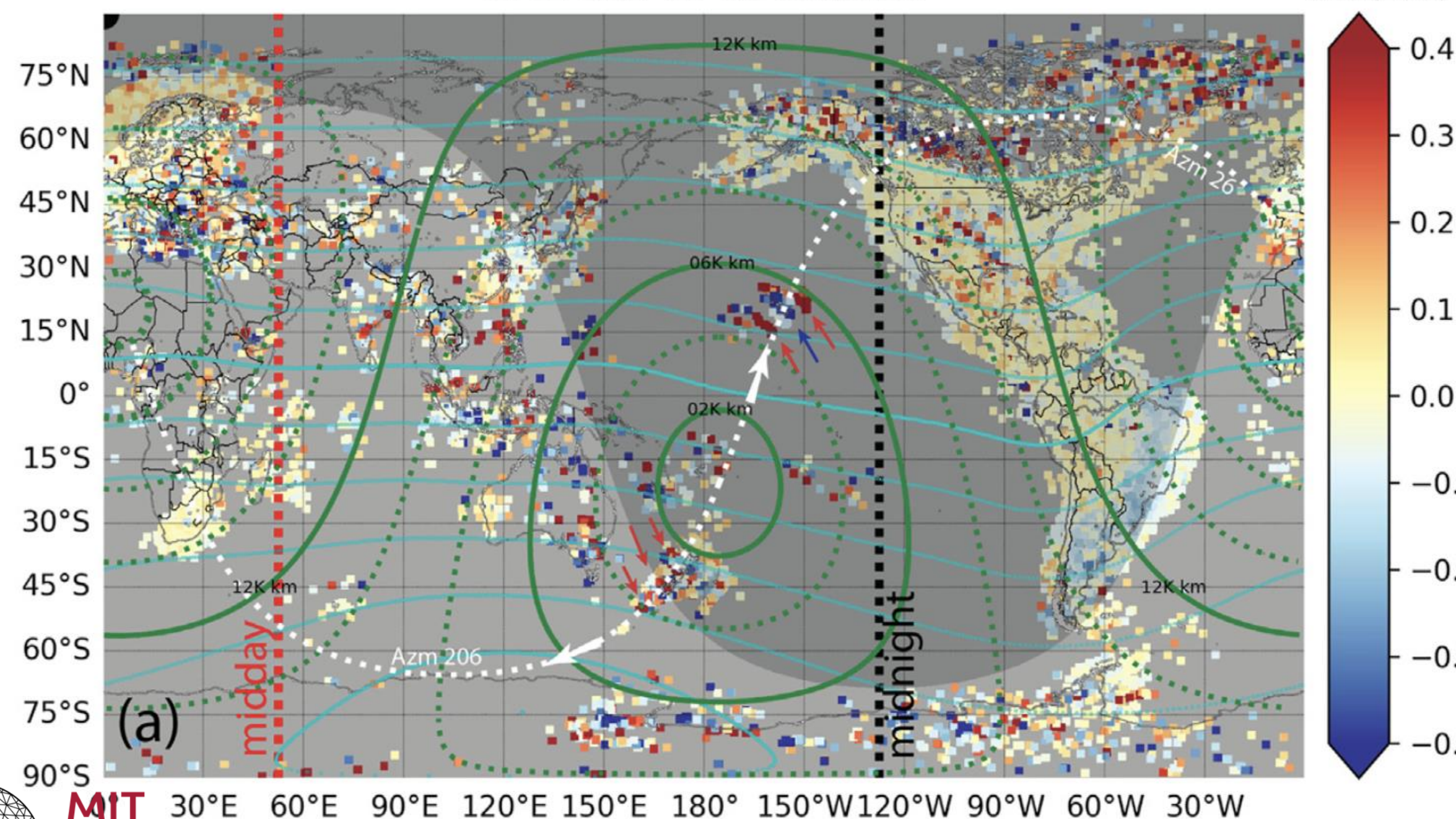
Es irregularity electric field
E-F layer coupling

Accurate TEC data: because of stationary ionospheric pierce point with fixed azimuth and elevation



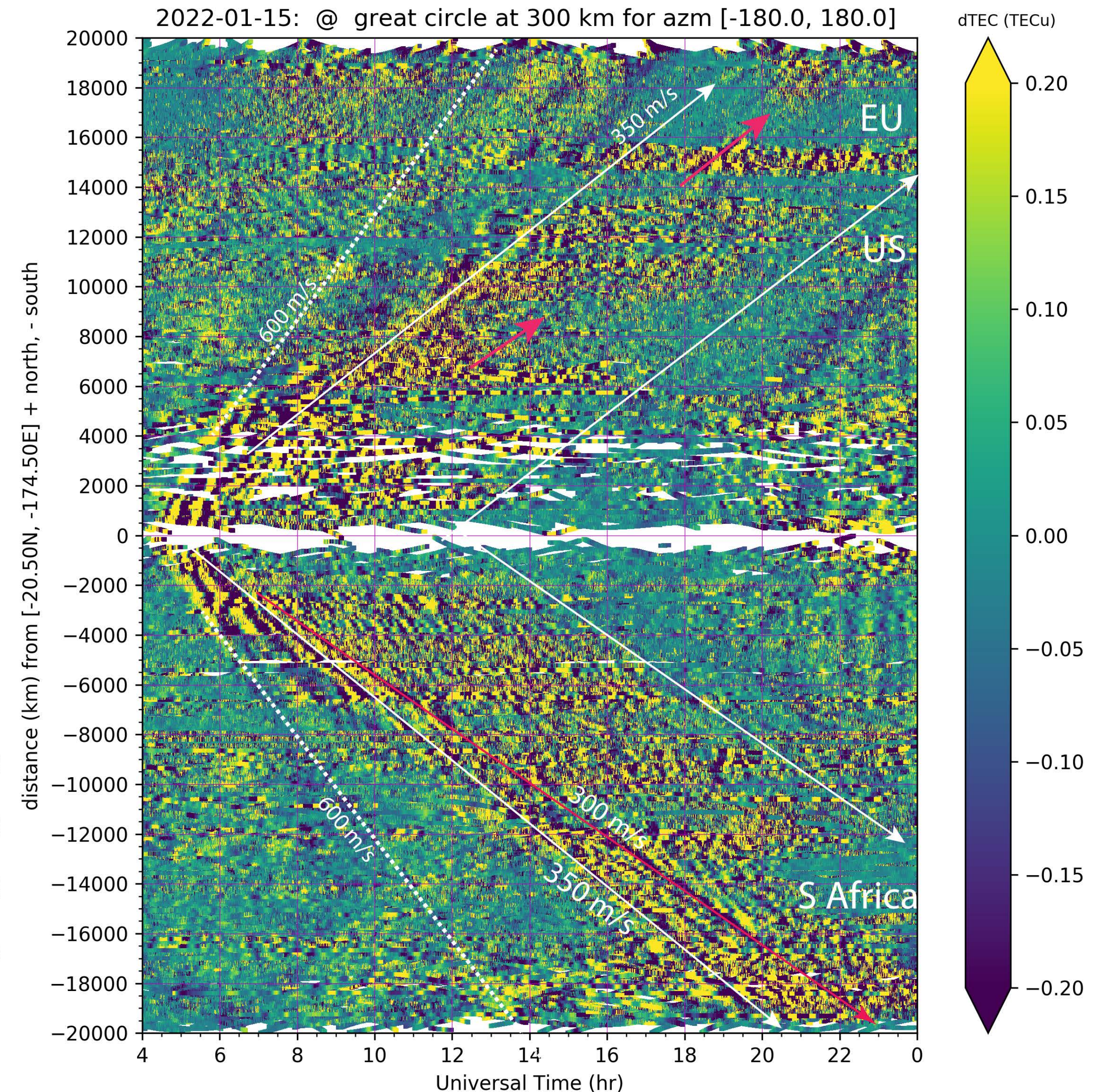
- ❖ Evident TID occurrence was based on the distance from the epic center;
- ❖ TIDs reached 20K km distance 17 hrs after the eruption;
- ❖ Shock fronts traveled globally at a persistent speed of ~ 350 m/s; **450 km m/s is unlikely globally**
- ❖ Regional disturbances lasted for 8-10 hrs
- ❖ Reminder: $AE > 500$ nT after 12 UTC

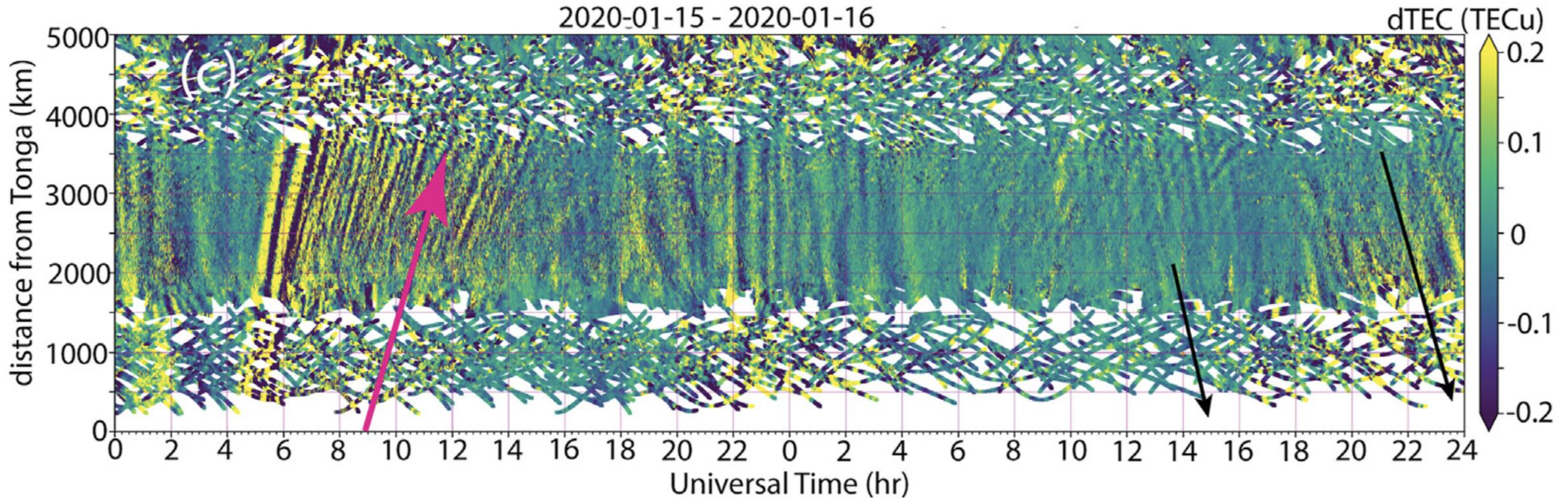
UTC 2022-01-15 08:30:00



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Zhang et al. (2022)

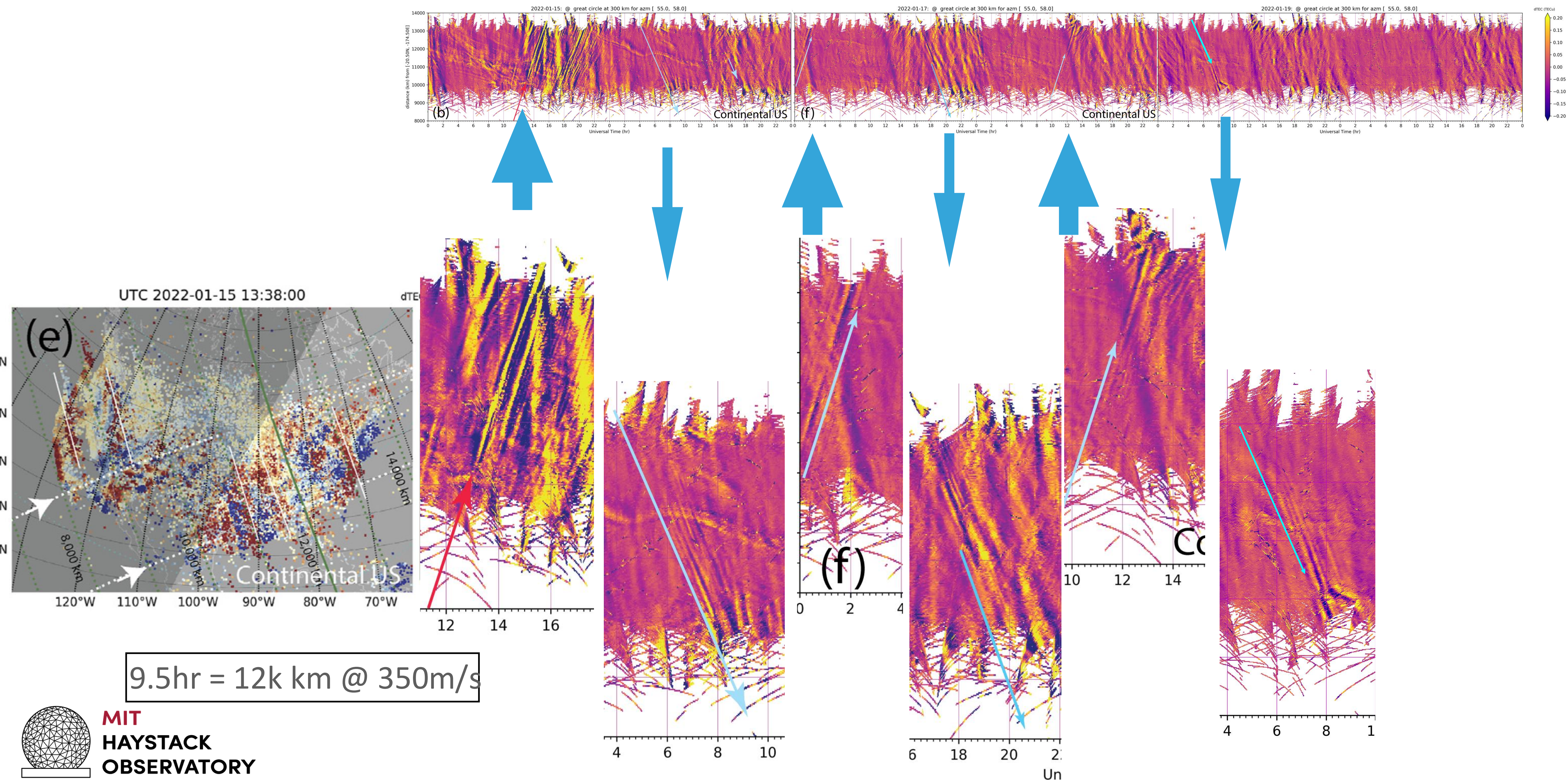




Key facts that link these disturbances to Tonga eruption is the slope (phase velocity) and arriving time

