Analysis of Ionospheric Anomalies Associated with the Maduo Ms7.4 Earthquake on 22 May 2021 in China Using GIM-TEC Data

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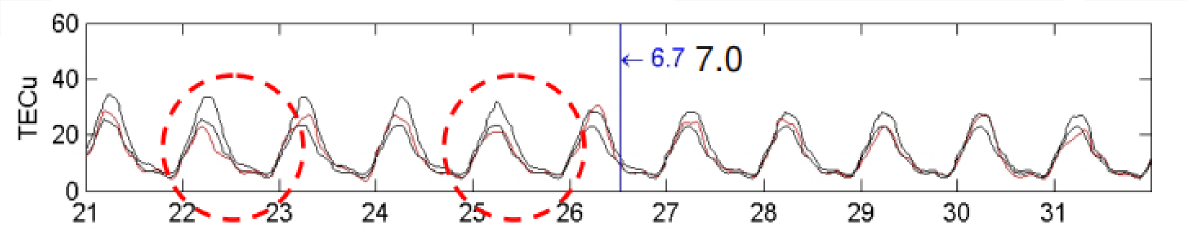
CONTENTS

01 Intoduction and Motivation

Introduction 1

Pre-earthquake ionospheric TEC anomalies may be related to the preparation process of earthquakes, and studying these anomalies holds potential value for earthquake forecasting.

- **Group 1** Setting **upper and lower boundaries** using mean and median values/ quartiles.



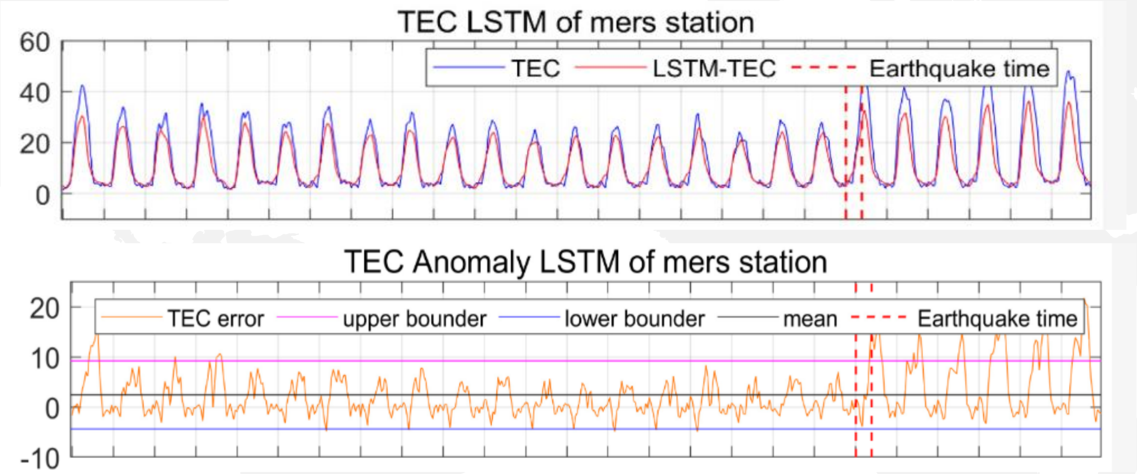
J.Y.Liu et al. (2009)

- Upper Bound = $\mu_T + k\sigma$
  Lower Bound = $\mu_T - k\sigma$
  This traditional statistical bounds always rely on empirical parameters.

Liu, J. Y., Chuo, Y. J., Shan, S. J., Tsai, Y. B., Chen, Y. I., Pulinets, S. A., & Yu, S. B. (2004, April). Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. In Annales geophysicae (Vol. 22, No. 5, pp. 1585-1593). Göttingen, Germany: Copernicus Publications.

Introduction 2

- **Group 2** **Deep Learning-based** TEC Anomaly Detection, such as the **LSTM** (long short temporal memory) etc.



J.D.Feng et al.(2024)

- Usually refer to Temporal waveform learning via neural networks.
- However, after predicting TEC through a neural network, it always requires a reasonable threshold to extract anomalies.

Feng, J., Xiao, Y., Chen, J., Sun, S., & Ke, F. (2023). A method for detecting ionospheric TEC anomalies before earthquake: the case study of Ms 7.8 earthquake, February 06, 2023, Türkiye. Remote Sensing, 15(21), 5175.

Motivation

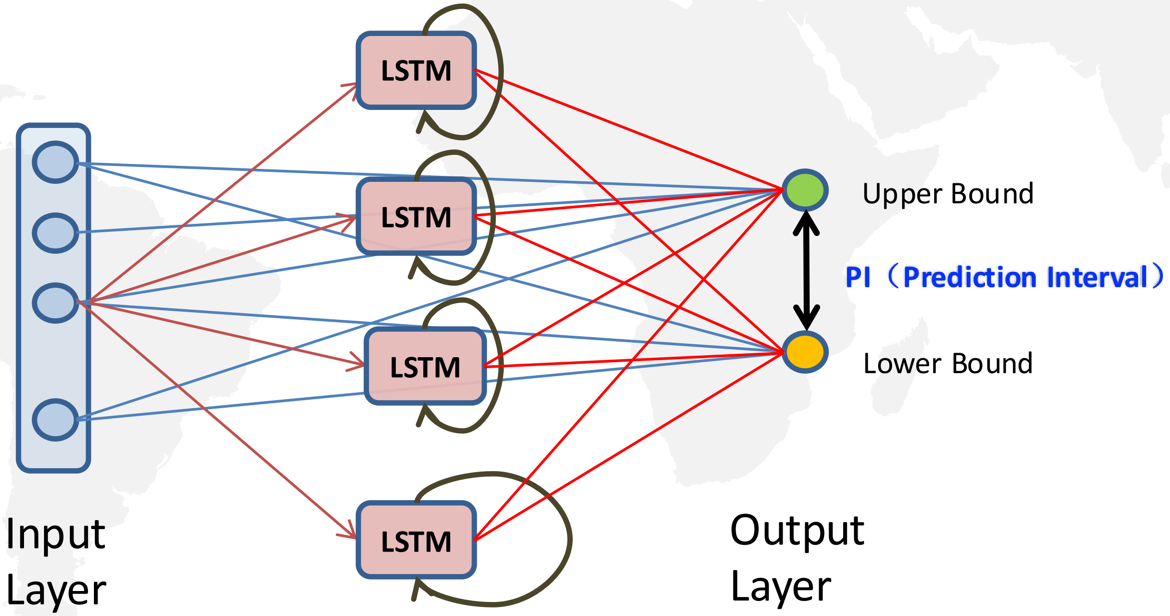
- Can we develop an **end-to-end model** that can generate prediction intervals while autonomously learning TEC time dependence ?

