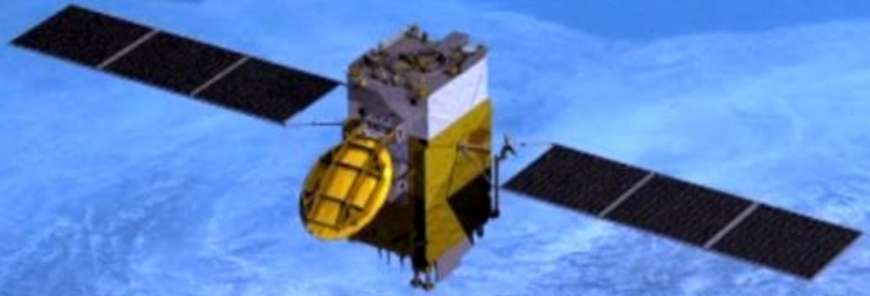
United Nations/Finland Workshop on the Applications of GNSS

Ionospheric space weather monitoring and its applications on GNSS



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Helsinki, 23-26 October 2023

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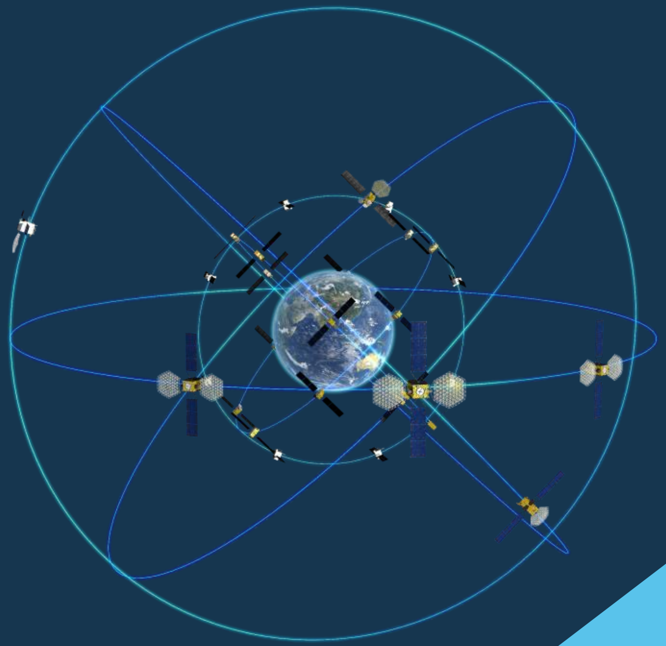
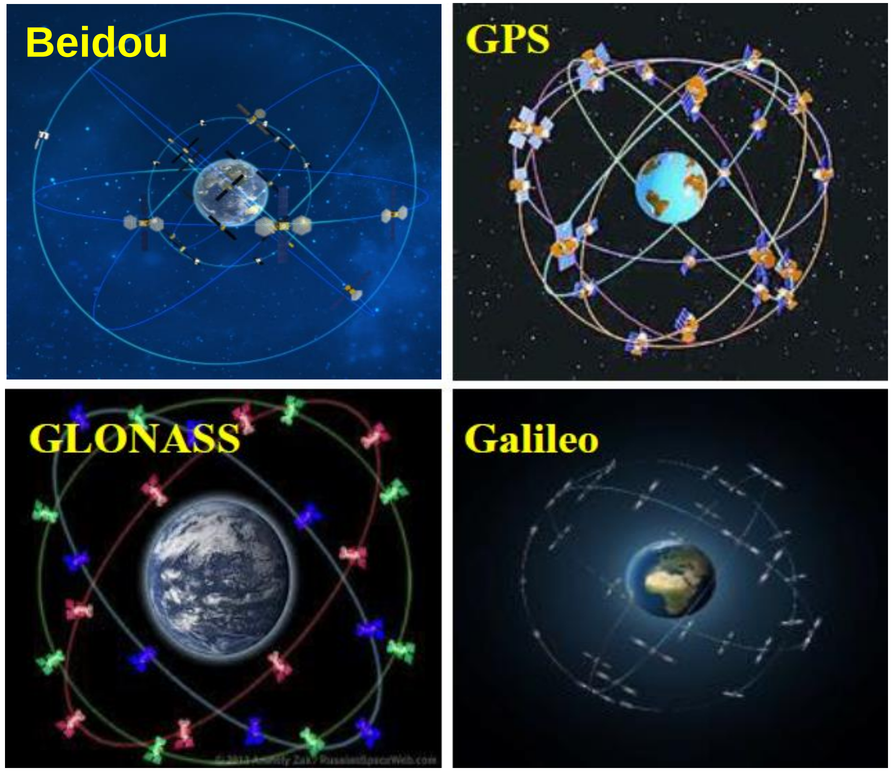


01

Satellite navigation and ionosphere

1. Satellite navigation and ionosphere

- **Global Navigation Satellite System (GNSS) has become one of the main technical means of navigation**