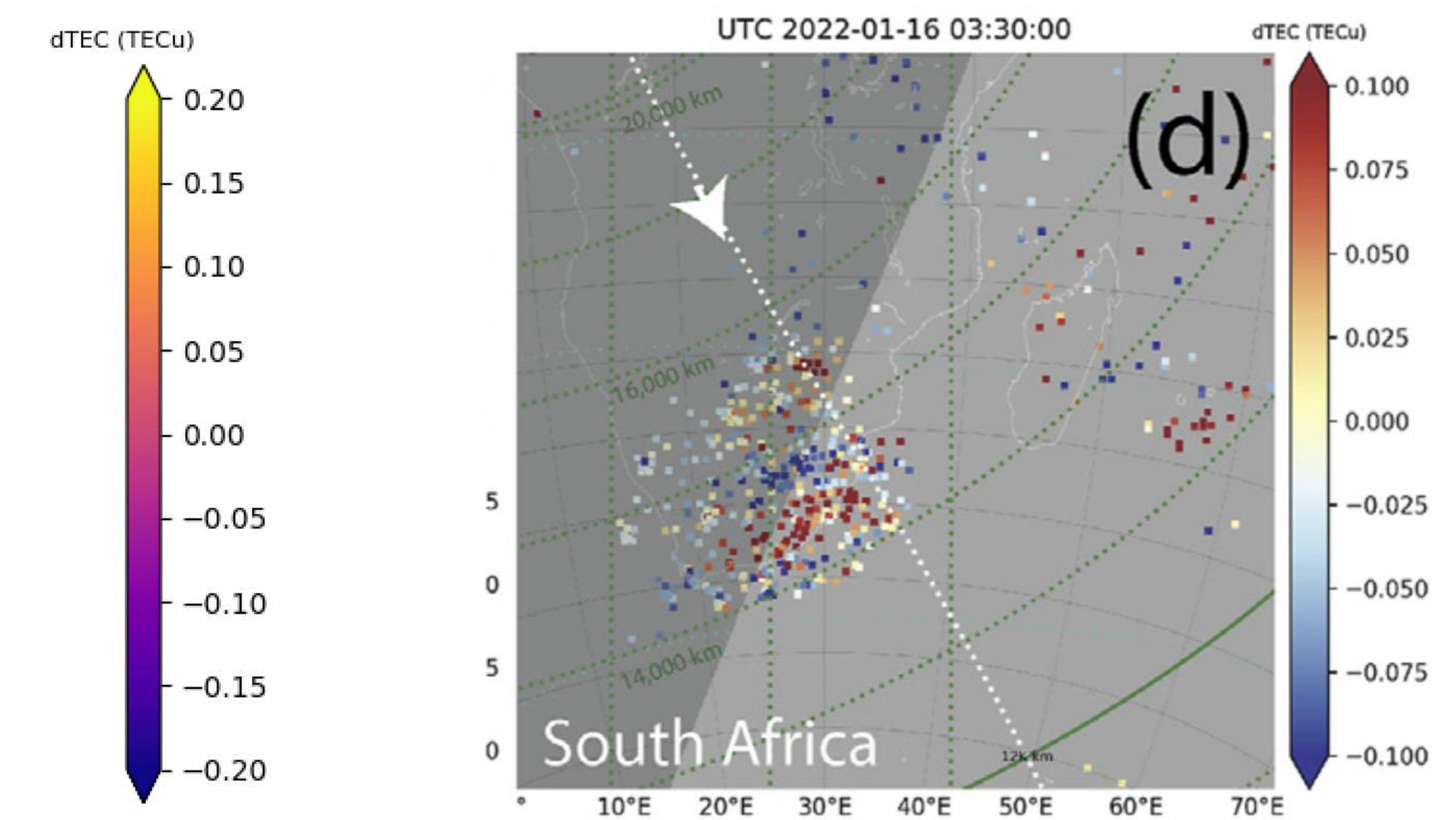
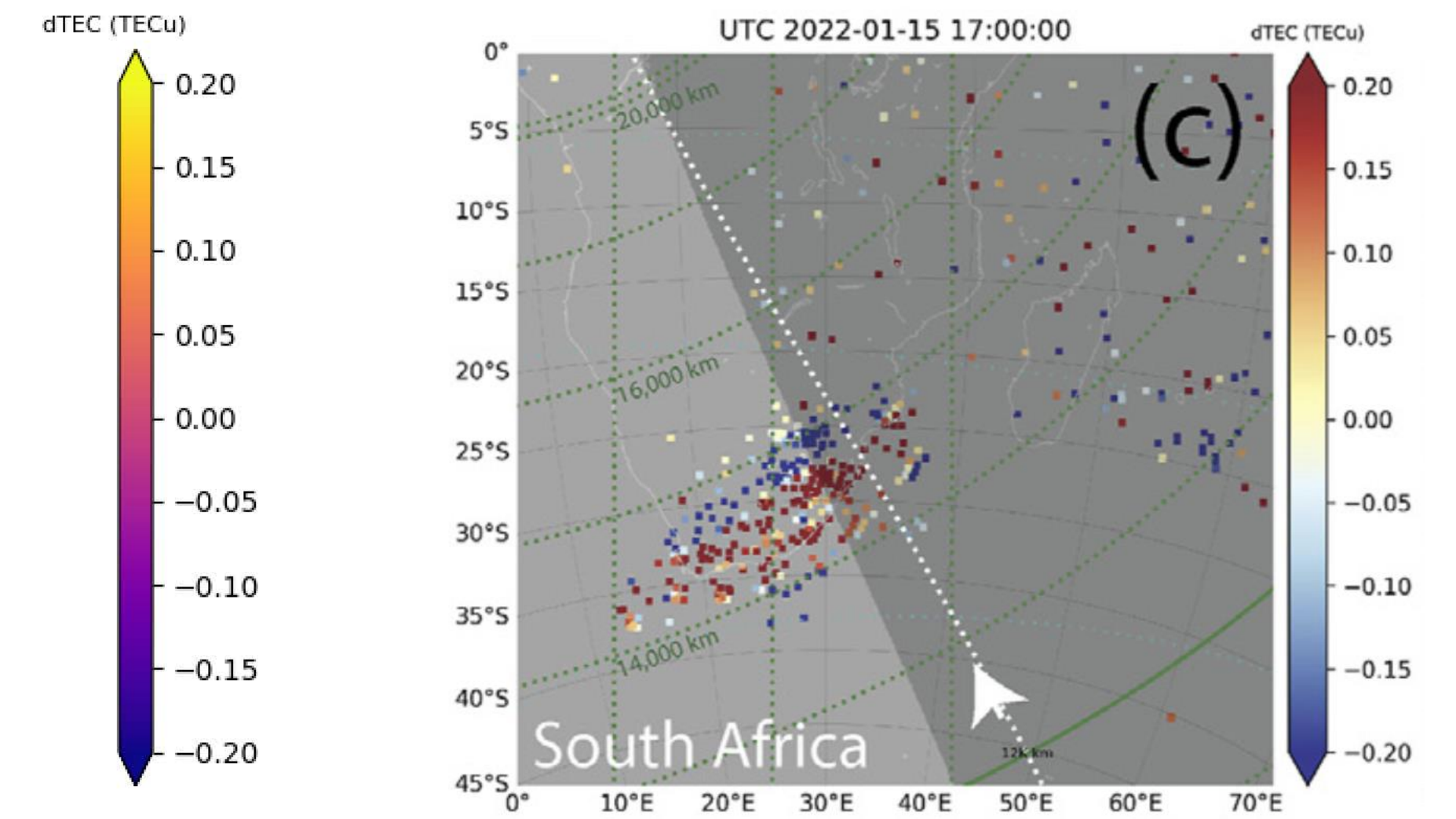
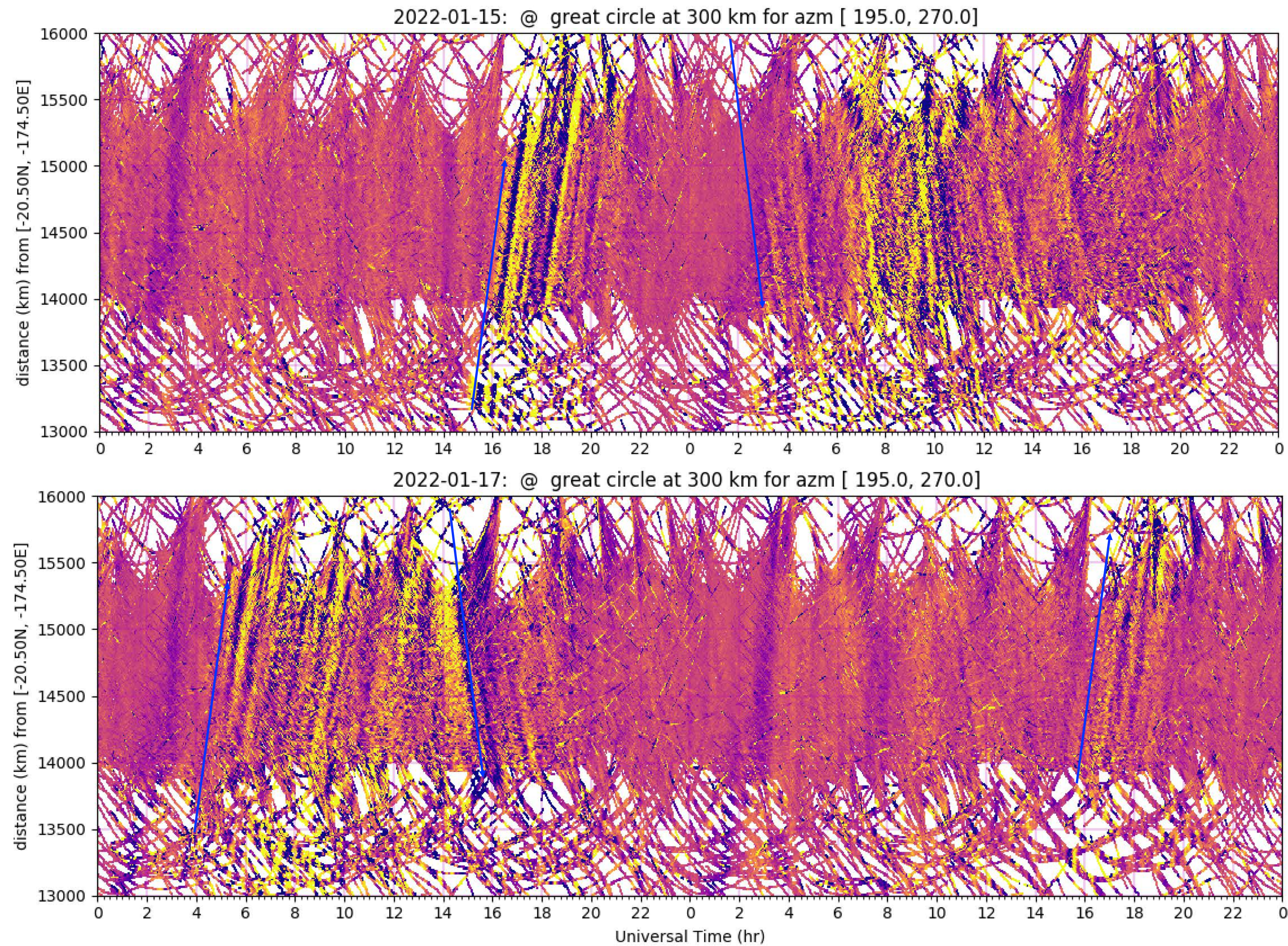
it takes ~ 34 hr to propagate from Tonga through the antipode to back at 350 m/s

Multi-day TID propagation over Continental US



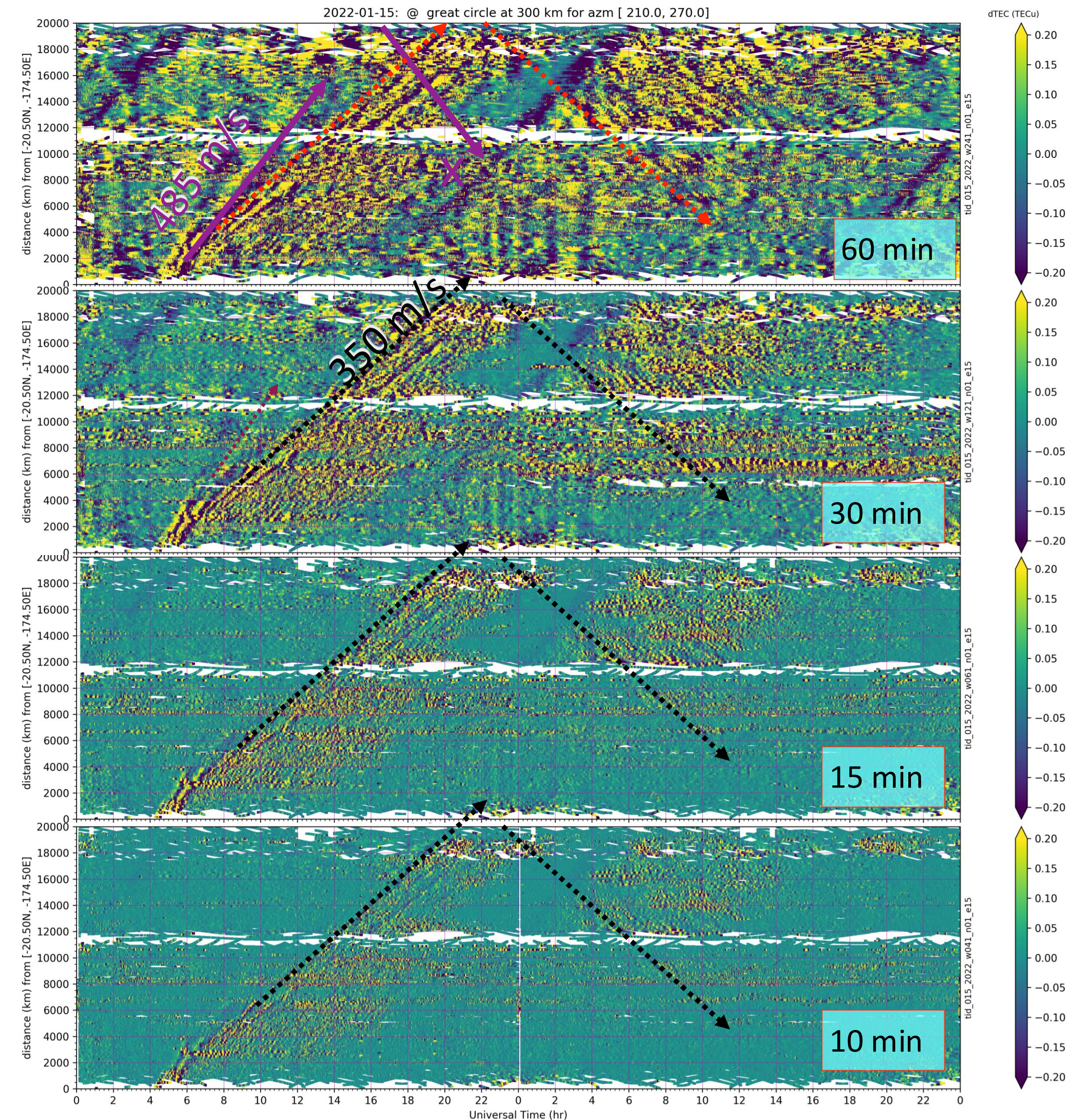
Multi-day TID propagation: Europe-Africa sectors

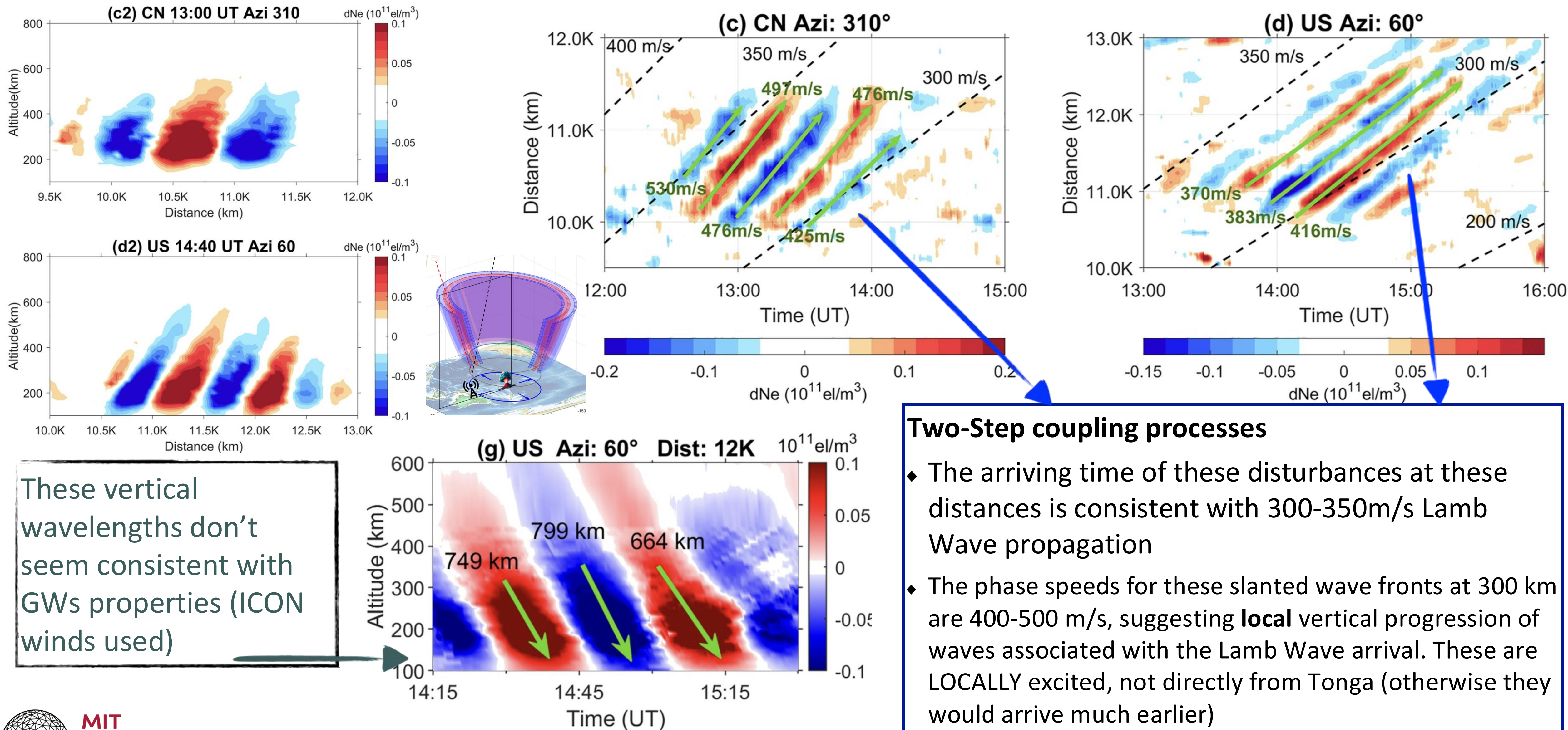
20

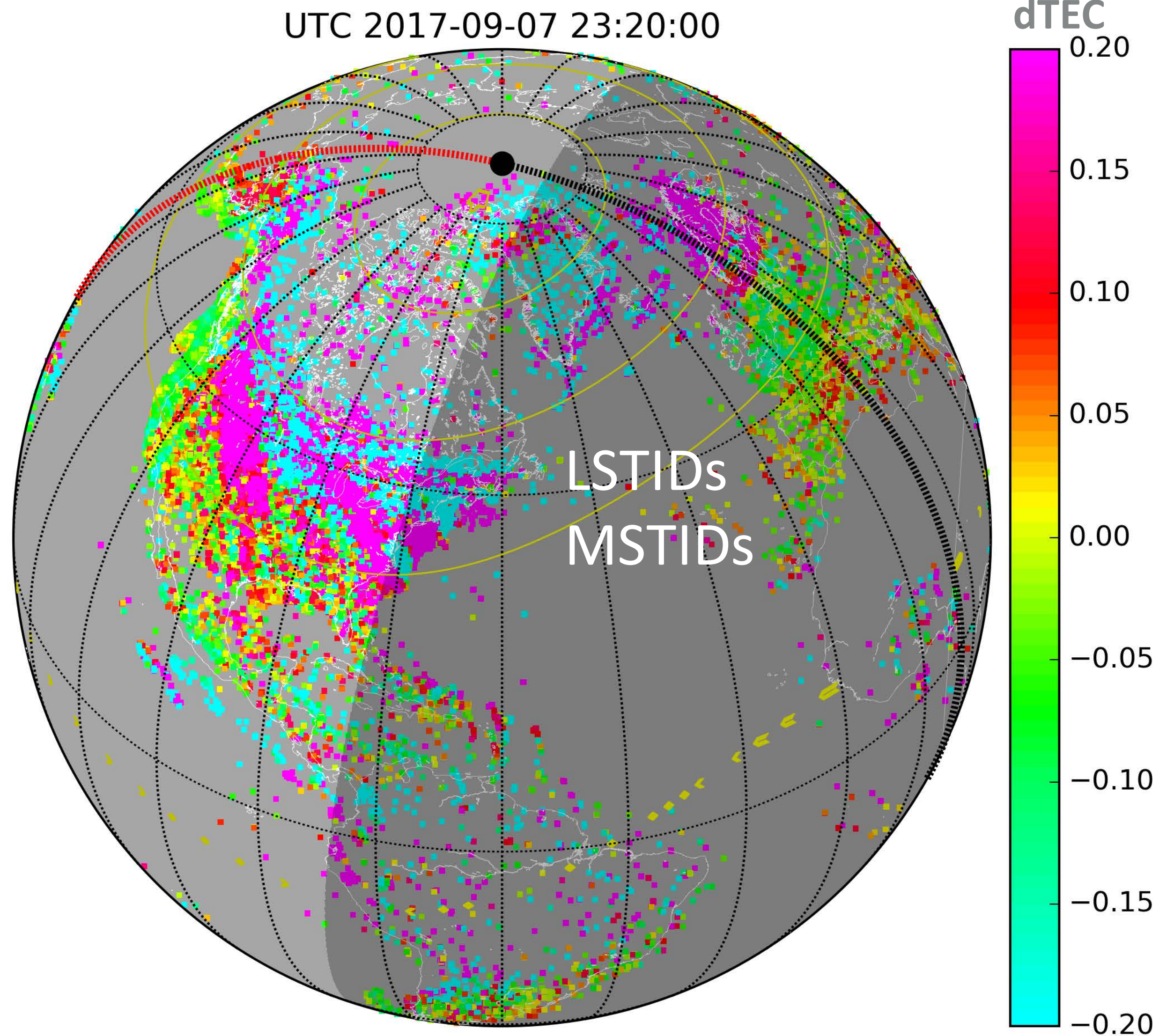


Using different detrending windows

- ❖ LSTIDs at 485 m/s, may have reached 18K km distance (near antipode) but don't seem to continue propagating
- ❖ They started at W-SW azimuth; not visible everywhere
- ❖ A large impulsive wavefront, of > 30 min width.
- ❖ MSTIDs at ~350 m/s were persistent globally, with a range of periods for <10 min (acoustic waves) as well as longer periods

