

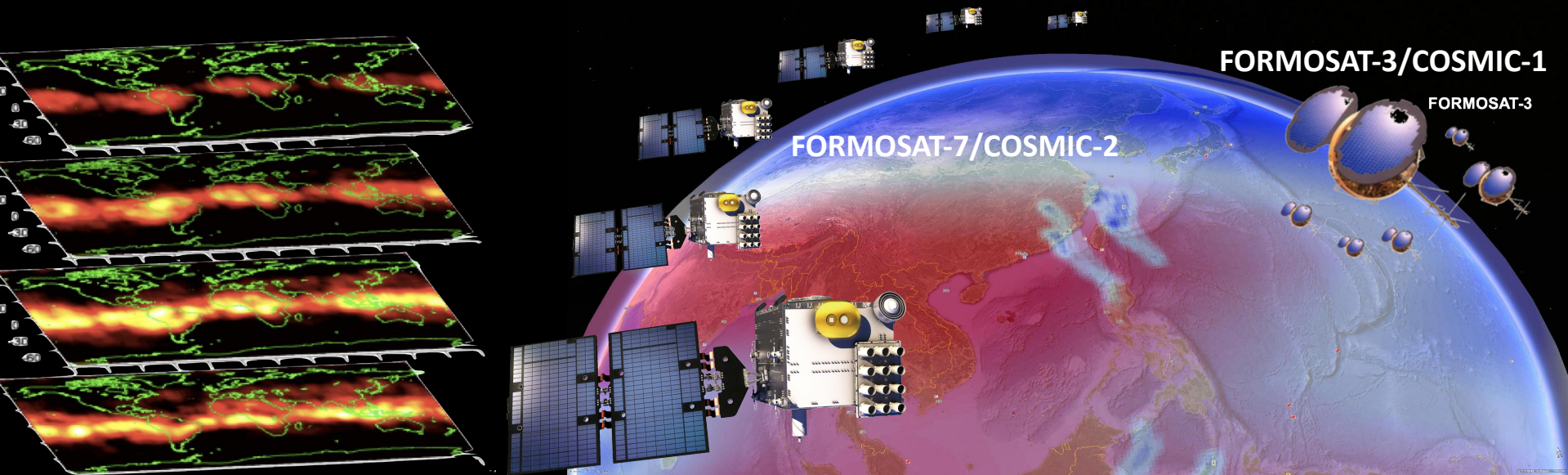
# FORMOSAT-7/COSMIC-2 observations of ionosphere responses to forcing from Sun to Earth's surface

Charles Lin, P. K. Rajesh, SP Chen, JT Lin  
National Cheng Kung University (NCKU), Taiwan,

Chi-Yen Lin,  
National Central University, Taiwan

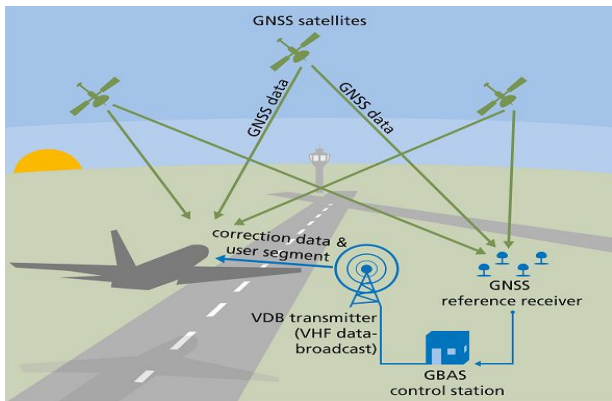
Tomoko Matsuo,  
University of Colorado Boulder, USA

Cheng-Yung Huang,  
Taiwan Space Agency (TASA), Taiwan

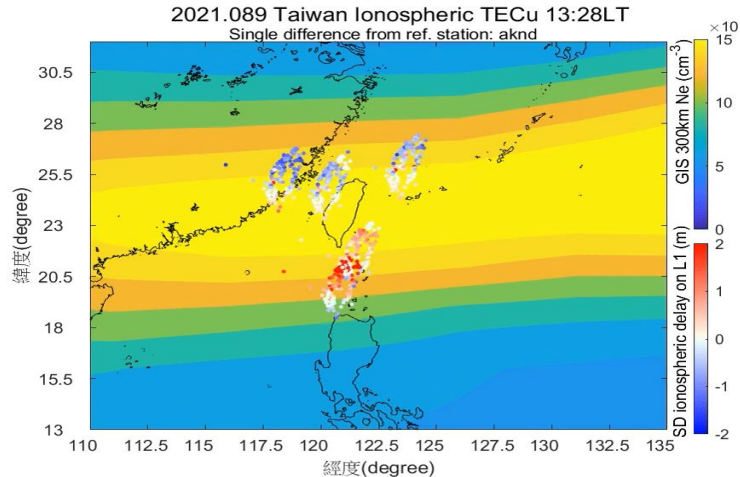


# Why 3-D ionosphere?

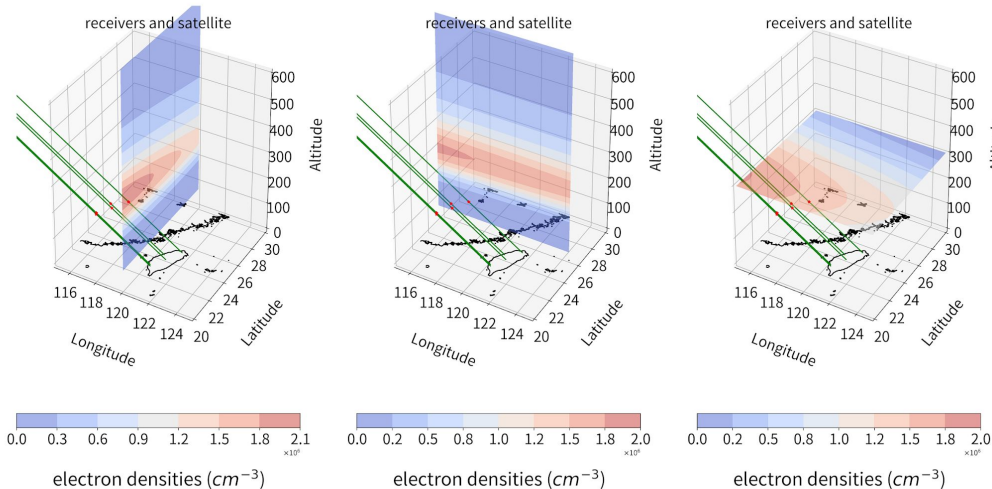
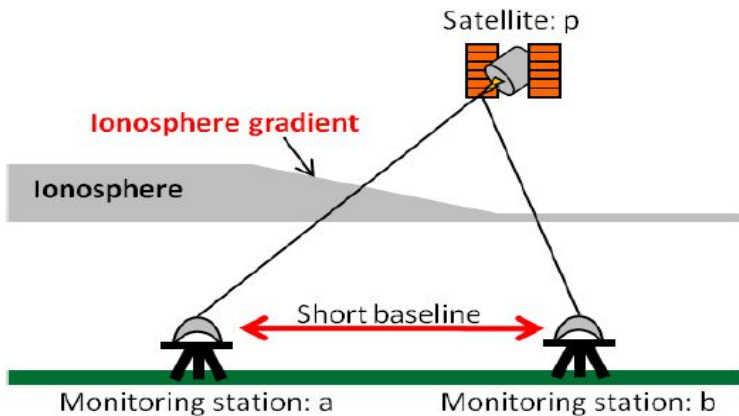
GNSS-Aided Civil Aviation utilizes single frequency difference to remove ionosphere delays