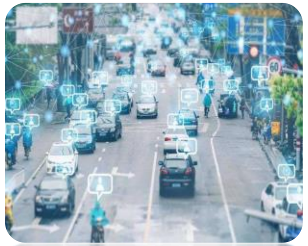

Marine Navigation


Car Navigation


Mobile Navigation


Aviation


Farming

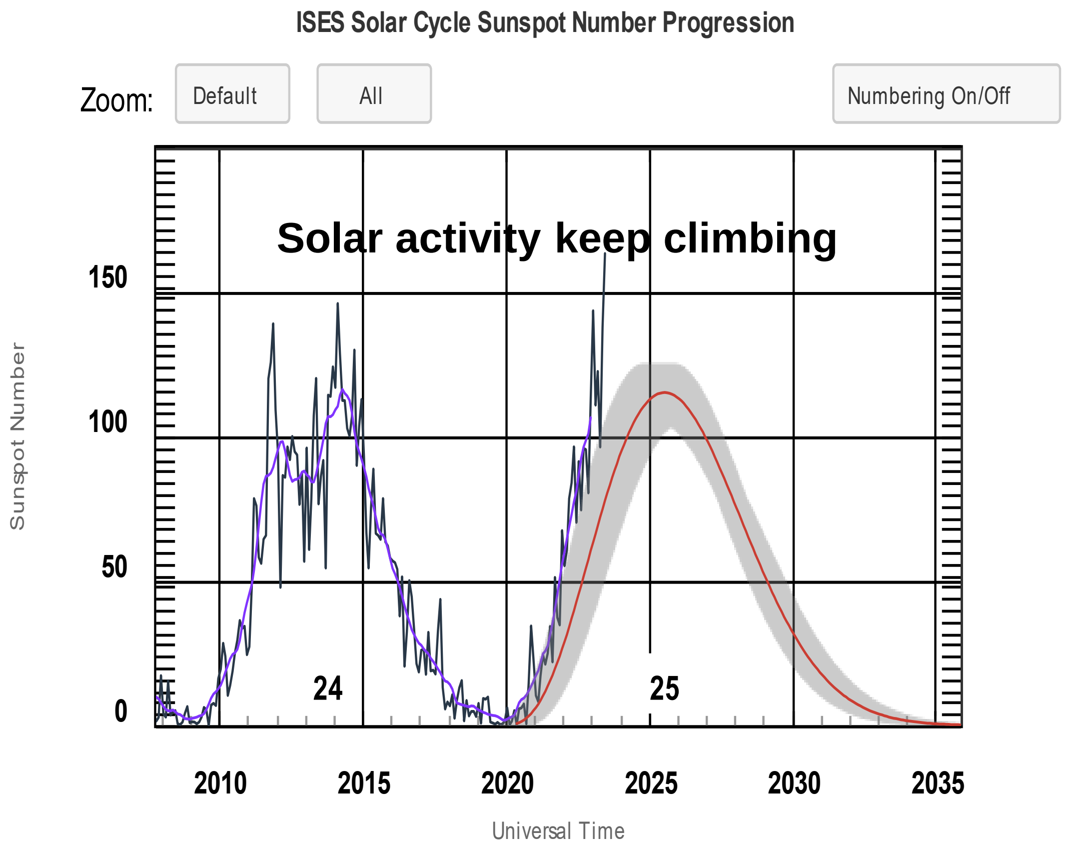

Transportation


Geomatics

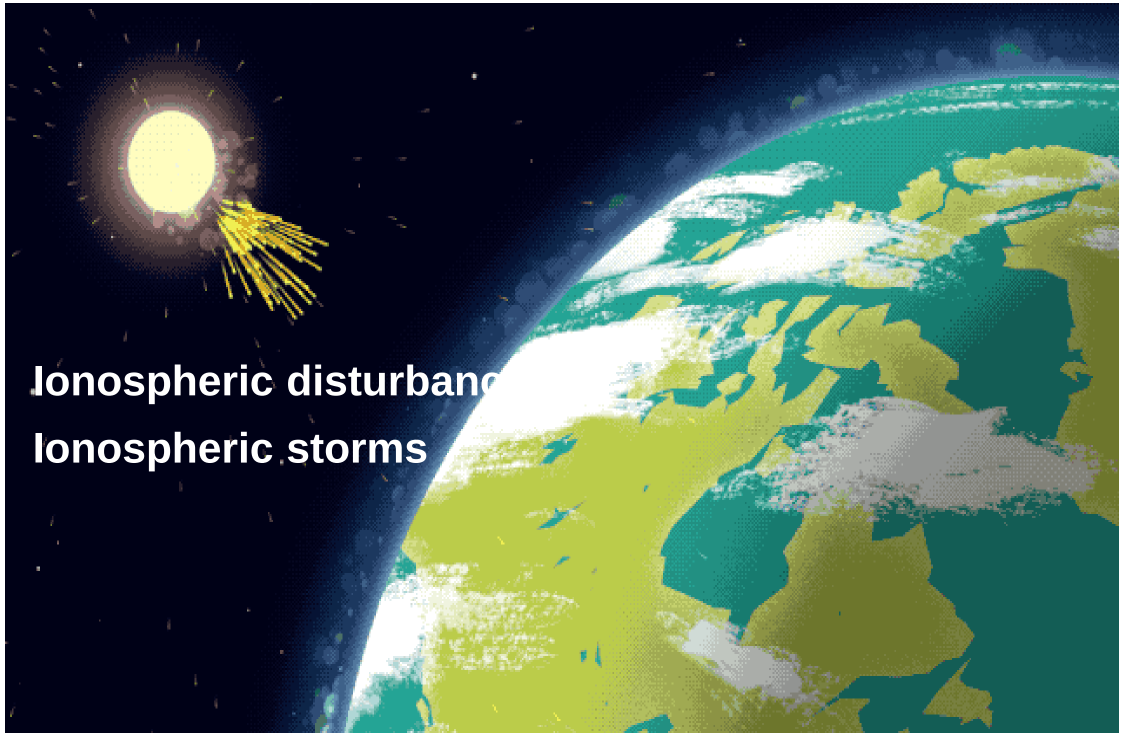

Earthquake Monitoring

1. Satellite navigation and ionosphere

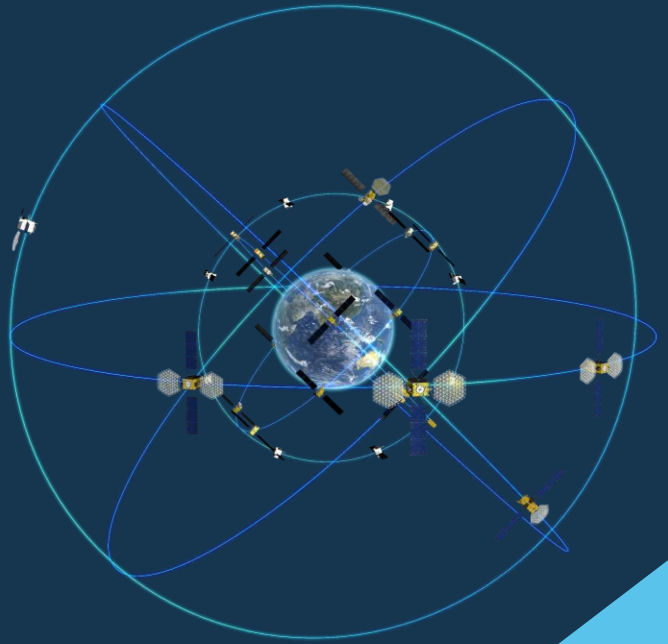
- **The 25th solar cycle is approaching its peak year, which is expected to be 2024-2028**
- **The occurrence and amplitude of ionospheric anomalies will be significantly increased**



The time series of Sunspot number
（*from NOAA*）



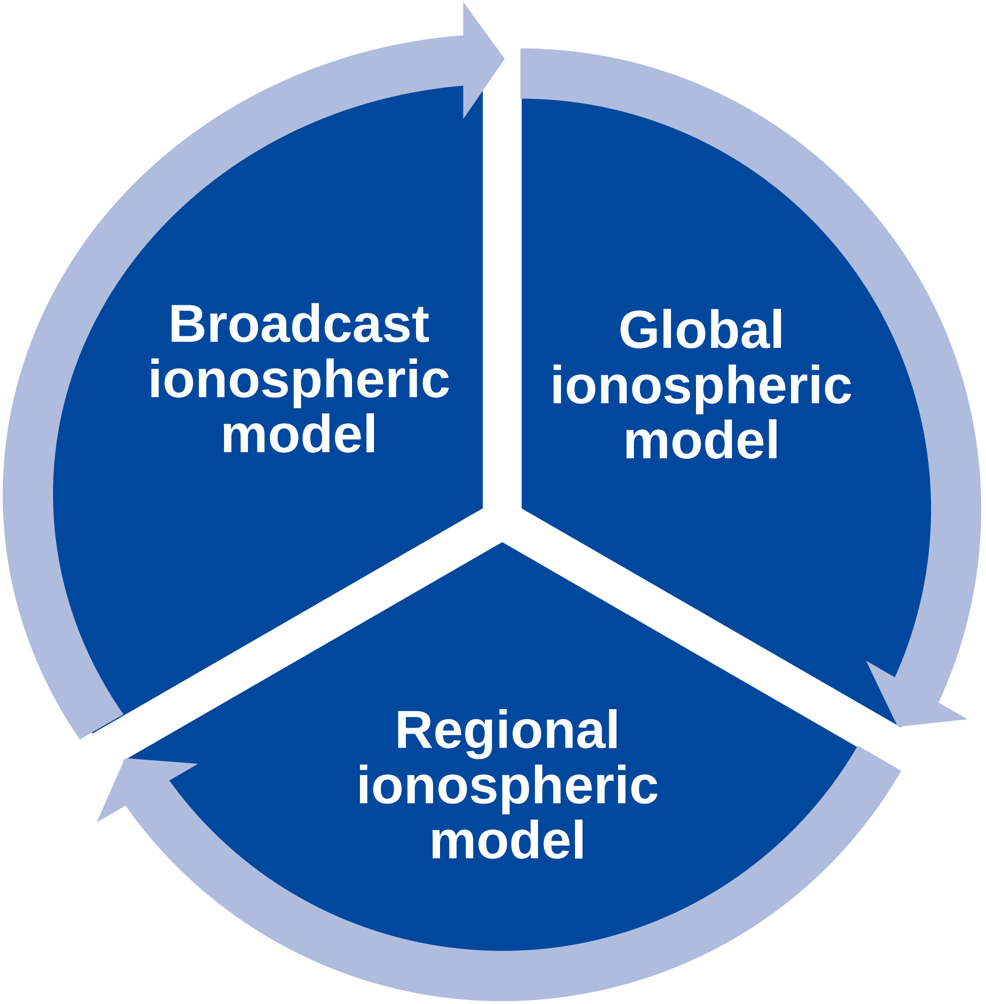
Solar activities is the main driver of ionospheric variations



02

Recent progress in ionospheric monitoring

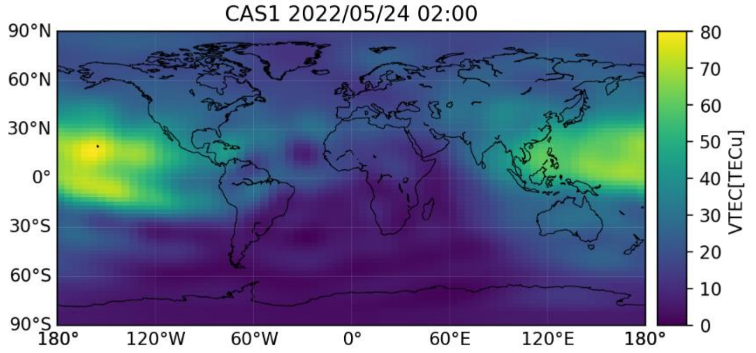
■ Ionospheric correction for GNSS



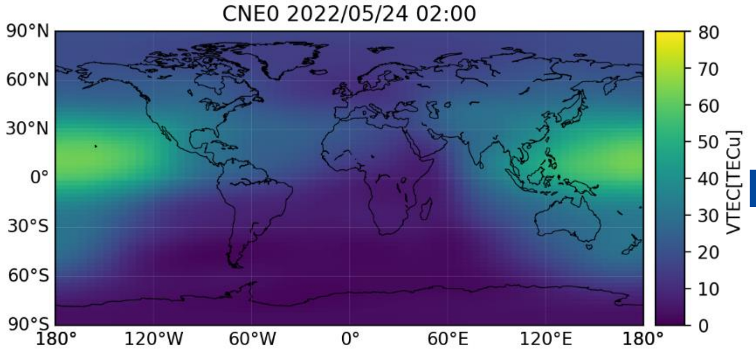
	Single-frequency Users	Multi-frequency Users
Single Point Positioning	The positioning accuracy	The convergency time
Precise Point Positioning	The convergency time and positioning accuracy	The convergency time
Real-Time Kinematic	Aid in ambiguity fixing	Aid in ambiguity fixing

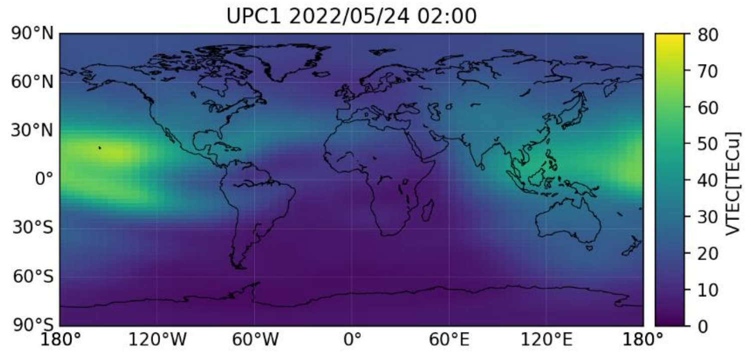
■ The cooperative real-time GIMs from International GNSS Service (IGS)

Chinese Academy of Sciences (CAS)

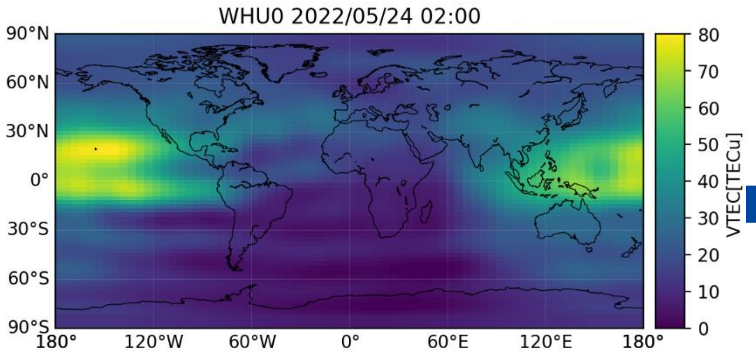


Centre national d'études spatiales (CNES)



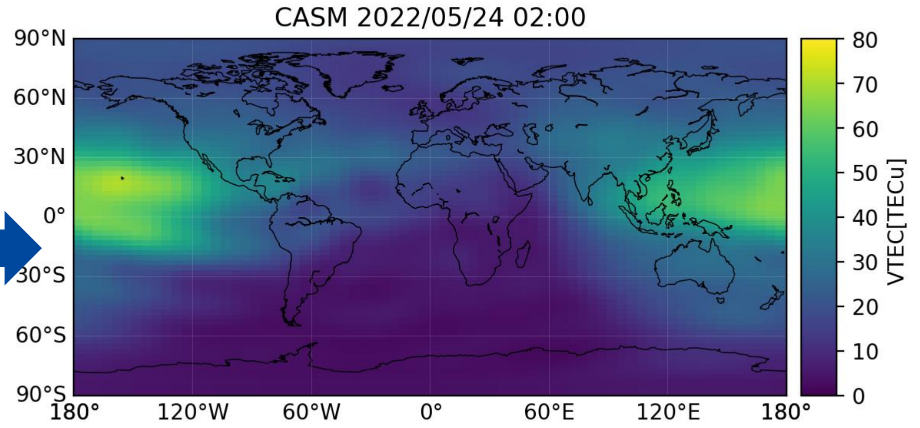


Universitat Politècnica de Catalunya (UPC)