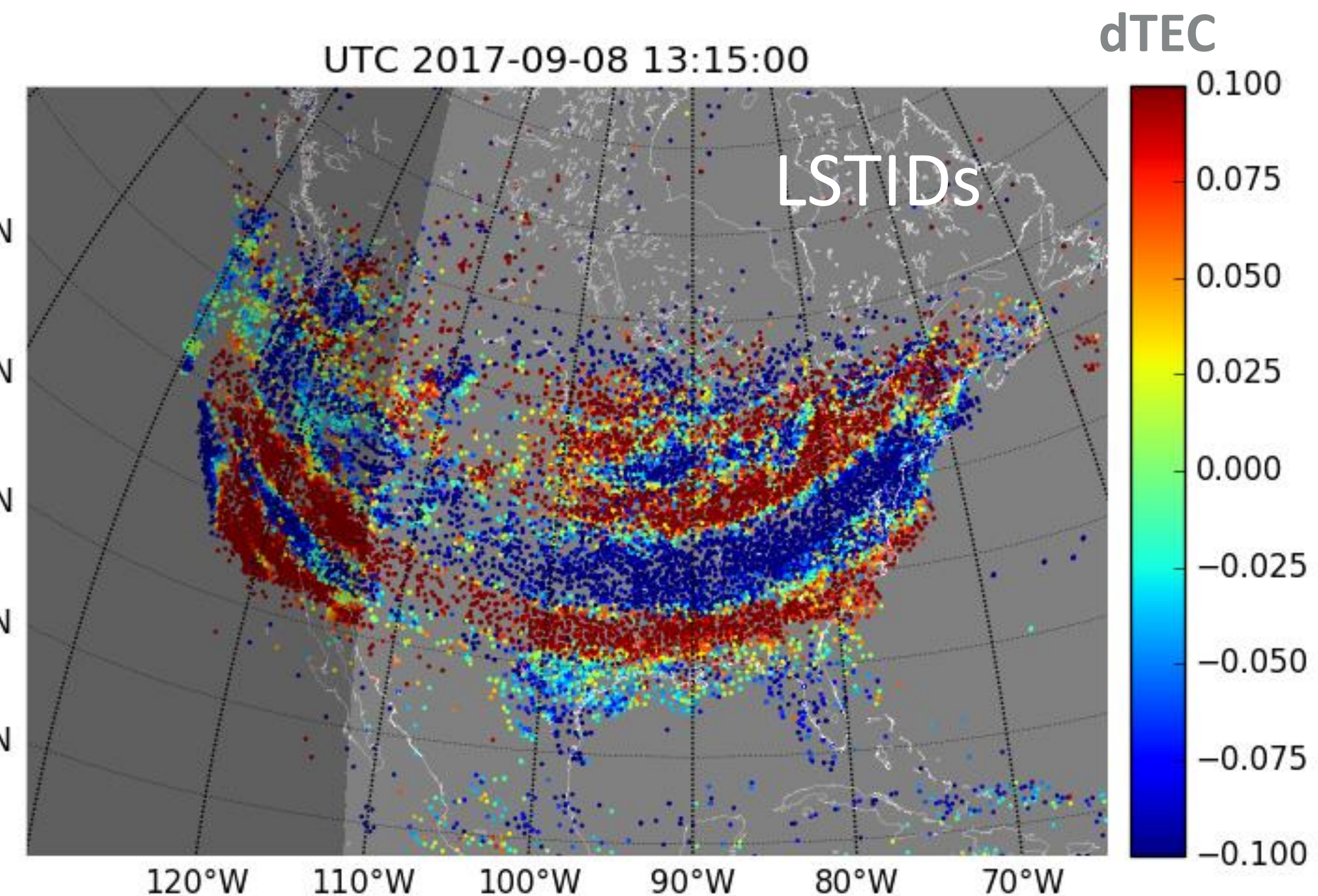


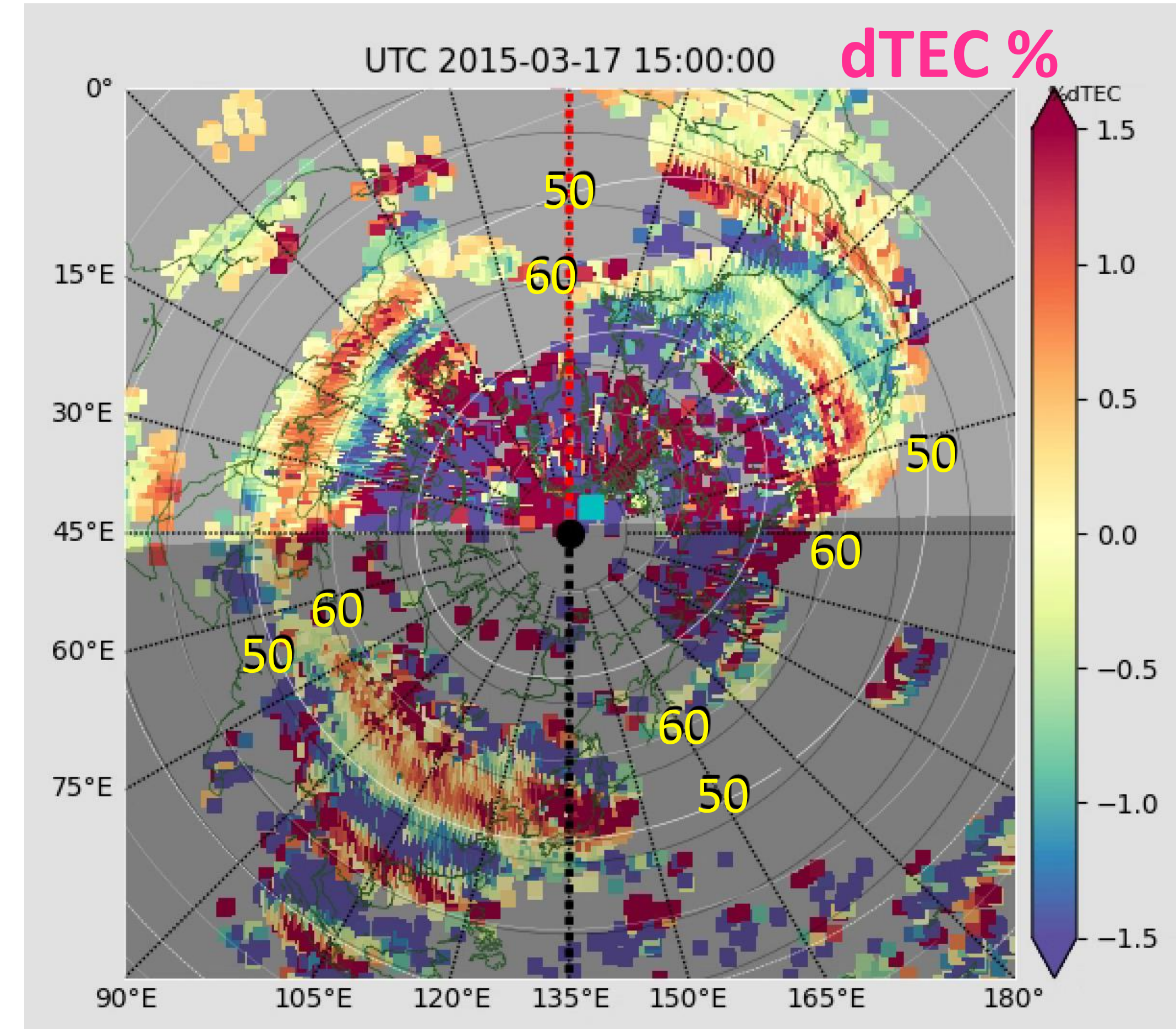
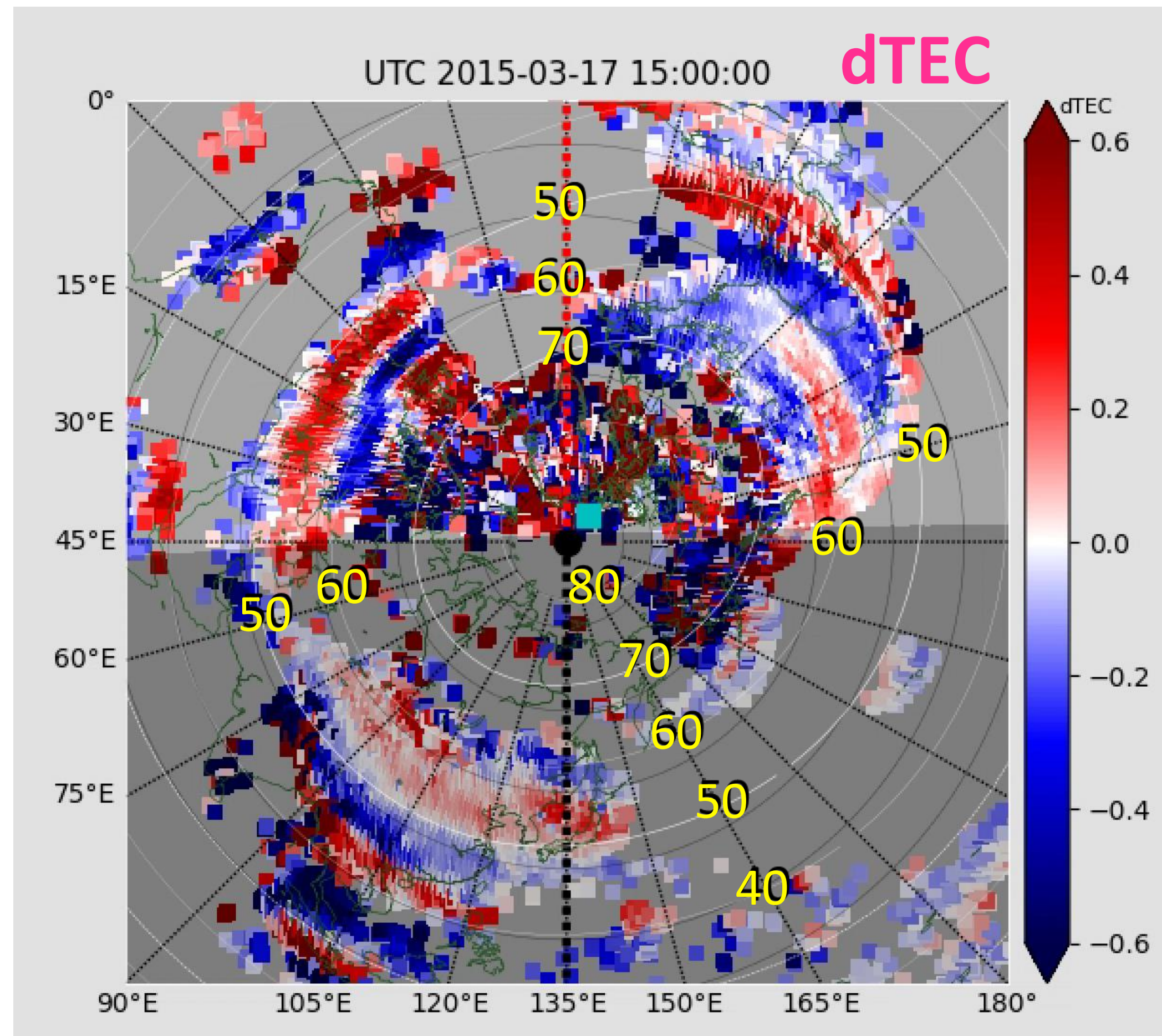




Stormtime injection of frictional heating and particle heating at high latitudes generates global effects through TIDs and TADs.

The spatial distribution of the injection and the background T-I conditions lead to significant variability in the storm's effects.