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

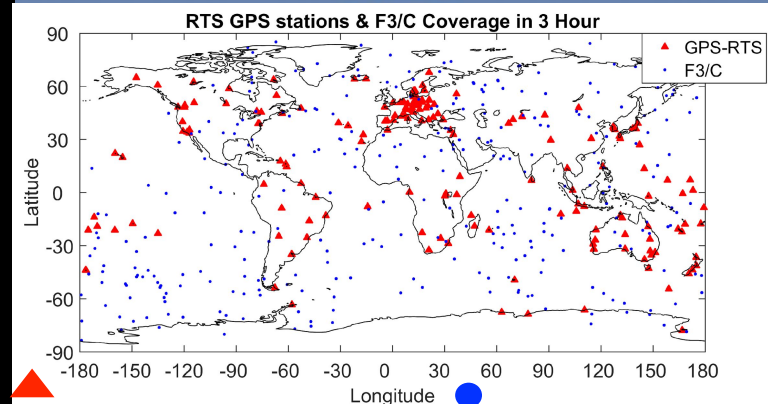
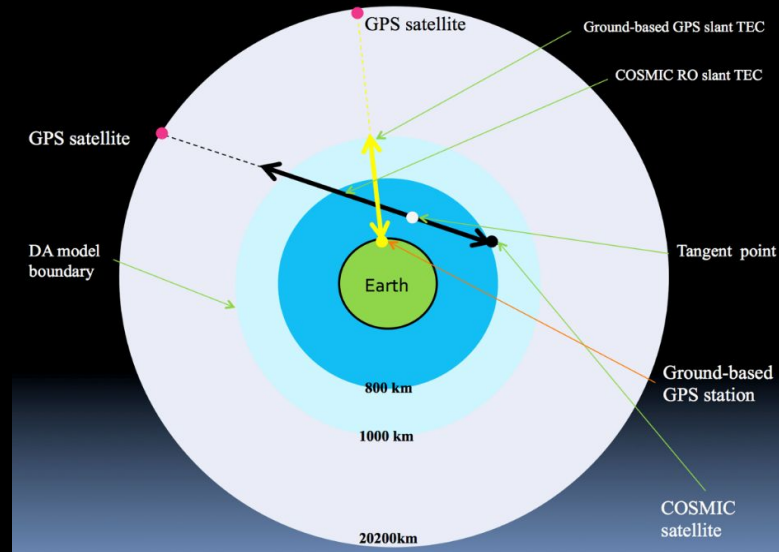
Grid resolution:

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)

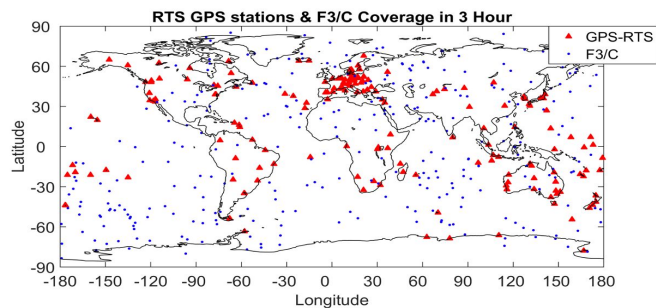
**Touring Point**



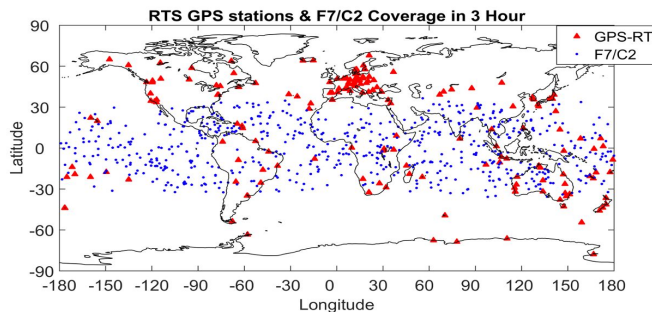
ROs - TEC < G-based GNSS

ROs - TEC > G-based GNSS

▲ Realtime GNSS ● COSMIC-3hrs



▲ Realtime GNSS ● COSMIC2—3hrs



## Gauss-Markov Kalman Filter

**Kalman filter Time Update Step**

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

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

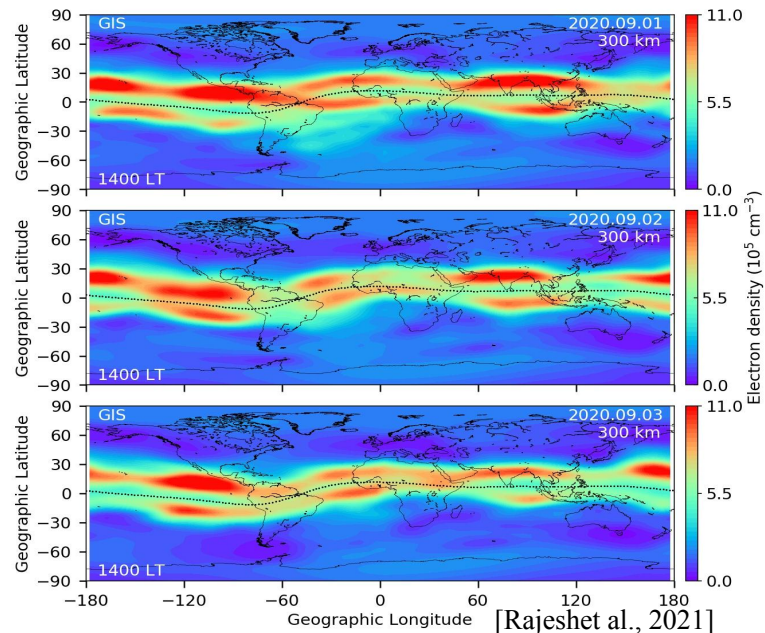
**Kalman filter Measurement Update Step**

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

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

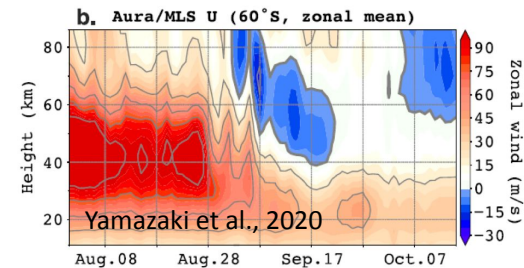
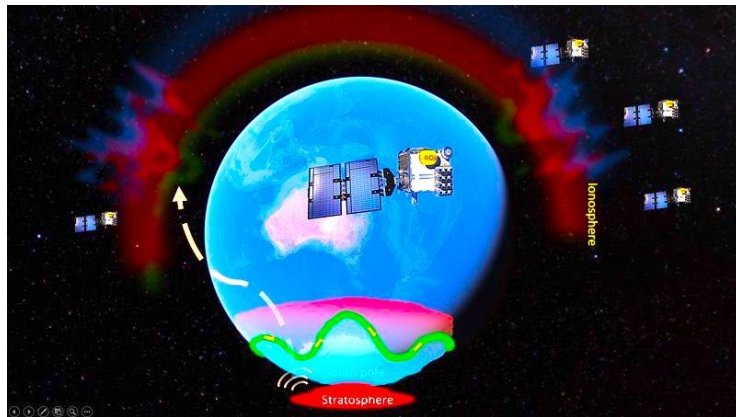
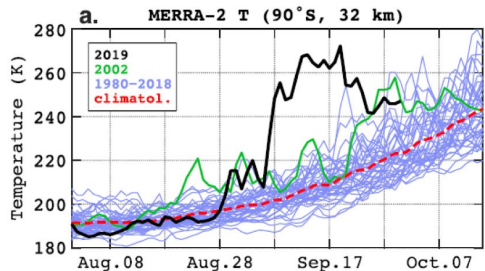
$$\mathbf{K}_k = \frac{\mathbf{P}_k^f \mathbf{H}_k^T}{\mathbf{H}_k \mathbf{P}_k^f \mathbf{H}_k + \mathbf{R}_k}$$