LSTM-LUBE

02 Methods

Methods —— Overview

- This is the LSTM-LUBE framework. We combine the two mainstream methods, by using the advantages of neural networks, followed by a lower upper bound estimation (LUBE), so that the output of the network is directly the upper and lower bounds of predicted TEC .



Methods —— LSTM

- **LSTM (Long Short-Term Memory)**

  Long-Term Dependency Modeling

  Gating Mechanism

  - **Forget Gate**

    $f_t = \sigma(W_f \cdot [h_{t\_}, x_t] + b_f)$
  - **Input Gate**

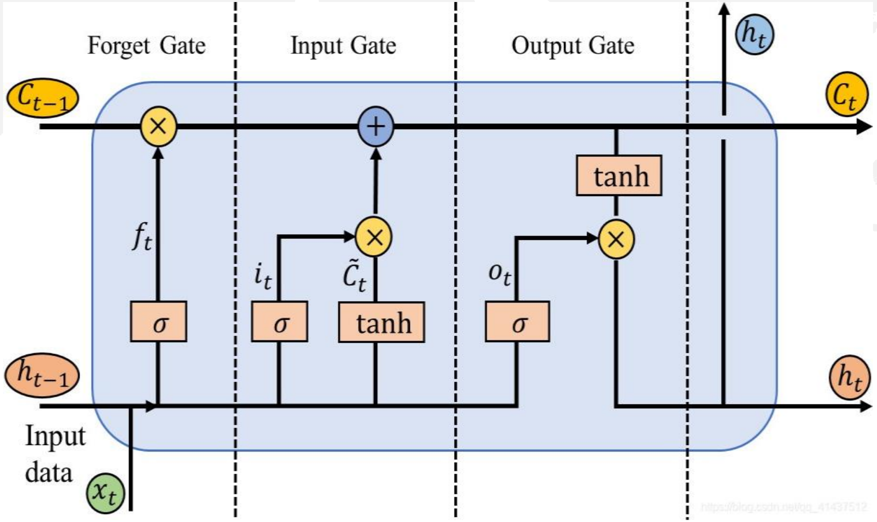
    $i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i)$

    $\widetilde{C}_t = tanh(W_c \cdot [h_{t-1}, x_t] + b_C)$

    $C_t = f_t \cdot C_t - 1 + i_t \cdot \widetilde{C}_t$
  - **Output Gate**

    $o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o)$

    $h_t = o_t \cdot tanh(C_t)$



Methods —— LUBE

- **LUBE (Lower Upper Bound Estimation)**

Automatically generate a prediction interval by optimizing both PICP and PINAW .

Prediction Interval Coverage Probability

$$\mathrm{PICP} = \frac{1}{n}\sum_{i=1}^{n} c_i$$

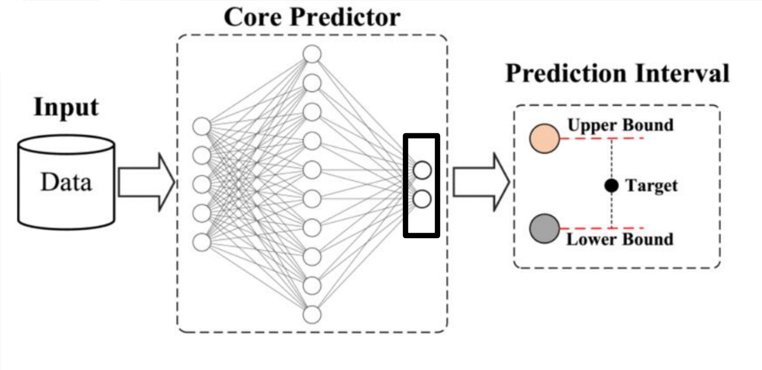
- n : Prediction sample size
- $c_i = \begin{cases} 1 \ , if\ y_i \in [L_i, U_i] \\ 0 \ , \quad else \end{cases}$

Normalized Average Width

$$\mathrm{PINAW} = \frac{1}{nR}\sum_{i=1}^{n}(U_i - L_i)$$

- R :target value range
- U_i : Upper bound
- L_i : Lower bound

Higher PICP
Lower PINAW



The loss of our model is achieved through the minimization of an interval objective function, which covers both two parameters.

