FORMOSAT-7/COSMIC-2 observations of ionosphere responses to forcing from Sun to Earth's surface

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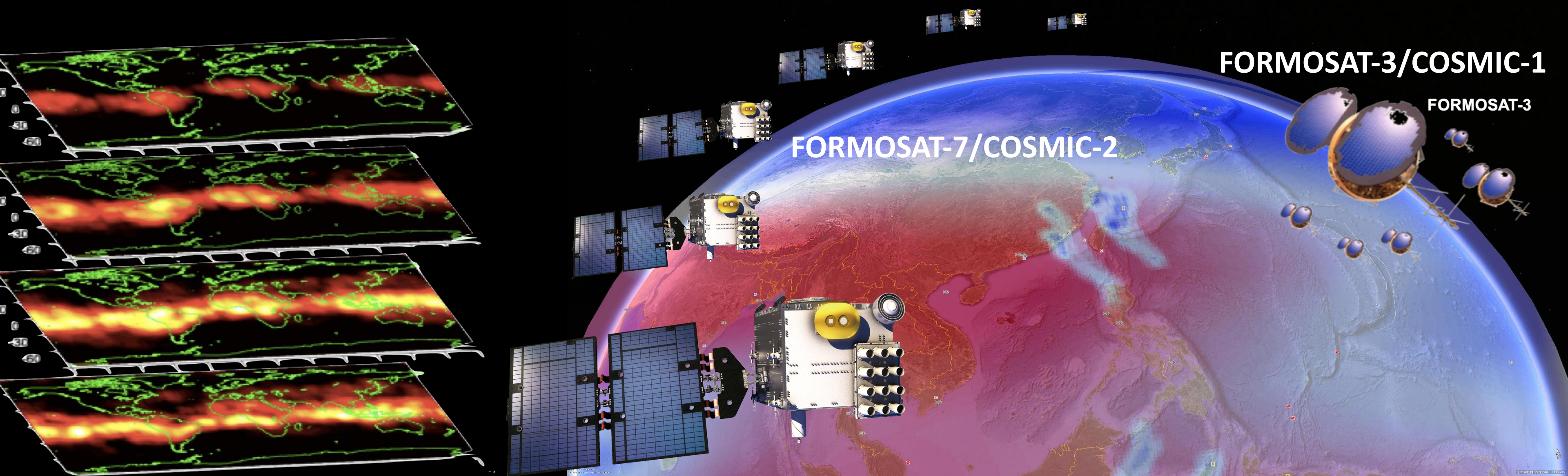
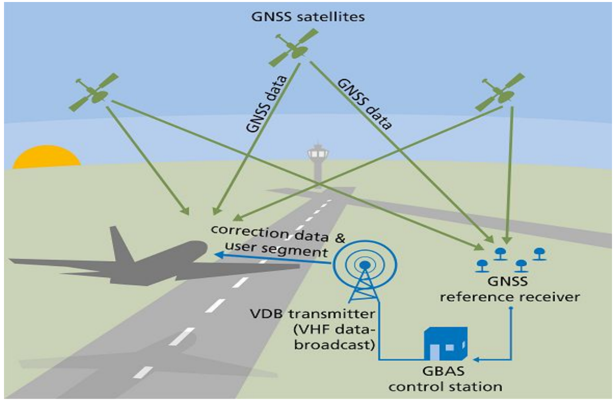
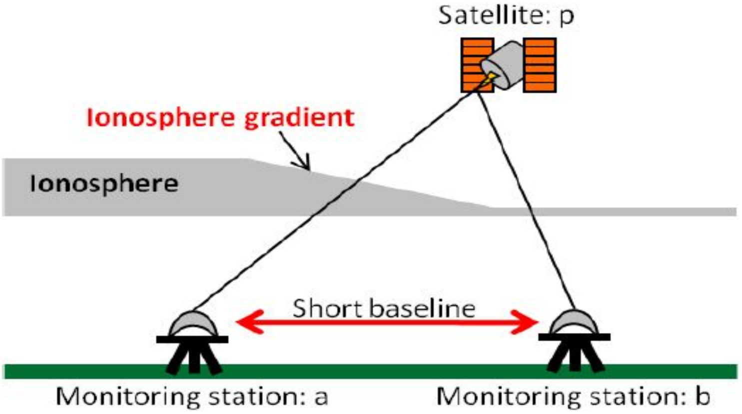


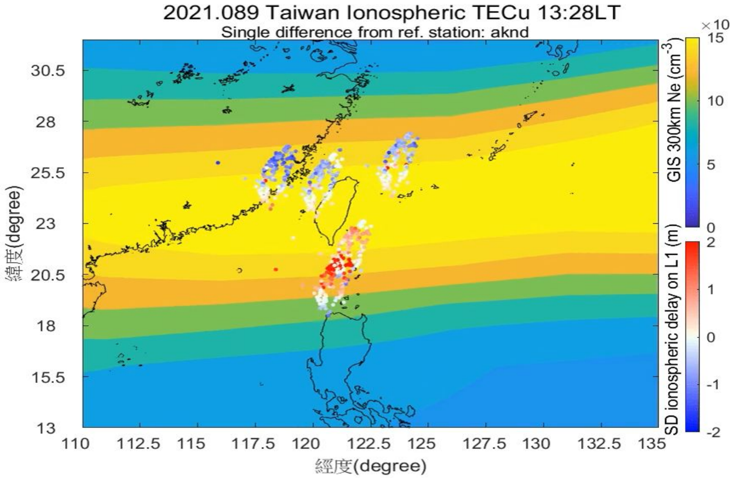
Why 3-D ionosphere?

GNSS-Aided Civil Aviation utilizes single frequency difference to remove ionosphere delays

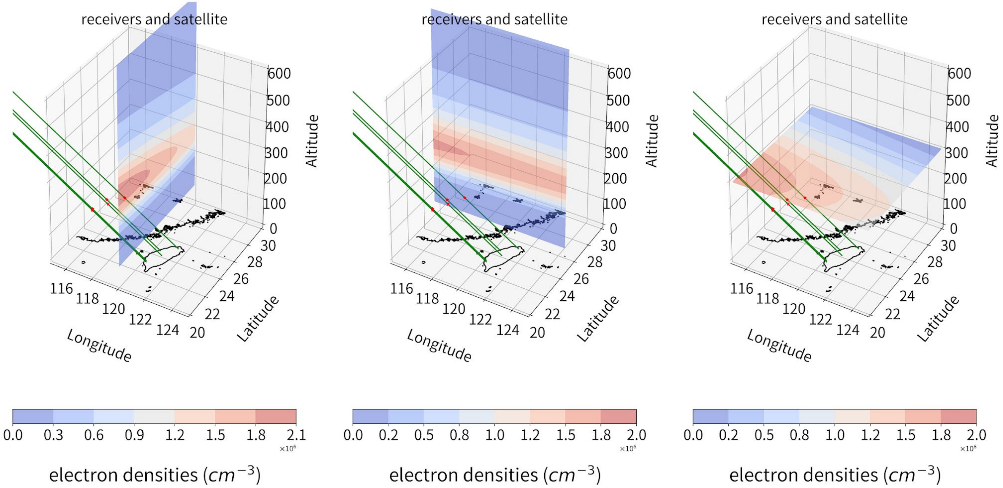




TEC (background) & single diff. ionosphere delays @ receivers



Geometry of the light of sight between receivers and satellites
2015073 1000UT electron densities from IRI model on XYZ-plane



3-D Global Ionospheric Specification (GIS): Gauss-Markov Kalman Filter

[C. Y. Lin et al., AMT 2015, JGR 2017, 2020]

- Develop nowcast three-dimensional(3-D) ionospheric electron density model by assimilating both ground-based GPS and space-based radio occultation slant total electron contents (sTEC) - 1 hour latency

- The model is written in FORTRAN MPI code that takes 10-15 mins to output 1 hour data