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

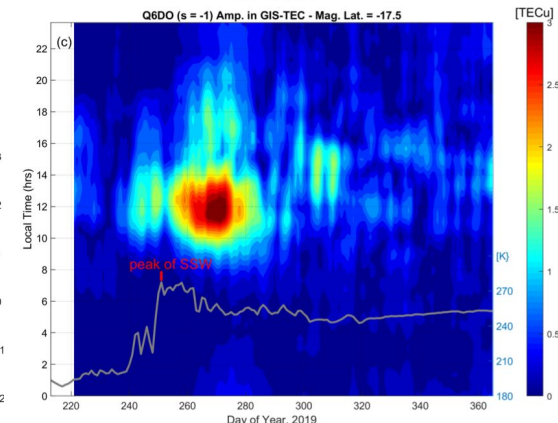
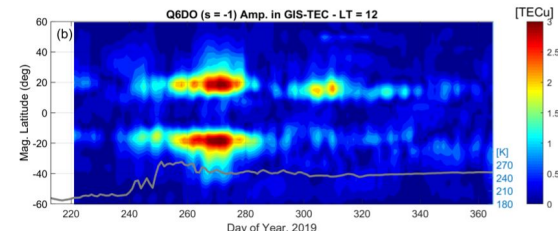
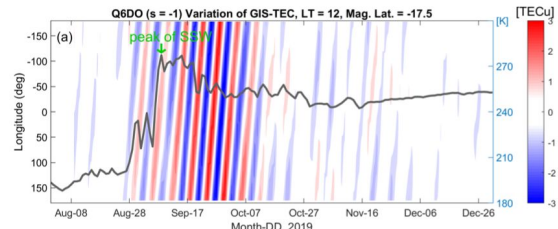
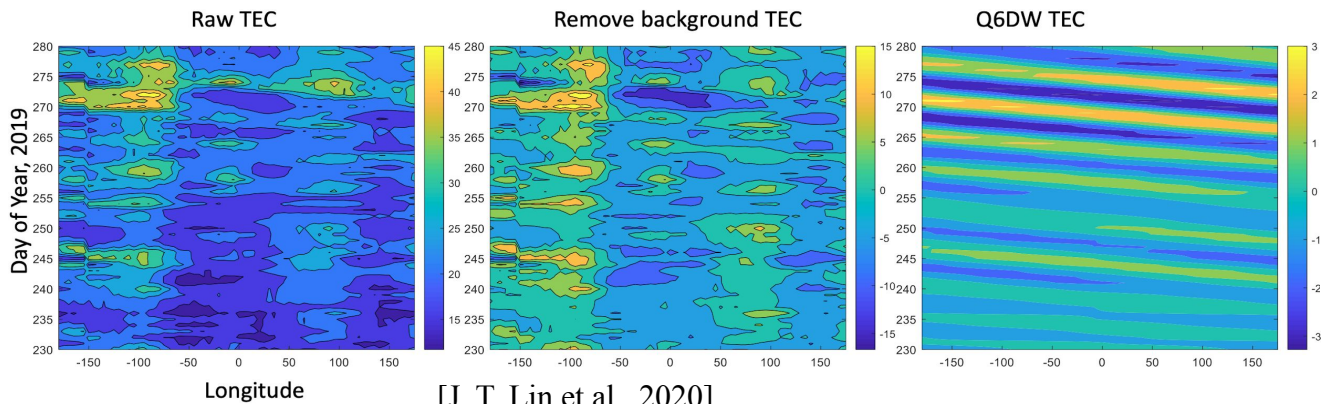


# 2019 Antarctic Stratospheric Sudden Warming

60K Temperature increase  
3rd time in the history strongest for rapid temp. increase



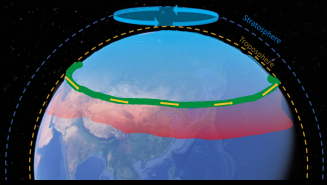
Extracting the quasi 6-day oscillation (Q6DO) in ionosphere from F7/C2 GIS



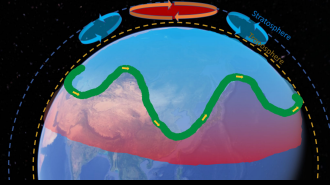
Fitting amplitude of Q6DO in latitude and local time

# 2019 Antarctic Stratospheric Sudden Warming

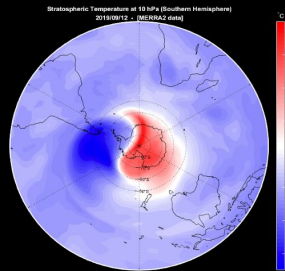
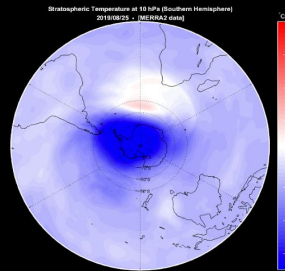
60K Temperature increase  
 3rd time in the history strongest in the history for rapid temp. increase  
 Strongest 6 day oscillation in ionosphere ~ 30%



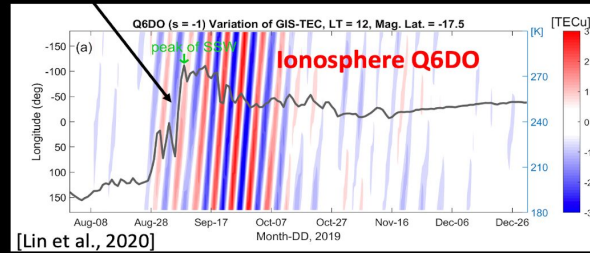
Antarctic Stratosphere



Antarctic SSW @2019

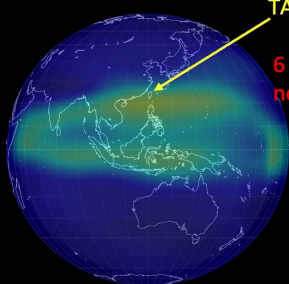


SSW temp. increase rapidly -65°C -> -5°C



## Global Ionosphere Specifications

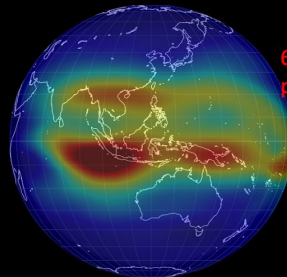
2019/09/27 12:00 LT  
 400 Km altitude



TAIWAN

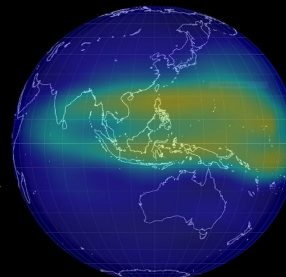
6 day oscillation  
 negative

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



6 day oscillation  
 positive

2019/10/03 12:00 LT  
 Km altitude



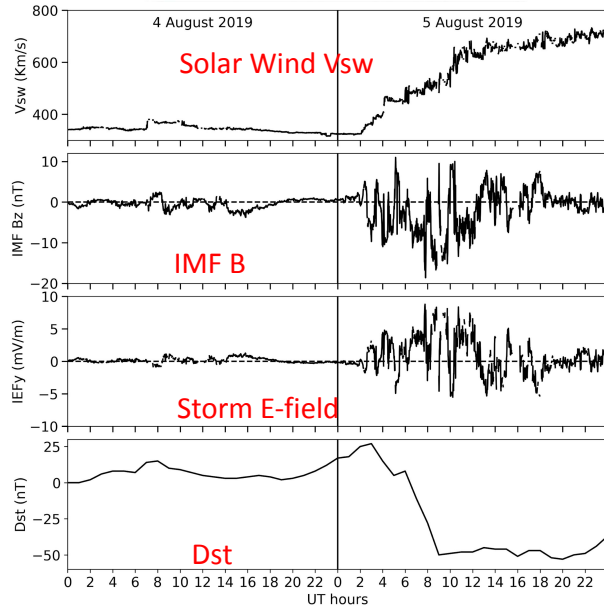
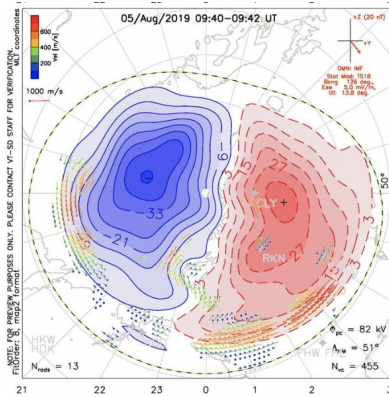
6 day oscillation  
 negative