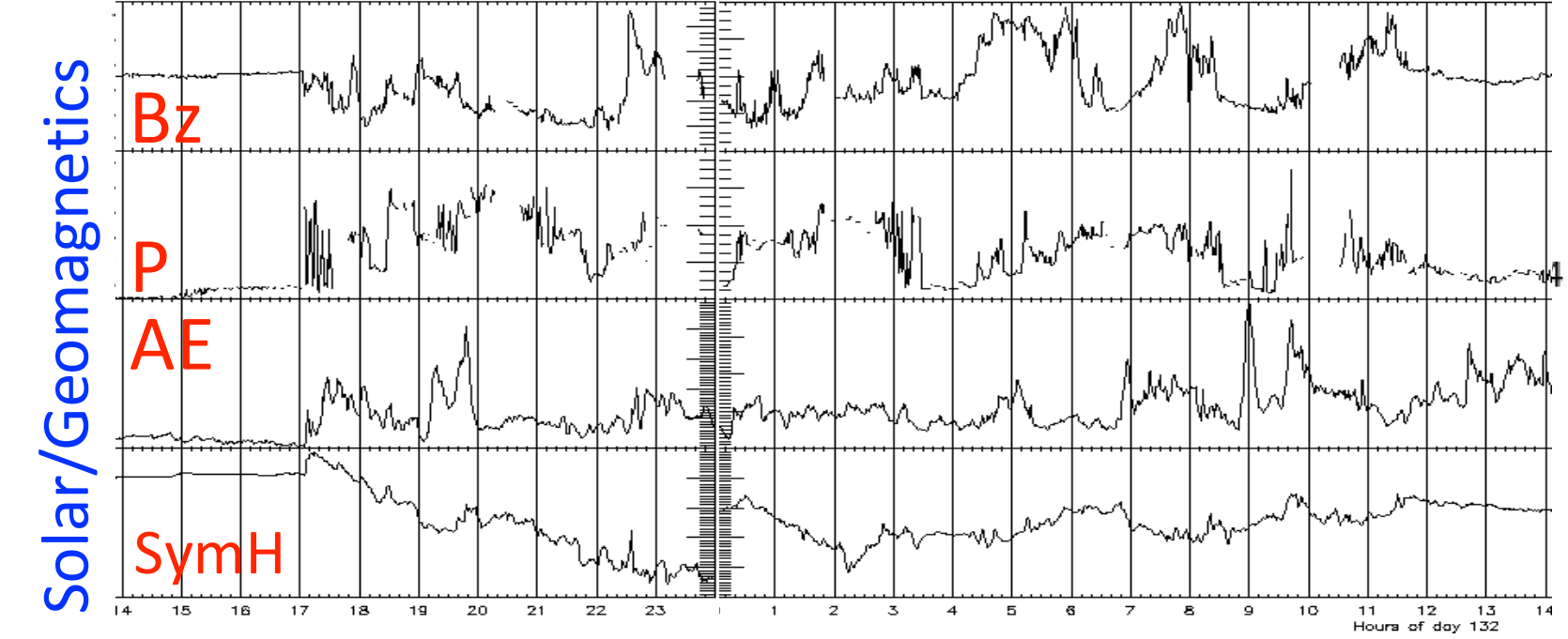
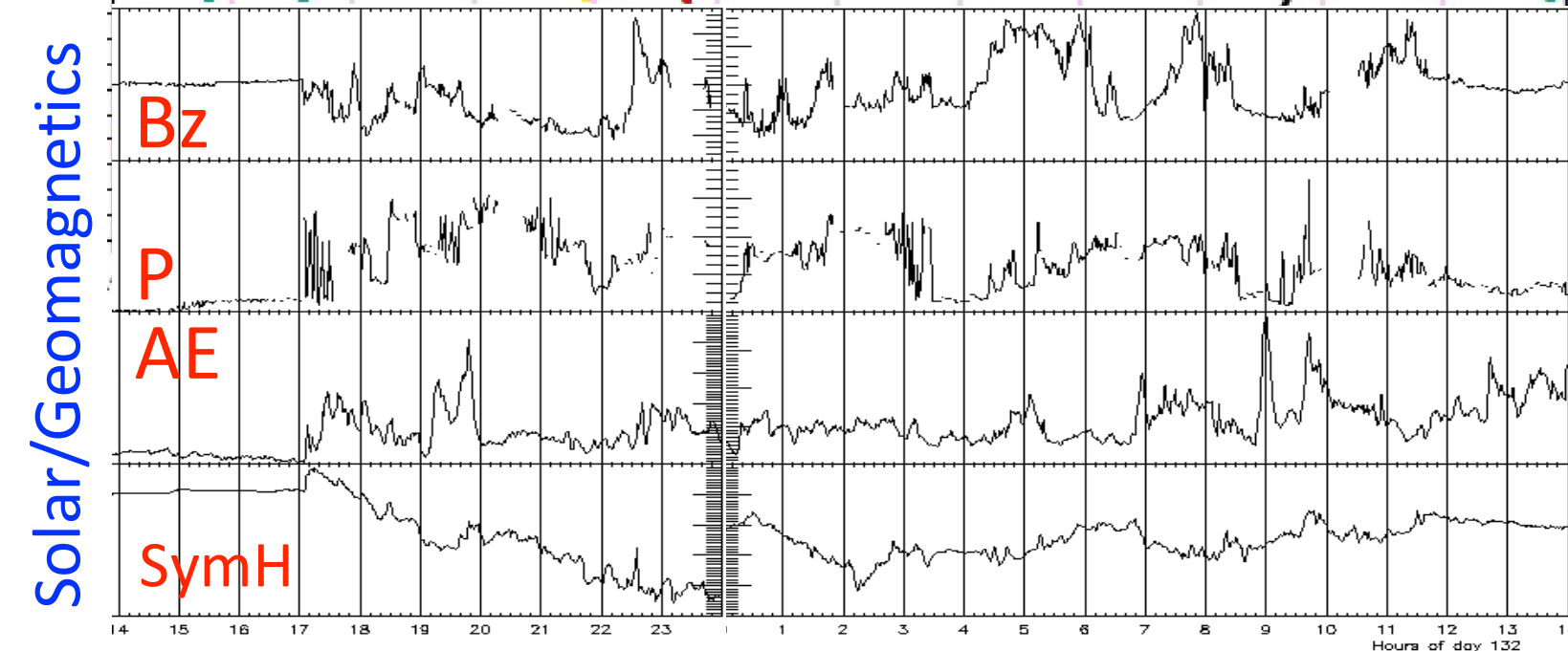
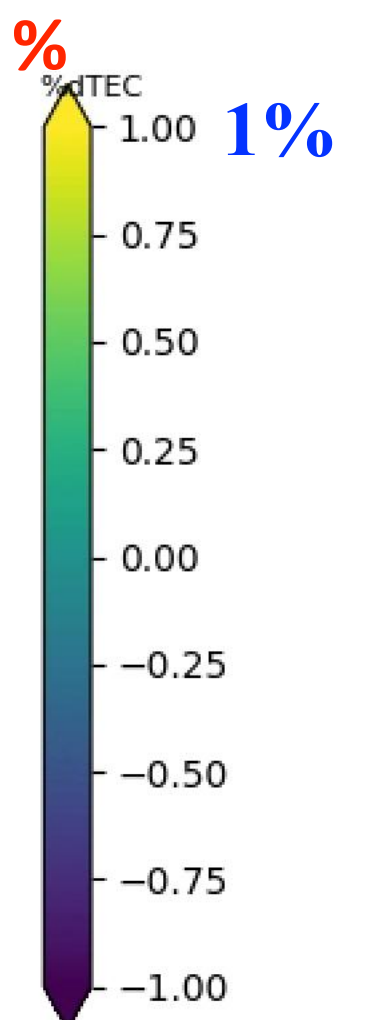
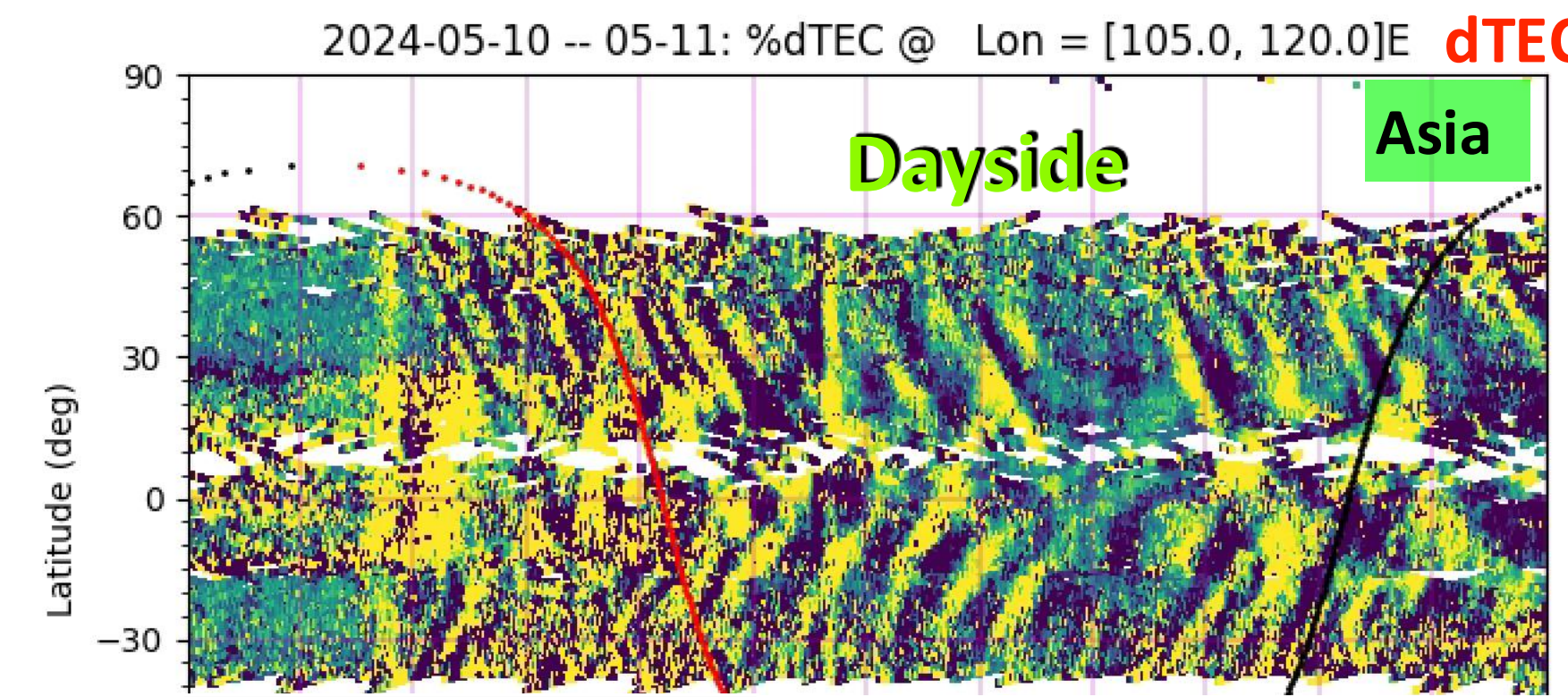
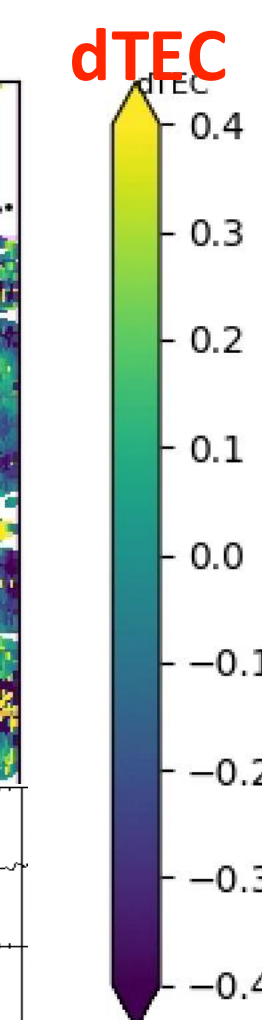
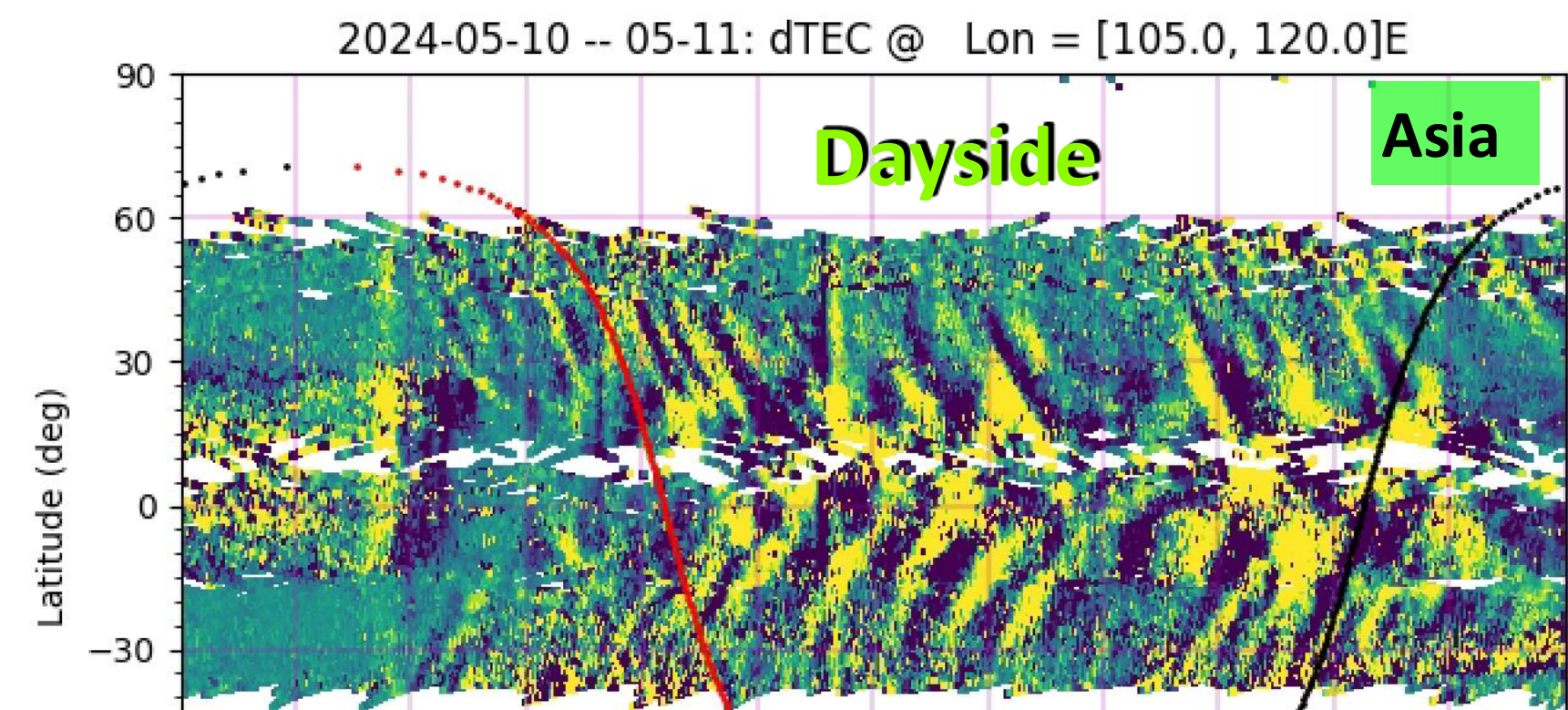
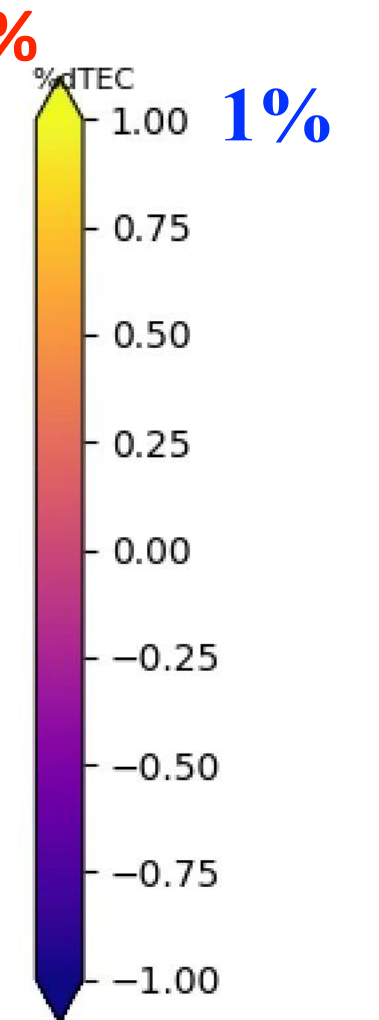
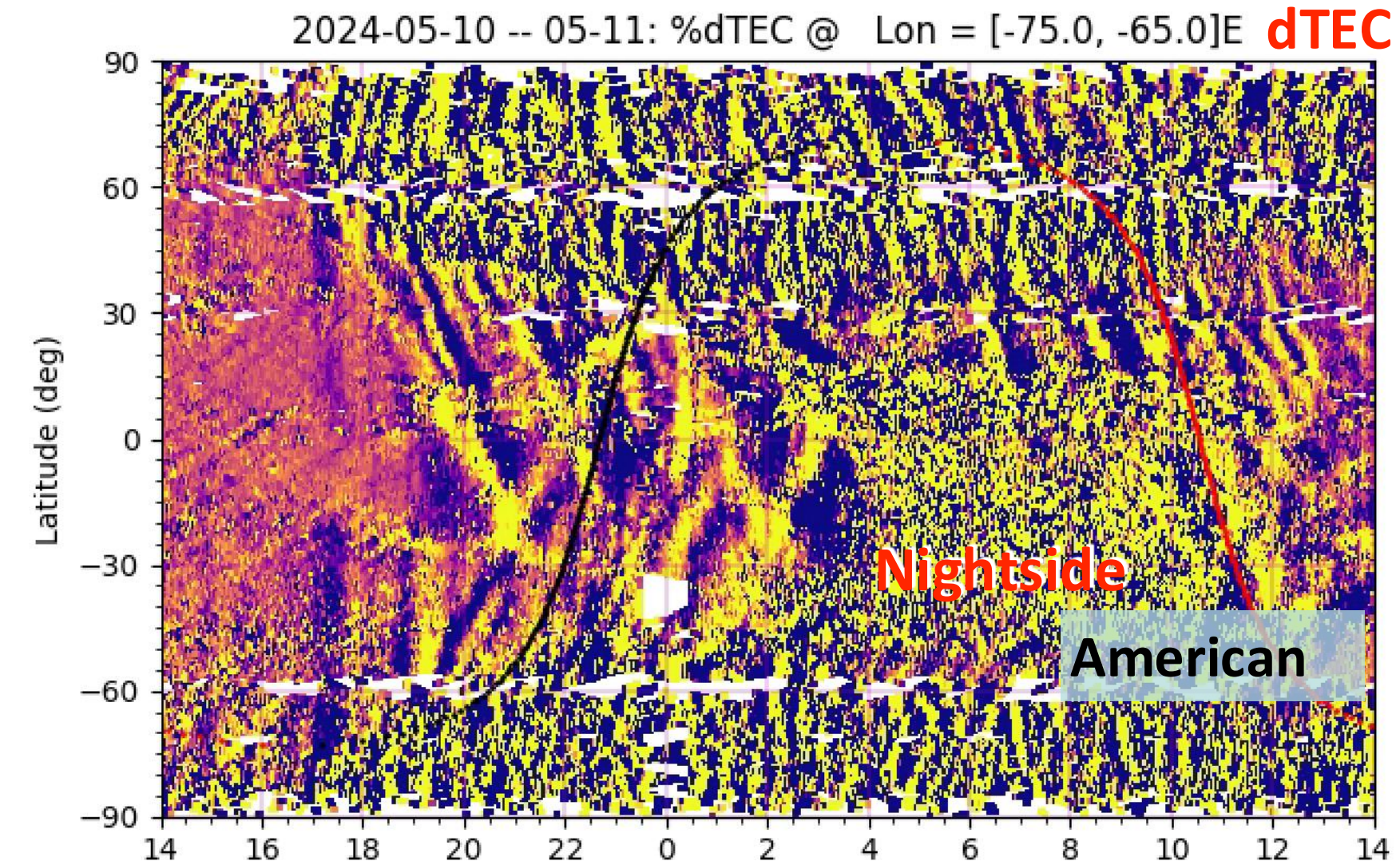
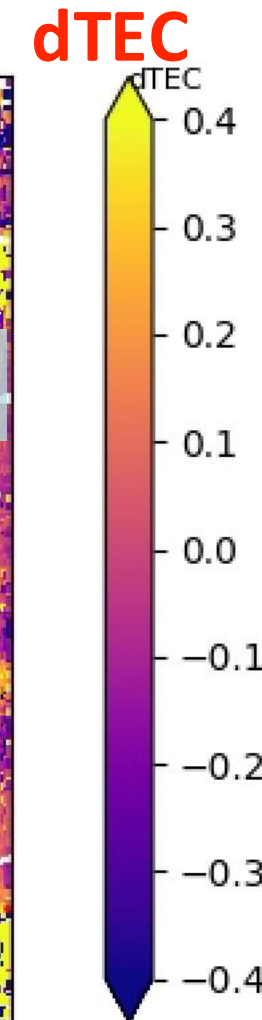
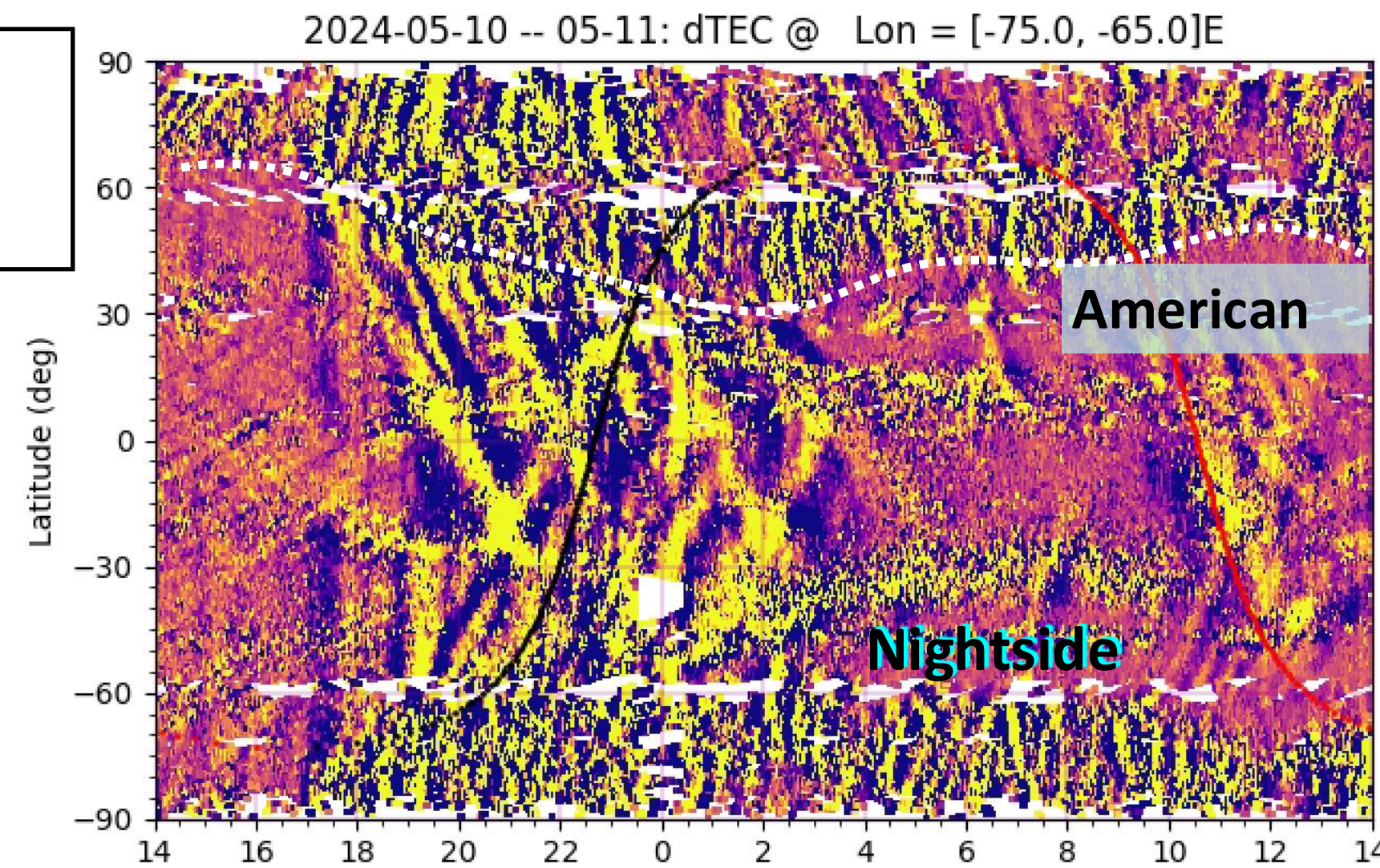


Are there fundamental differences between TIDs on dayside and nightside?