Coverage: Global 100-1,000 km

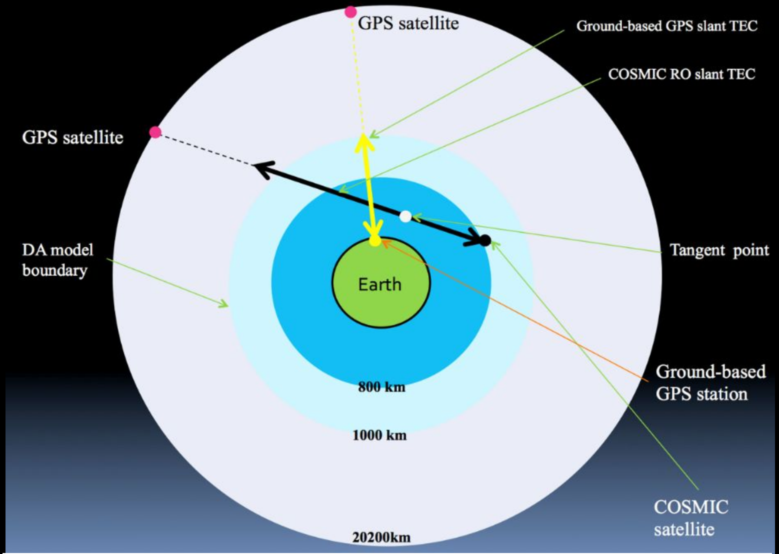
Grid resolution:

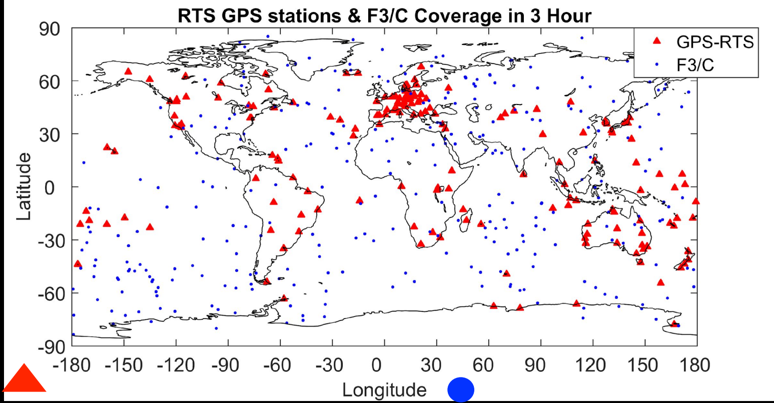
Longitude: 5° / 2.5°

Latitude: 2.5°

Altitude: 20 / 5km

Time resolution: 1 hour / 20 mins



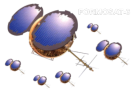


realtime GNSS

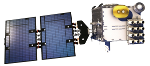
realtime RO

F7/C2 3-D Global Ionospheric Specification (GIS)

Touring Point

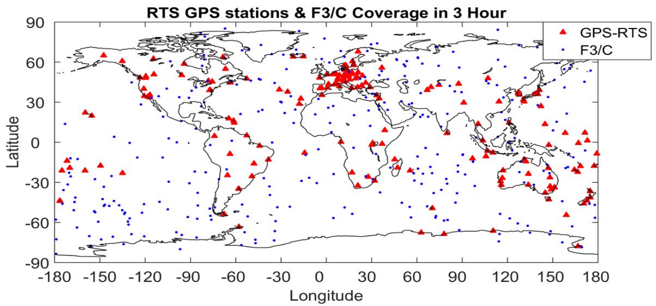


ROs - TEC < G-based GNSS

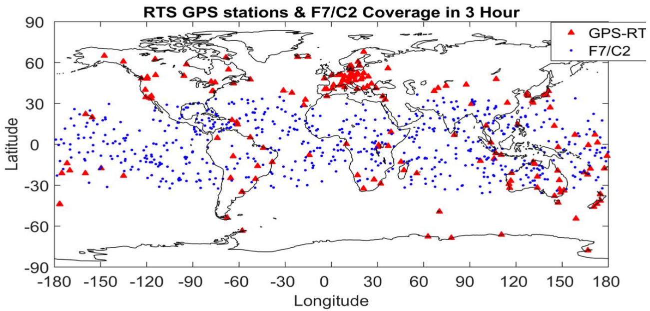


ROs - TEC > G-based GNSS

▲ Realtime GNSS ● COSMIC-3hrs



▲ Realtime GNSS ● COSMIC2—3hrs



Gauss-Markov Kalman Filter

Kalman filter Time Update Step

$$\mathbf{x}^{\mathrm{f}}_{k+1} = B\mathbf{x}^{\mathrm{MS}}_{k} + (1 - B)\mathbf{x}^{\mathrm{b}}_{k+1}$$

$$\mathbf{P}^{\mathrm{f}}_{k+1} = \mathbf{A}\mathbf{P}^{\mathrm{a}}_{k}\mathbf{A}^{\mathrm{T}} + C\mathbf{P}^{\mathrm{b}}_{k+1}$$

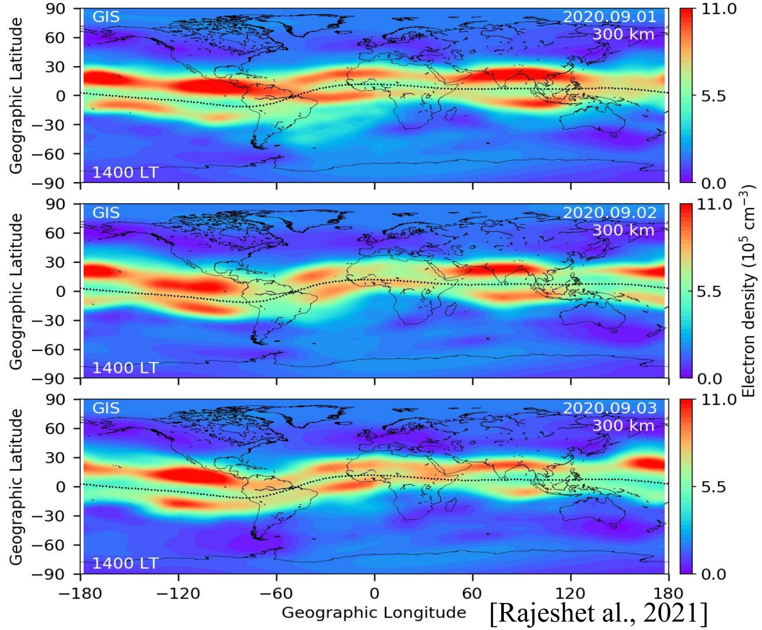
Kalman filter Measurement Update Step

$$\mathbf{x}^{\mathrm{a}}_{k} = \mathbf{x}^{\mathrm{f}}_{k} + \mathbf{K}_{k}(\mathbf{y}_{k} - \mathbf{H}_{k}\mathbf{x}^{\mathrm{f}}_{k})$$

$$\mathbf{P}^{\mathrm{a}}_{k} = (\mathbf{I} - \mathbf{K}_{k}\mathbf{H}_{k})\mathbf{P}^{\mathrm{f}}_{k}$$

$$\mathbf{K}_{k} = \frac{\mathbf{P}^{\mathrm{f}}_{k}\mathbf{H}^{\mathrm{T}}_{k}}{\mathbf{H}_{k}\mathbf{P}^{\mathrm{f}}_{k}\mathbf{H}_{k} + \mathbf{R}_{k}}$$

[C. Y. Lin et al., AMT 2015, JGR 2017, 2020]

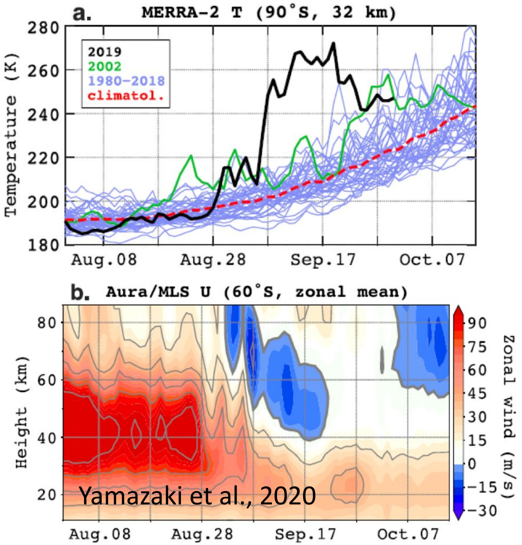


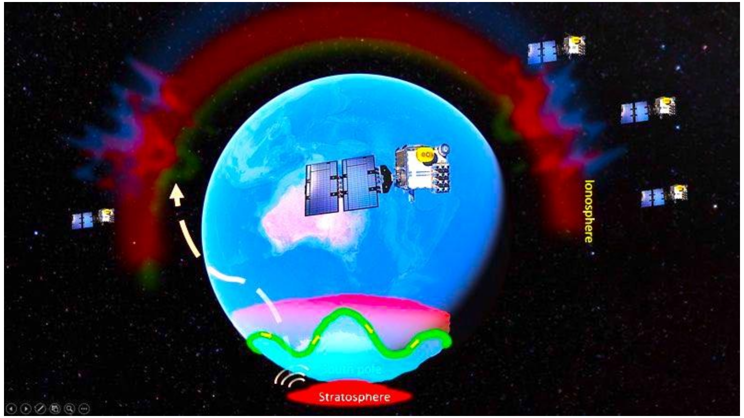
[Rajeshet al., 2021]