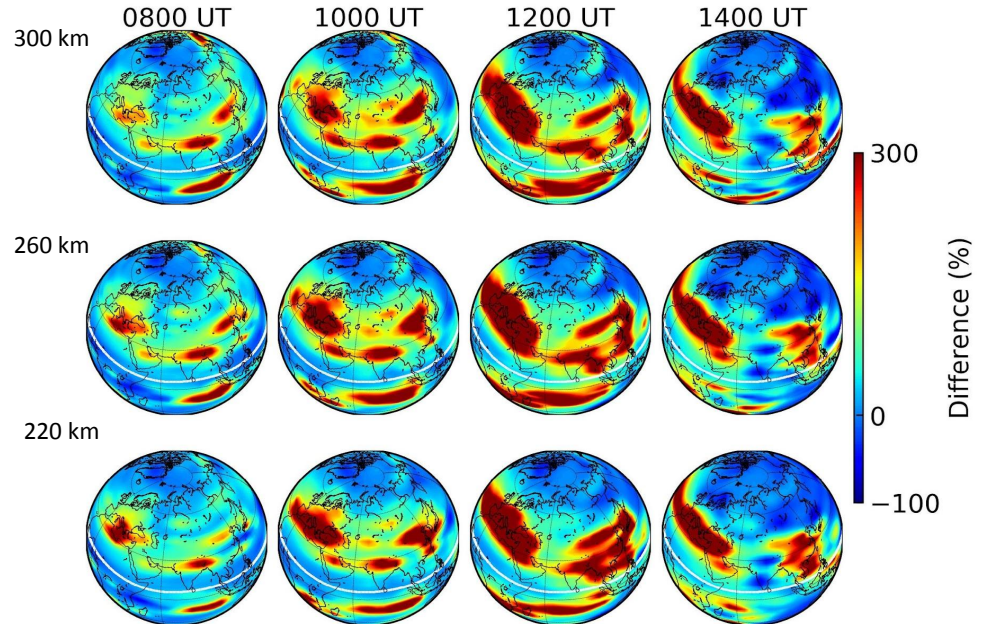
## 2019-08-05 G1 Minor Magnetic Storm

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, e2020JA028261 <https://doi.org/10.1029/2020JA028261>

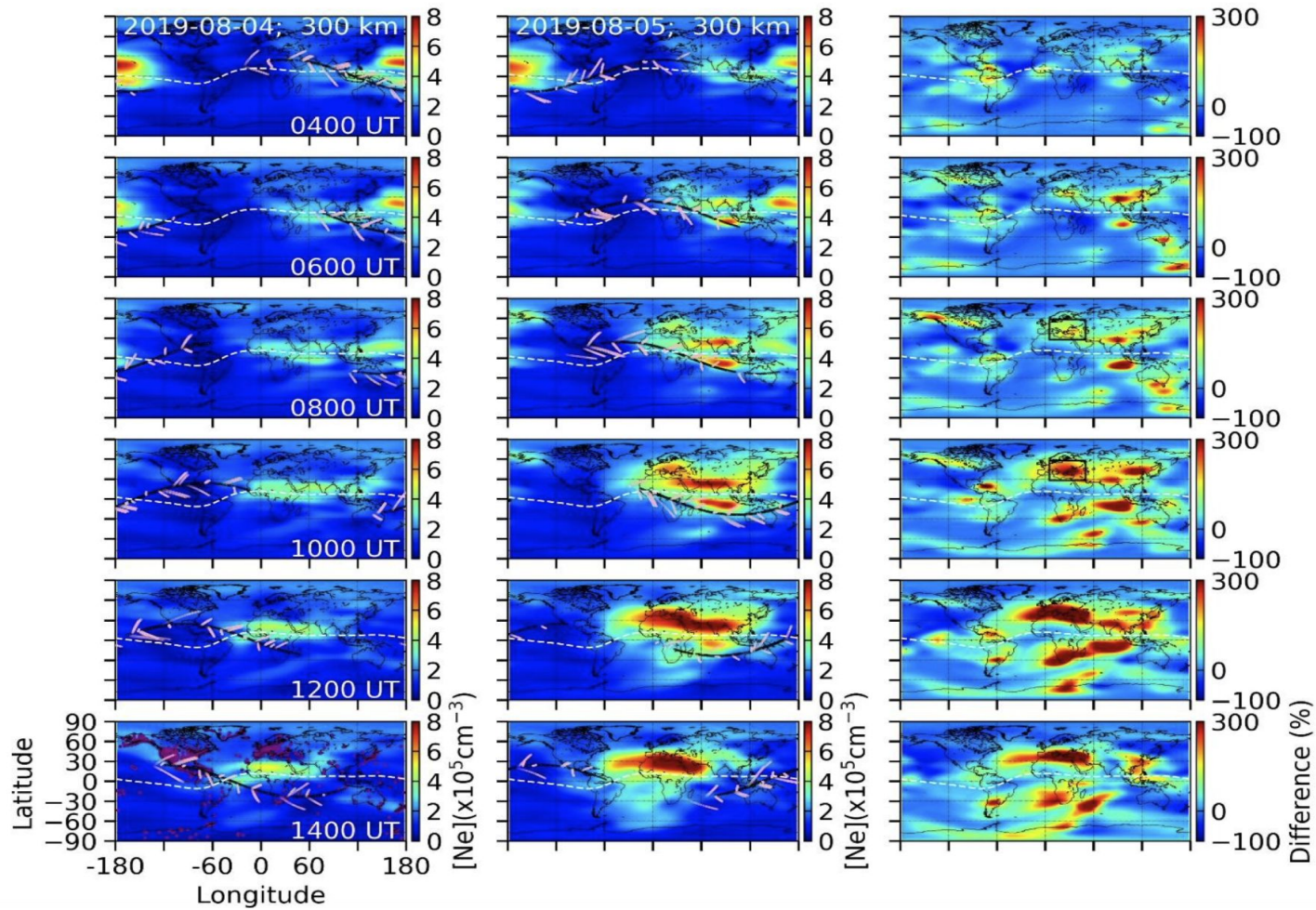
High Latitude  
convection  
intensified



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

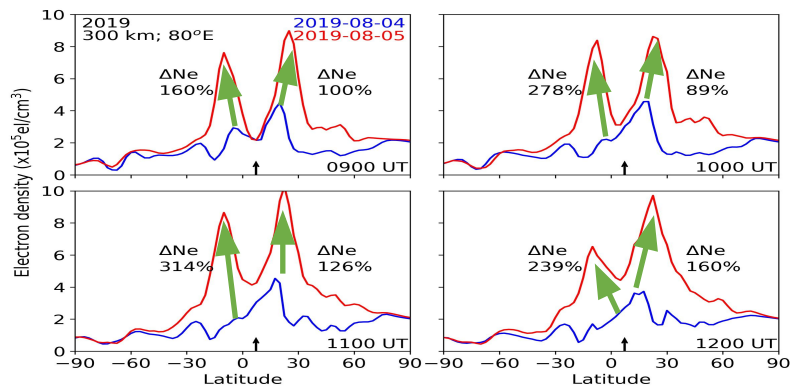


## Strong Positive Storm Effects!

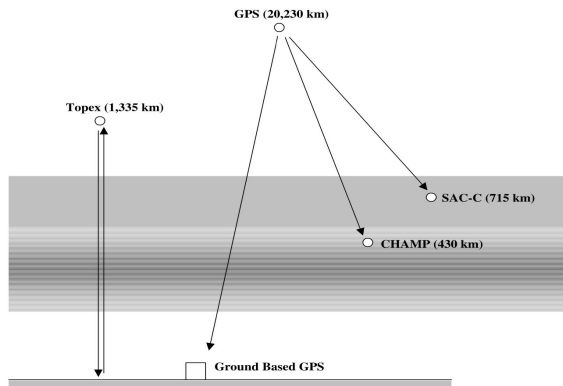




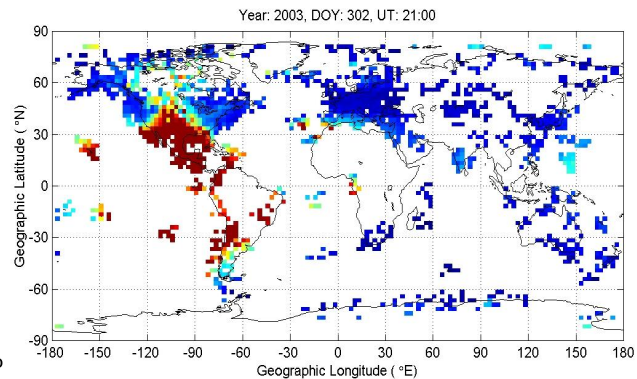
# G1 Minor storm in August 2019



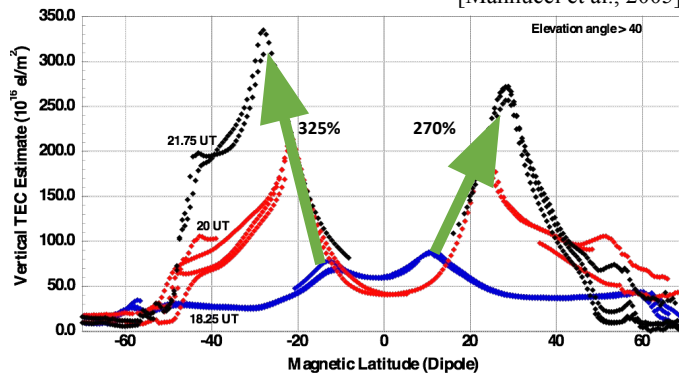
[Rajesh et al., 2020]