- are there source locations at the same magnetically latitudes?
- dayside and nightside auroral latitudes are different

Polar latitudes: Both equatorward and poleward TIDs

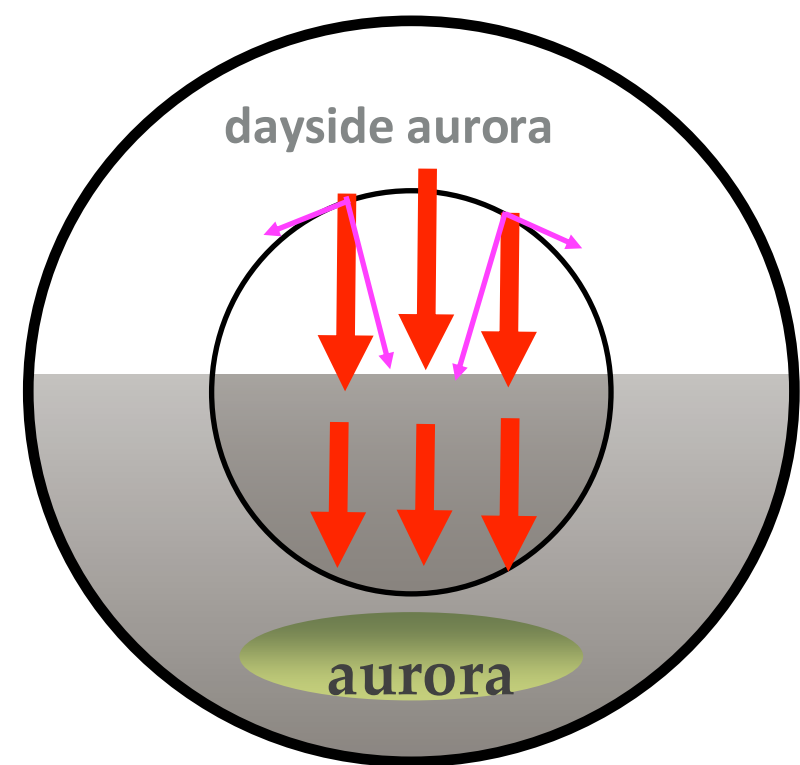
- ◆ Dayside: intense LSTIDs
- ◆ Nightside: weak (or non-exist); not always can propagate to low latitudes unless during storm
 - Nightside source latitude is not as apparent
- ◆ Dayside: intense LSTIDs
- ◆ Nightside: relative amplitude is strong



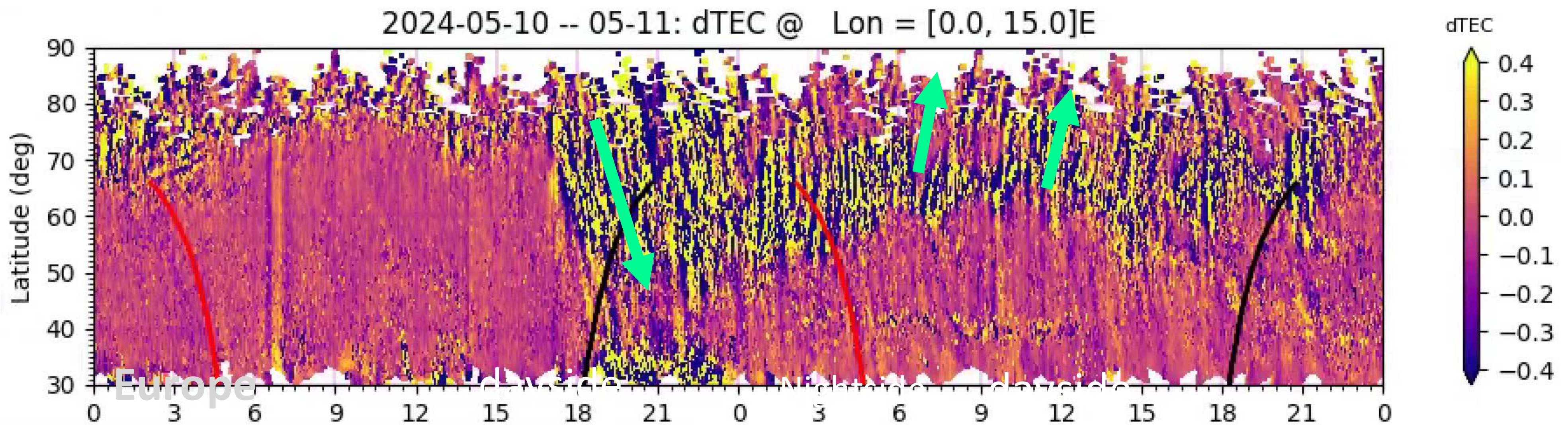
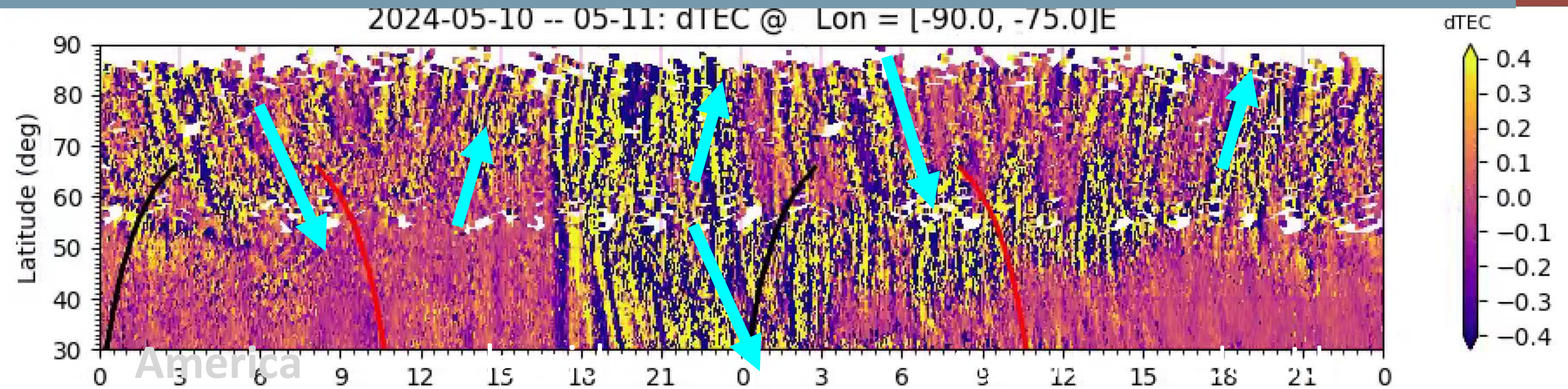
Transpolar TIDs: GWs driven by auroral heating?

Anti-sunward propagation from dayside to nightside during Bz southward events

- highly repeatable
- 700-900 m/s, consistent with GW propagation

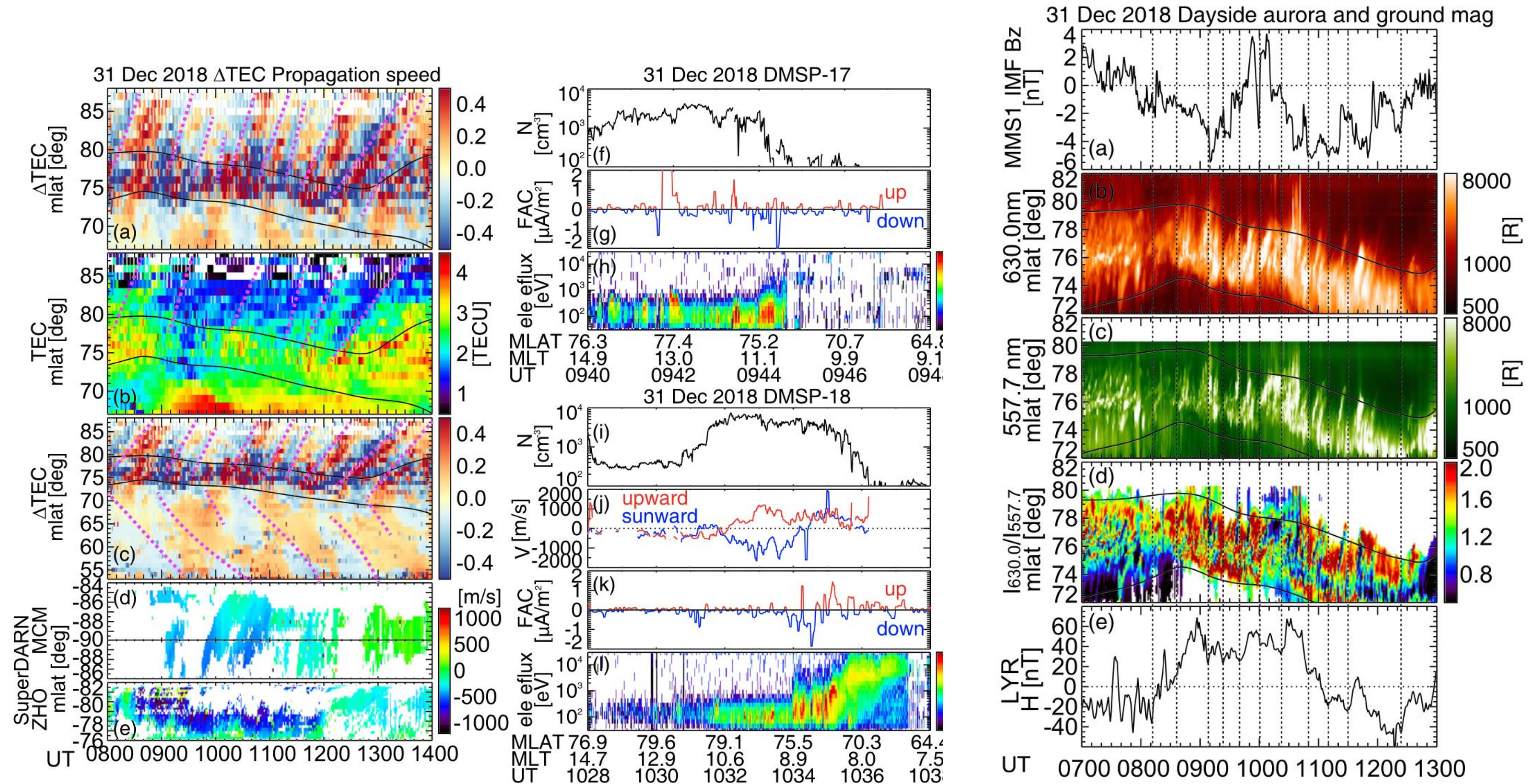


TIDs associated with GWs excited by dayside aurora heating ?



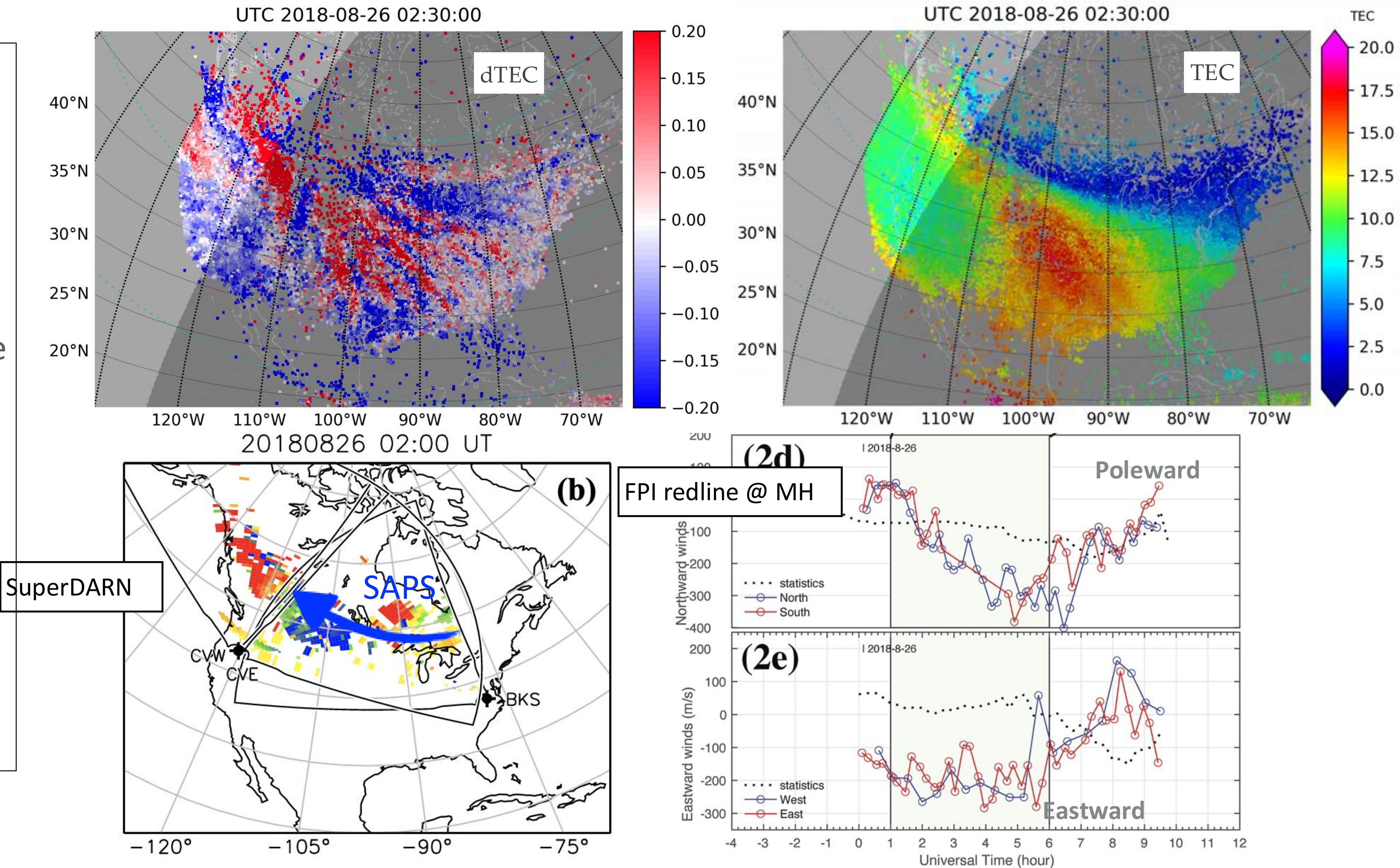
Are these small version of polar plasma patches?

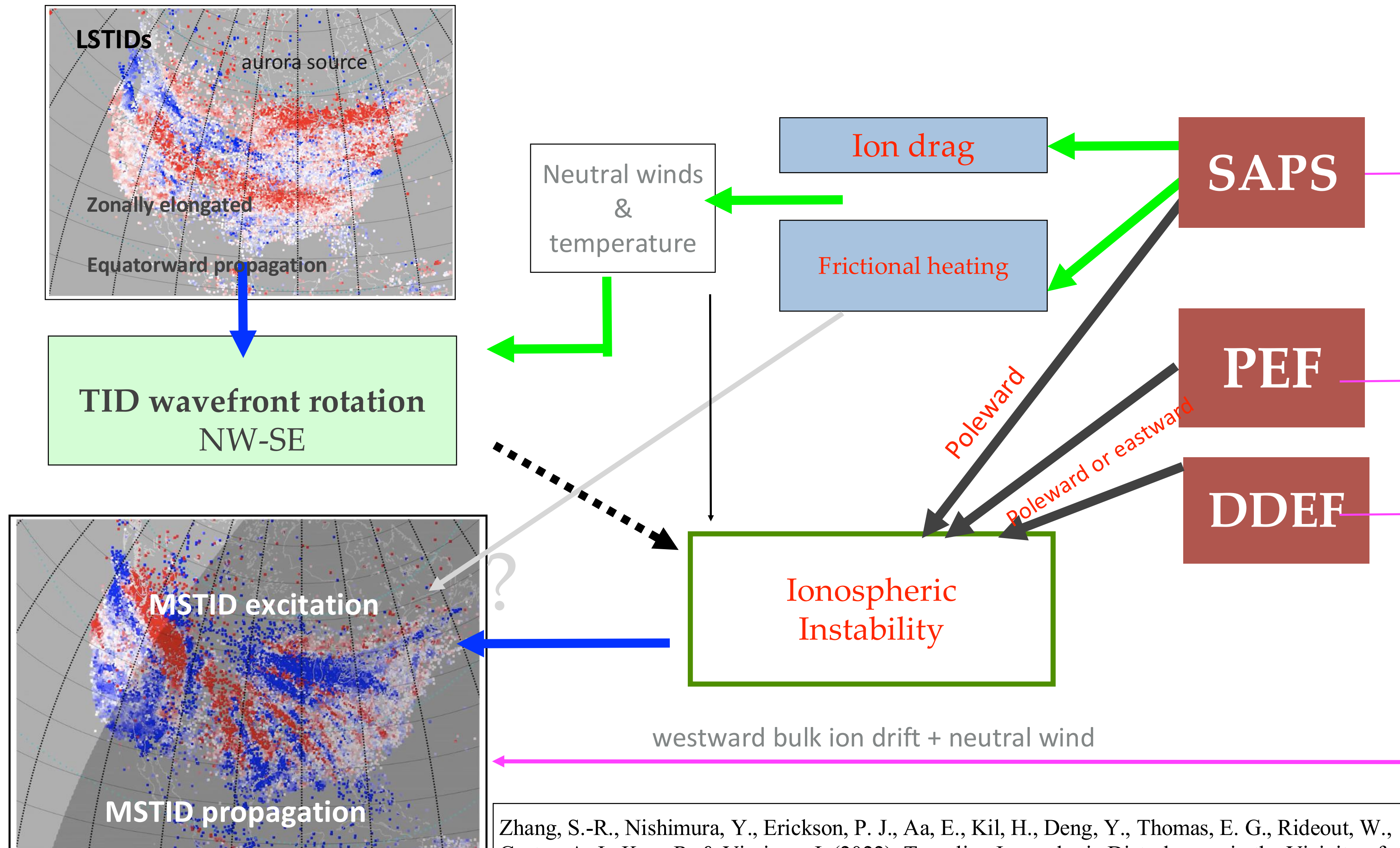
- TIDs are driven by anti-sunward flow
- TID phase velocity is approximately consistent with superDARN convection
- patches are contributed by aurora generated plasma



Nishimura, Y., Zhang, S.-R., Lyons, L. R., Deng, Y., Coster, A. J., Moen, J. I., et al. (2020). Source Region and Propagation of Dayside Large-Scale Traveling Ionospheric Disturbances. *Geophysical Research Letters*, 47(19), 619. <http://doi.org/10.1029/2020GL089451>

- Finger-bone like TIDs
- nightside during intense storms
 - overlap with nighttime SED base
 - SAPS (poleward electric field)
 - No apparent Es
 - Preceded by LSTIDs
 - Moving southwestward