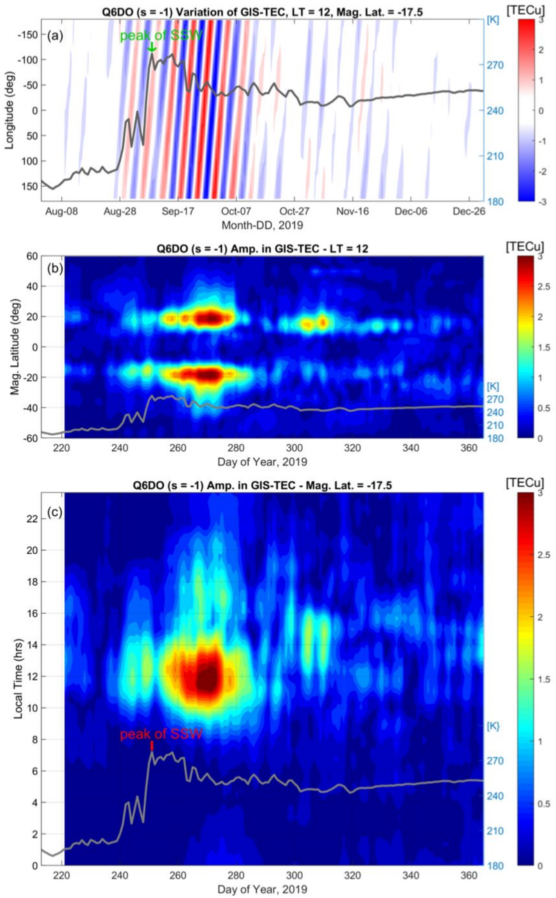
2019 Antarctic Stratospheric Sudden Warming

60K Temperature increase

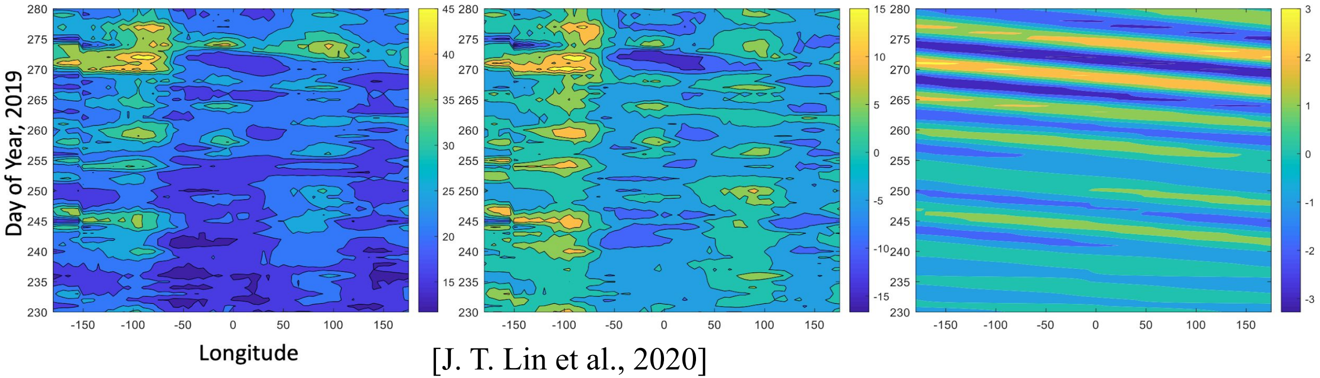
3rd time in the history strongest for rapid temp. increase







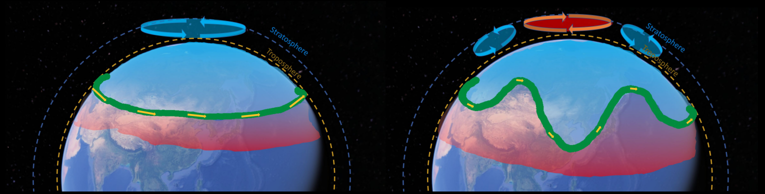
Extracting the quasi 6-day oscillation (Q6DO) in ionosphere from F7/C2 GIS



[J. T. Lin et al., 2020]

Fitting amplitude of Q6DO in latitude and local time

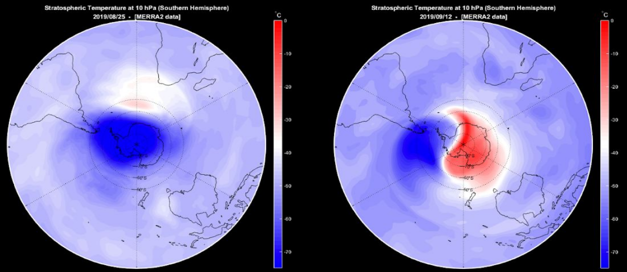
2019 Antarctic Stratospheric Sudden Warming



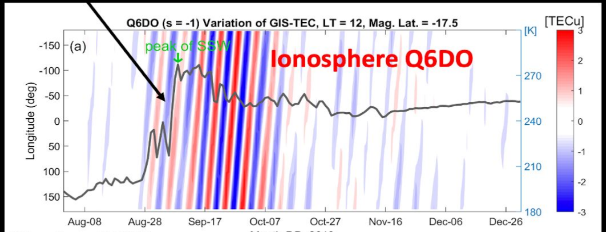
60K Temperature increase
3rd time in the history strongest in the history for rapid temp. increase
Strongest 6 day oscillation in ionosphere ~ 30%

Antarctic Stratosphere

Antarctic SSW @2019



SSW temp. increase rapidly -65°C -> -5°C



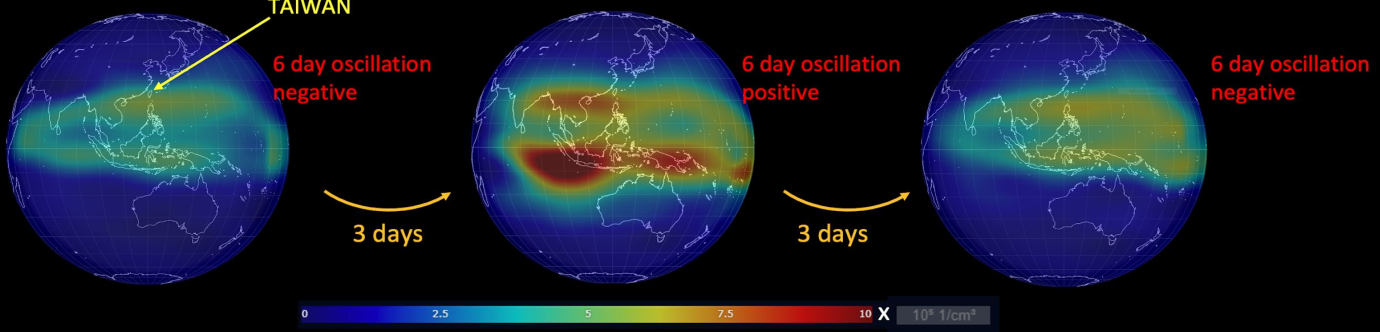
[Lin et al., 2020]