# Super storm effects during solar maximum October 2003



[Mannucci et al., 2005]

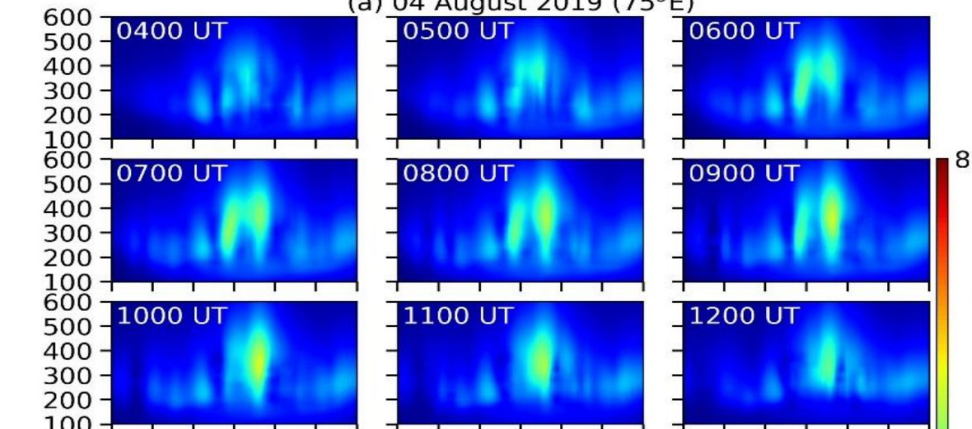


# Latitude-Altitude-Ne @ 75°E Longitude

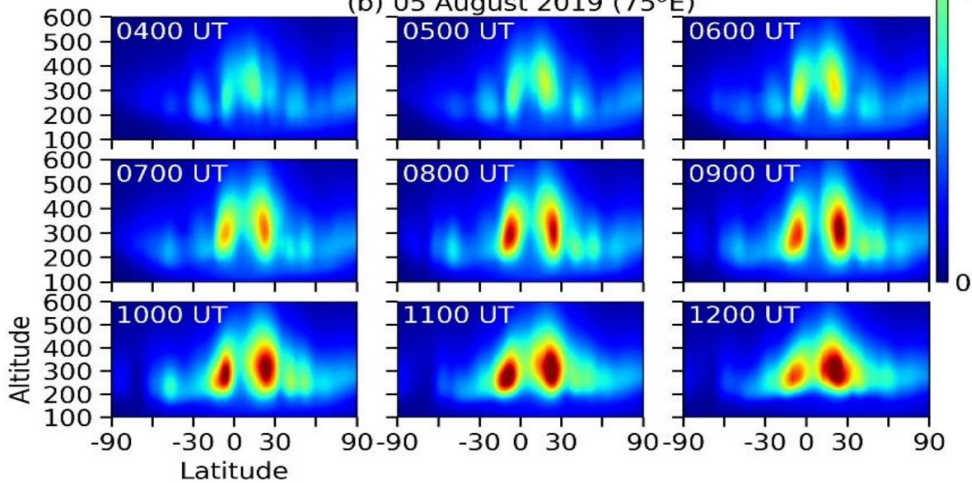
2019-08-05 G1 Minor Magnetic Storm

Pre-storm

(a) 04 August 2019 (75°E)



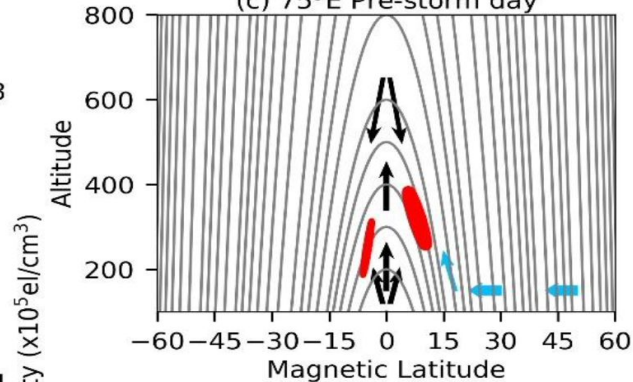
(b) 05 August 2019 (75°E)



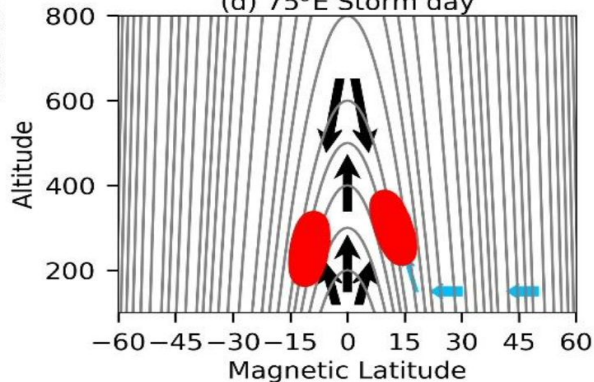
Storm

[Rajesh et al., 2020]