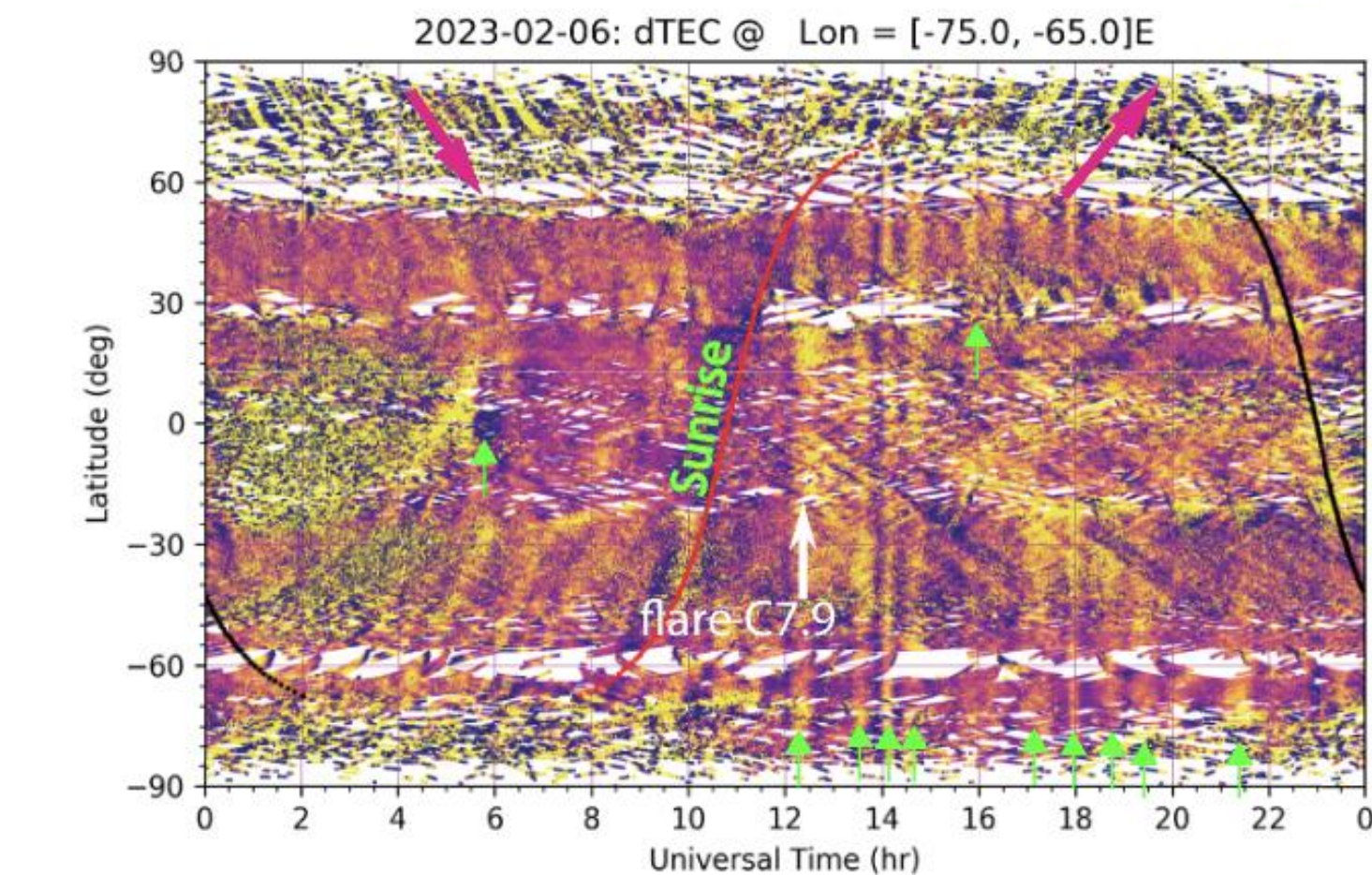
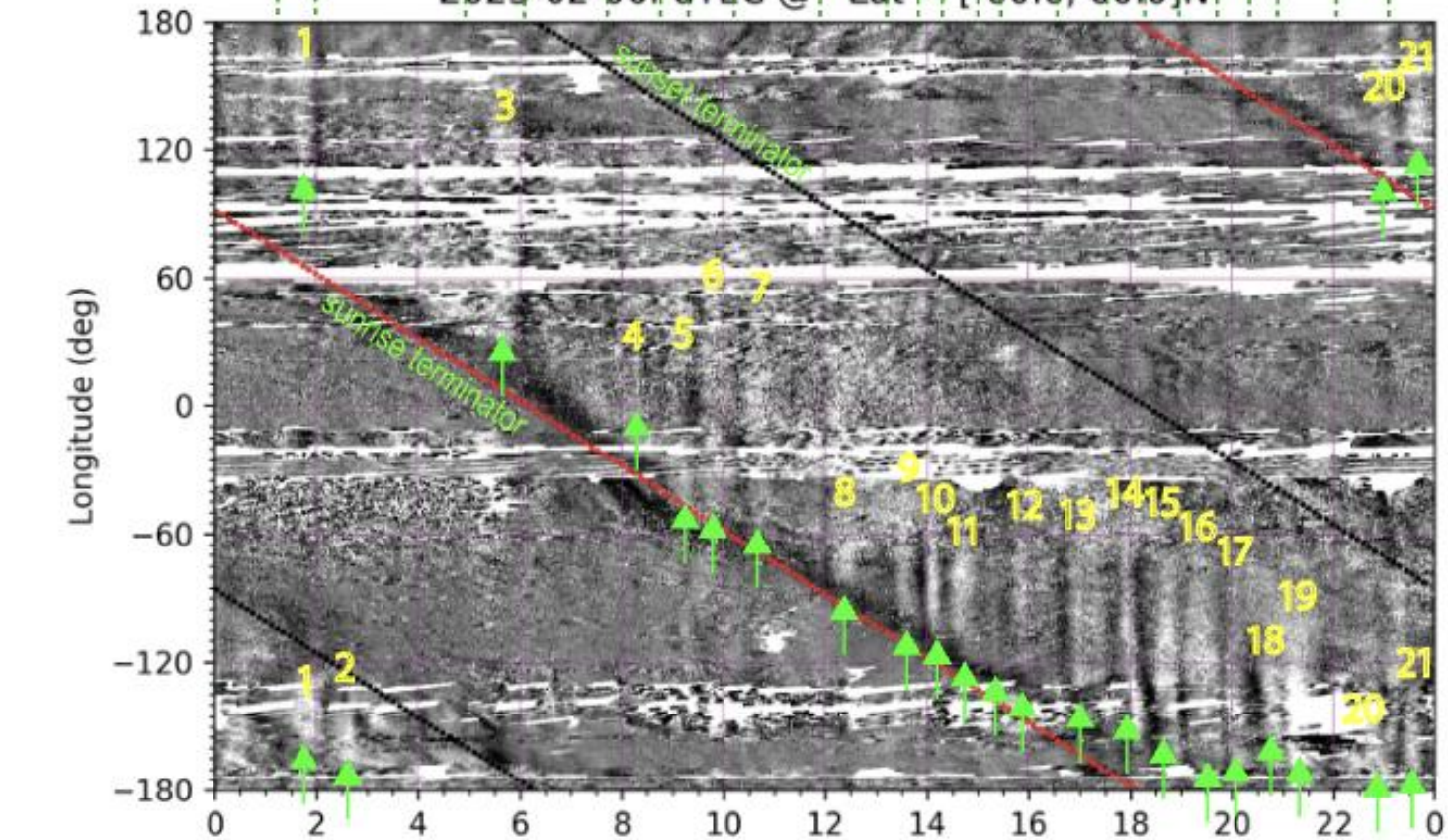
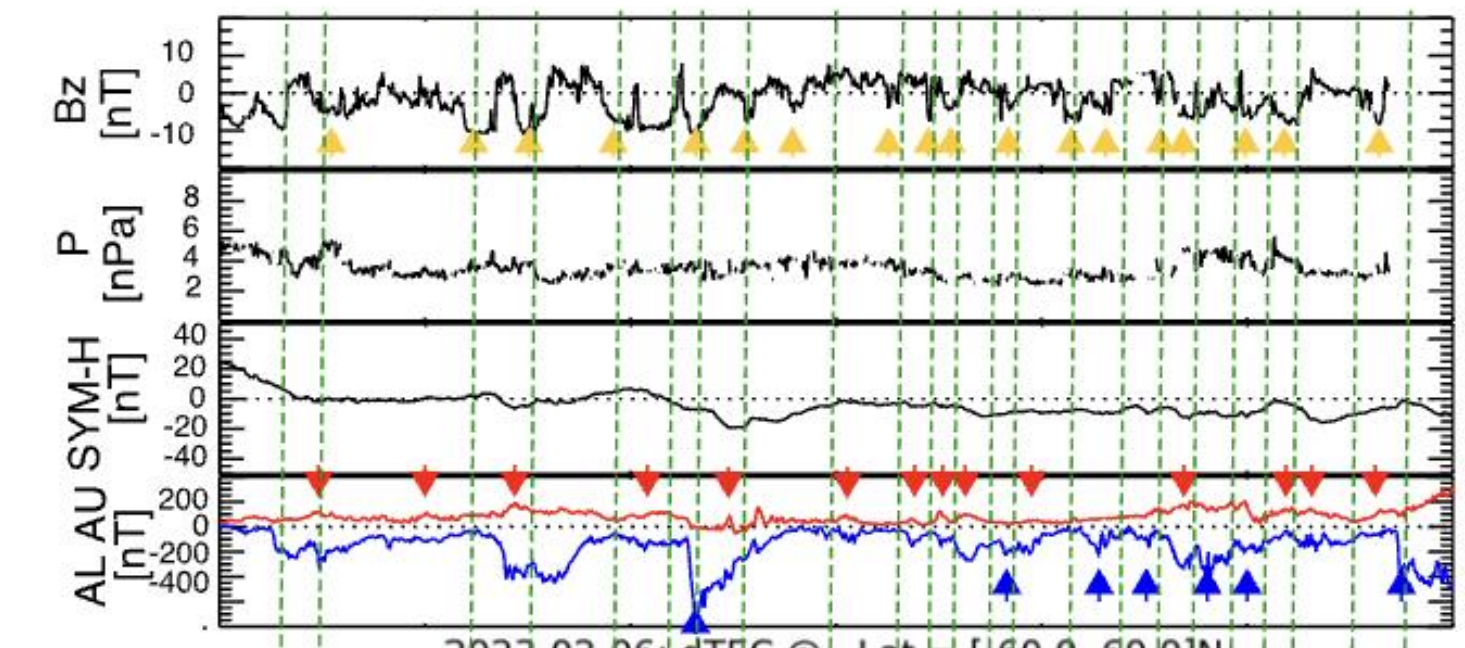
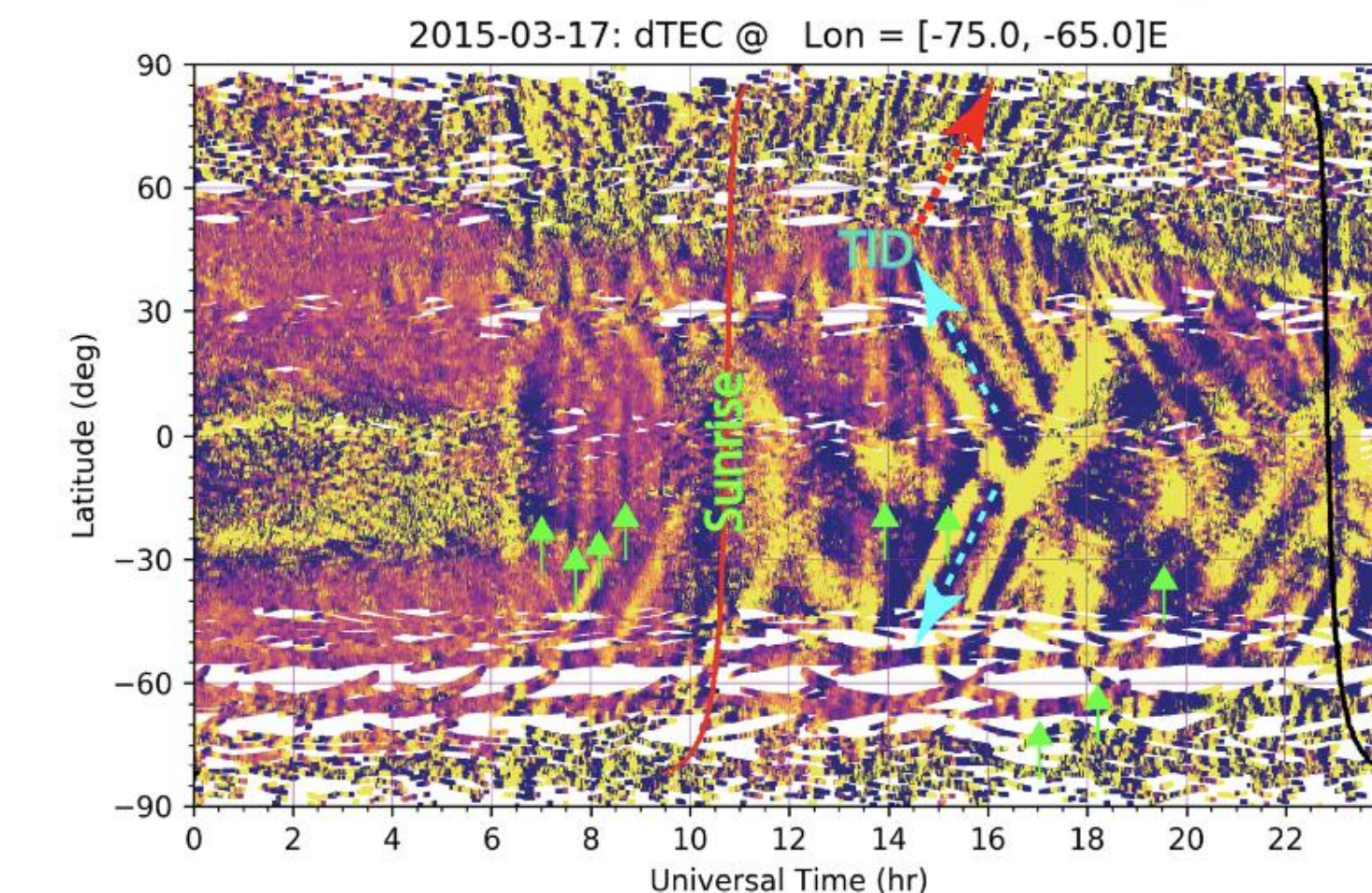
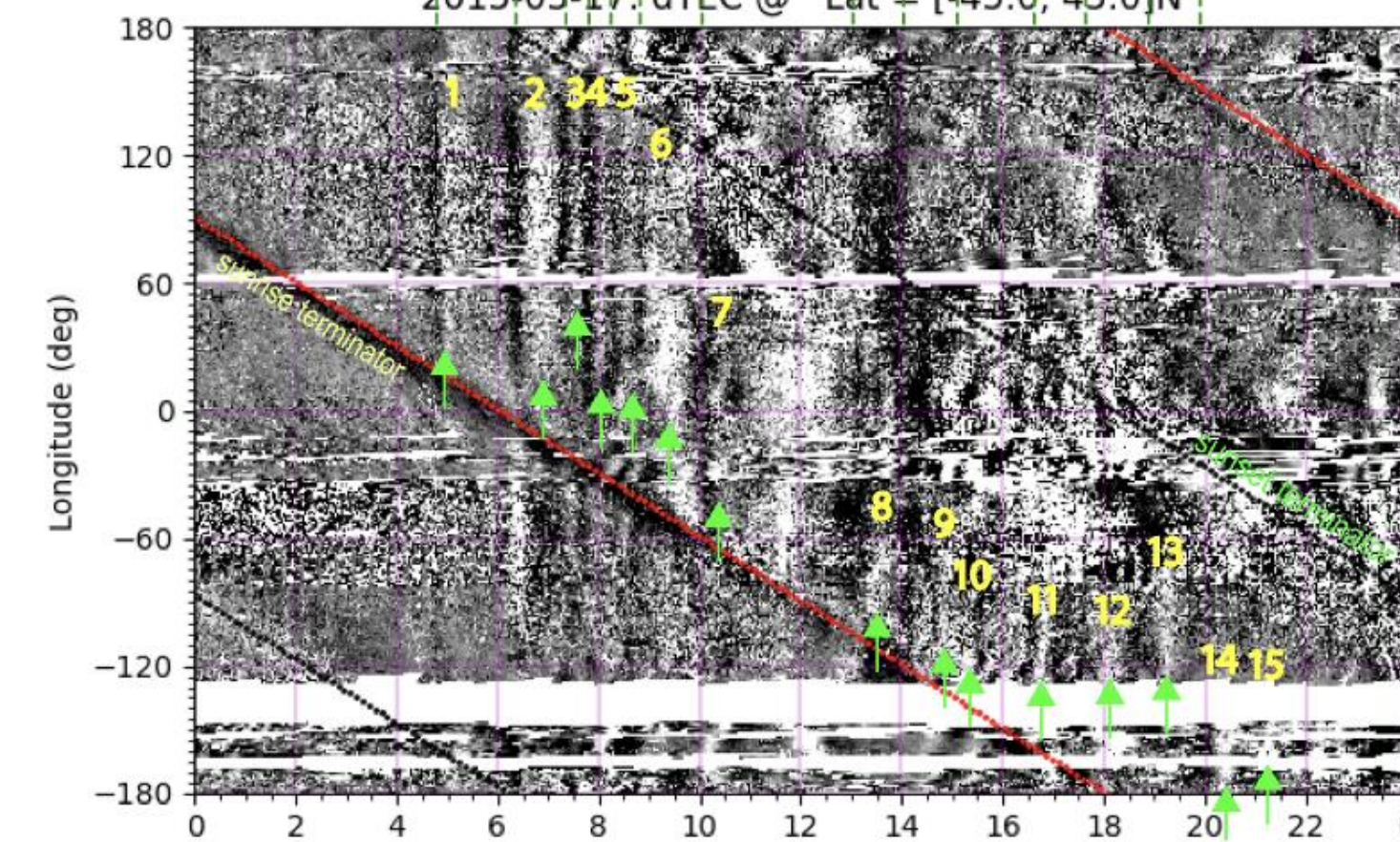
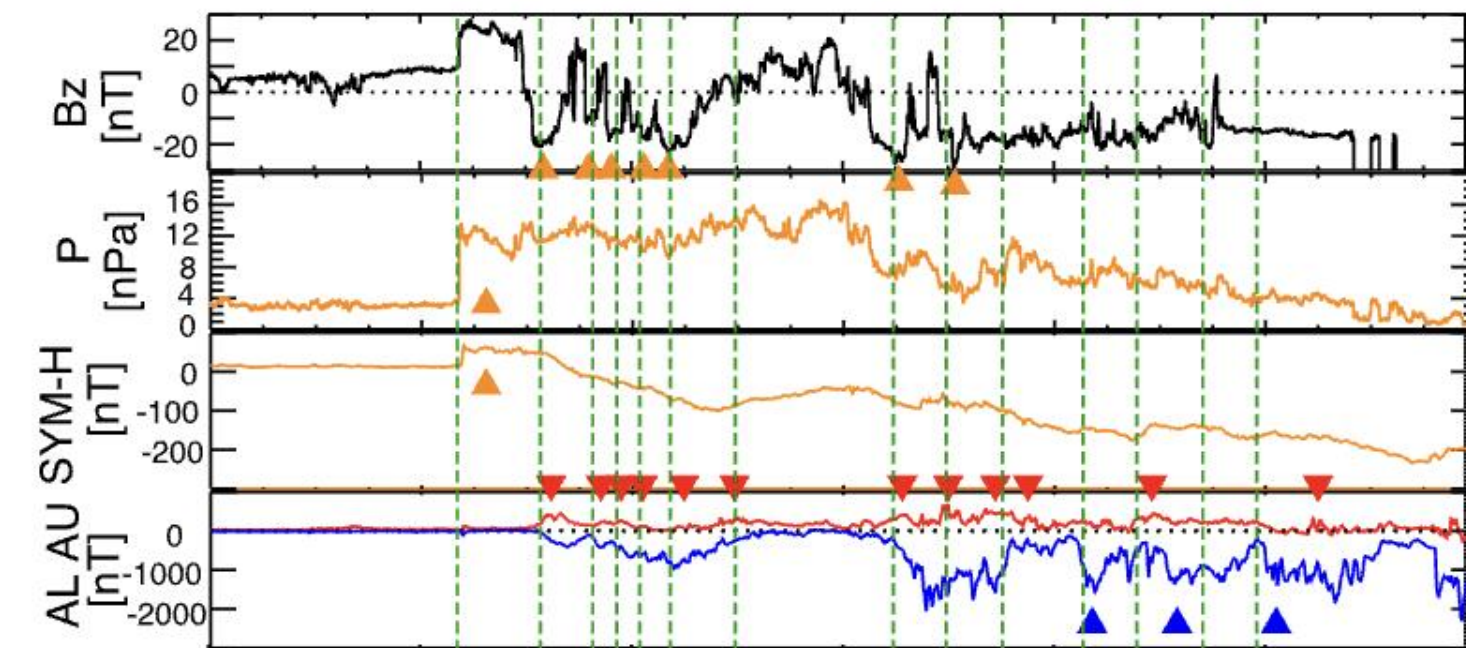
Zhang, S.-R., Nishimura, Y., Erickson, P. J., Aa, E., Kil, H., Deng, Y., Thomas, E. G., Rideout, W., Coster, A. J., Kerr, R. & Vierinen, J. (2022). Traveling Ionospheric Disturbances in the Vicinity of Storm-Enhanced Density at Midlatitudes. *Journal of Geophysical Research: Space Physics*, 127(8), e2022JA030429.