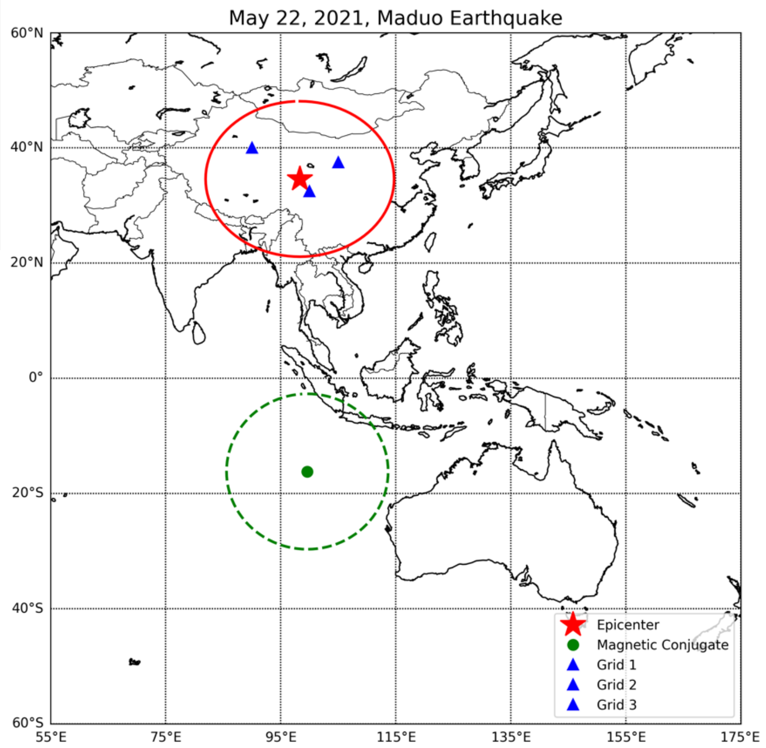
$$\boxed{Loss} = \frac{1}{N}\sum_{I=1}^{N}[ReLU(y_{lower} - {}_{true}) + ReLU(y_{true} - {}_{upper})]$$

$$+\ \alpha \cdot (ReLU(q - \underbrace{\frac{1}{N}\sum_{I=1}^{N}\|y_{lower} \le y_{true} \le y_{upper})^2}_{\mathrm{PICP}}$$

$$\underbrace{+\ \frac{1}{N}\sum_{i=1}^{N}(y_{upper} - {}_{lower})}_{\mathrm{PINAW}}$$

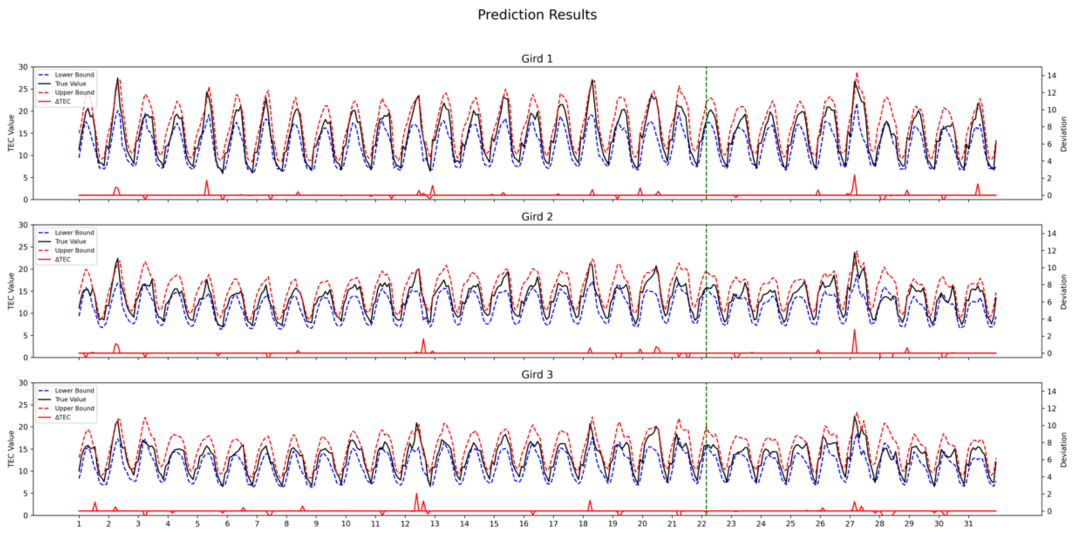
03 Results

Results——Case Study

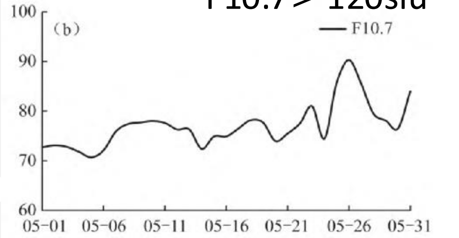


- ✓ **Earthquake**
  2021 Maduo Earthquake, China, on May 22, 2021
- ✓ **Magnitude and Focal Depth**
  Mw 7.4, focal depth of 17 km
- ✓ **Epicenter Location**
  34.59° N, 98.34° E
- ✓ **Test Period**
  May 1 to May 30