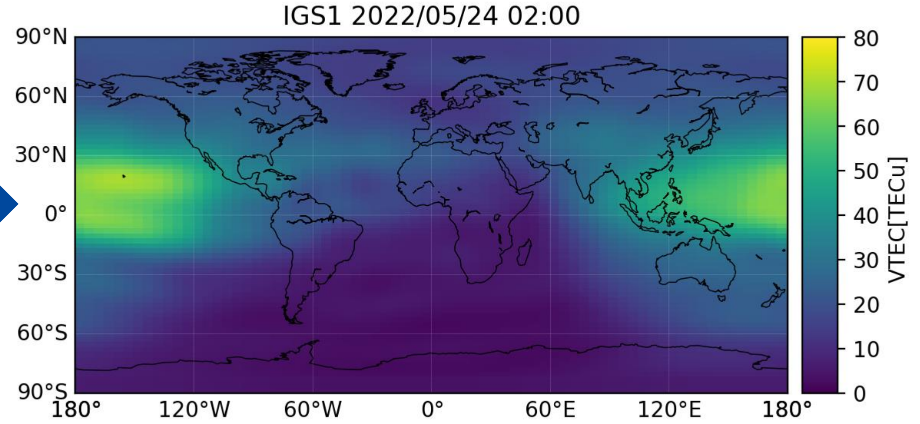


Wuhan University (WHU)

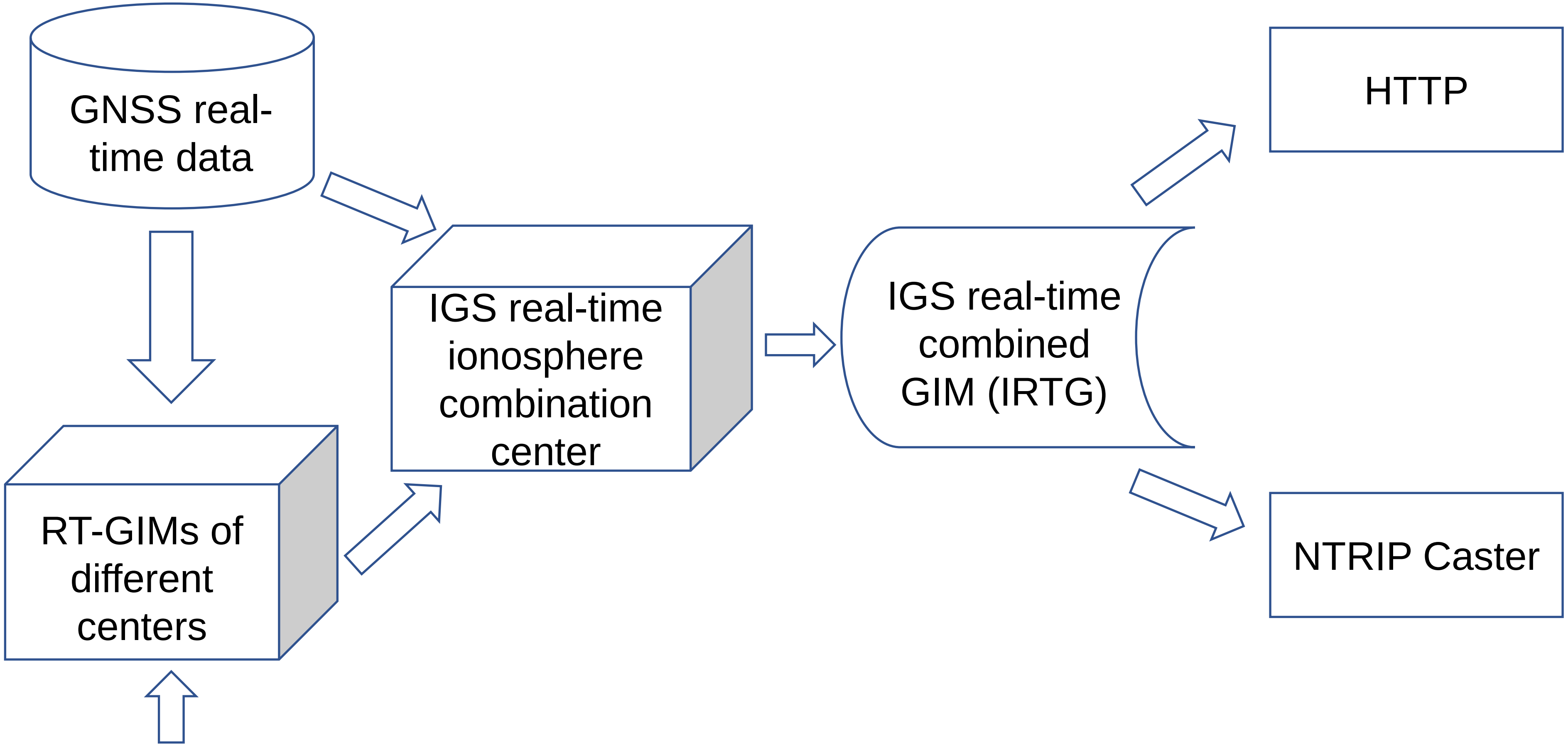
CAS real-time combined GIM



HENU+UPC real-time combined GIM



■ The cooperative real-time GIMs from IGS



CAS, CNES, UPC, WHU

[Liu+, 2021 ESSD; Wang+ 2022 URSI]

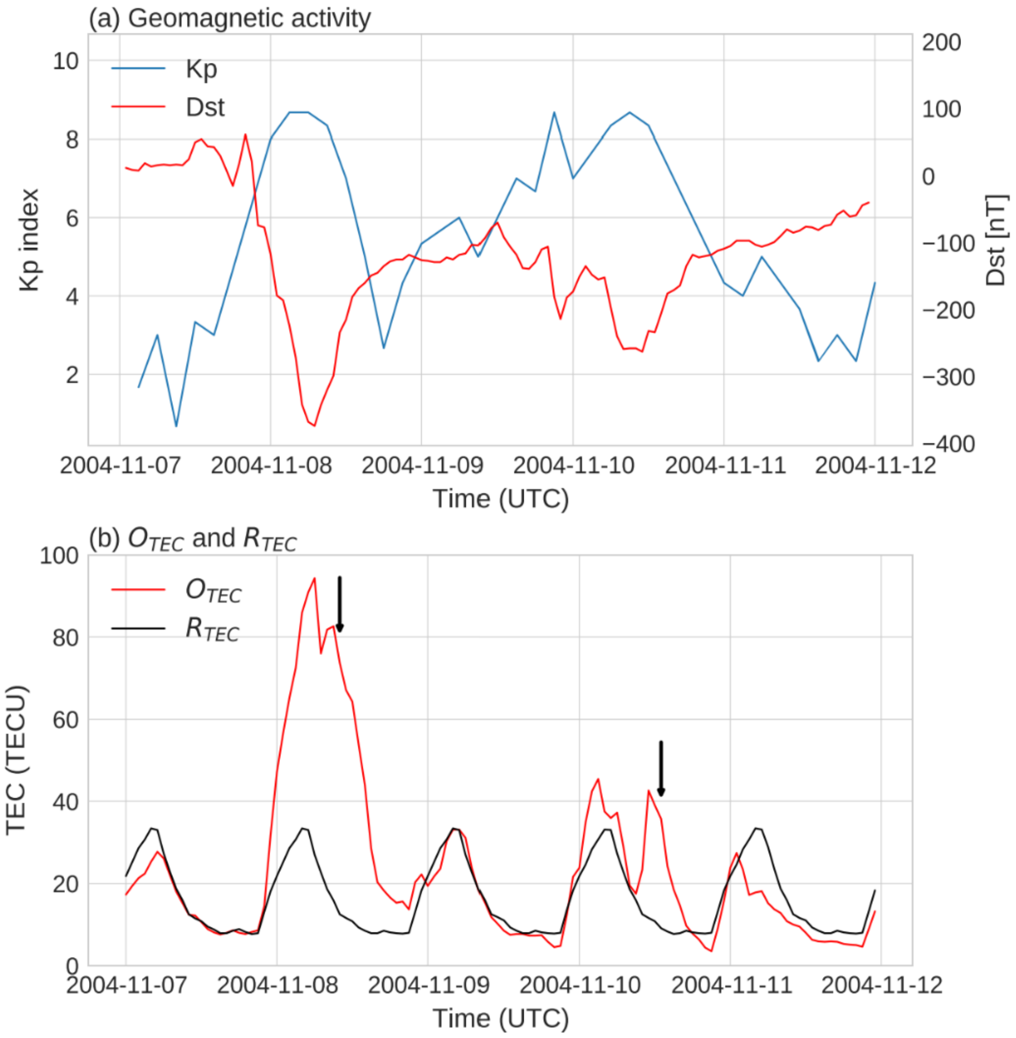
■ The characterization of Ionospheric storm in global scale

✓ Propose a standardized scale of ionospheric storm based on GIM

$$P_{TEC} = \frac{100 \times (O_{TEC} - R_{TEC})}{R_{TEC}}$$

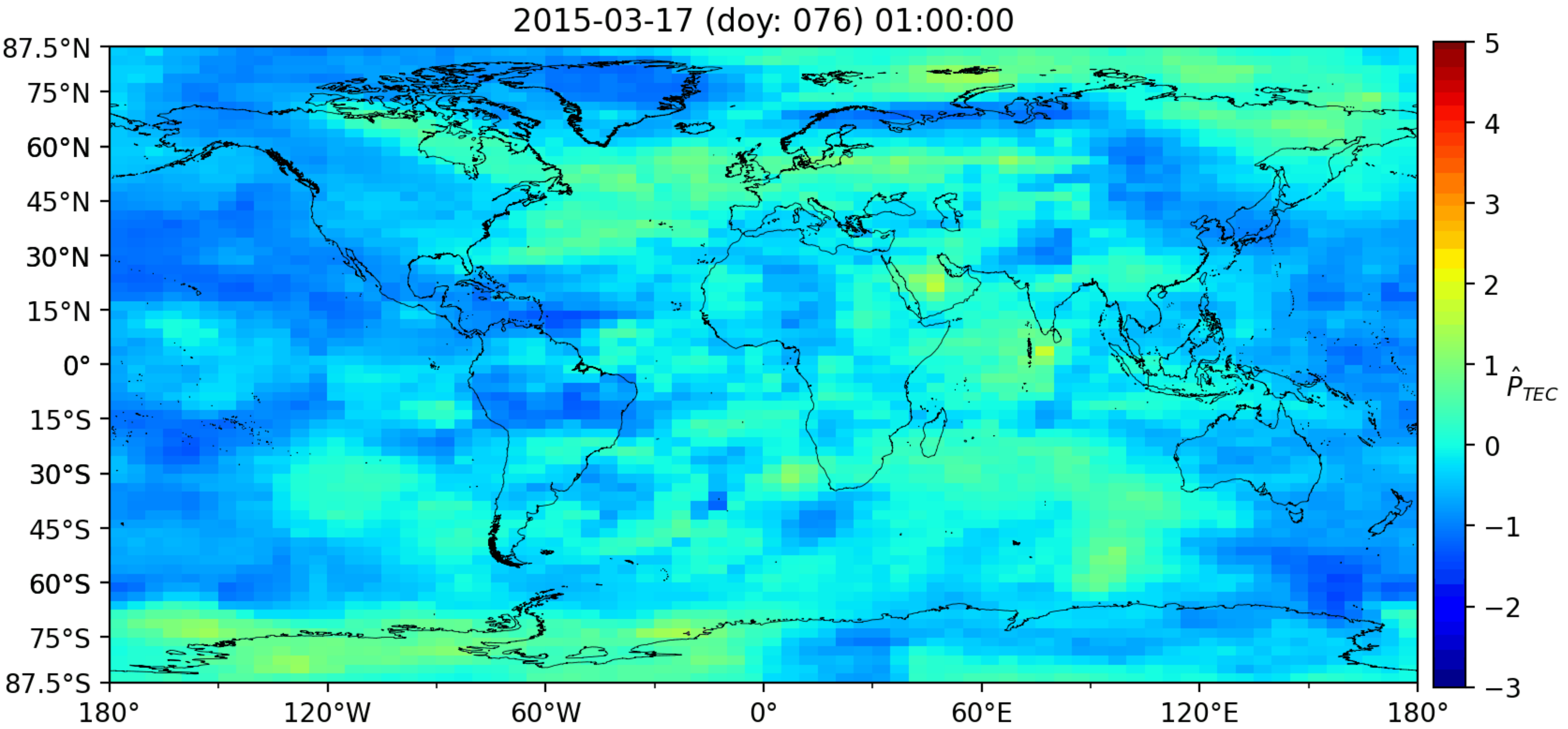
$$\hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma}$$