Global Ionosphere Specifications

2019/09/27 12:00 LT
400 Km altitude

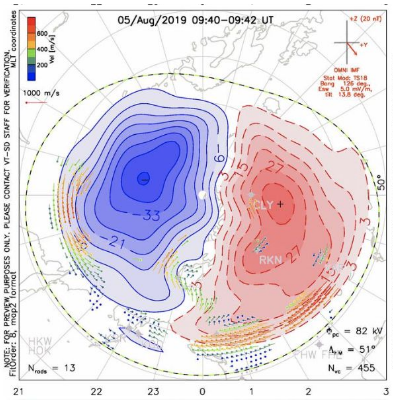
2019/09/30 12:00 LT
400 Km altitude

2019/10/03 12:00 LT
Km altitude

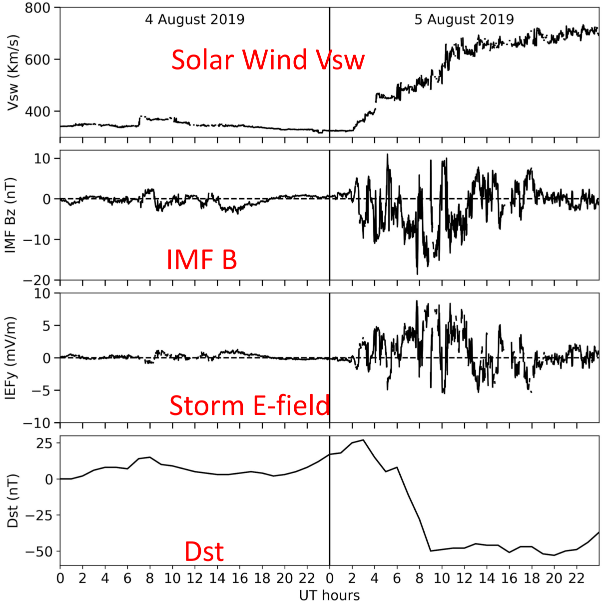


2019-08-05 G1 Minor Magnetic Storm

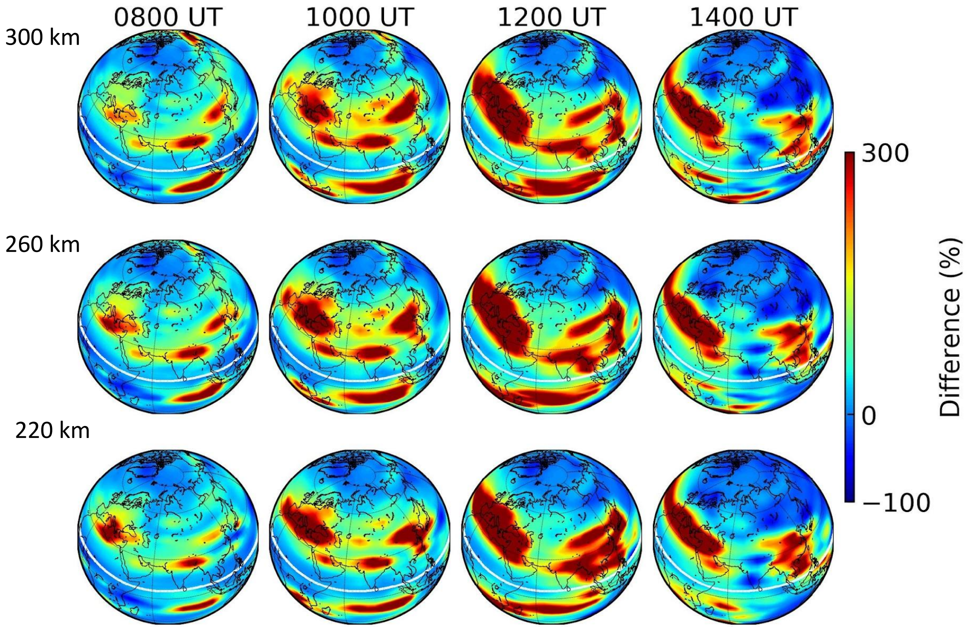
High Latitude convection intensified



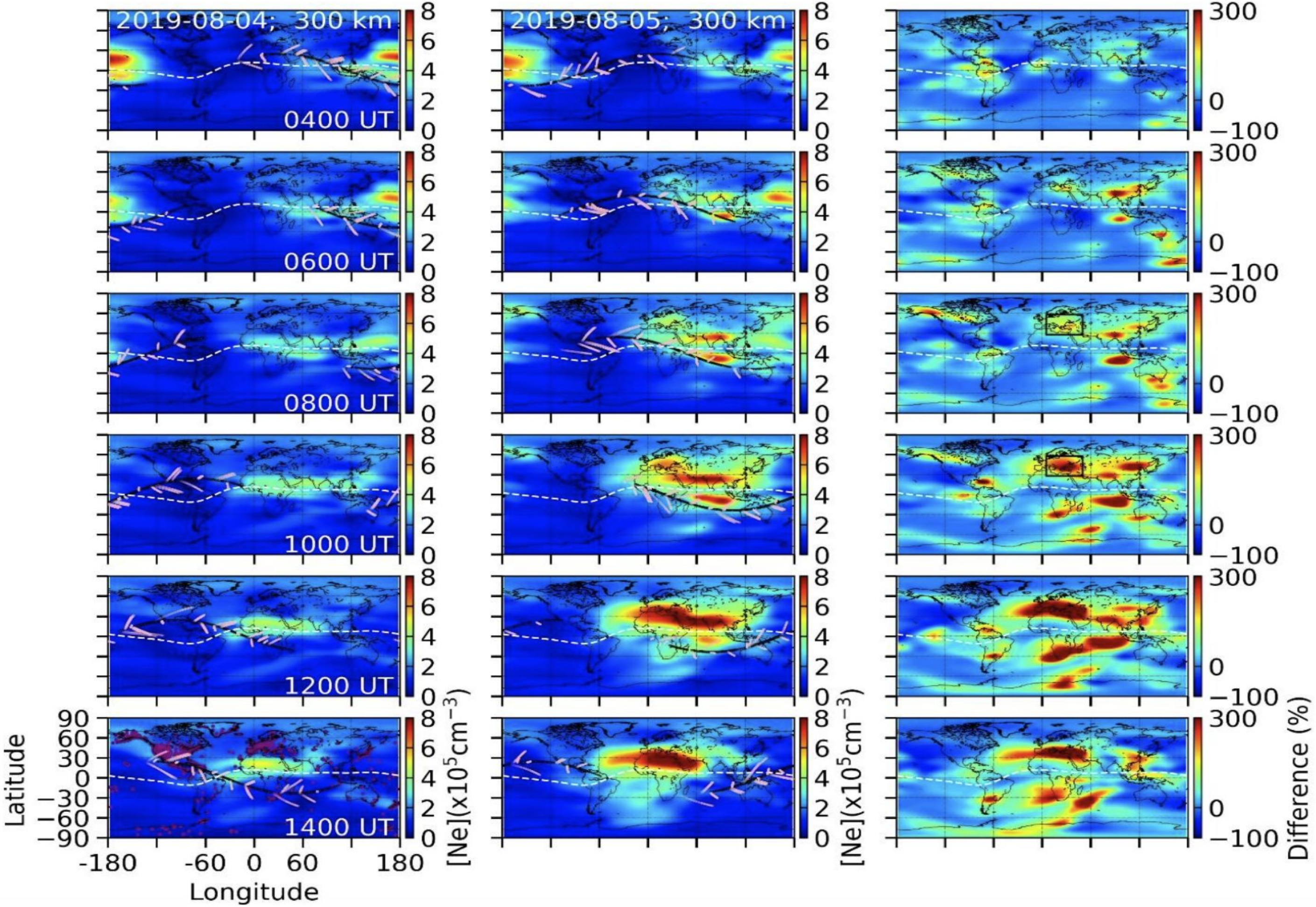
Rajesh, P. K., Lin, C. H., Lin, C. Y., Chen, C. H., Liu, J. Y., Matsuo, T., et al. (2021), Extreme Positive Ionosphere Storm Triggered by a Minor Magnetic Storm in Deep Solar Minimum Revealed by FORMOSAT-7/COSMIC-2 and GNSS Observations, *Journal of Geophysical Research: Space Physics*, 125, e2020JA028261https://doi.org/10.1029/2020JA028261



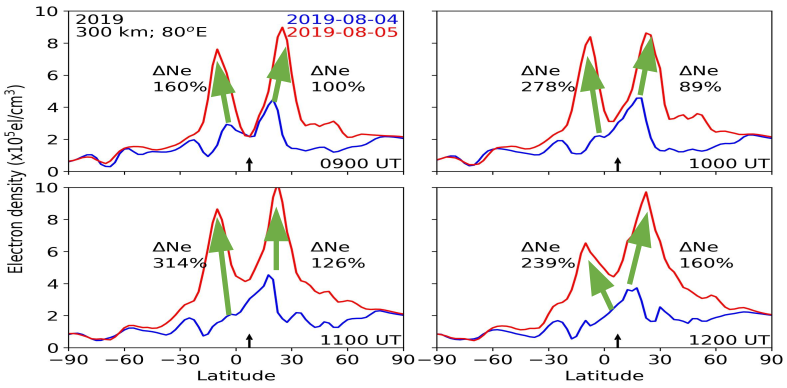
Triggered strong ionosphere electron density increase @ India、Europe、Africa with 300-800% increase



Strong Positive Storm Effects!