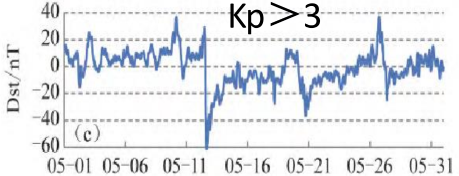
Results —— Temporal Results 1



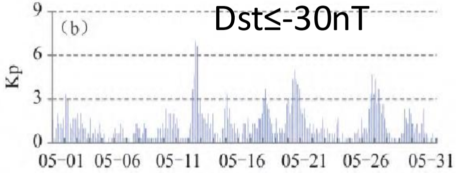
F10.7＞120sfu



Kp＞3

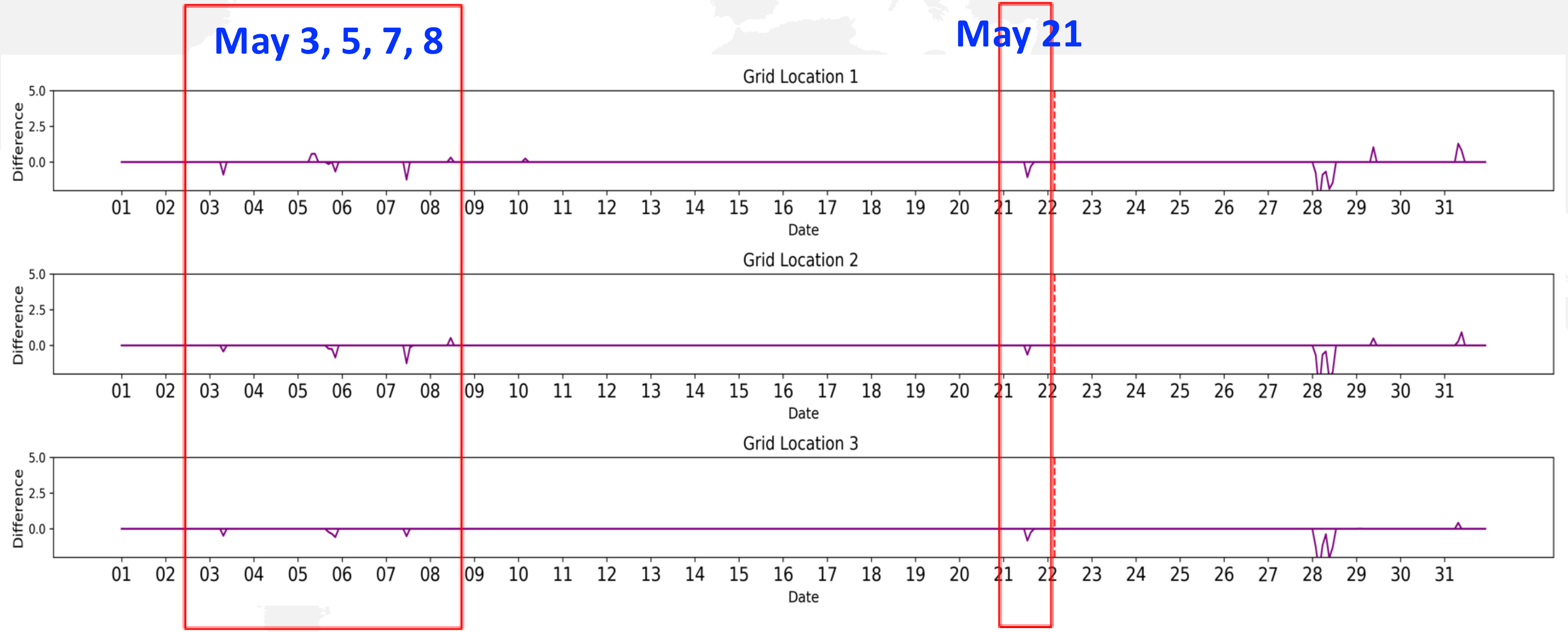


Dst≤-30nT



Results —— Temporal Results 2

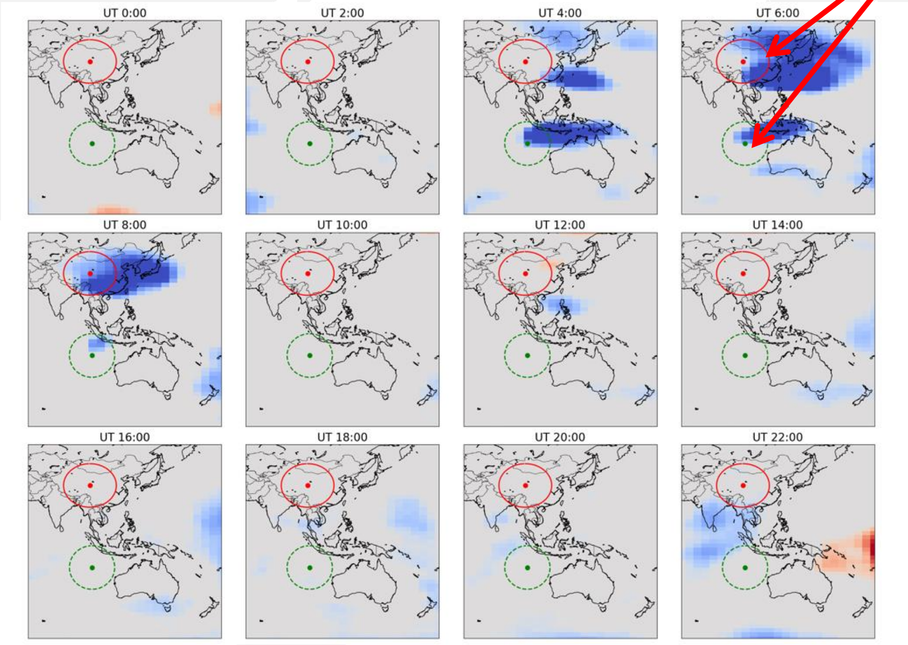
- After excluding solar and geomagnetic disturbances
- Dates of anomaly occurrence