IsUG	Description	Definition	Probability on a global scale (%)
IP3	Severe positive storm	$5 < \hat{P}$	0.17
IP2	Strong positive storm	$3 < \hat{P} \leq 5$	0.72
IP1	Moderate positive storm	$1 < \hat{P} \leq 3$	12.43
I0	Quiet	$-1 < \hat{P} \leq 1$	73.96
IN1	Moderate negative storm	$-2 < \hat{P} \leq -1$	11.72
IN2	Strong negative storm	$-3 < \hat{P} \leq -2$	0.95
IN3	Severe negative storm	$\hat{P} < -3$	0.06



[Liu+, 2021 Space Weather] (130°E, 30°N)

■ Evolution of ionospheric storm on 2015 St. Patrick's Day storm



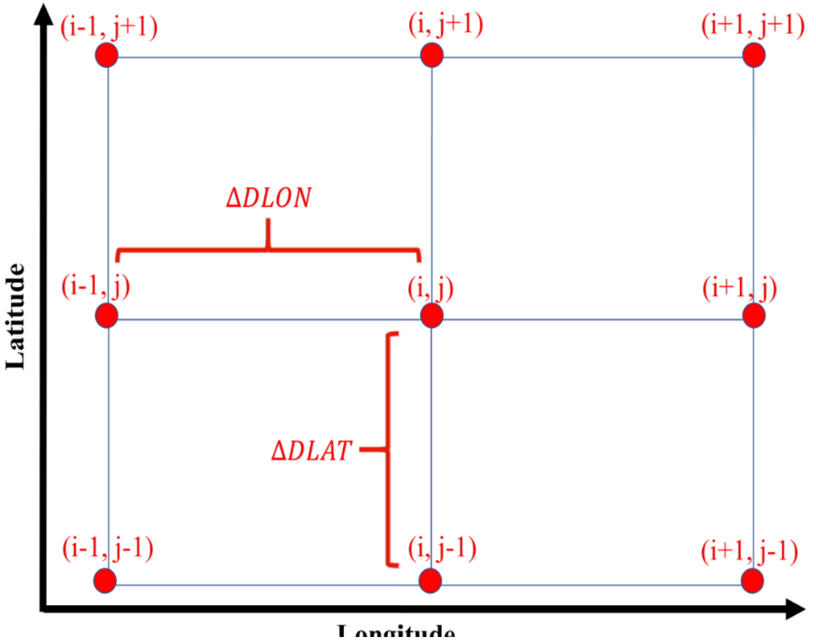
■ The characterization of ionospheric gradient

✓ Propose the ionospheric spatial gradient (non-relative) indices based on GIM

$$\begin{cases} \overline{\nabla V_x} = \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{x,i,j} / N_S \\ \nabla V_{x,P_{95+}} = P_{95}(\nabla V_{x,i,j,p}) \\ \nabla V_{x,P_{95-}} = -P_{95}(|\nabla V_{x,i,j,n}|) \\ \overline{\nabla V_y} = \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{y,i,j} / N_S \\ \nabla V_{y,P_{95+}} = P_{95}(\nabla V_{y,i,j,p}) \\ \nabla V_{y,P_{95-}} = -P_{95}(|\nabla V_{y,i,j,n}|) \end{cases}$$

$$\begin{cases} \overline{\nabla V} = \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{i,j} / N_S \\ \sigma_{\nabla V} = \sqrt{\left(\sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{i,j}{}^2\right) / N_S - \overline{\nabla V}^2} \\ \nabla V_{P_{95}} = P_{95}(\nabla V_{i,j}) \end{cases}$$

Regional indices

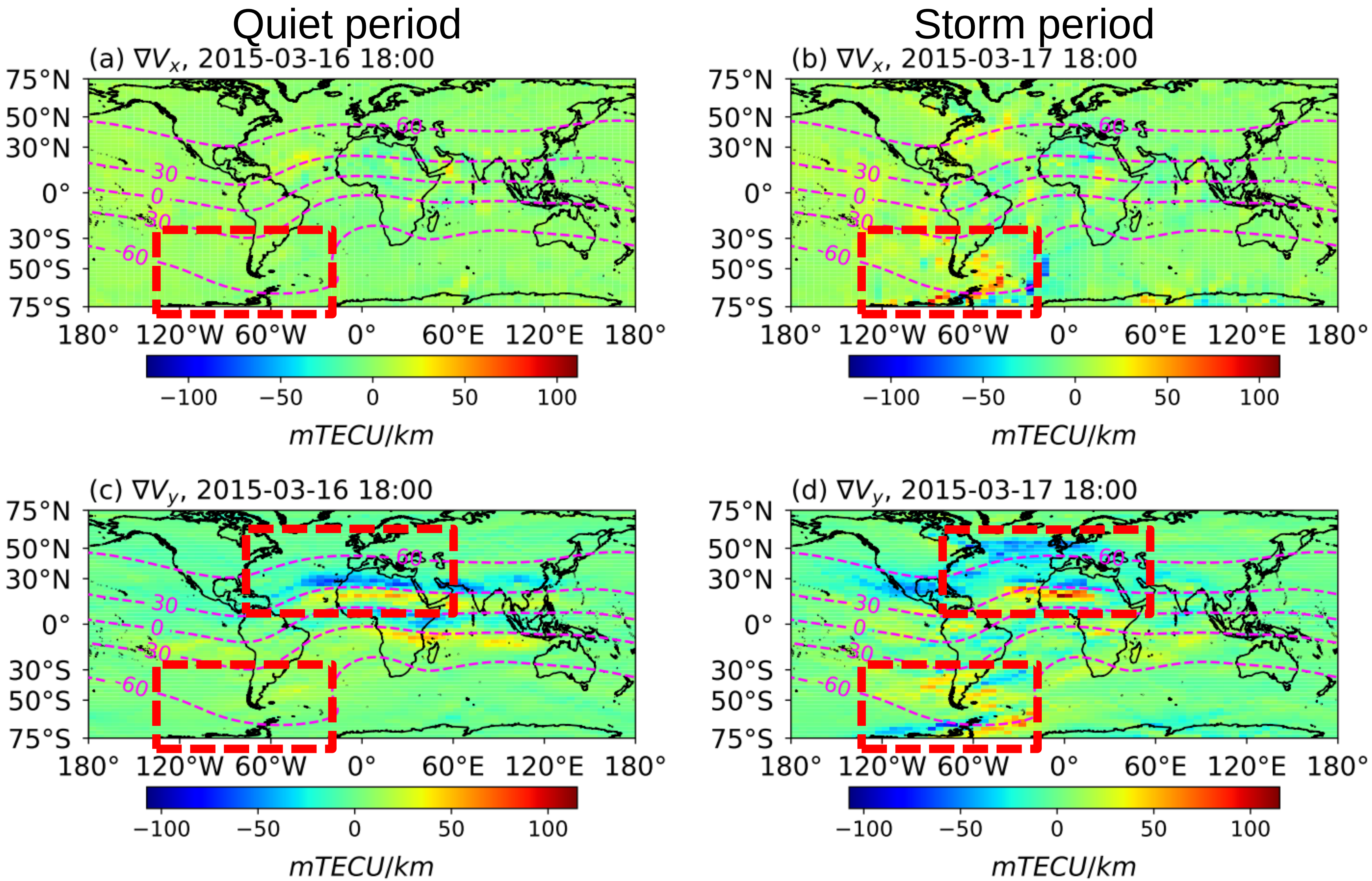


$$\begin{cases} \nabla V_{x,i,j} = (VTEC_{i,j} - VTEC_{i-1,j}) / \Delta DLON \\ \nabla V_{y,i,j} = (VTEC_{i,j} - VTEC_{i,j-1}) / \Delta DLAT \\ \nabla V_{i,j} = \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2} \\ \vec{\nabla V} = (\nabla V_{x,i,j}, \nabla V_{y,i,j}) \end{cases}$$