(c) 75°E Pre-storm day

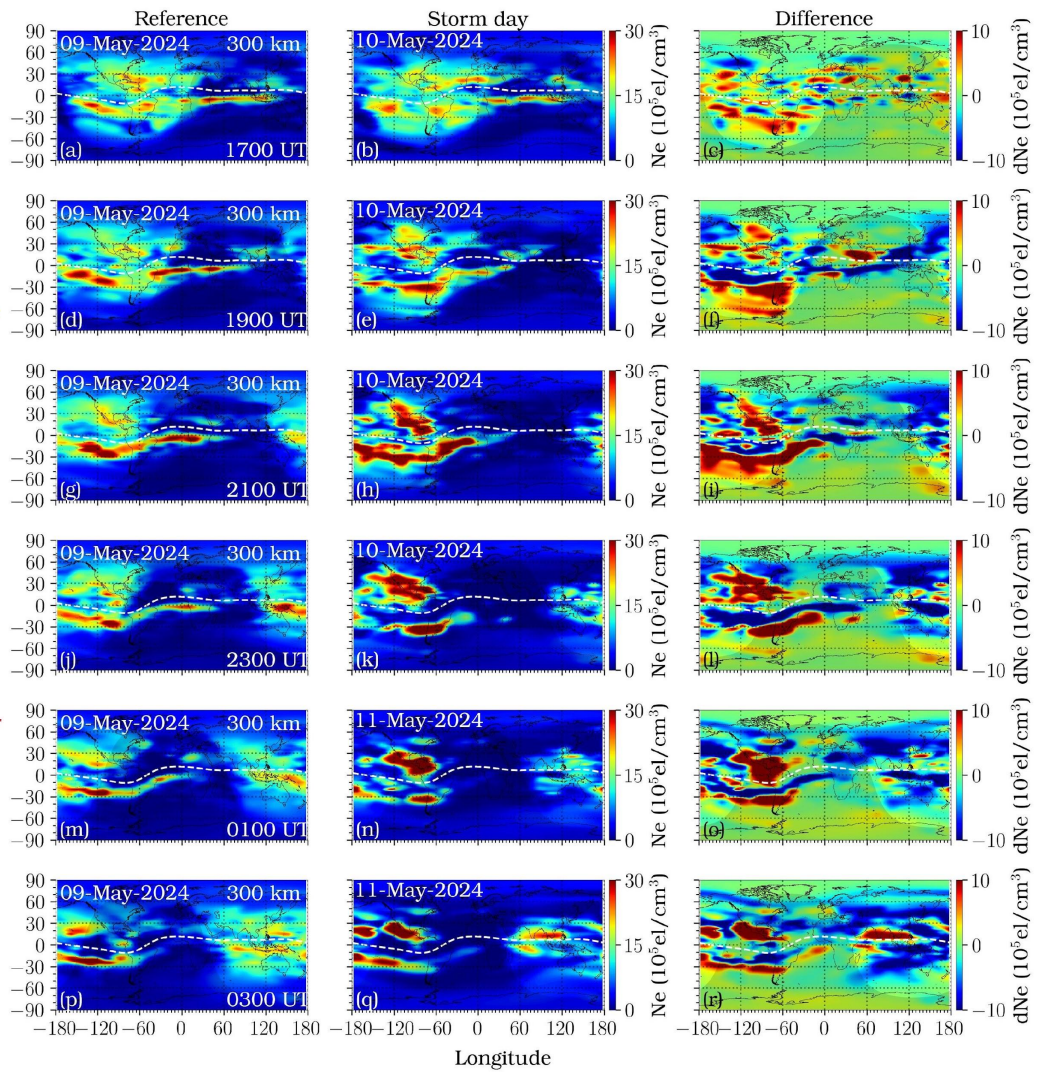
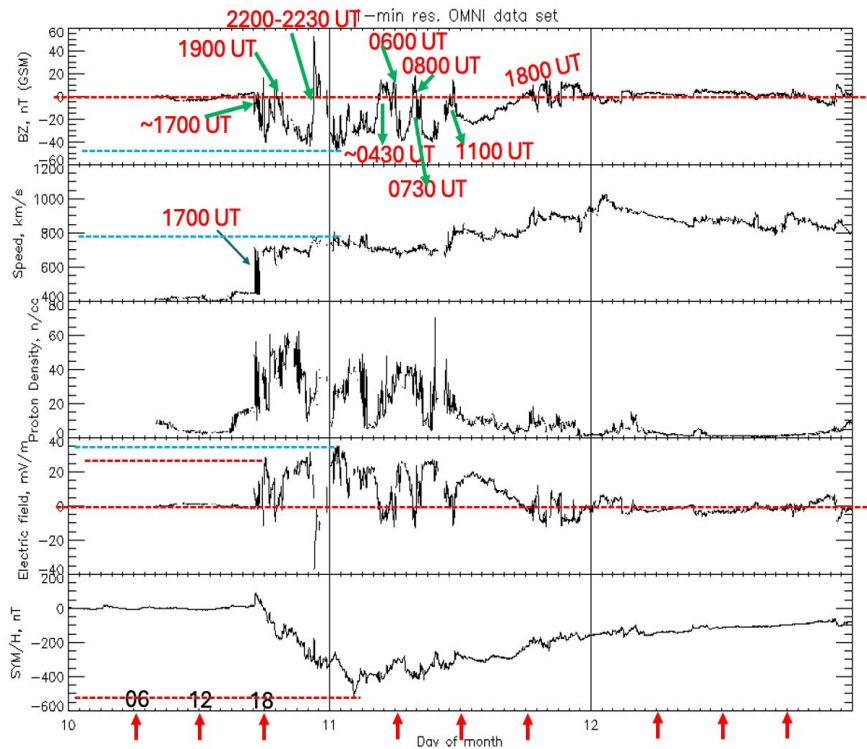


(d) 75°E Storm day

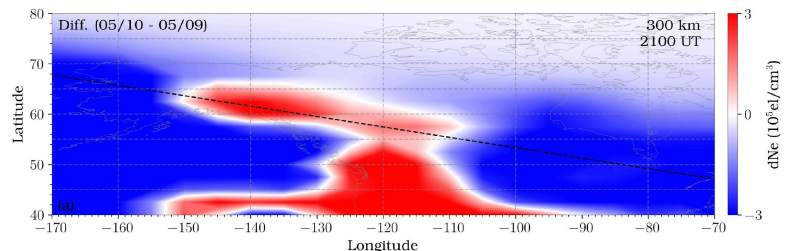
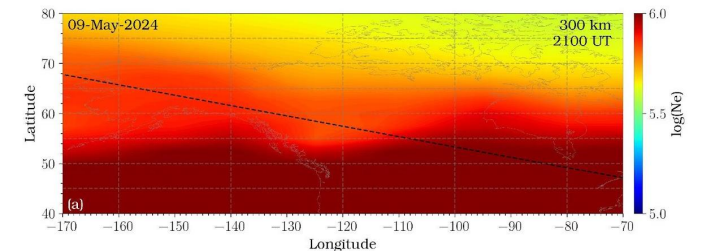


# Magnetic storm (G5) on 10-11 May 2024

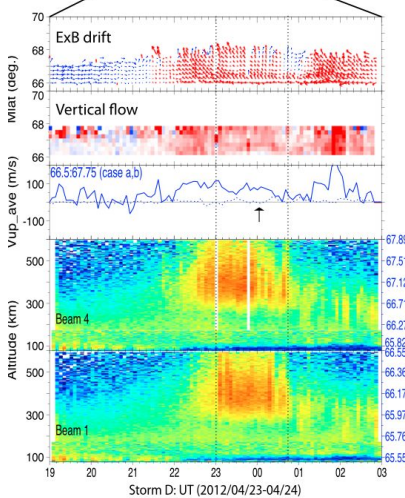
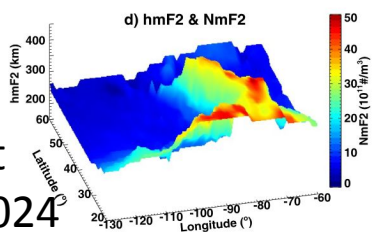
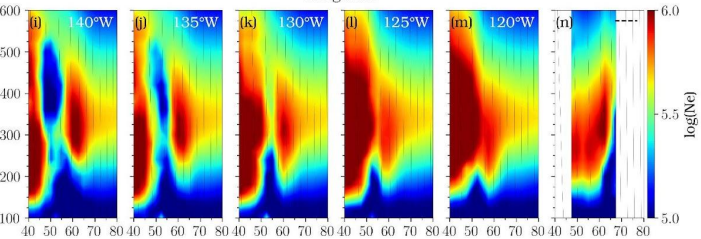
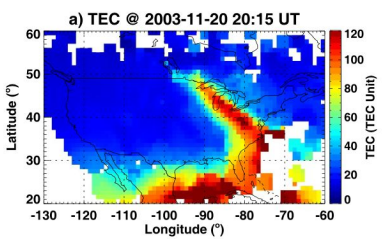
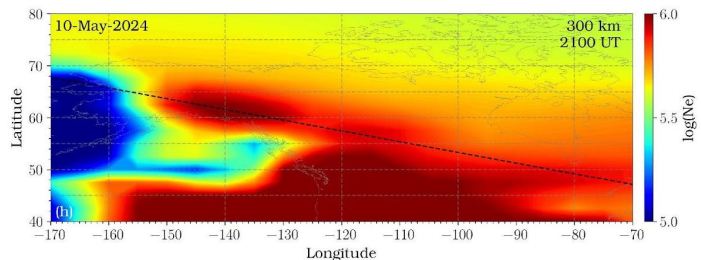
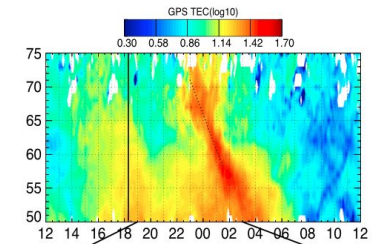
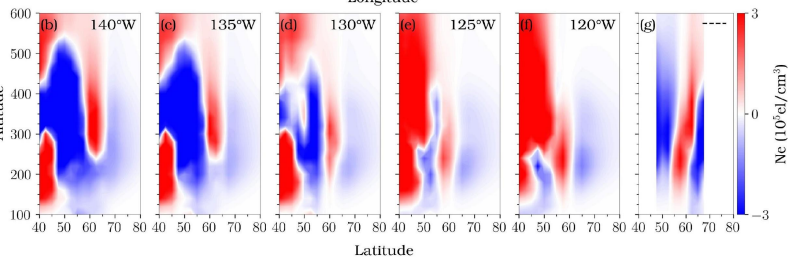
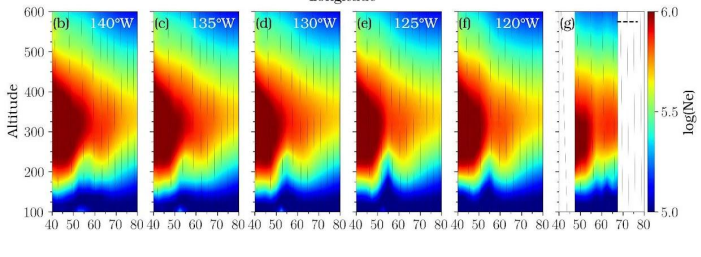
## Storm Enhanced Density & PPEF