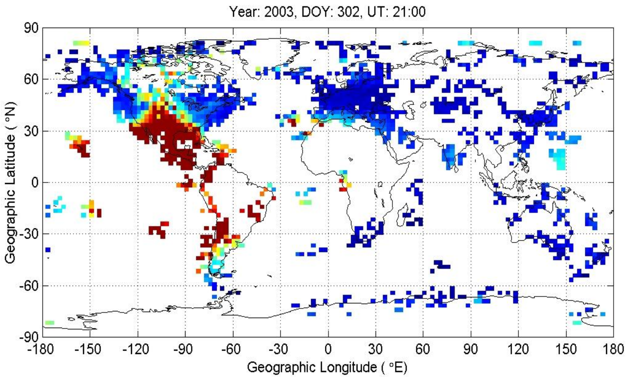


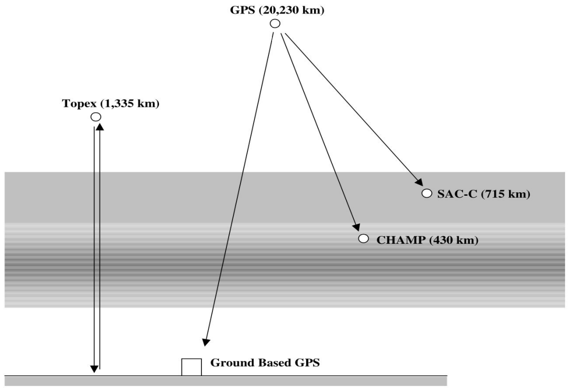
G1 Minor storm in August 2019



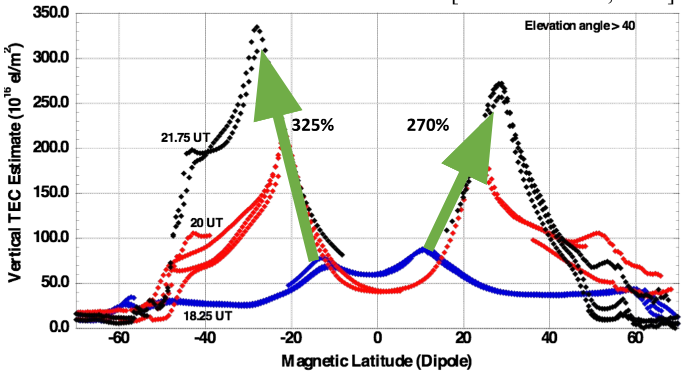
[Rajesh et al., 2020]

Super storm effects during solar maximum October 2003





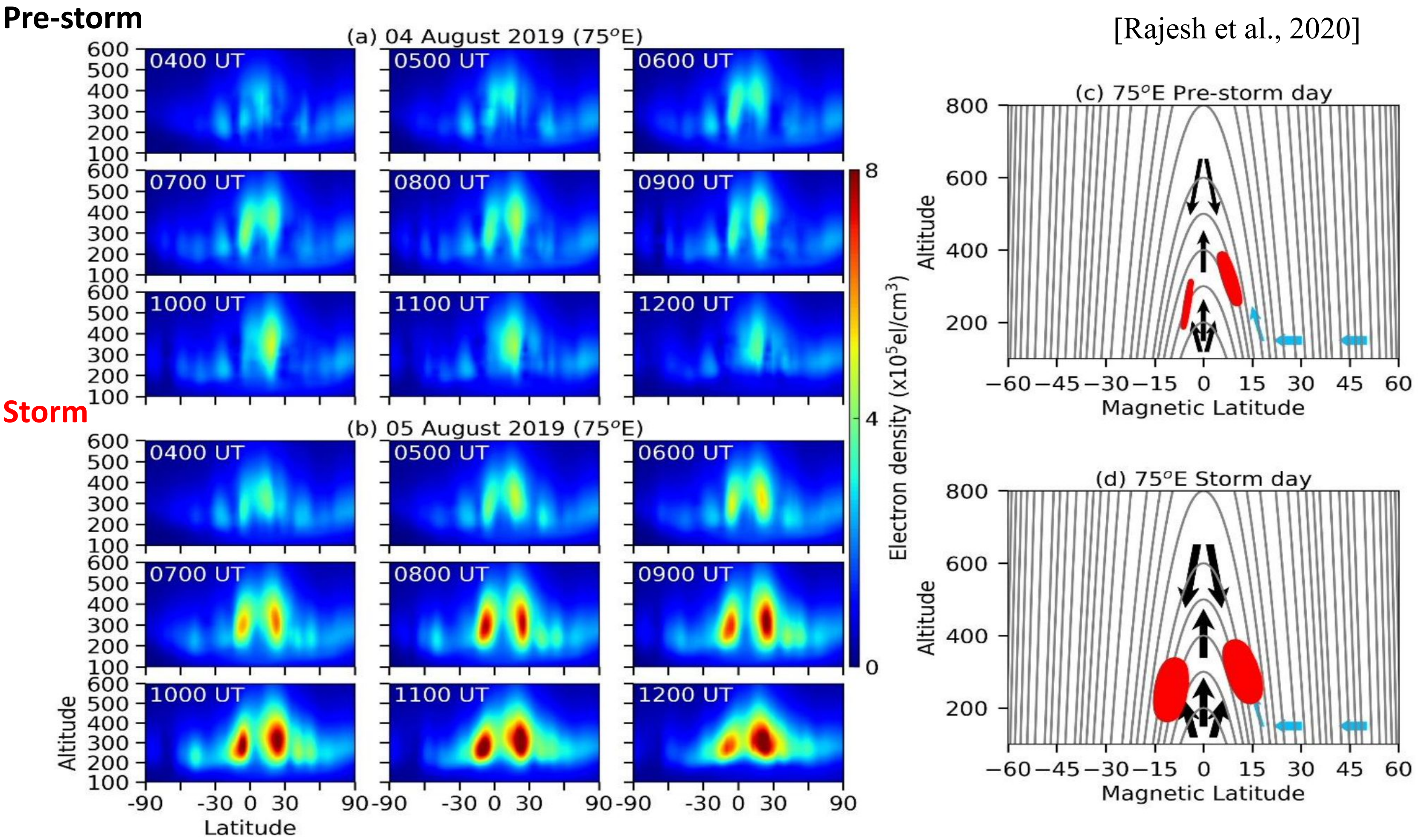
[Mannucci et al., 2005]