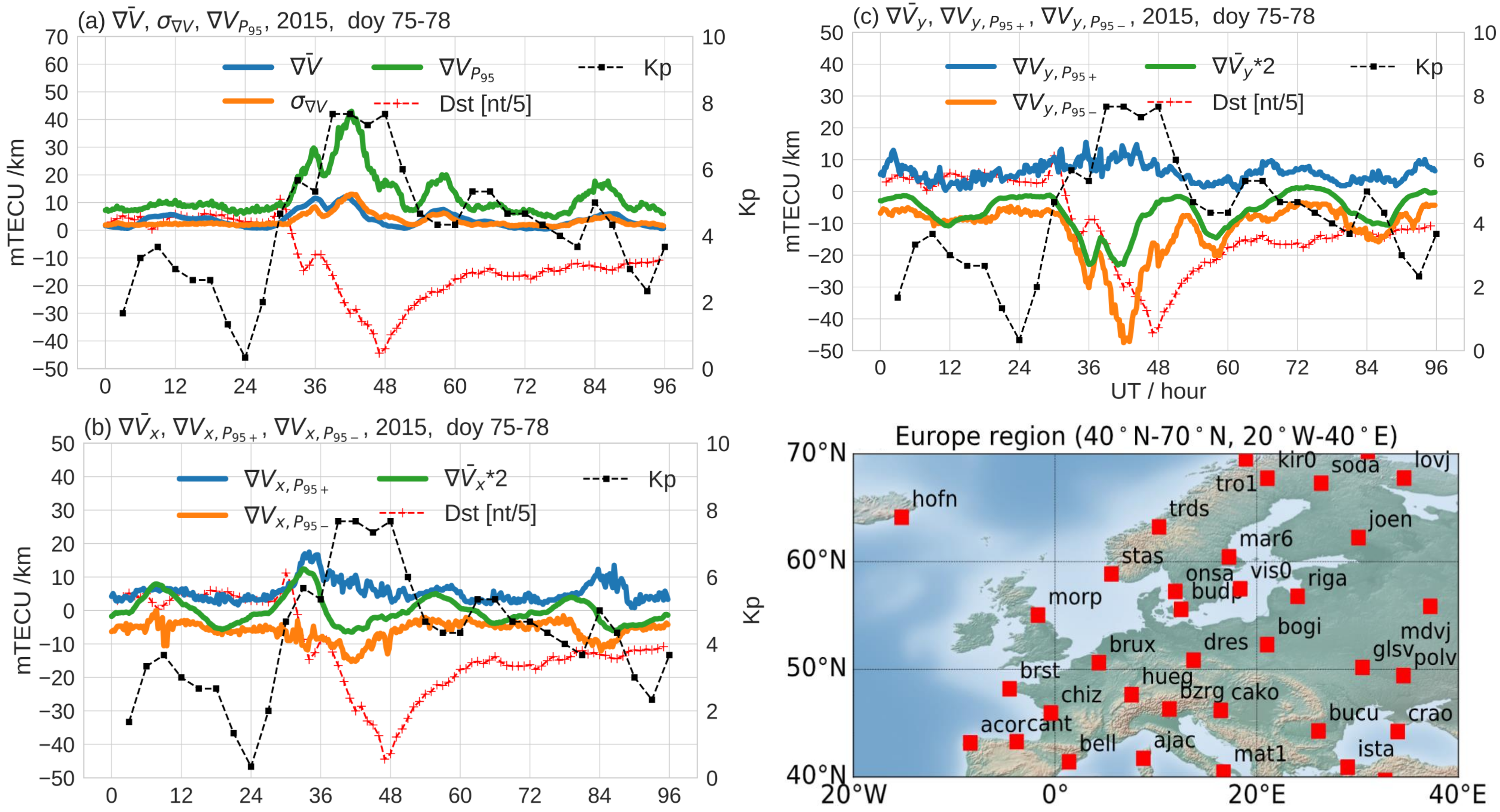
Grid indices

[Liu+, 2022 Space Weather]

■ Comparison of the quiet and storm periods around 2015 St. Patrick's Day

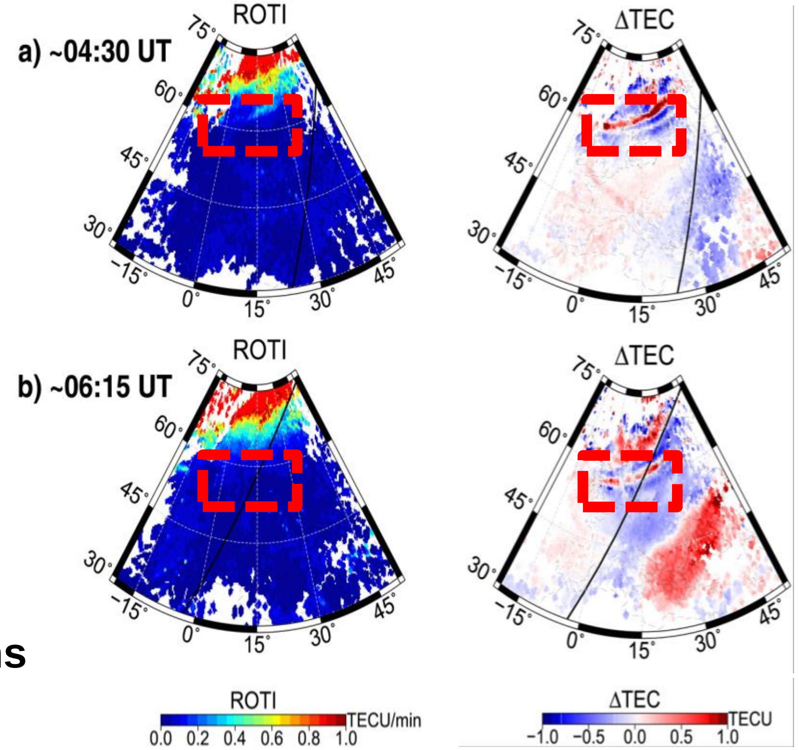


■ The regional ionospheric gradient indices on 2015 St. Patrick's Day storm



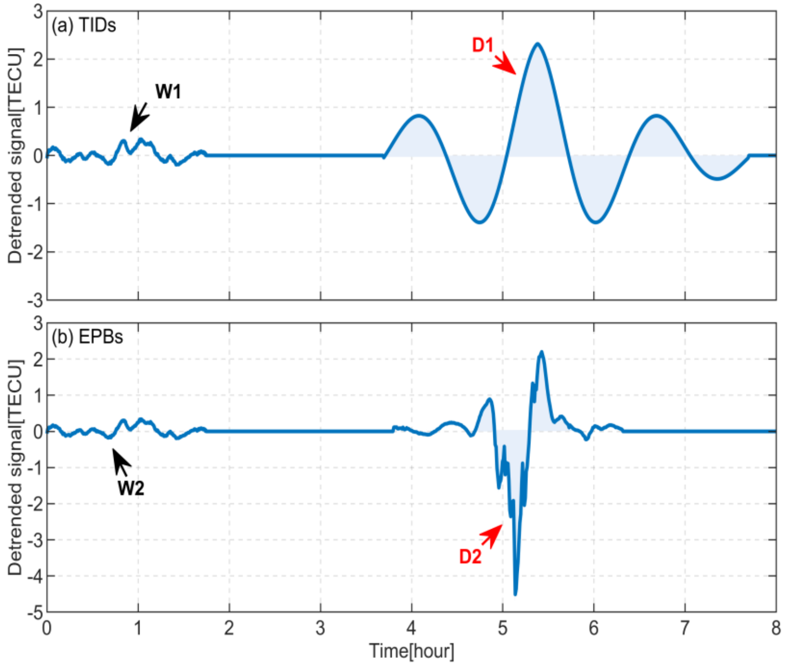
■ The characterization of ionospheric perturbation

ROTI fail to detect TEC slow variations



$$ROT = \frac{STEC_i^k - STEC_{i-1}^k}{t_i - t_{i-1}}$$

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}$$



$$IDTEC = \sum_{i=1}^{n} DTEC(i) \cdot \Delta t$$

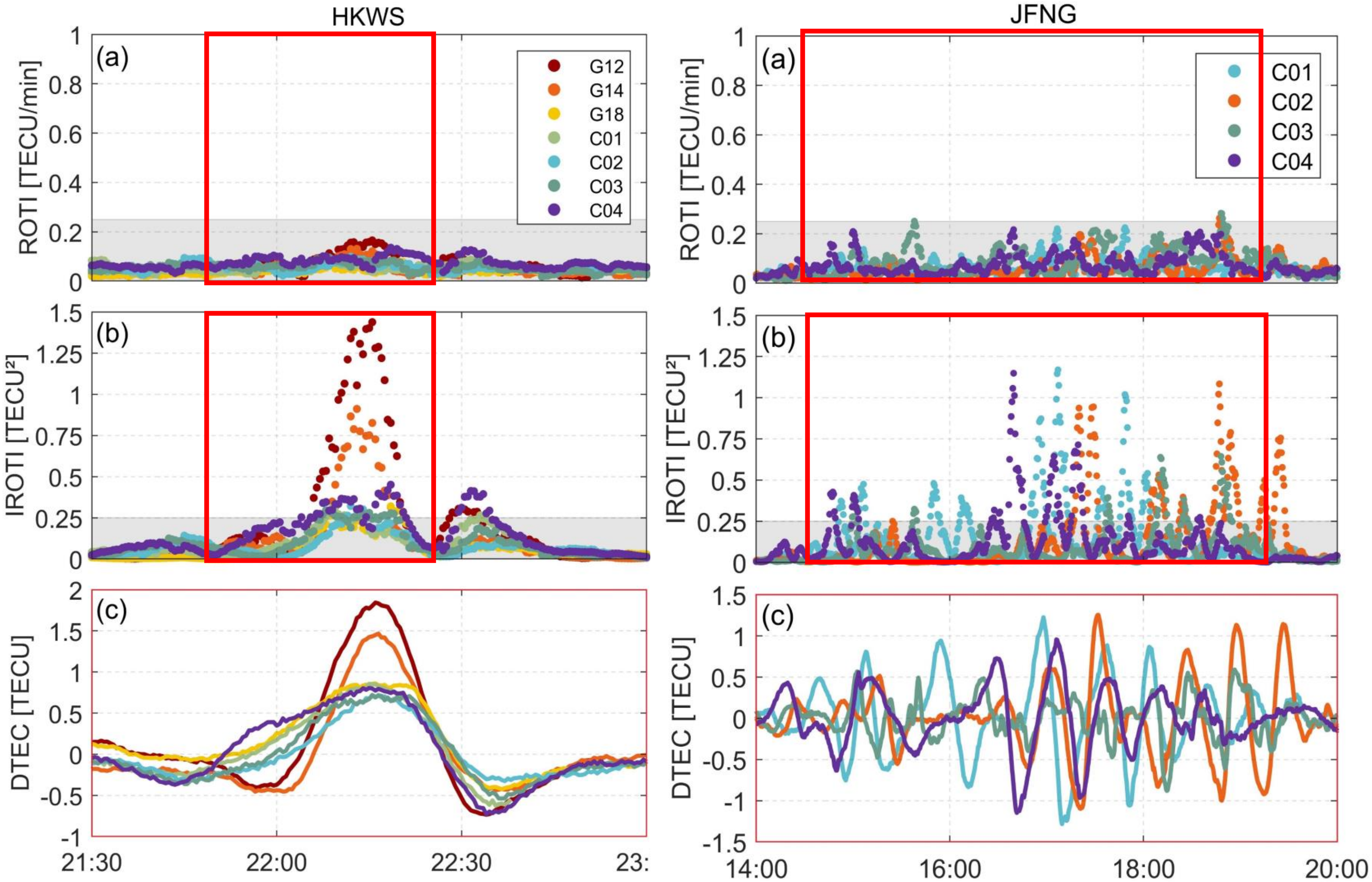
$$IROTI = IDTEC \cdot ROTI$$

$$\mathrm{DTEC}(i) = \mathrm{STEC}(i) - \frac{1}{N}\sum_{j=i-N/2}^{j=i+N/2} \mathrm{STEC}(j)$$