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



Zou et al., 2014



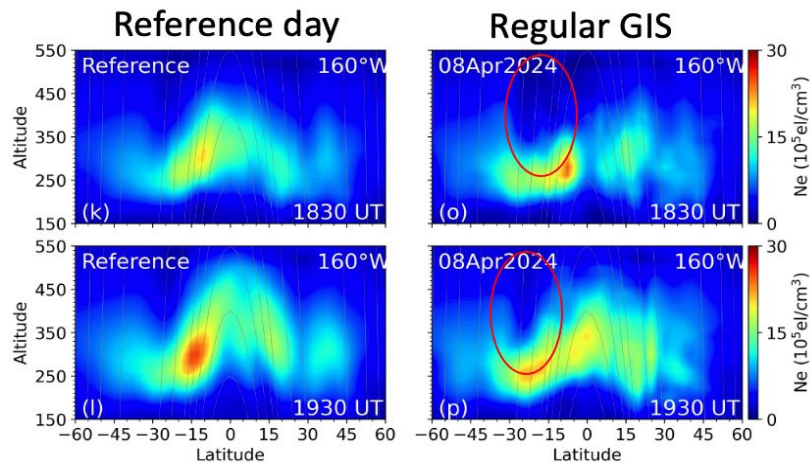
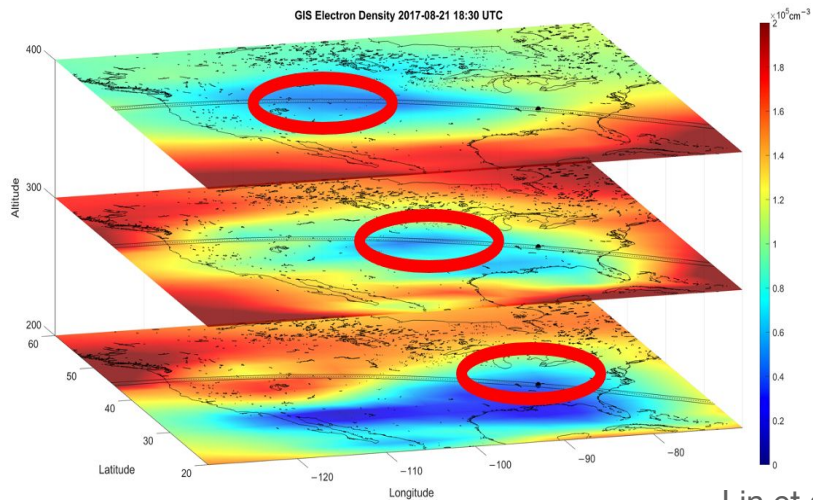
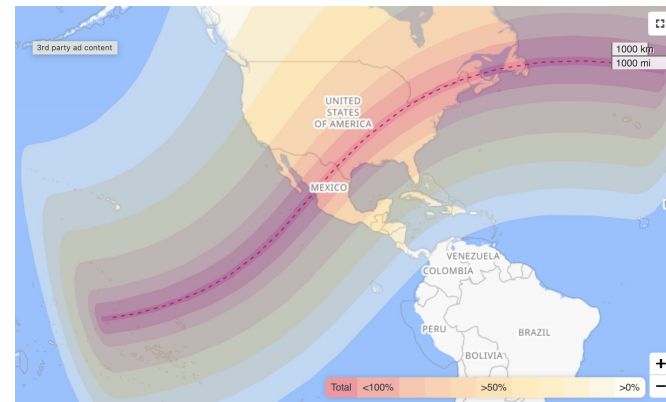
Aa et al., 2024

PFISR Obs.

# 2017 Solar Eclipse using FORMOSAT-3/COSMIC



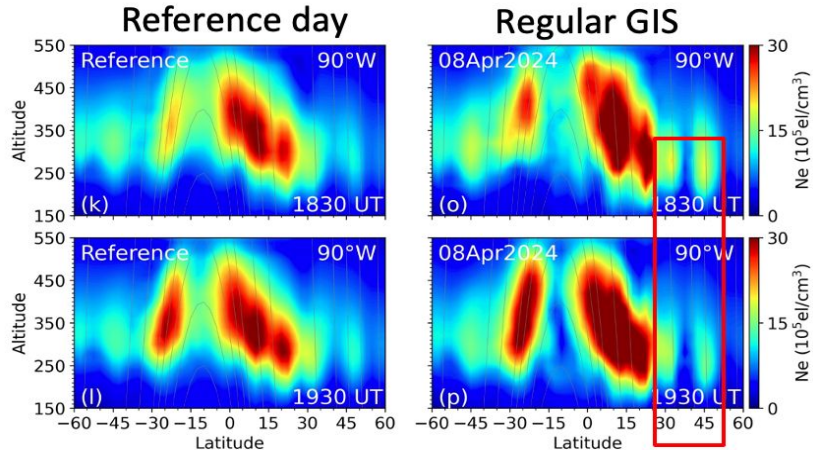
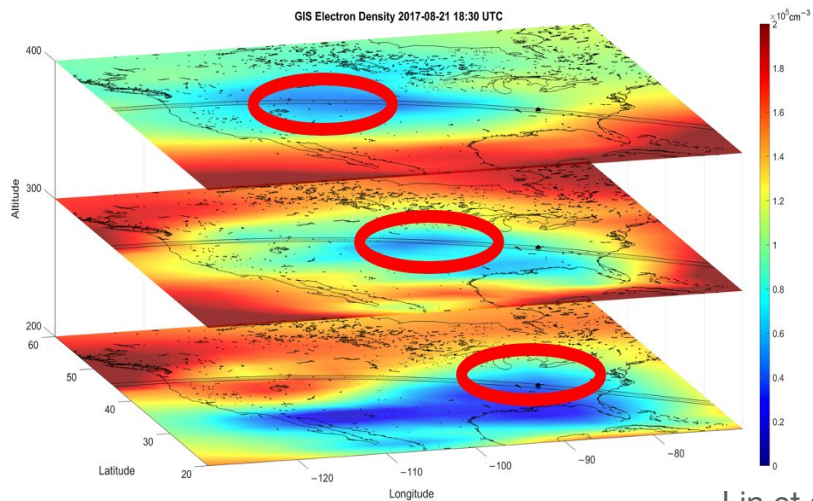
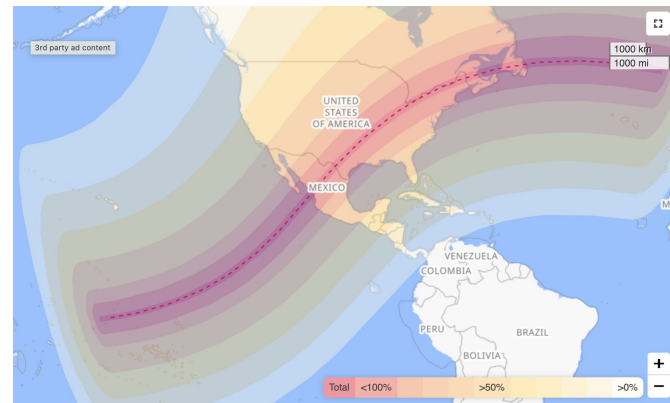
# 8 April 2024 Solar Eclipse



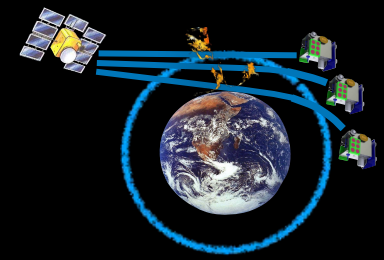
# 2017 Solar Eclipse using FORMOSAT-3/COSMIC