New Applications: Using dTEC to detecting Penetration Electric Field (PEF)

30

- ▶ Simultaneous global ionospheric disturbances (SGDs) are often observed even during minor solar and geomagnetic disturbances.
- ▶ SGDs occur predominately on dayside and are related to penetration electric fields (PEFs) of solar wind and geomagnetic disturbance origin
- ▶ Solar wind/magnetosphere drives some short-term ionospheric variability perhaps on a regular basis
- ▶ Global GNSS networks offer a novel and effective technique for continuous PEF monitoring, providing rich datasets for further study.

Zhang, S., Nishimura, Y., Vierinen, J., Lyons, L. R., Knipp, D. J., Gustavsson, B. J., et al. (2023). Simultaneous Global Ionospheric Disturbances Associated With Penetration Electric Fields During Intense and Minor Solar and Geomagnetic Disturbances. *Geophysical Research Letters*, 50(19), e2023GL104250.
<https://doi.org/10.1029/2023gl104250>

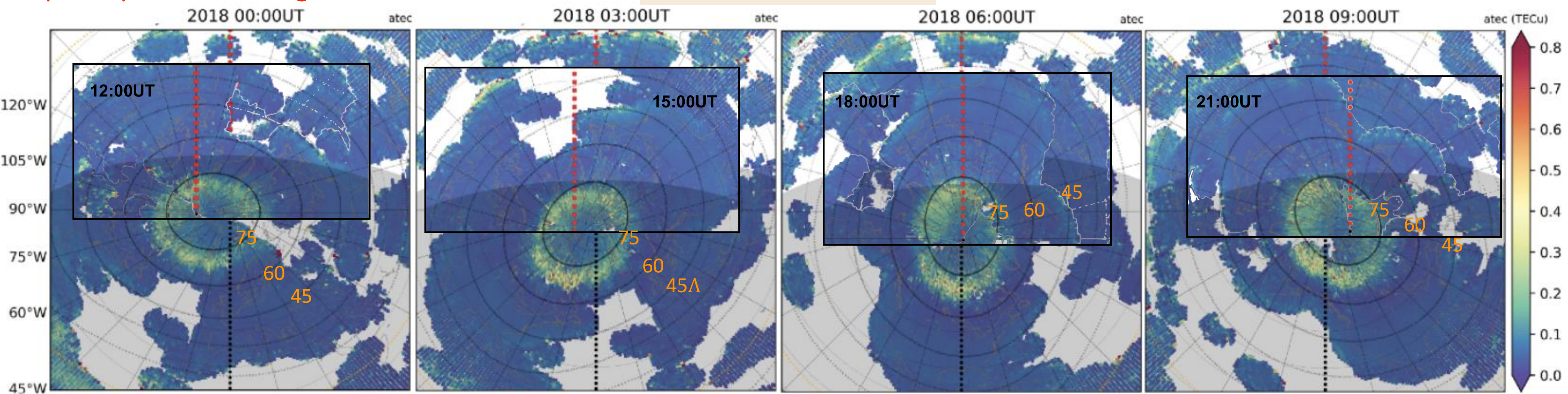


New Applications: Irregularity Intensity Oval at different UTs

31

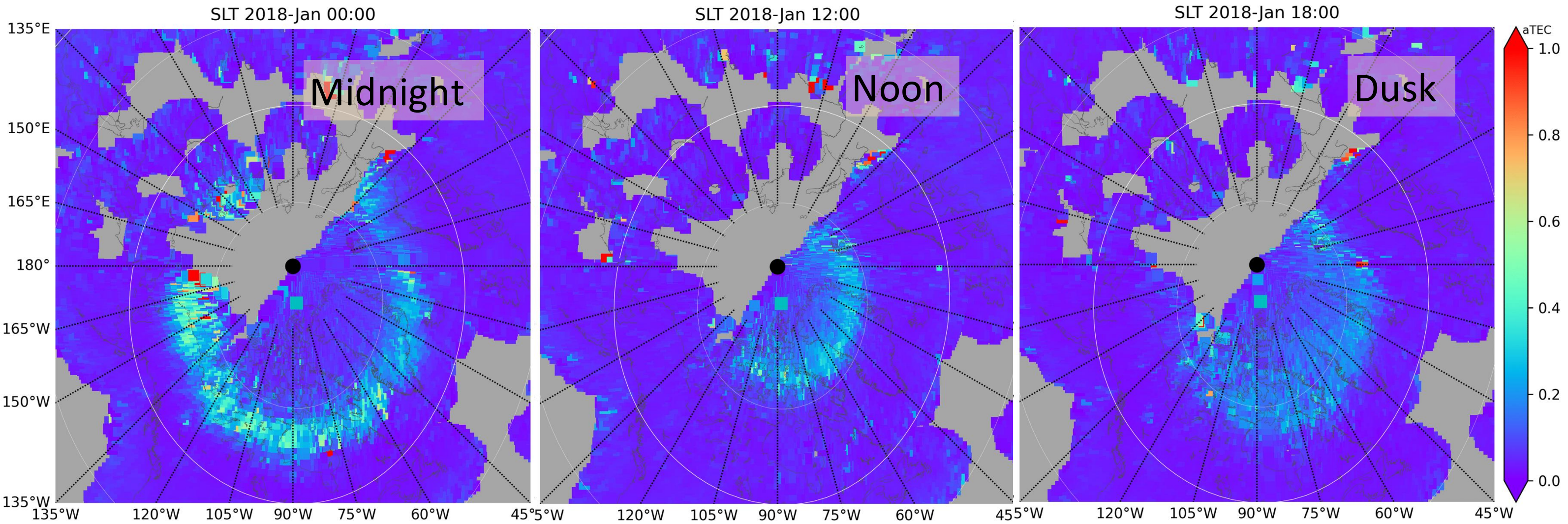
|dTEC| annual average over 2018

Composed from two UTs



Irregularity intensity oval overlaps with auroral oval

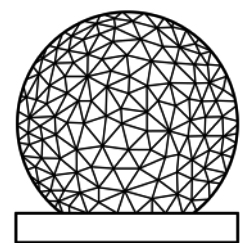
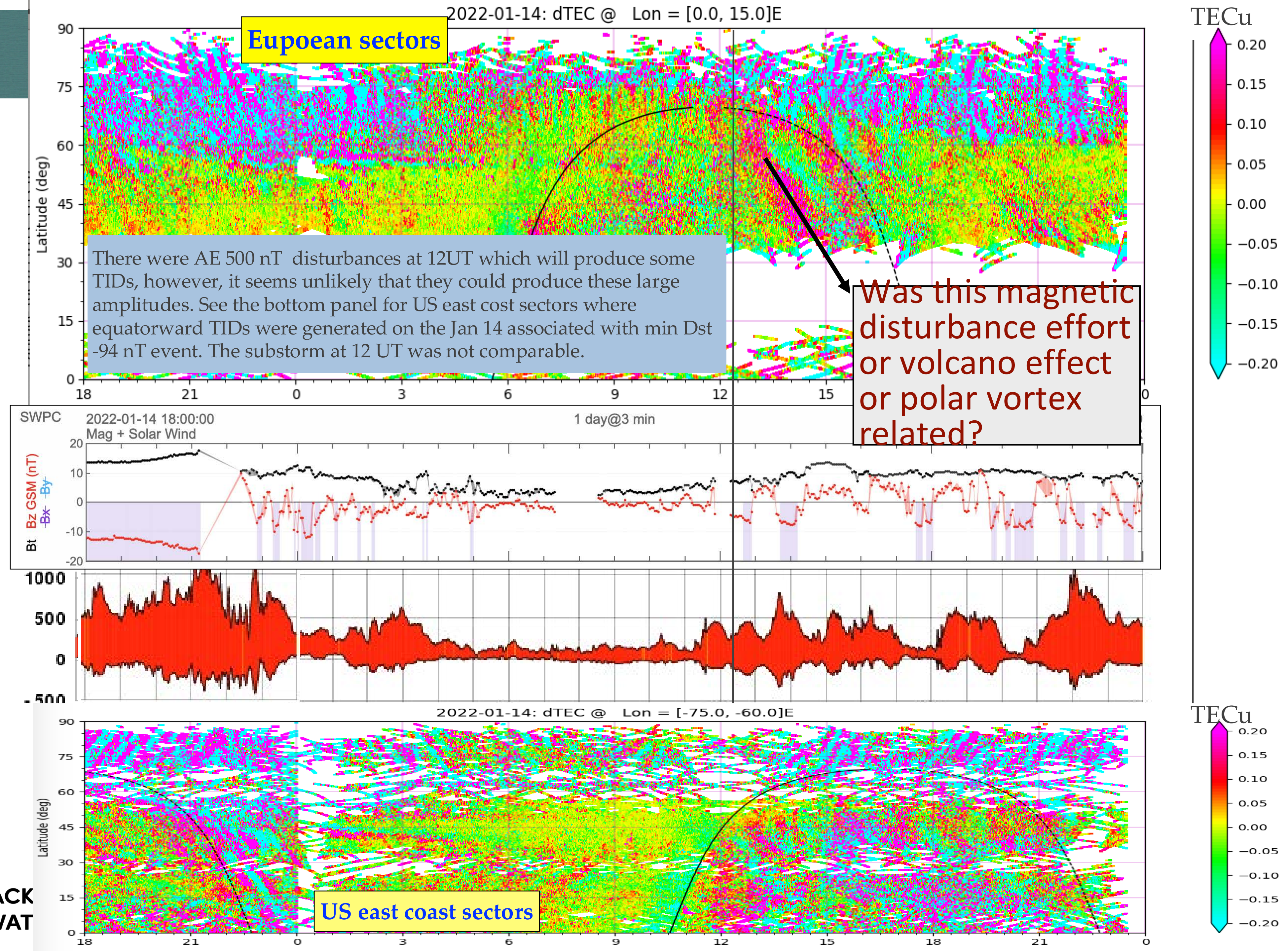
Zhang, S.-R., Coster, A. J., Erickson, P. J., Goncharenko, L. P., & Liu, J. (2025). Mesoscale Ionospheric Irregularity Oval at High Latitudes Observed by Global GNSS Networks (2010–2024). *Journal of Astronomy and Space Sciences*, 42(4), 119–134. <https://doi.org/10.5140/jass.2025.42.4.119>



- Detecting TEC fluctuations presents numerous opportunities to explore various scenarios of geospace dynamics.
- TIDs are ubiquitous. Here we demonstrate that some of them have known sources and established coupling processes. However, exploring new forms of excitation sources remain an intriguing subject.
- Future directions
 - ☑ TIDs in 3D (GNSS tomography + ISRs + ionosondes)
 - ❖ to resolve vertical propagation
 - ☑ Data, data, data
 - ❖ Improved GNSS coverage for appropriate resolution
 - ❖ Coincident ground-based and in situ neutral data from MLT to thermosphere
 - ☑ AI/ML aided TID statistics
 - ☑ New applications of GNSS TEC data
 - ☑ Physics-based simulations
 - ❖ Vertical dynamical coupling via GWs
 - ❖ GW-TID physical connection via ion-neutral coupling is well established
 - ❖ Ionospheric dynamics induced TIDs, especially during storms
 - ❖ Polar TID/patches