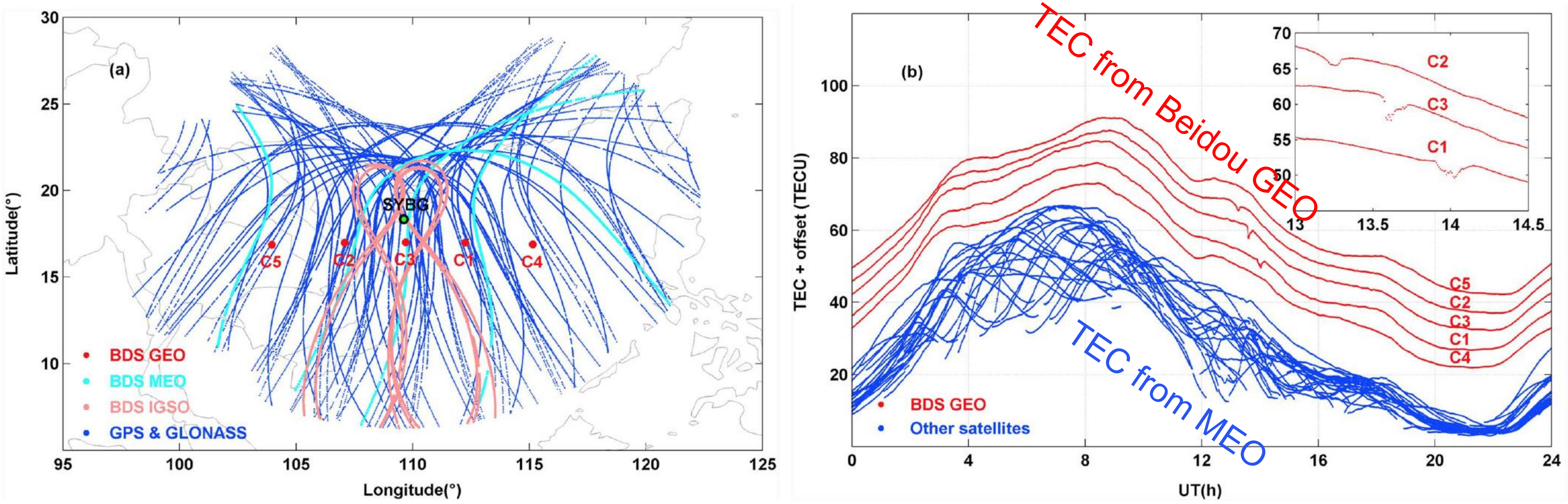
■ Comparison of ROTI and IROTI when TID occurs

ROTI

IROTI



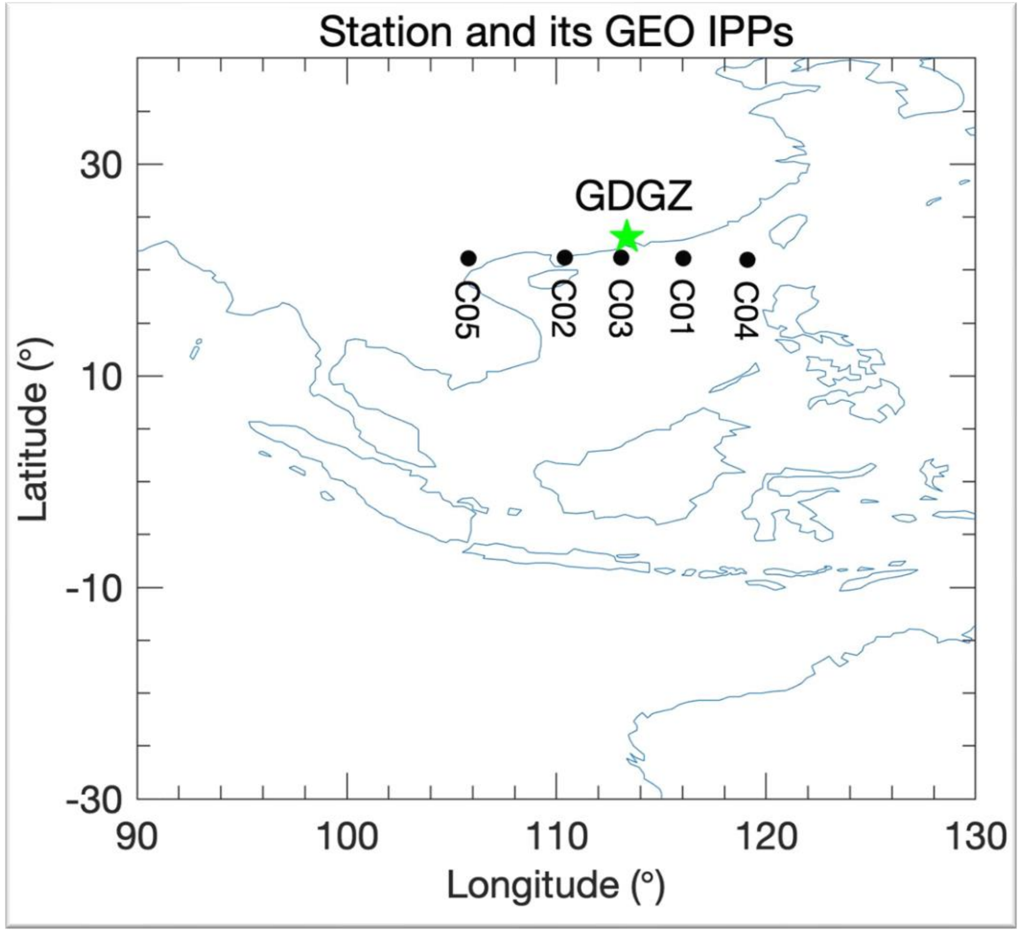
■ Total Electron Content (TEC) extracted from Beidou GEO satellite



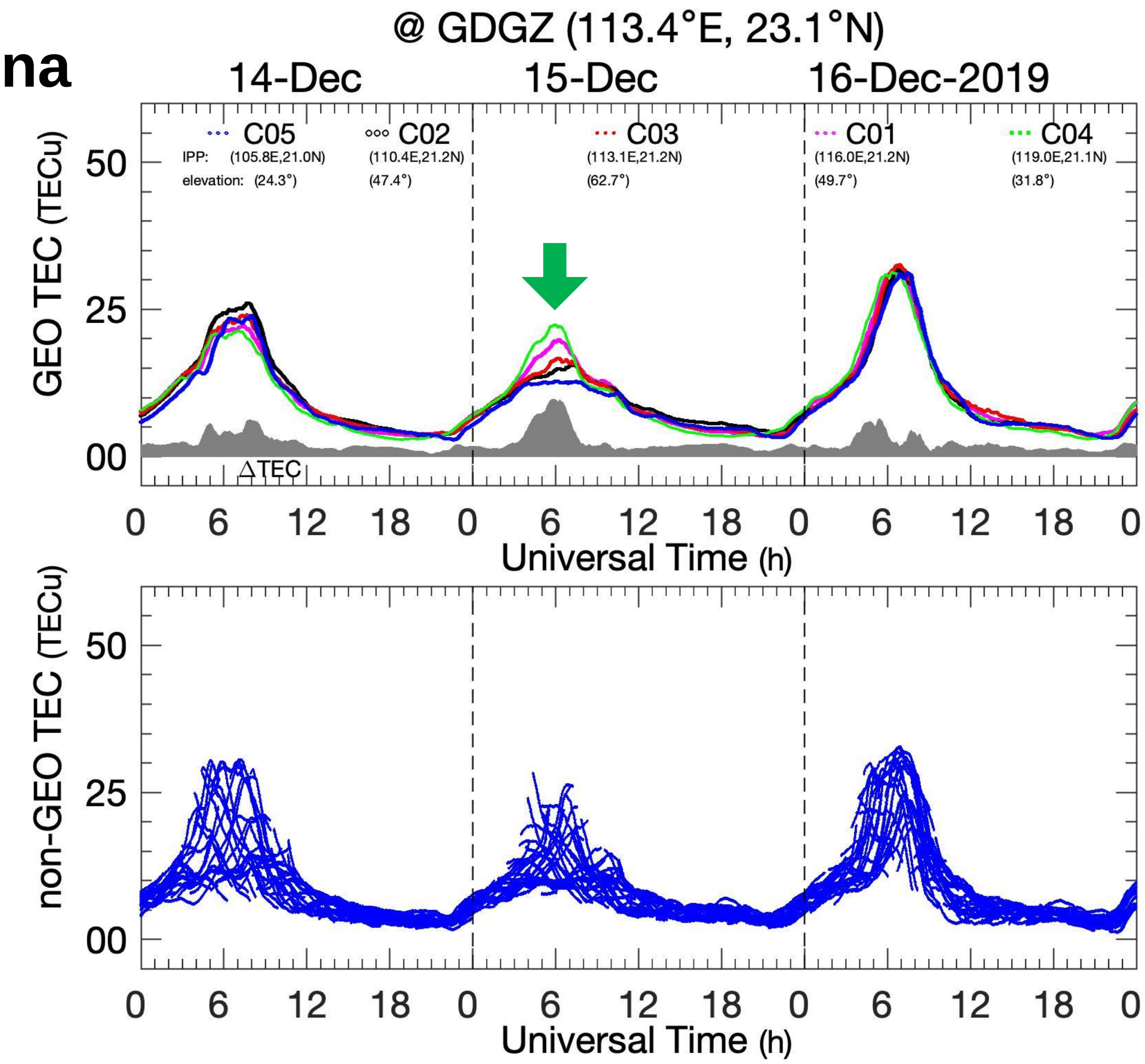
✓ Ionospheric spatio-temporal TEC monitoring based on Beidou GEO

[Hu +, 2017 Space Weather; Liu +, 2023 JGR; Yang +, 2022 RS]