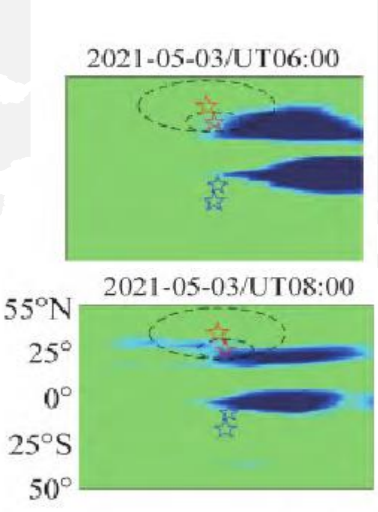


Results —— Spatiotemporal Results 1

negative TEC perturbation

UT 6:00 to UT 8:00 on May 3



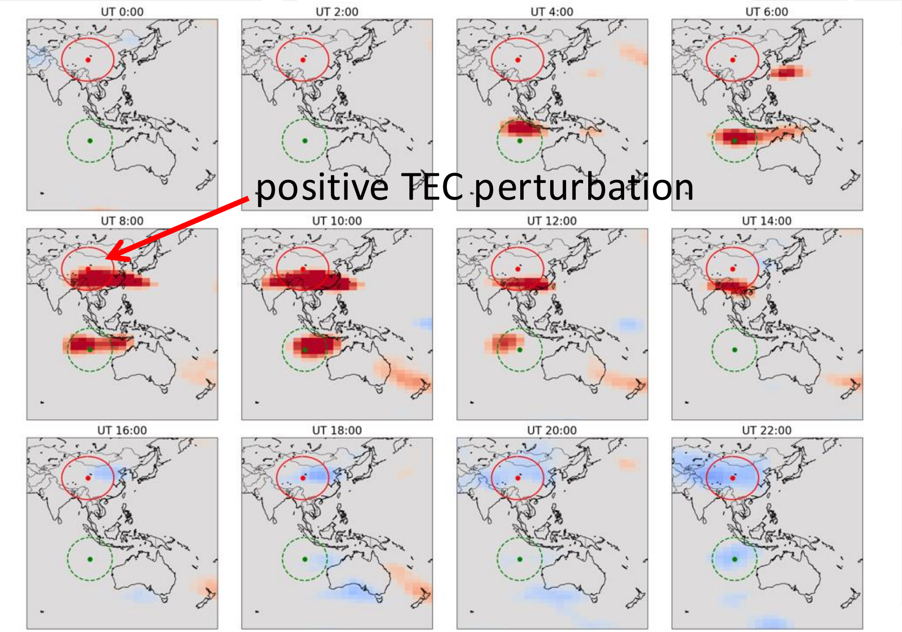


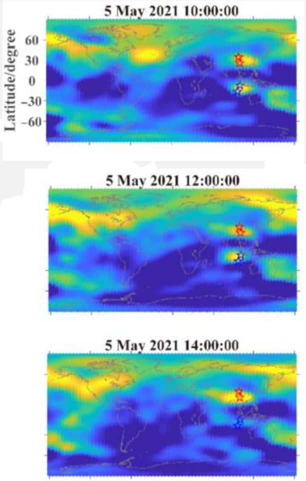
张学民等. (2022)

张学民,刘静,周煜林,等.2021年云南漾濞MS6.4地震和青海玛多MS7.4地震前后的电离层扰动[J].地震,2022,42(03):1-20.

Results —— Spatiotemporal Results 2

UT 8:00 to UT 10:00 on May 5



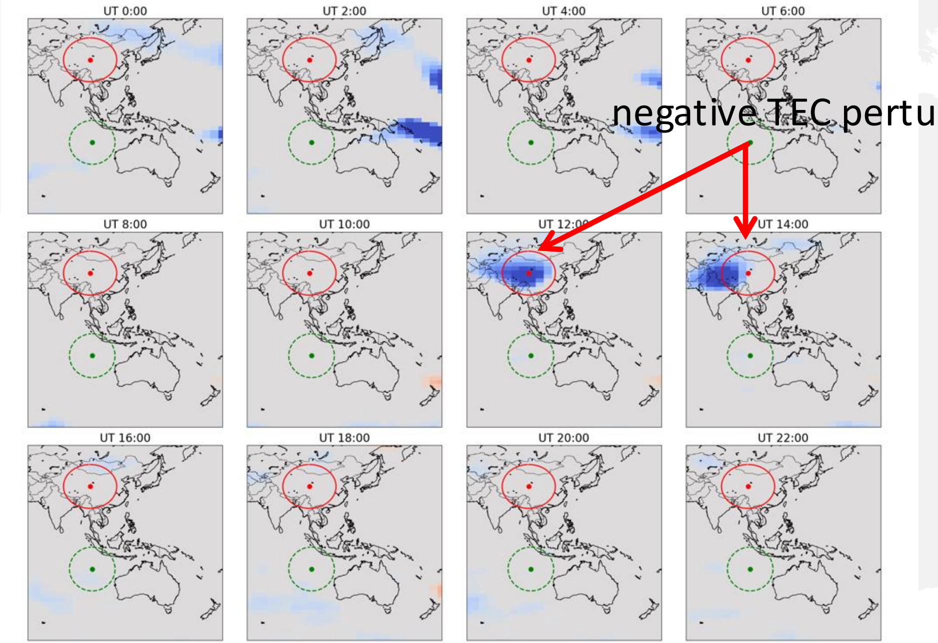


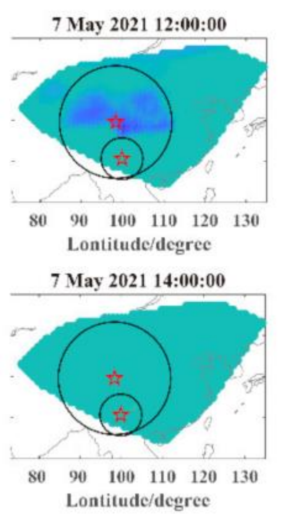
Lei Dong et al. (2022)

Dong, Lei, Xuemin Zhang, and Xiaohui Du. "Analysis of ionospheric perturbations possibly related to Yangbi Ms6. 4 and Maduo Ms7. 4 earthquakes on 21 May 2021 in China using GPS TEC and GIM TEC data." Atmosphere 13, no. 10 (2022): 1725.