Latitude-Altitude-Ne @ 75°E Longitude

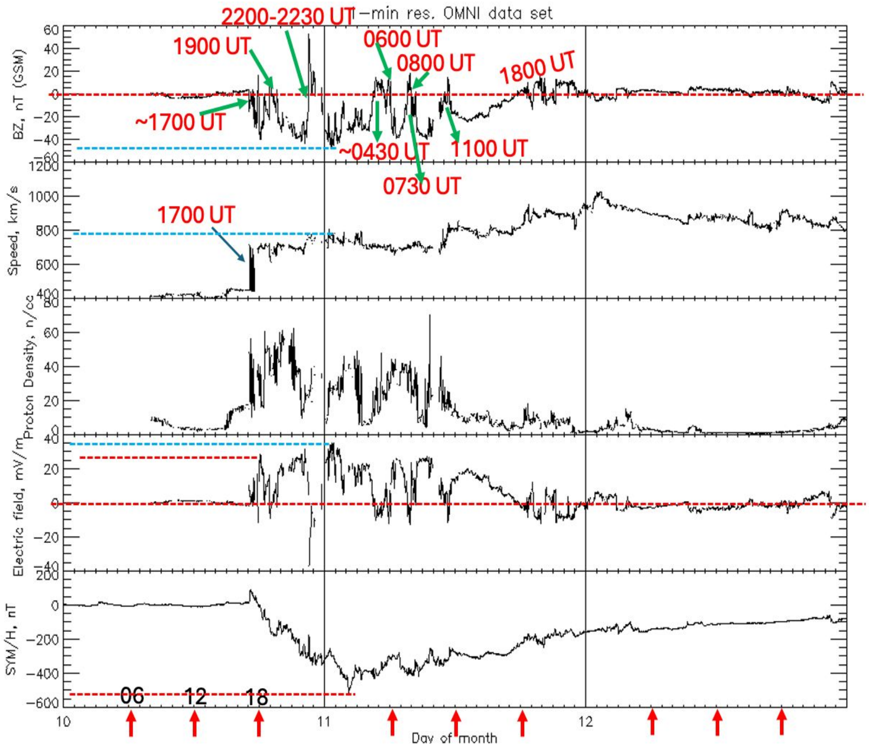
2019-08-05 G1 Minor Magnetic Storm

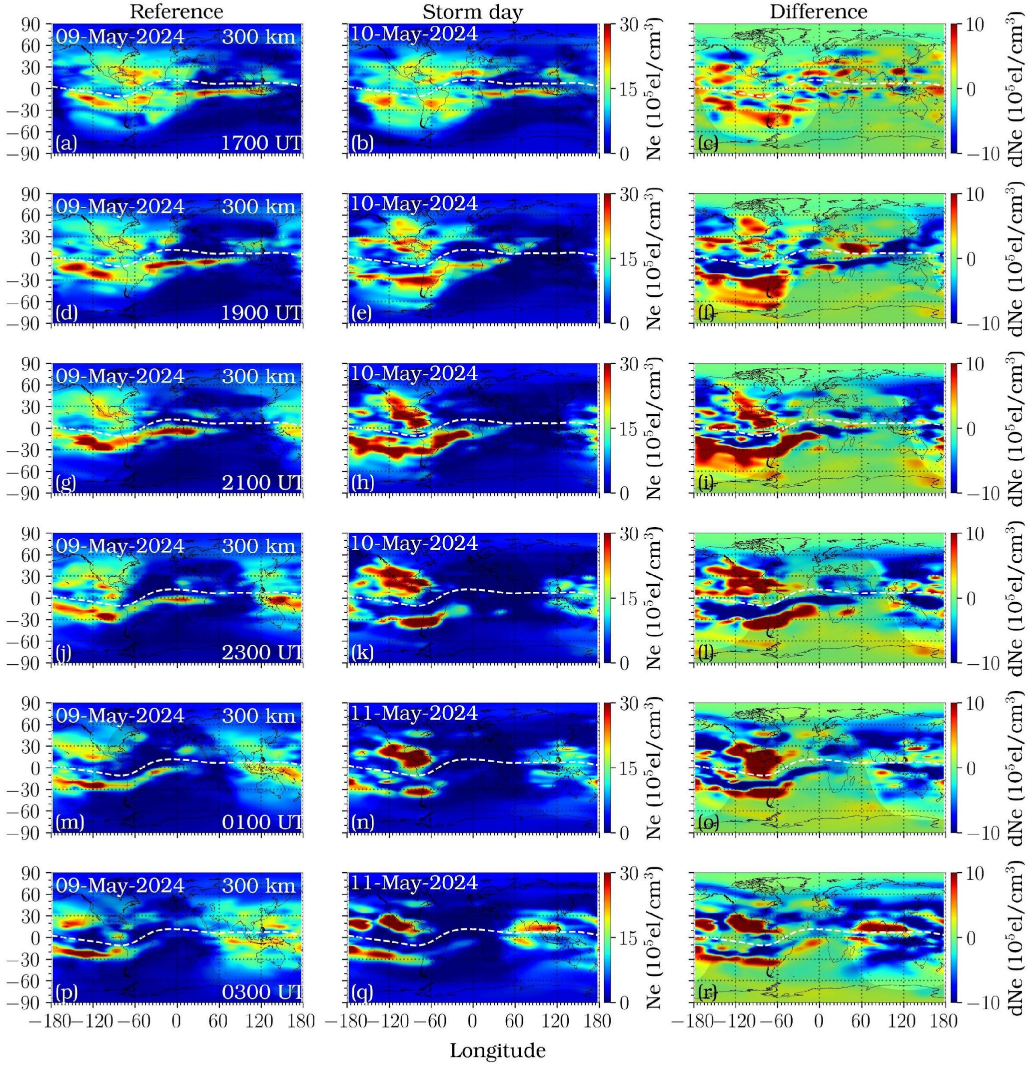
[Rajesh et al., 2020]



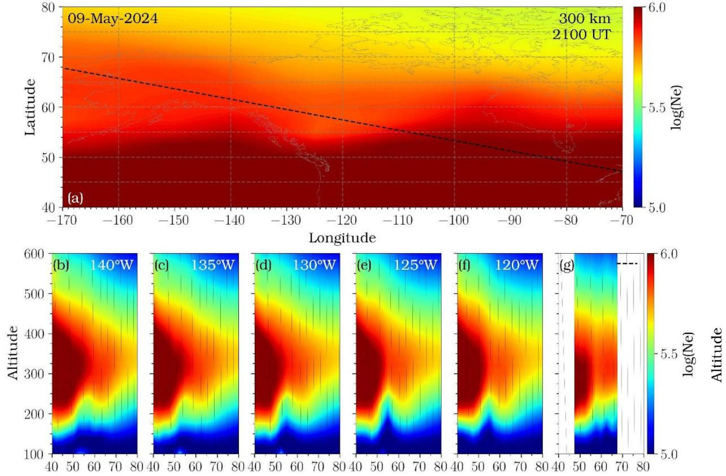
Magnetic storm (G5) on 10-11 May 2024

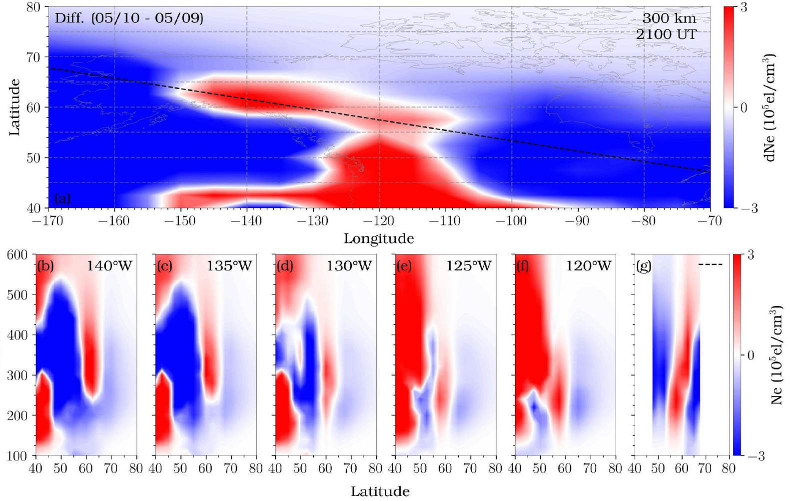
Storm Enhanced Density & PPEF



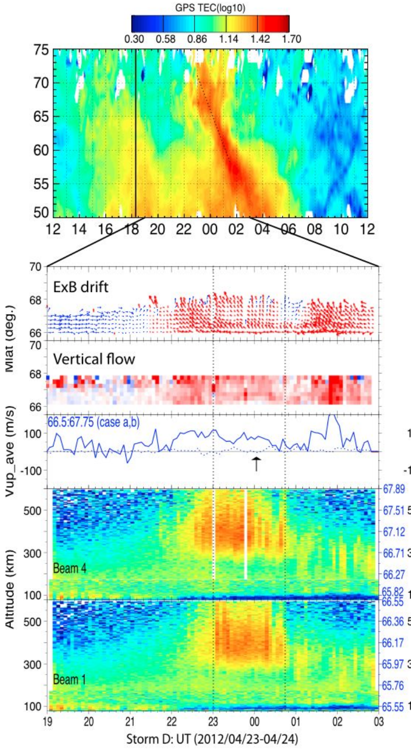


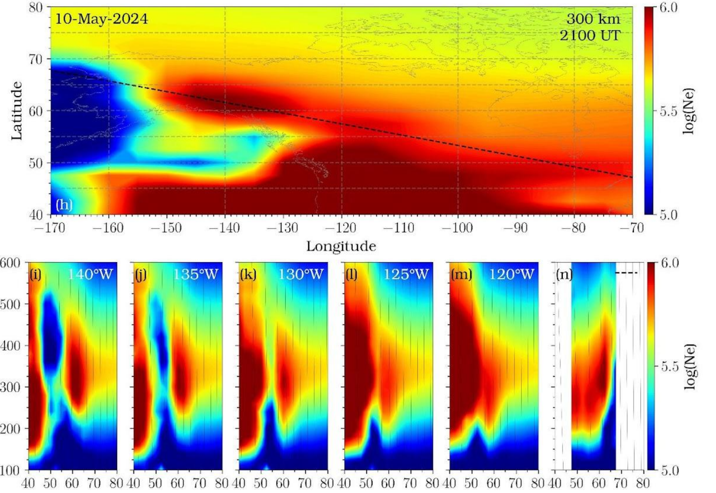
Storm Enhanced Density & Plume structure seen by GIS showing field aligned enhancement of plume