■ GEO spatiotemporal monitoring in China

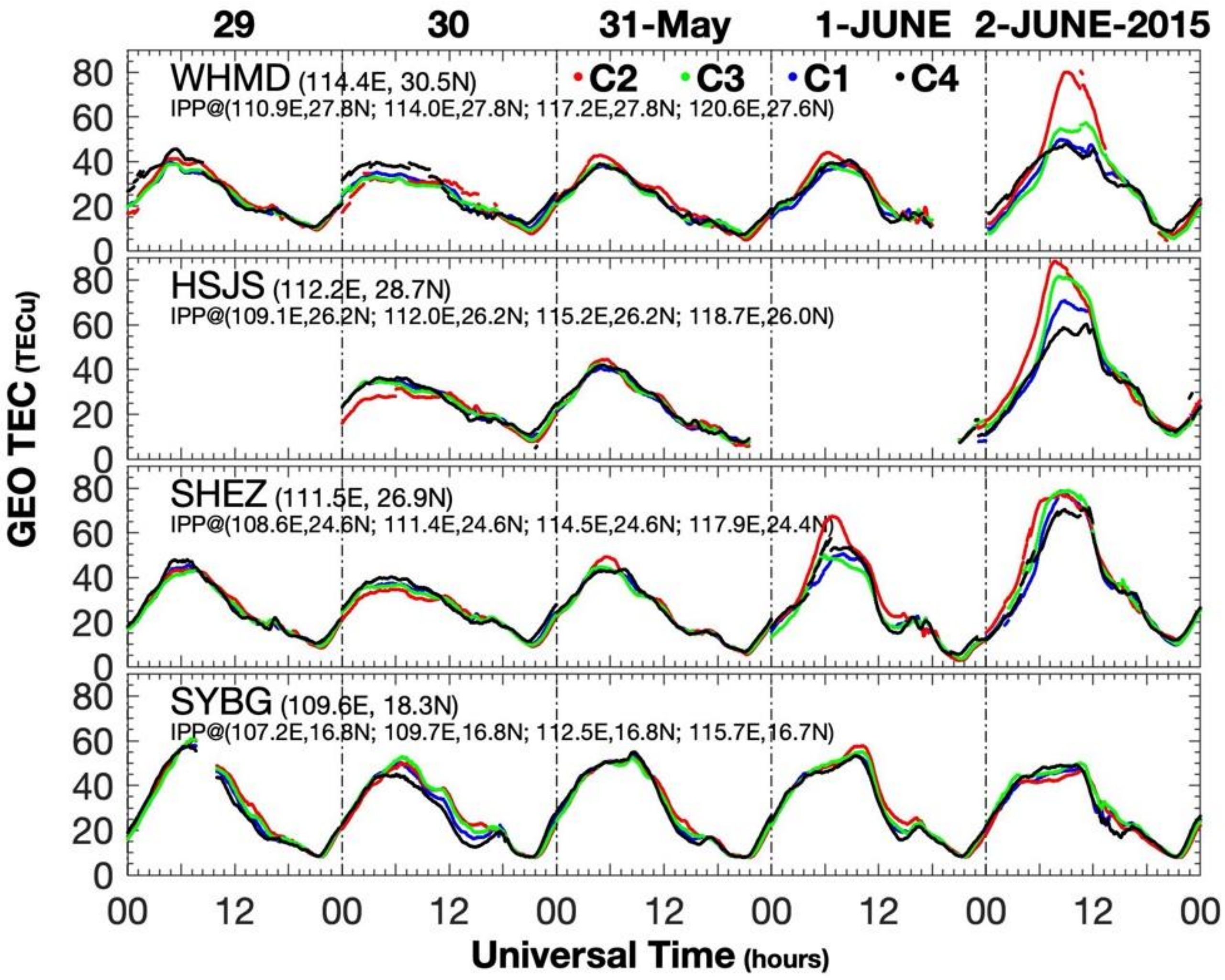


[Liu+, 2022 RS]



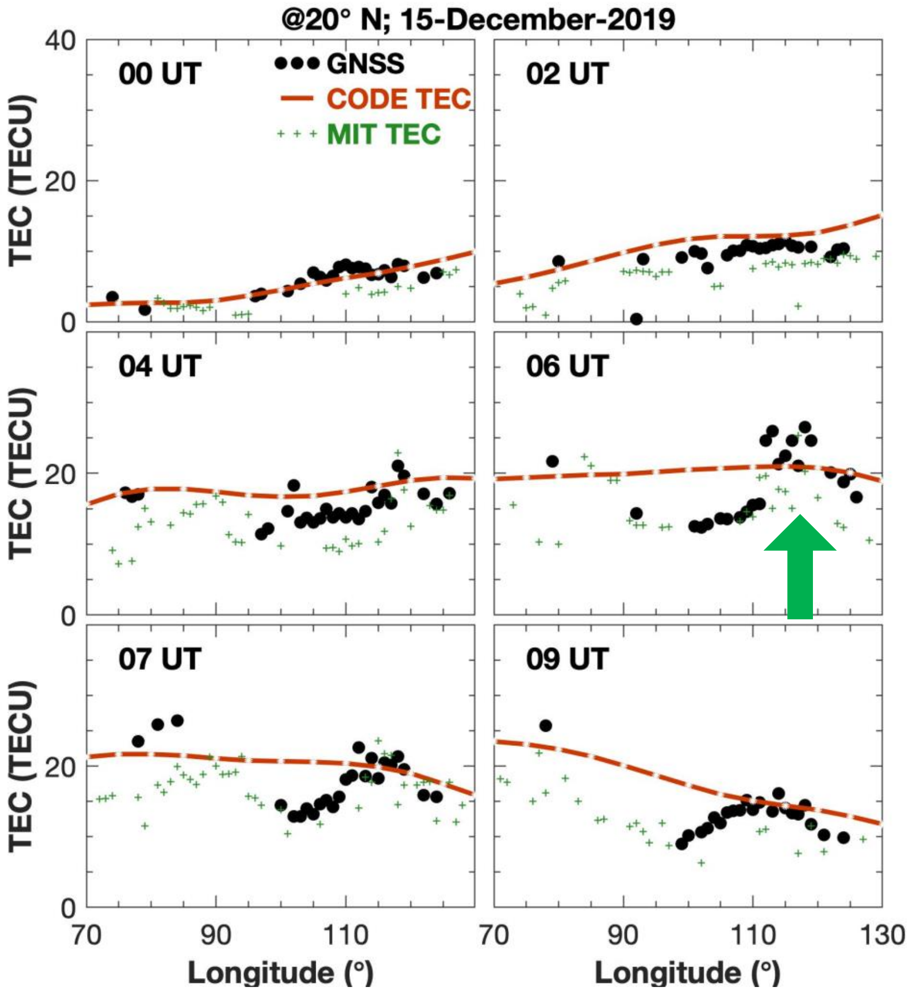
✓ **Obvious day-to-day and zonal differences**

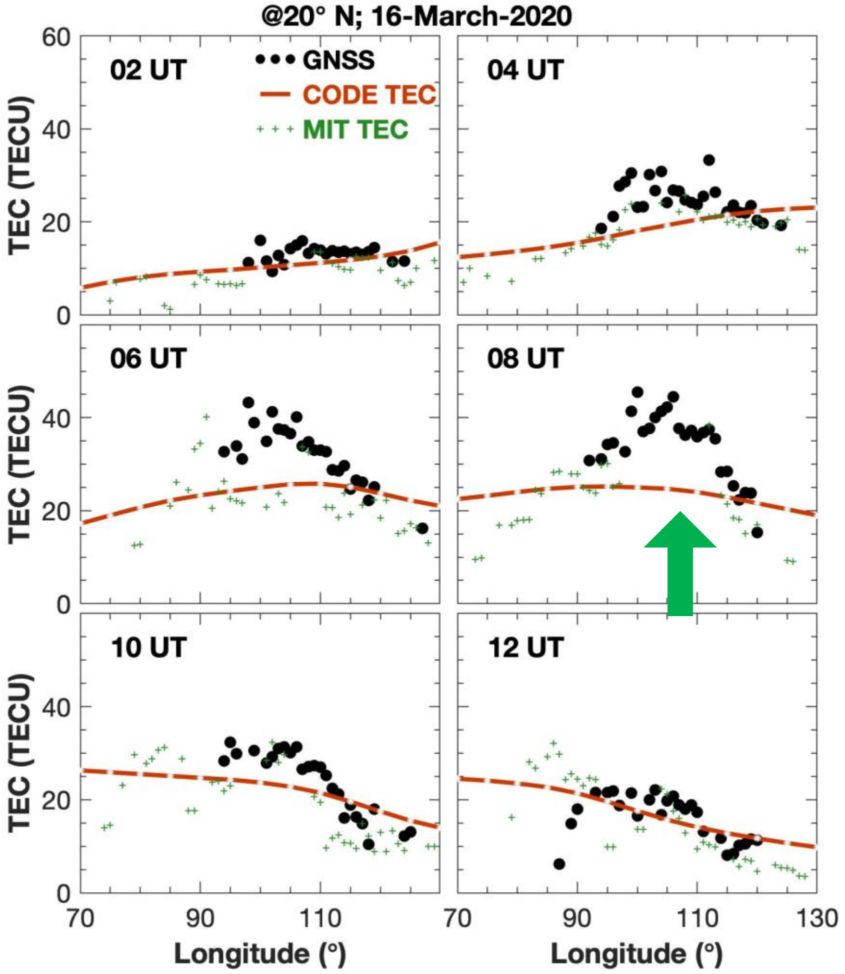
■ GEO spatiotemporal monitoring in China



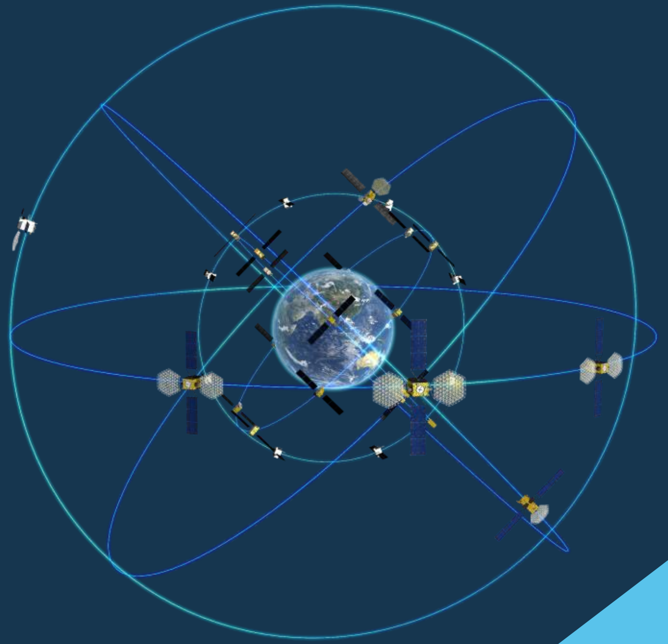
✓ **Drastic ionospheric fine structure occurs in narrow latitude band**