Results —— Spatiotemporal Results 3

UT 12:00 to UT 14:00 on May 7





Lei Dong et al. (2022)

Dong, Lei, Xuemin Zhang, and Xiaohui Du. "Analysis of ionospheric perturbations possibly related to Yangbi Ms6. 4 and Maduo Ms7. 4 earthquakes on 21 May 2021 in China using GPS TEC and GIM TEC data." Atmosphere 13, no. 10 (2022): 1725.

Results —— Spatiotemporal Results 4

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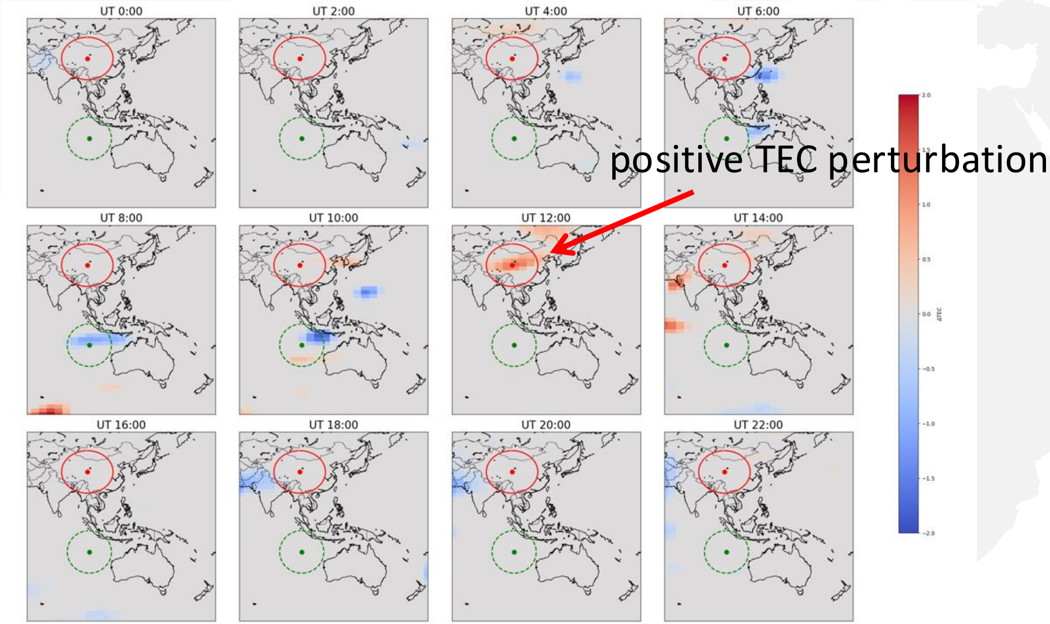
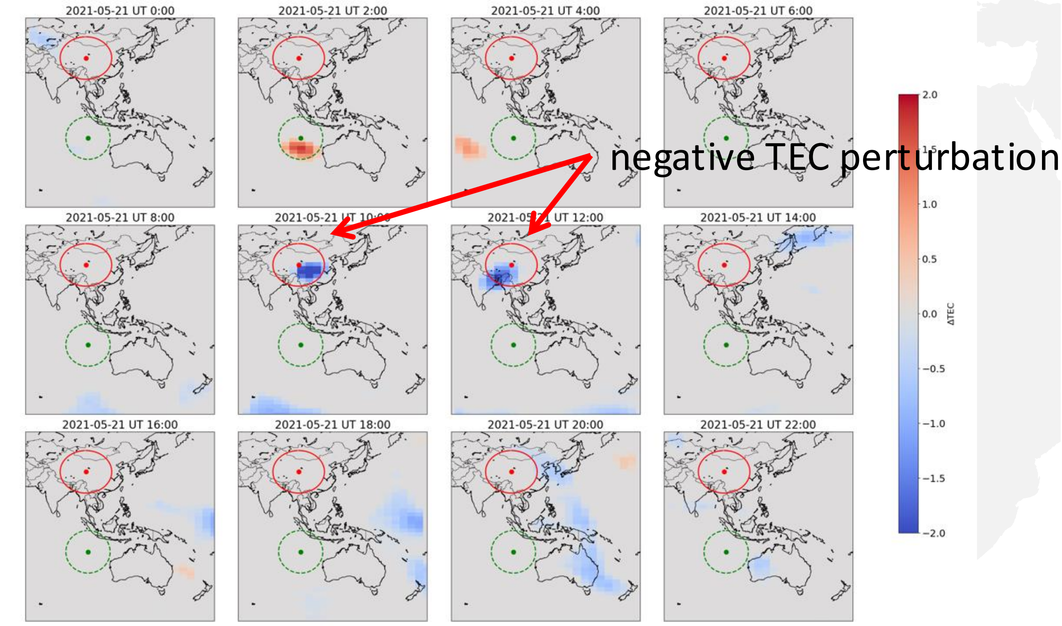
UT 12:00 to UT 14:00 on May 8