# 8 April 2024 Solar Eclipse



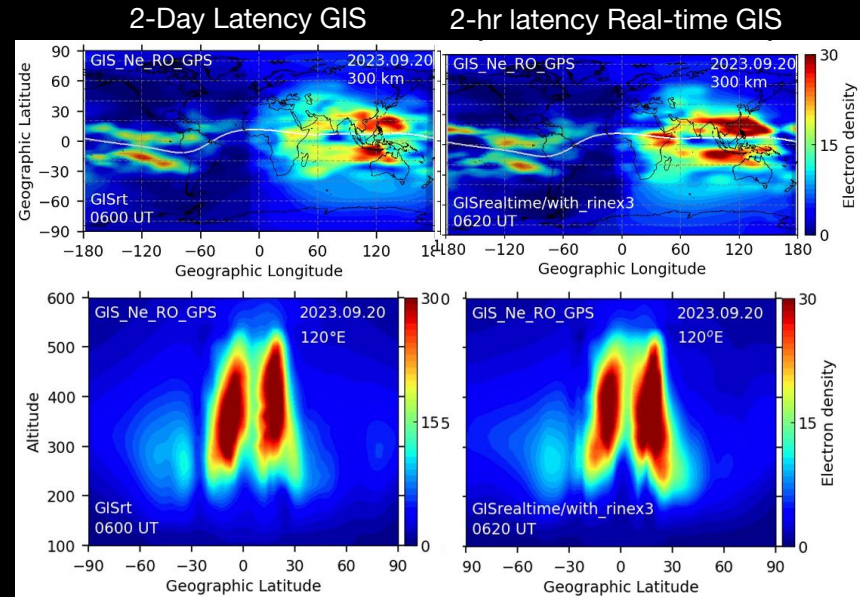
# Summary



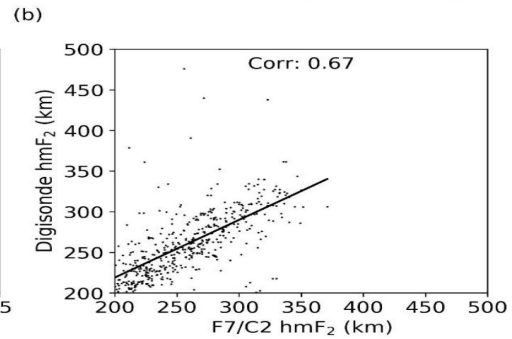
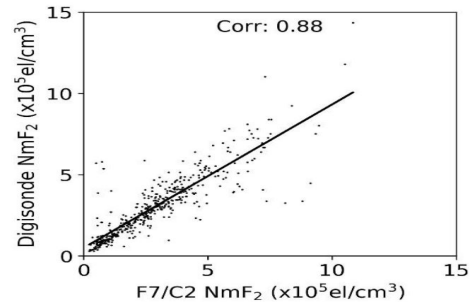
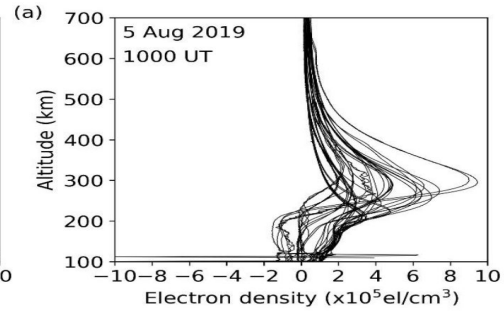
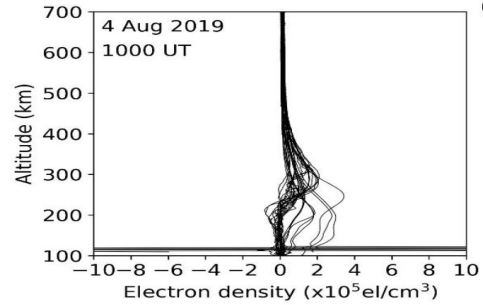
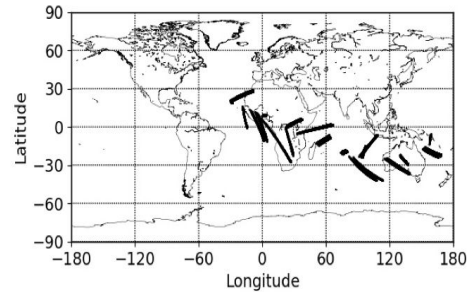
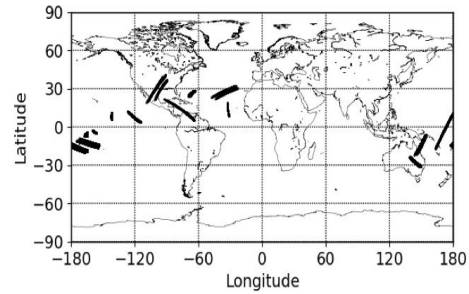
1. F7/C2 based GIS has shown prominent day-to-day variability of ionosphere
2. Day-to-day obs. are useful to see the vertical coupling (SSW & quasi 6 day oscillation).
3. GIS has been applied to investigate 3 storms (G1, G3 & G5) showing peculiar phenomena (positive storm, SED & plume).
4. GIS observes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



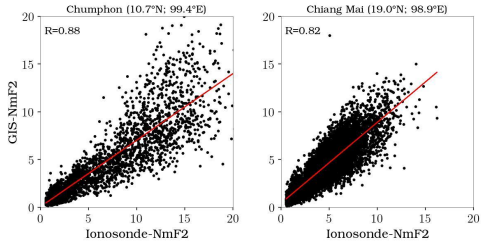
# Validation of the Ne-profiles





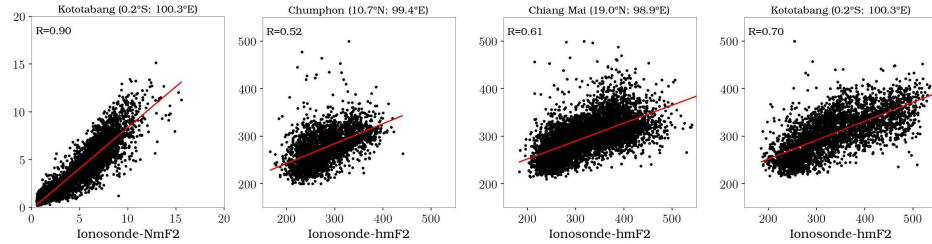
# GIS –validation using NICT SEALION network

## GIS and Ionosonde NmF2

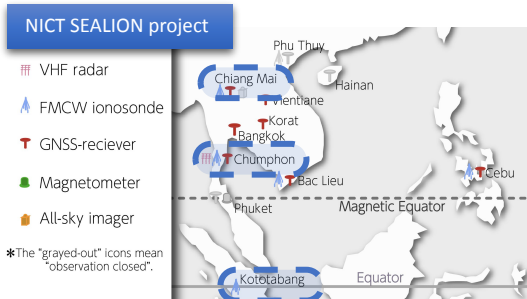


NmF2 shows a correlation of about 0.8 to 0.9

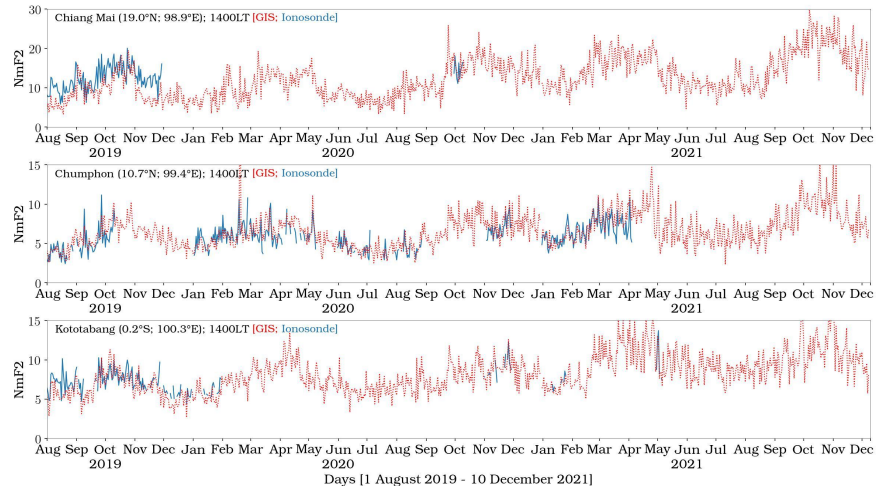
## GIS and Ionosonde hmF2 (2019-2021)



hmF2 gives a correlation of about 0.5 to 0.7



\*The "grayed-out" icons mean "observation closed".



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