■ Zonal structure of TEC in GIM products





✓ **GIMs need to improve the ability to capture ionospheric zonal structures**



The applications of ionospheric monitoring

03

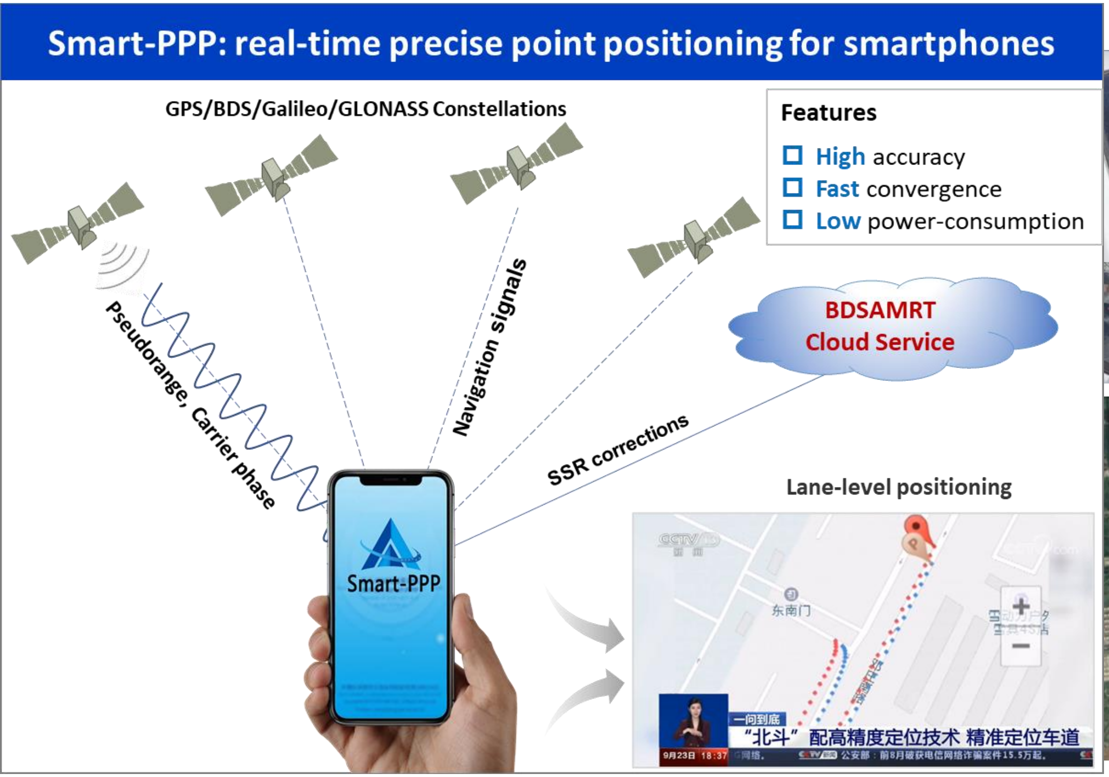
■ Ionospheric correction for GNSS positioning

- BDGIM: BDS-3 Global broadcast Ionospheric Model; IGRG: IGS rapid-GIM;
- IONO00IGS1: HENU+UPC-combined RT-GIM; IONO01IGS1: CAS-combined RT-GIM;

Horizonal and vertical accuracy of SF-PPP using different ionospheric models (95% percentile)

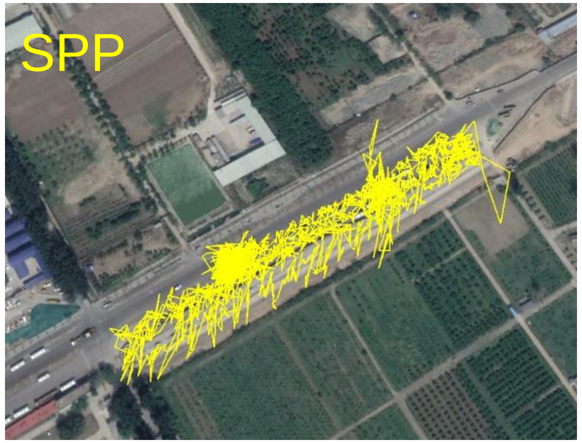
Items	Ionospheric models	Mean / m	Minimum / m	Maximum / m
Horizonal component	BDGIM	1.84	0.51	6.20
	IONO00IGS1	1.48	0.47	5.69
	IONO01IGS1	1.50	0.48	4.97
	IGRG	1.41	0.48	4.70
Vertical component	BDGIM	3.31	1.16	8.68
	IONO00IGS1	3.12	1.03	7.76
	IONO01IGS1	3.08	1.05	8.13
	IGRG	2.94	0.91	7.53

■ Ionospheric correction for smartphone navigation (Huawei)

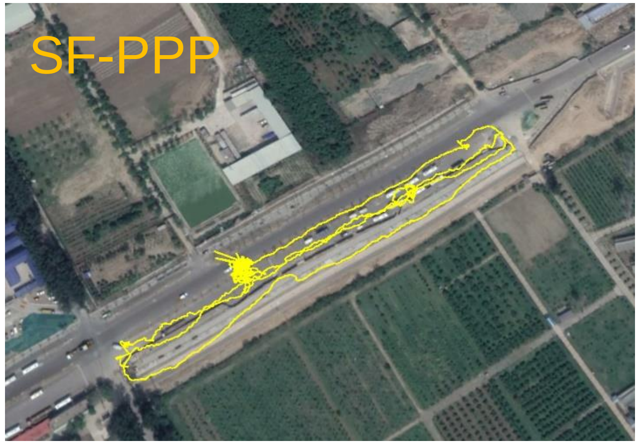


(Wang et al. 2020, 2022)

■ Ionospheric correction for smartphone navigation (Huawei)

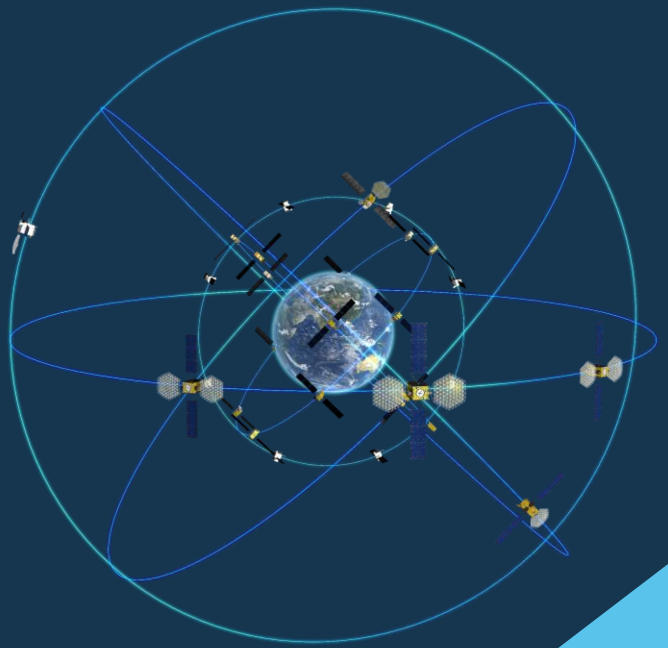


RT orbit, clock offset*,
ionosphere and bias
corrections



Horizontal Pos.	RMS / m	CEP 68 / m	CEP 95 / m
Android raw location	2.93	2.90	5.26
RT-PPP	1.25	1.09	2.66
Improvement	57.3%	62.6%	49.4%

* RT orbit and clock offset corrections are also available from *Galileo HAS* or *BDS-3 B2b-PPP* services



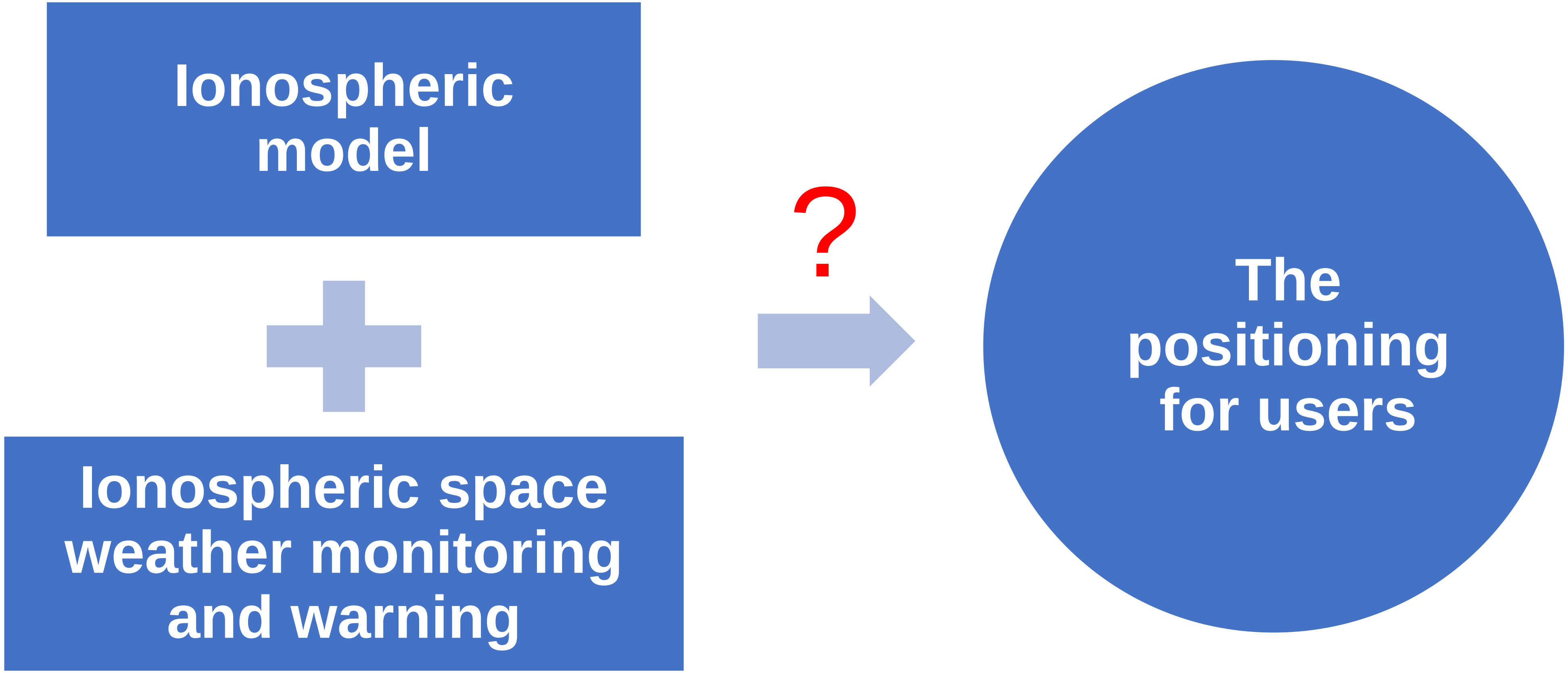
04 Conclusions and outlooks

4. Conclusions and outlooks

- **Beidou GEO is a powerful tool for detecting the regional zonal structure of ionosphere**
- **Ionospheric storm and ionospheric gradient methods can facilitate the monitoring of ionospheric space weather and warning**
- **The real-time high-precision ionospheric model can effectively improve the positioning of GNSS users such as mobile phone navigation**
- **It is necessary to improve the ability to capture the fine structure of ionosphere. The mass low-cost GNSS receivers might be the extra data source for ionospheric sounding.**

4. Conclusions and outlooks

- It is recommended that more countries and scientific research organizations will participate in the joint monitoring and early warning service of the global ionosphere and its application in positioning



Thank you !

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