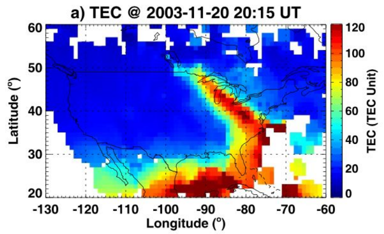


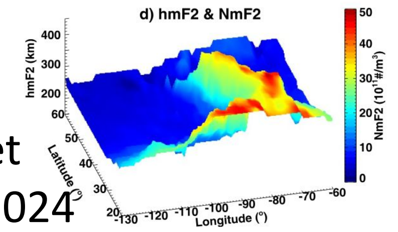


Zou et al.,2014





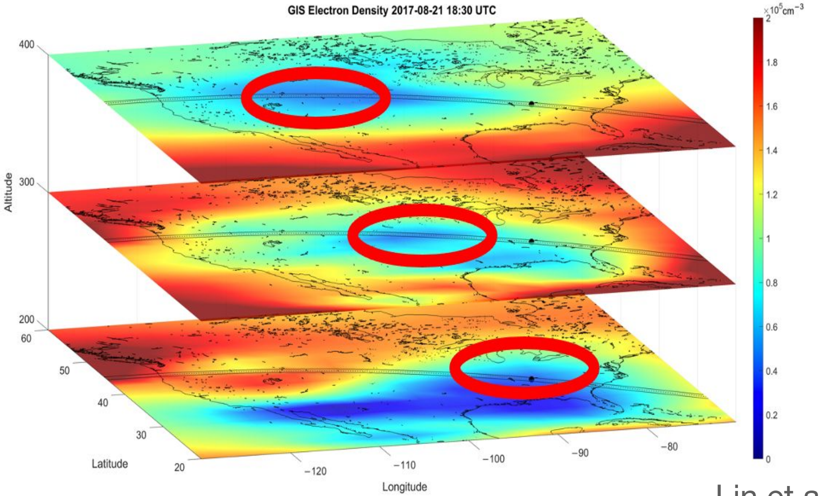




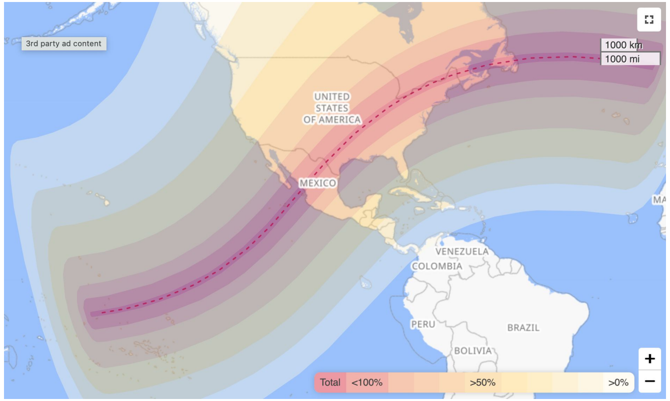
Aa et al.,2024

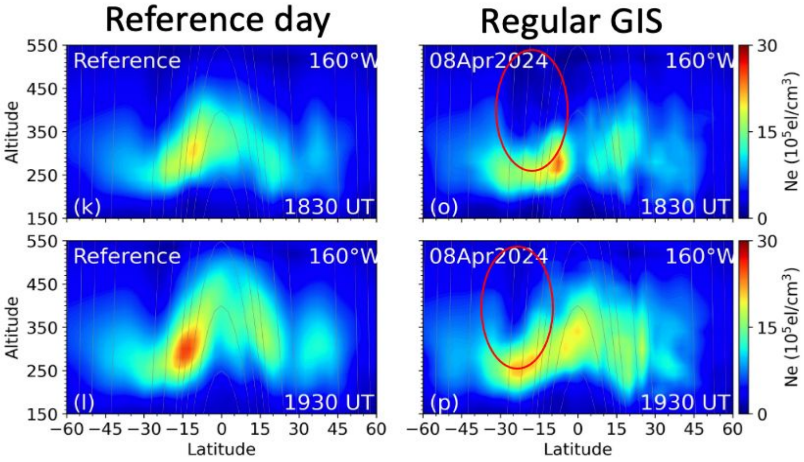
PFISR Obs.