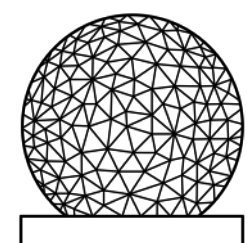
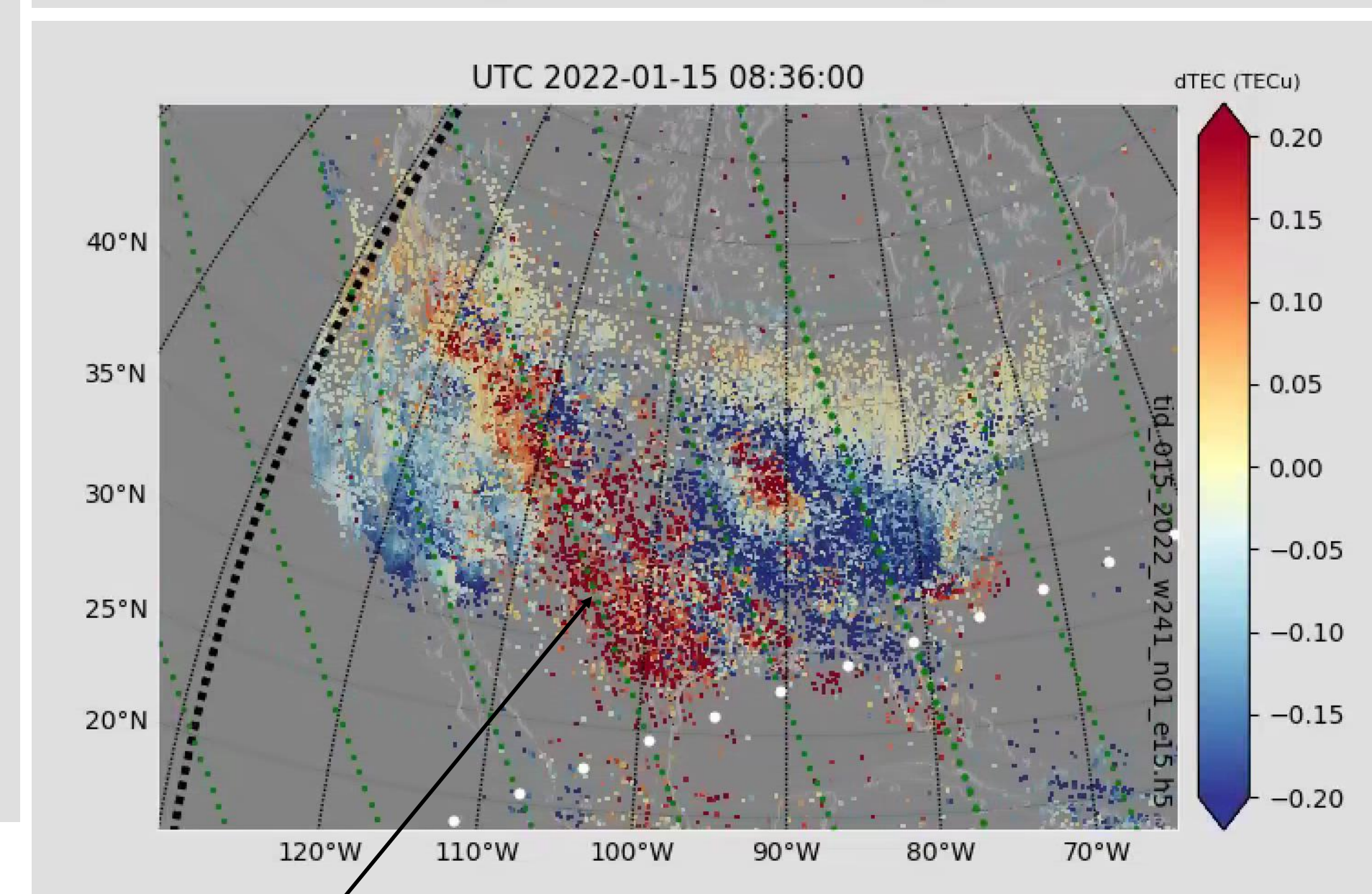
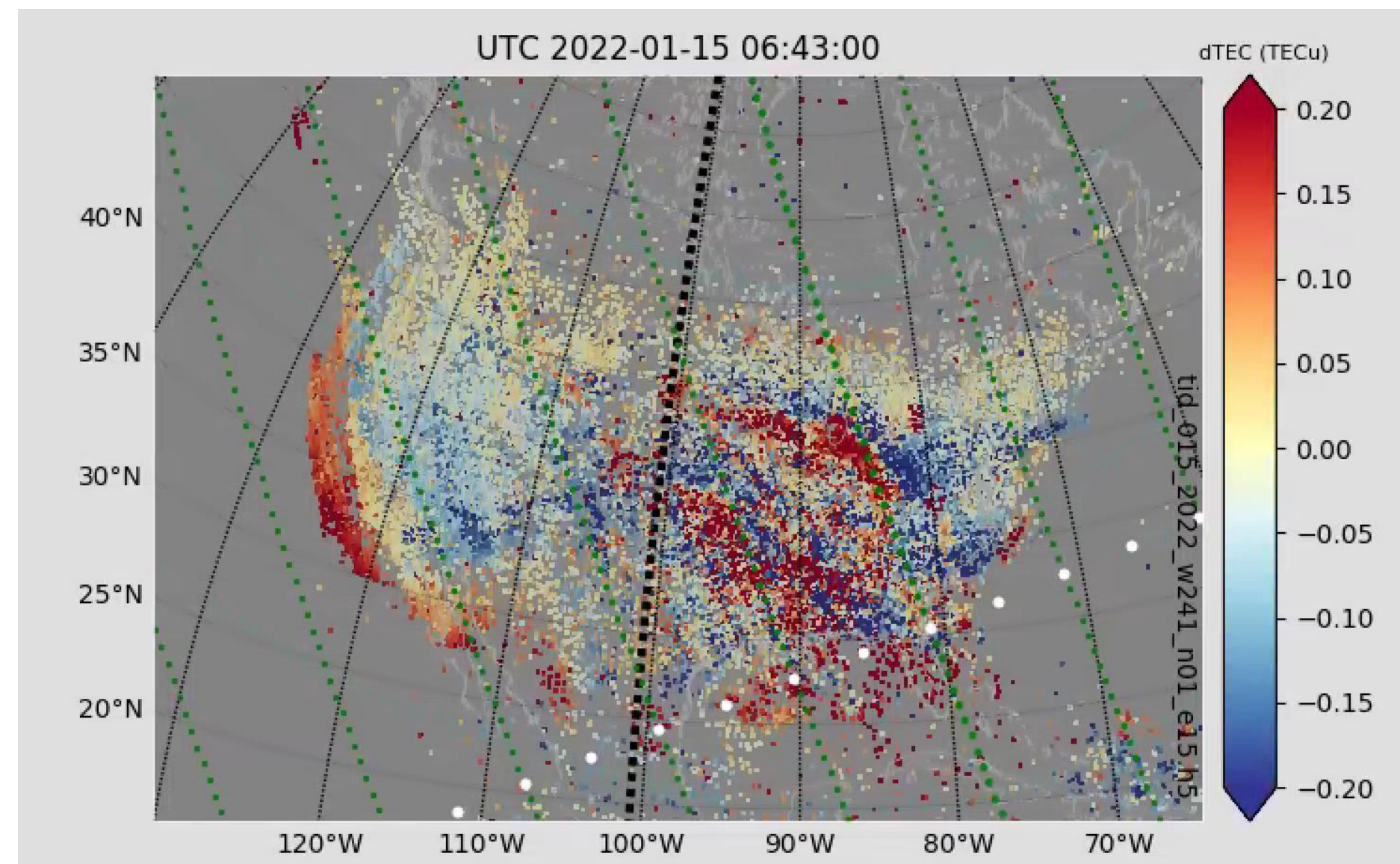
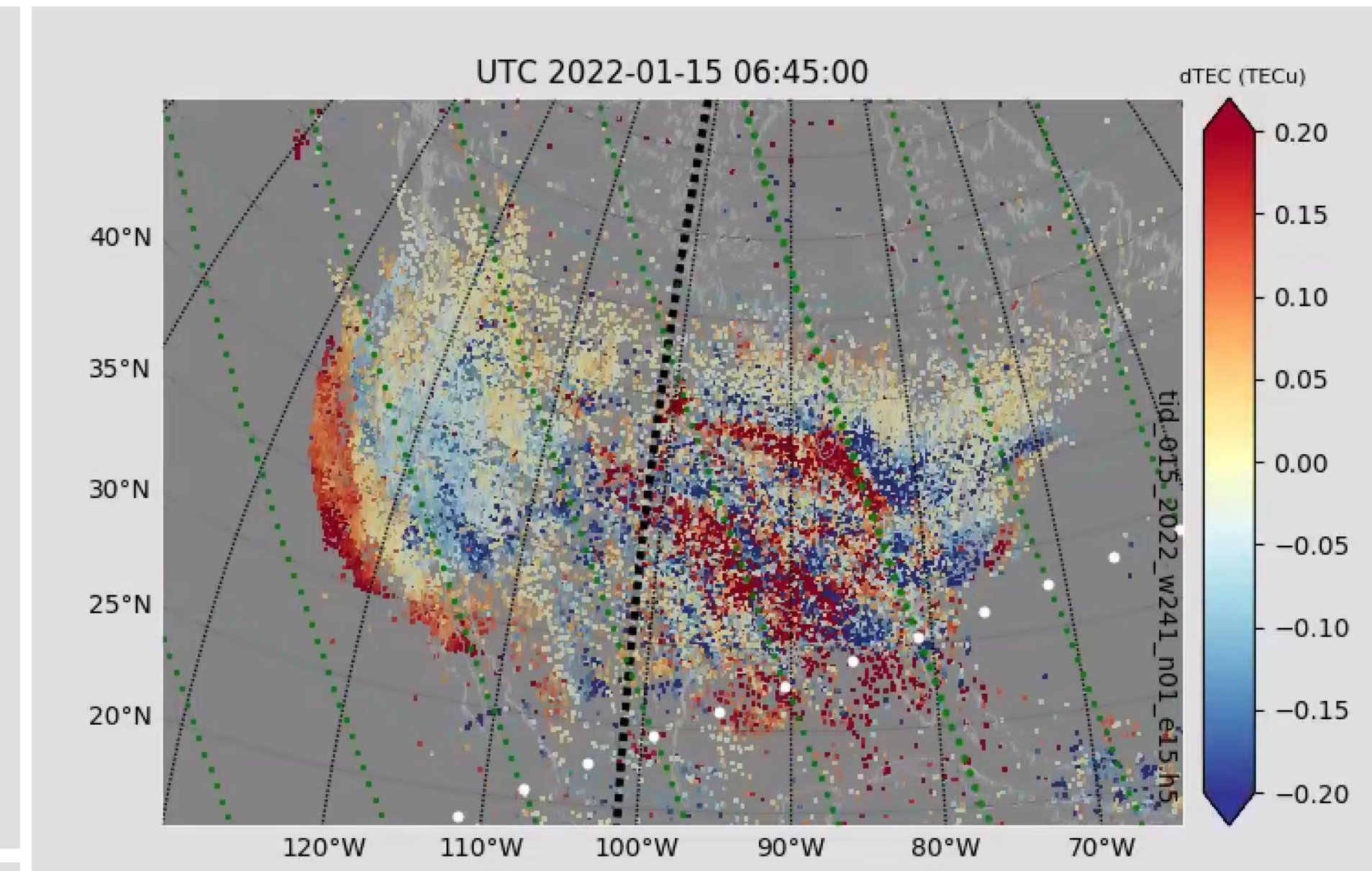
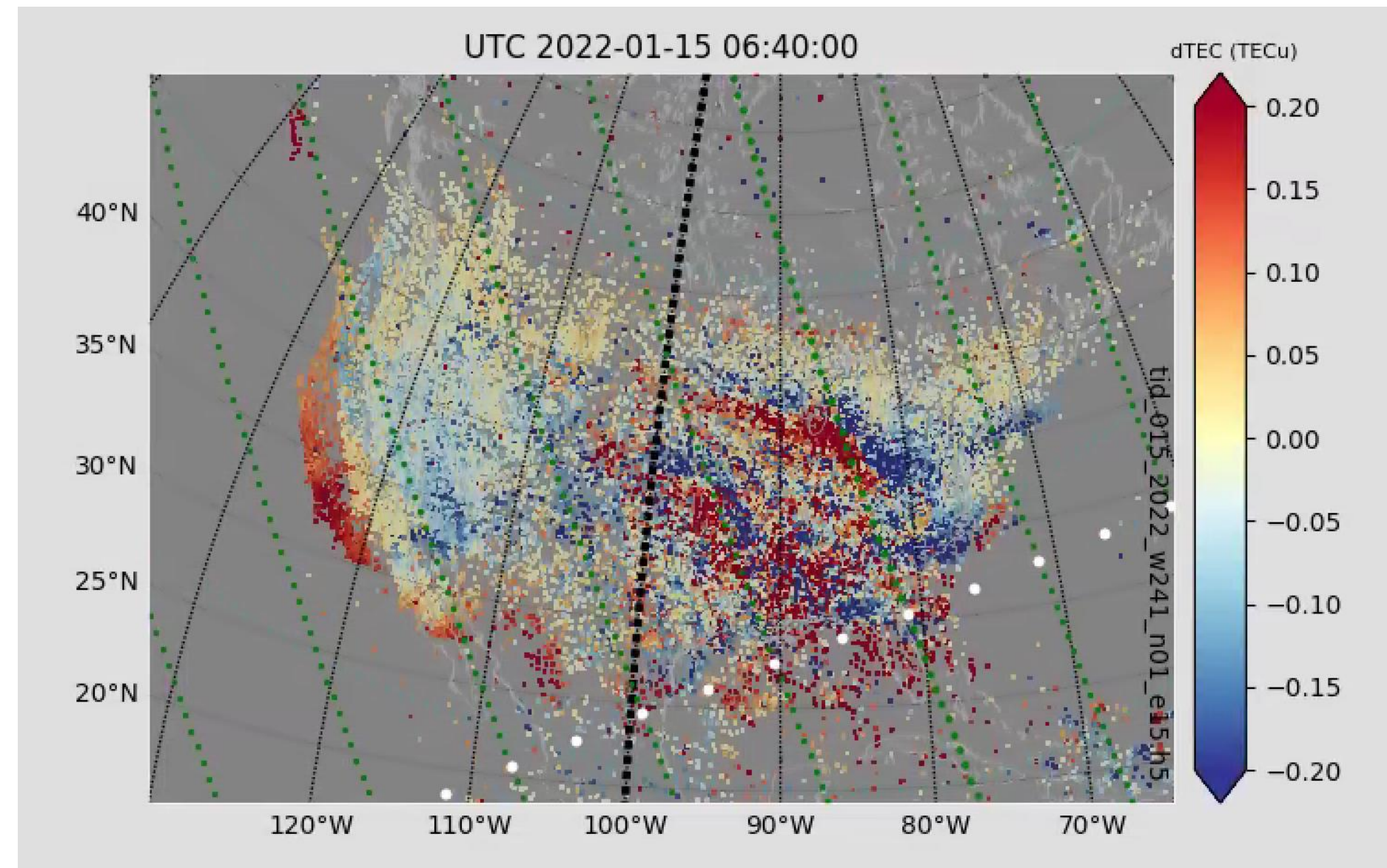
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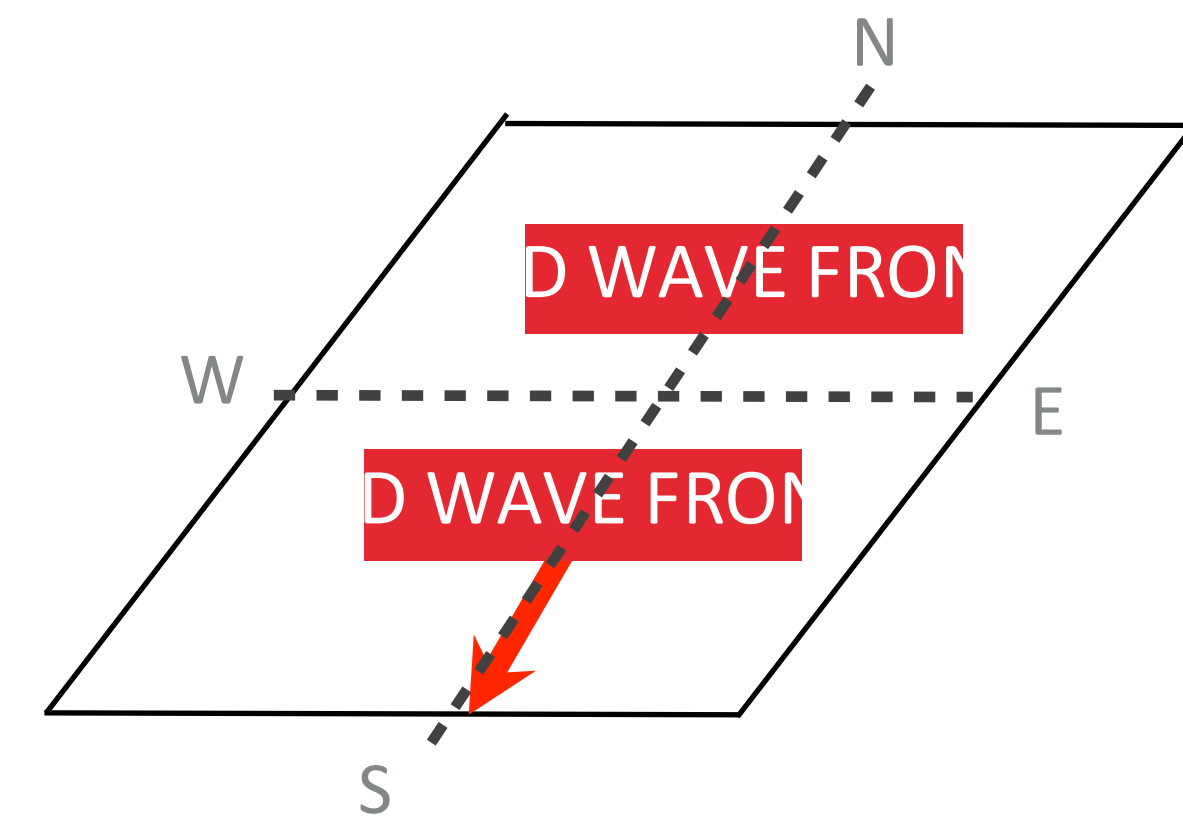
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TIDs over Central US: when did the Tonga TID arrive?

37





without SAPS nor other E-fields

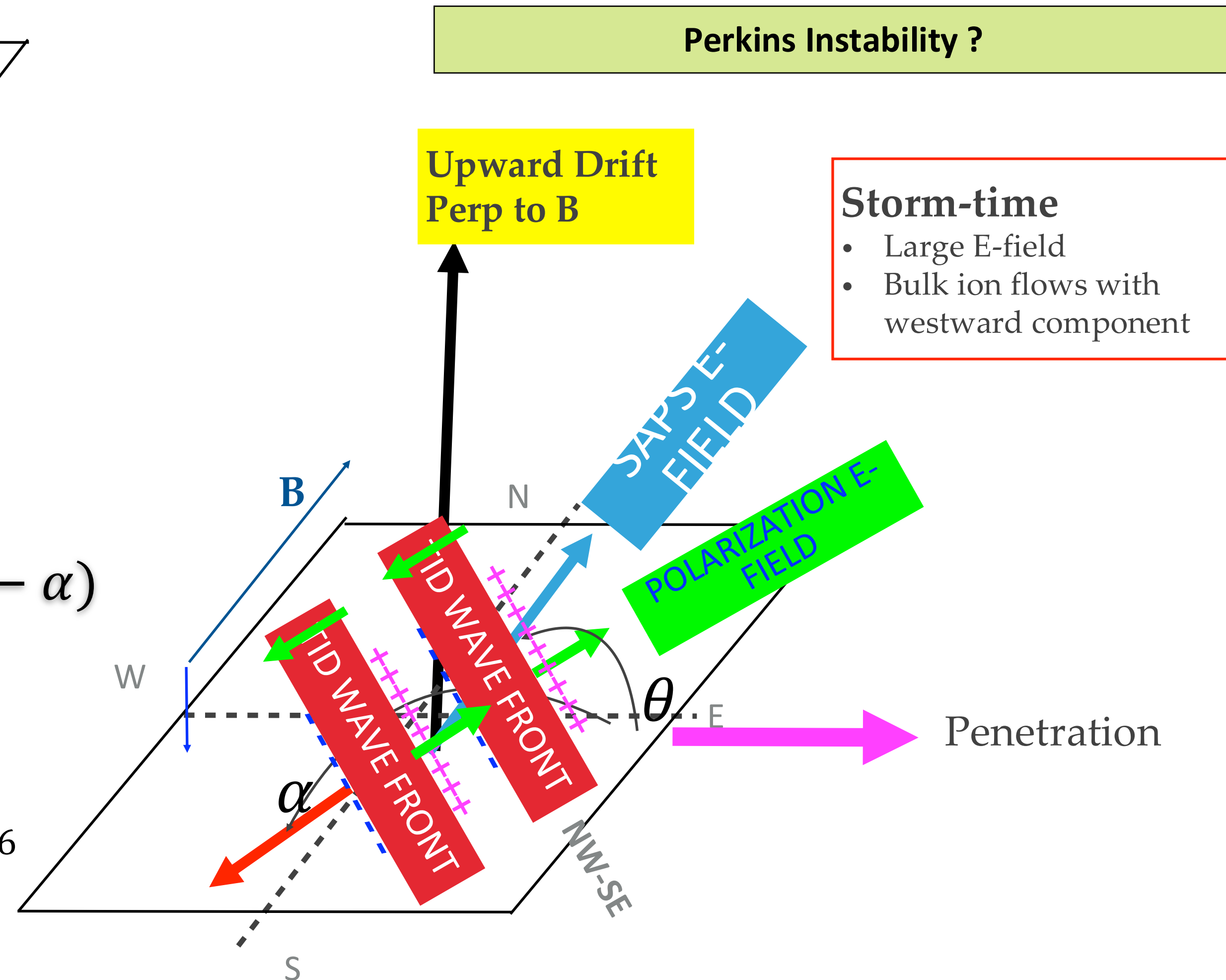
$$\gamma = \frac{E_0^* \cos I}{B H} \sin \alpha \sin(\theta - \alpha)$$

$$E_0^* = E + \mathbf{U} \times \mathbf{B};$$

$$\theta = 90^\circ; \alpha = -135^\circ; I = 68^\circ$$

$$\sin \alpha \sin(\theta - \alpha) \sim 0.5; \cos I \sim 0.36$$

$$\gamma \sim 5 - 8 \times 10^{-3} s^{-1}$$



Storm-time

- Large E-field
- Bulk ion flows with westward component

PI problems for non-storm MSTIDs

- Growth rate
- Structure should propagate with background plasma flow in $\mathbf{E} \times \mathbf{B}$ direction (NE)

Storm-time PI

- Large E-field
- Bulk ion flows with westward components

Excitation