Methods	Anomaly on May 8
LSTM-LUBE (ours)	√
CNN-LUBE	√
GRU-LUBE	×
BILSTM-LUBE	√
Attention-LUBE	√
Transformer-LUBE	√
Sliding Quartile	×

Results —— Spatiotemporal Results 4

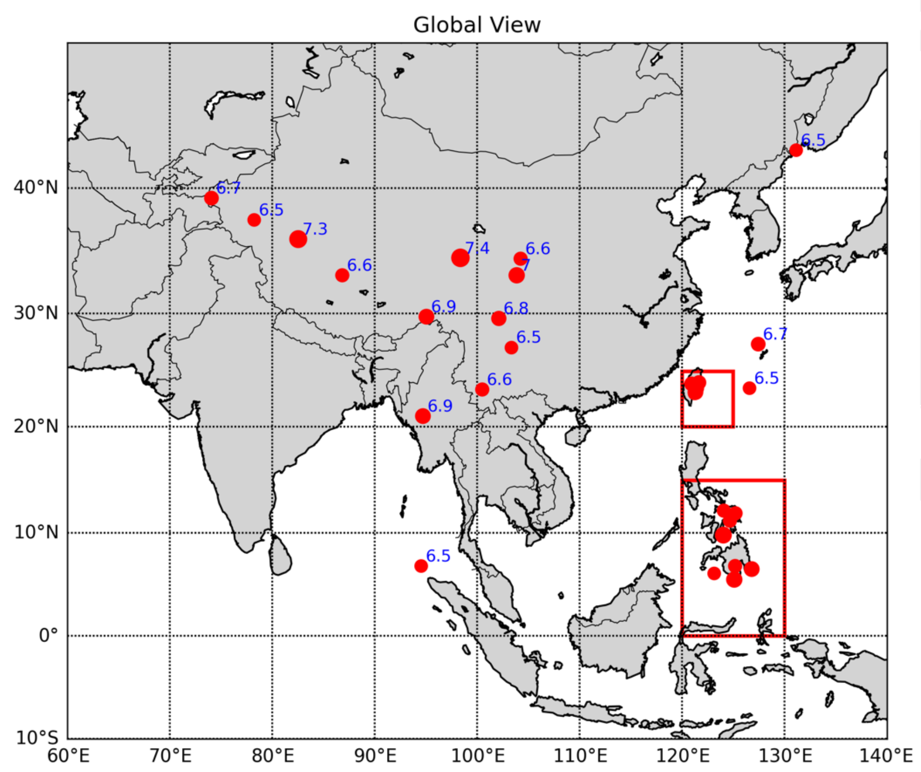
UT 10:00 to UT 12:00 on May 21

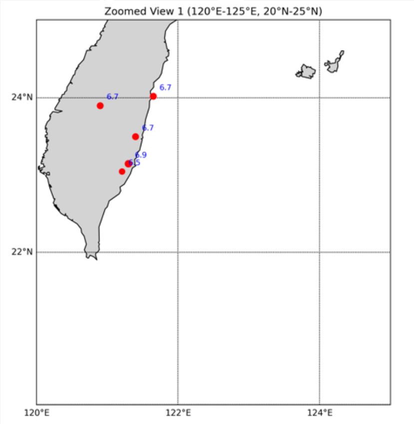


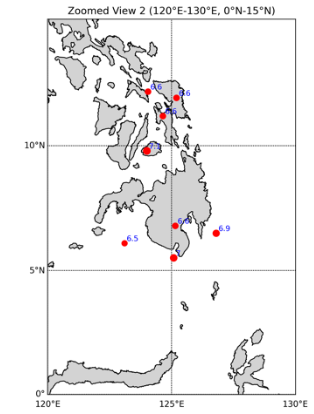
Methods	Anomaly on May 21
LSTM-LUBE (ours)	√
CNN-LUBE	×
GRU-LUBE	√
BILSTM-LUBE	√
Attention-LUBE	√
Transformer-LUBE	×
Sliding Quartile	×

Results —— Statistical Studies

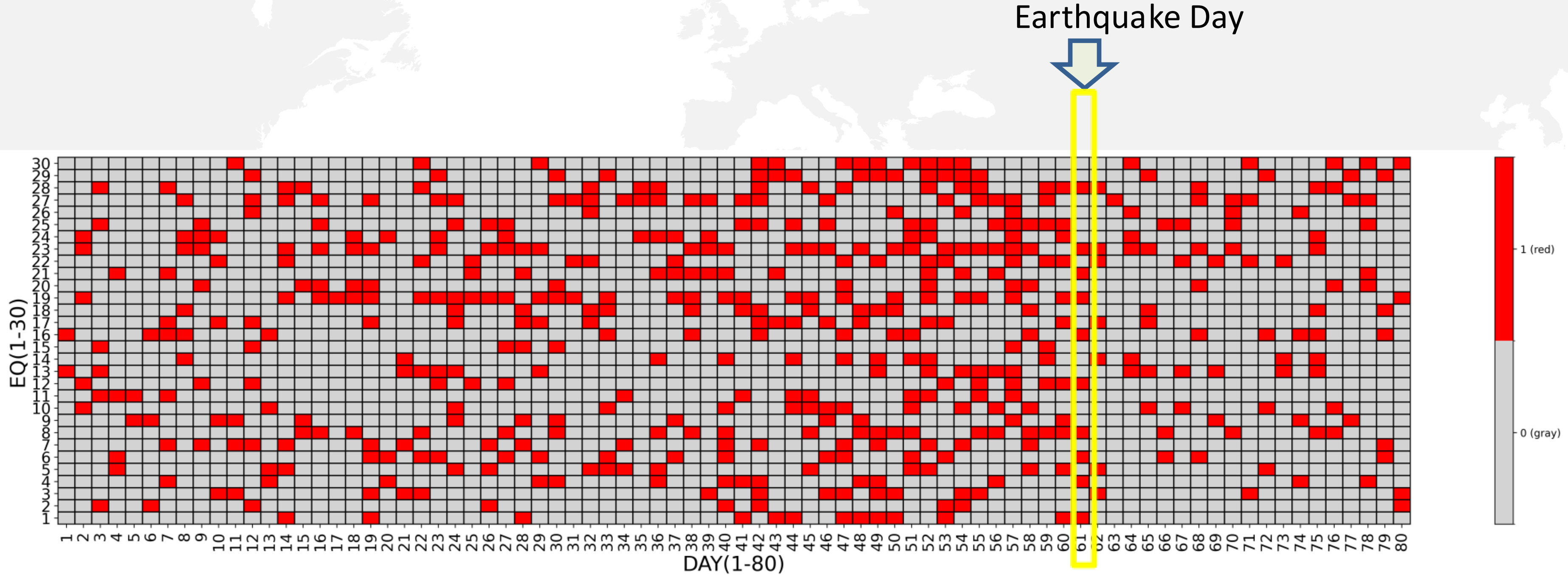
30 global earthquake events with Ms≥6.5 between 2016-2020