2017 Solar Eclipse using FORMOSAT-3/COSMIC



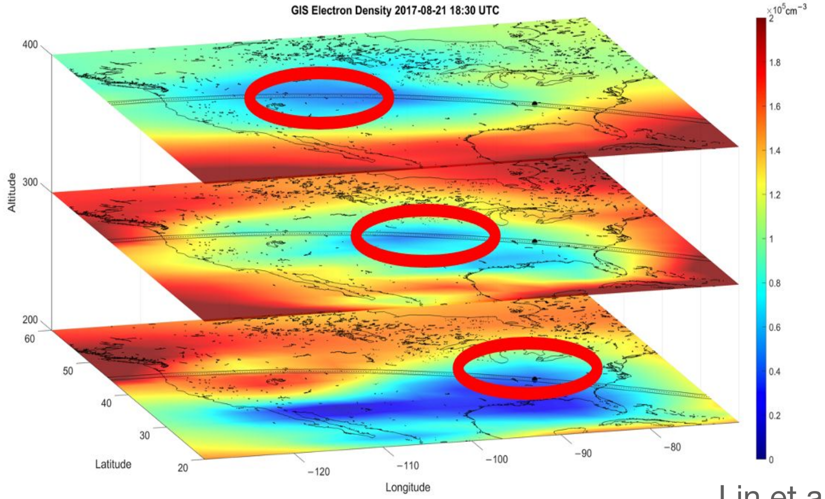
8 April 2024 Solar Eclipse



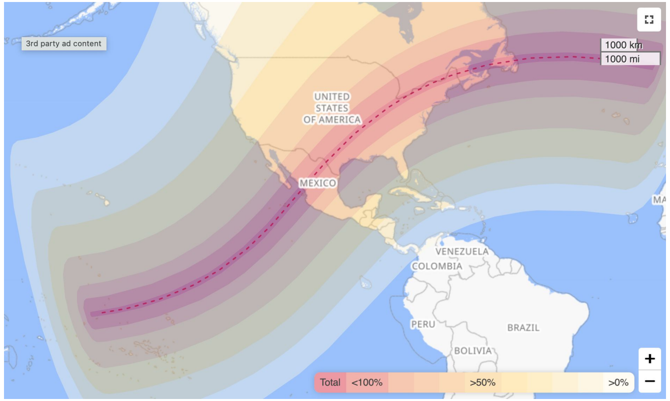


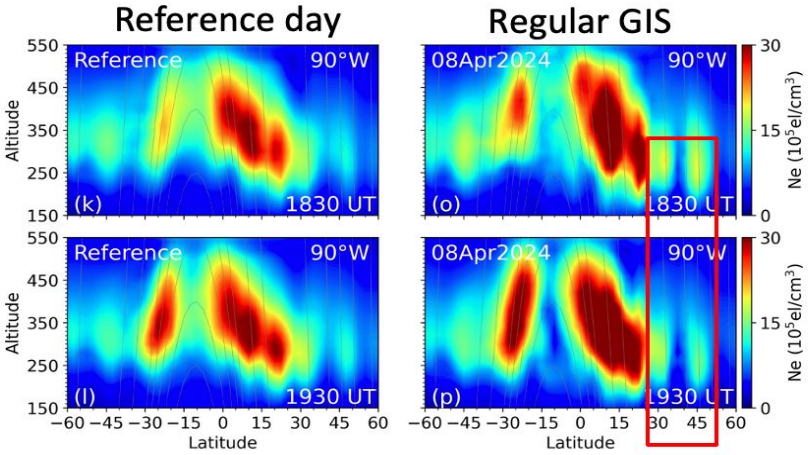
Lin et al., 2023

2017 Solar Eclipse using FORMOSAT-3/COSMIC



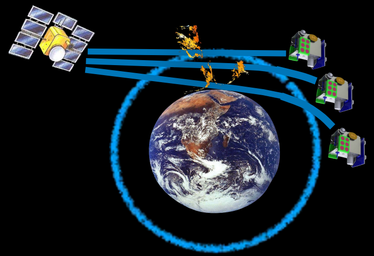
8 April 2024 Solar Eclipse





Lin et al., 2023

Summary

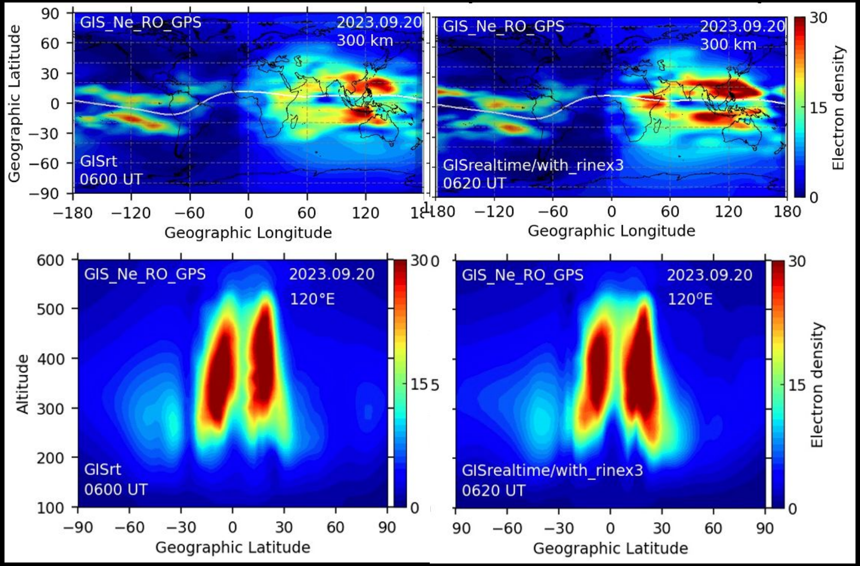


1. F7/C2 based GIS has shown prominent day-to-day variability of ionosphere
2. Day-to-day obs. are useful to see the vertical coupling (SSW & quasi 6 day oscillation).
3. GIS has been applied to investigate 3 storms (G1, G3 & G5) showing peculiar phenomena (positive storm, SED & plume).
4. GIS observes eclipse induced plasma depletions showing tilting depletion in altitudes

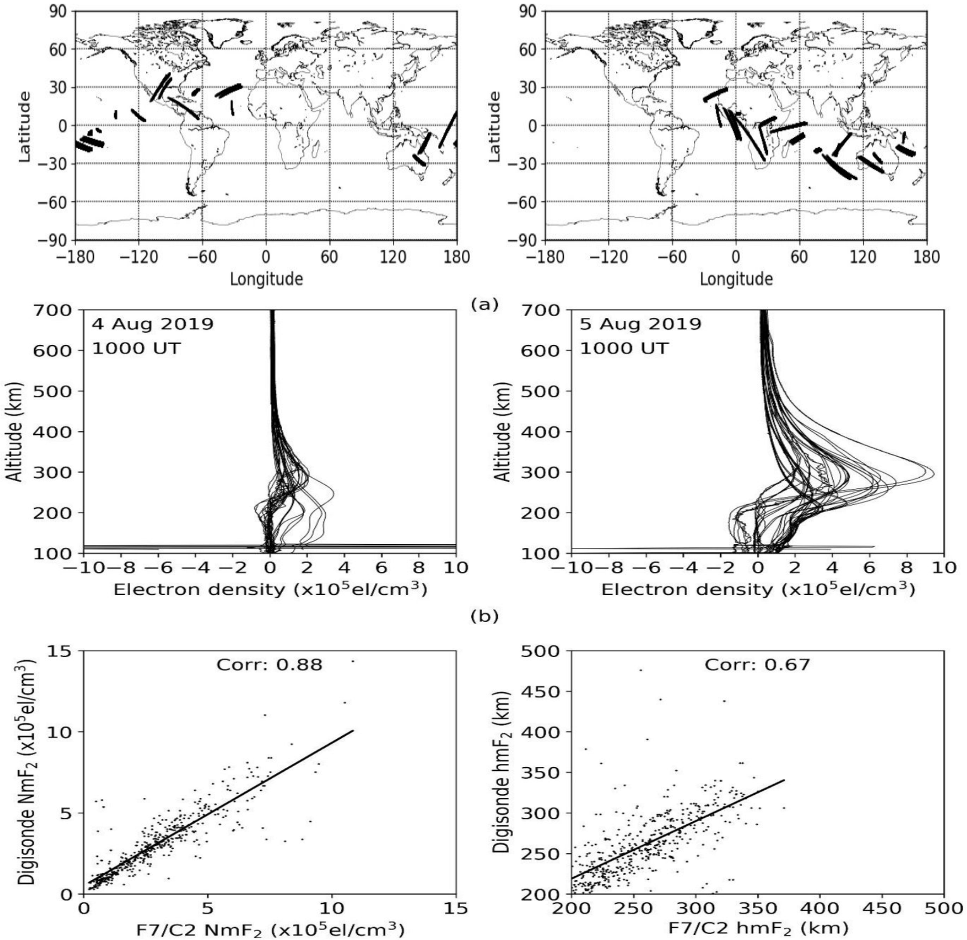
Next: making real-time and adaptive grid GIS & assimilate commercial data at mid- high latitudes

1. Current GIS (1 hr time resolution) waits for two days latency because of ground-based GNSS stations.
2. We are making it to 2 hrs latency with 20 mins resolution as real-time GIS.
3. Mid- and high-latitude observations are important. Commercial data may help.
4. We're testing a version having upper boundary at 20,200 km

2-Day Latency GIS | 2-hr latency Real-time GIS

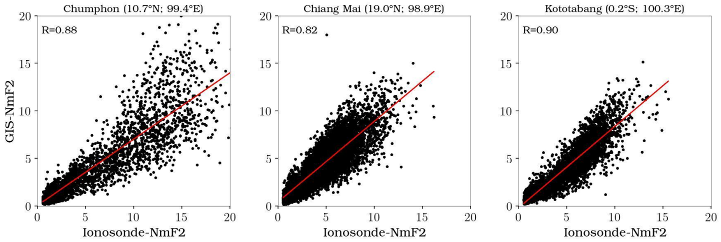


Validation of the Ne-profiles



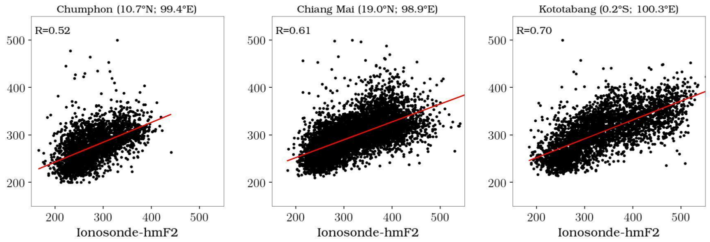
GIS –validation using NICT SEALION network

GIS and Ionosonde NmF2

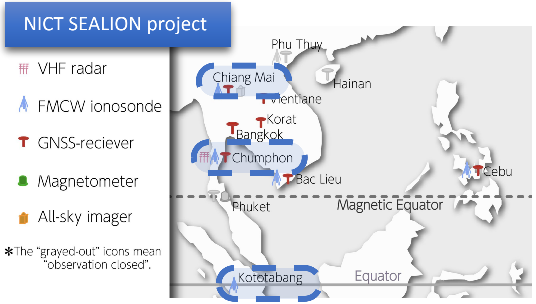


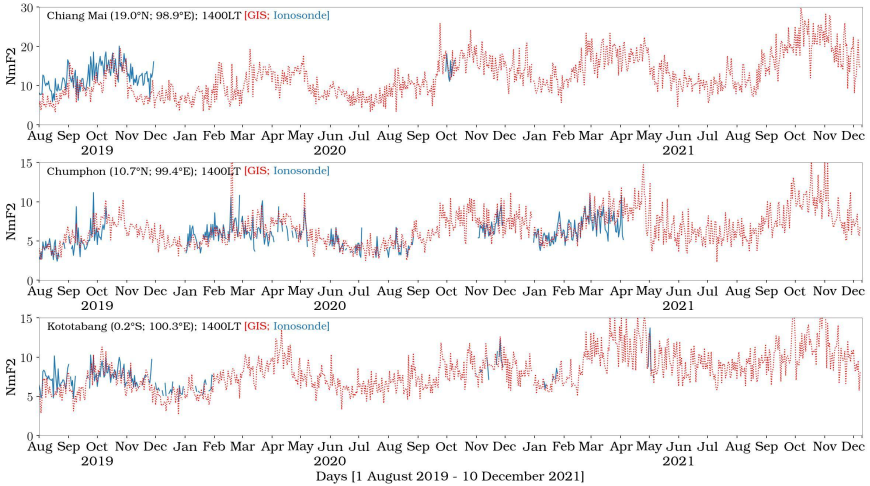
NmF2 shows a correlation of about 0.8 to 0.9

GIS and Ionosonde hmF2 (2019-2021)



hmF2 gives a correlation of about 0.5 to 0.7





8 April 2024 Solar eclipse effects – depletion at lower heights then extending to higher altitudes - from CY Lin