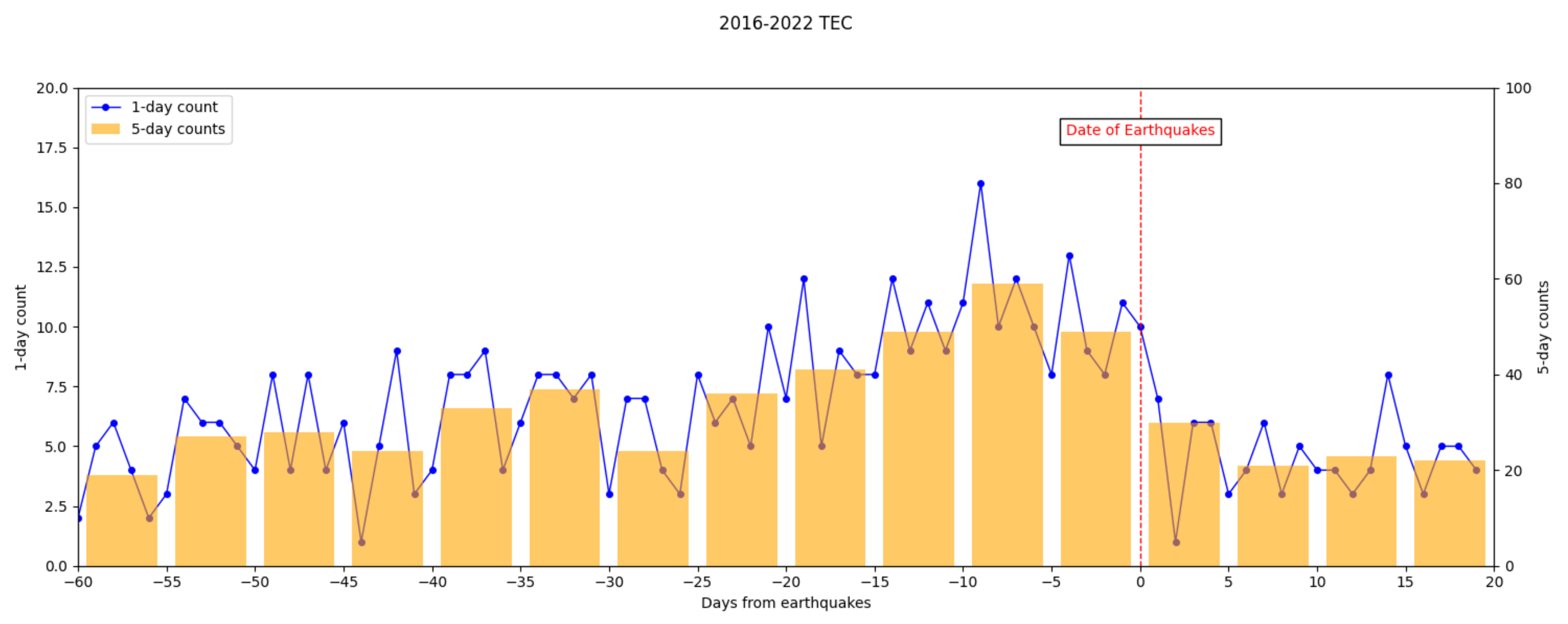


Results —— Statistical Results 1



The anomaly is colored in red.
It seems that TEC anomalies are increasing before earthquakes.

Results —— Statistical Results 2



The statistical results reveal a correlation: TEC anomalies begin to increase 20 days before the earthquake, and are most significant 10 days before the earthquake.

03 Conclusions

Conclusions

Our study establishes three key findings:

- ✓ LSTM-LUBE is simpler and more direct way to detect TEC anomalies, which achieves more accurate identification of anomalies before Maduo Earthquake compared with traditional methods.
- ✓ LSTM-LUBE can be extended to various NN- LUBE, which can be applied to any problem related to prediction intervals.
- ✓ TEC perturbations exhibit spatiotemporal anomaly patterns before major quakes: The 20-day pre-earthquake window shows statistically significant ionospheric responses .

Thank you for your listening!

Zining Yu