Investigation of the Ionosphere TEC Anomalies for Earthquake Precursor detection using Machine Learning Models

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Abstract

Real-time forecasting of anomalies in the Ionosphere TEC is attempted using machine learning models such as Autoregressive Integrated Moving Average (ARIMA) and Long Short-Term Memory (LSTM). The Performances of both models were demonstrated on three Earthquakes (EQs), i.e. Mw 6.8, 2020 Indonesia, Mw 8.0, 2019 Peru and Mw 7.8, 2015 Nepal EQs. In this study, GNSS-derived TEC values from the CODE server have been utilized and the statistical boundary limits have been defined with 95% confidence level for anomaly detection in daily TEC variations. The training and test TEC dataset was divided into 8:2 ratio. After the data processing the hyper model parameters were optimized for the training dataset following which the TEC anomalies were validated by comparing the forecasted and actual TEC values on the test dataset. For ARIMA analysis, we start with the ADF test to check for stationarity of TEC data and after observing the test-statistics critical values and p-value we reject the null hypothesis. On calculating the ACF and PACF plots we select model parameters values in accordance with the lowest AIC value. While, for the LSTM model, we start with standardizing the training data to have zero mean and unit variance. The model is fit using the 'Adam' version of stochastic gradient descent, optimized using the 'mse' loss-function and run through 250 epochs using the rectified linear activation-function (ReLU) for better performance. Both the models were successfully able to detect and predict significant evidence for pre-seismic ionospheric TEC anomalies on 01 May 2020, 20 May 2019 and 11 April 2015 respectively before the occurrences of Indonesia, Peru and Nepal EQs. The time series analysis of forecasted TEC data revealed that the RMSE and MAPE error on the anomalous day was found to be significantly higher than the preceding non-anomalous day error and the overall forecasted error. Both ARIMA and LSTM models performed well for Indonesia and Peru EQs, forecasting TEC anomalies accurately within the 5-6 day window before the EQ, but the LSTM model outshined the former in long term TEC forecasting for the Nepal EQ performing well in the 11 day window before the EQ. Overall, the LSTM model was found to be more precise especially in long term forecasting and was also able to detect the weaker TEC anomalies which went unnoticed in the ARIMA model.

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Real-time forecasting of anomalies in the Ionosphere TEC is attempted using machine learning models such as Autoregressive Integrated Moving Average (ARIMA) and Long Short-Term Memory (LSTM). The Performances of both models were demonstrated on three Earthquakes (EQs), i.e. Mw 6.8, 2020 Indonesia, Mw 8.0, 2019 Peru and Mw 7.8, 2015 Nepal EQs. In this study, GNSS-derived TEC values from the CODE server have been utilized and the statistical boundary limits have been defined with 95% confidence level for anomaly detection in daily TEC variations.

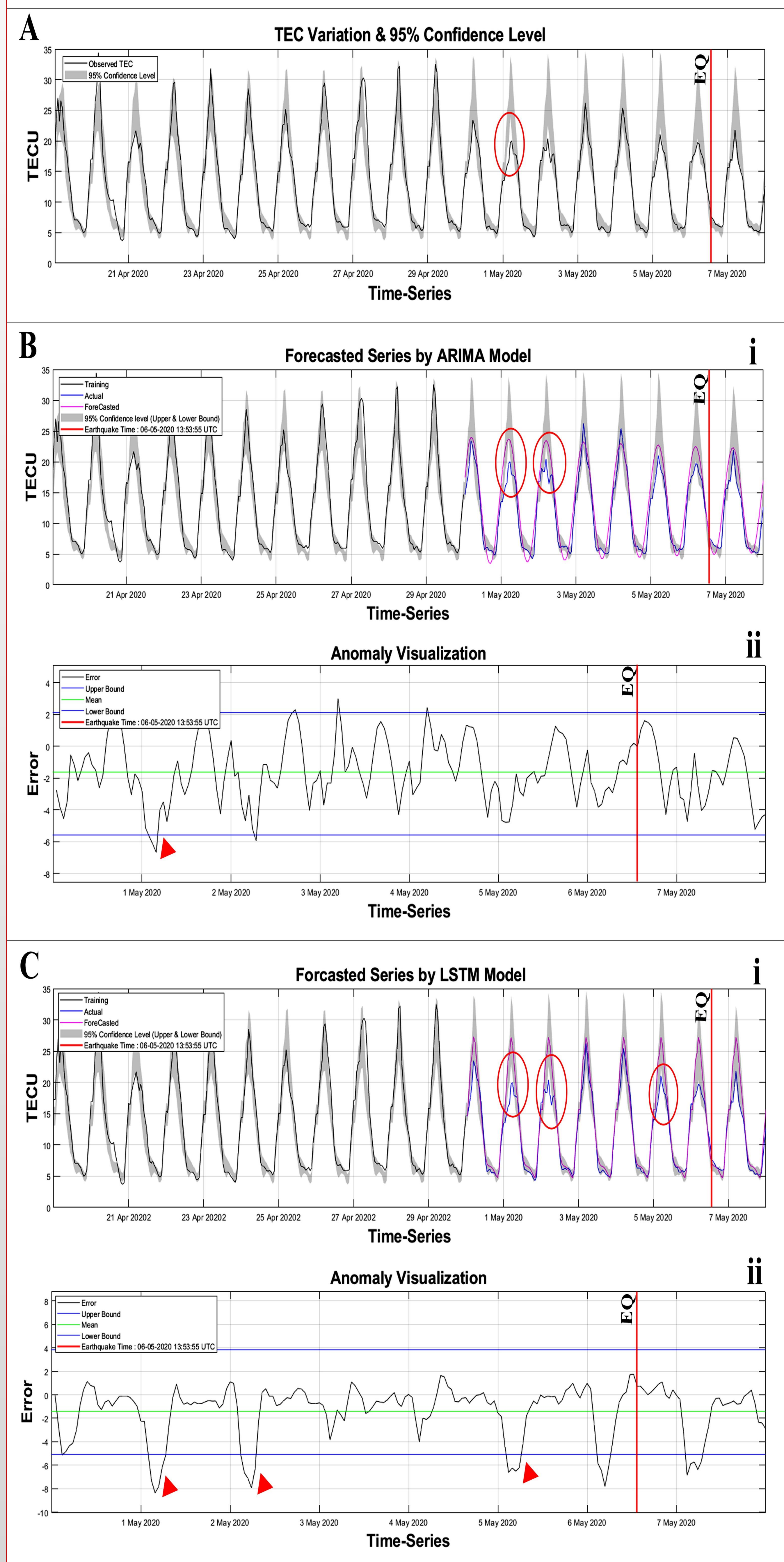
INTRODUCTION

Natural disasters like earthquakes (EQs) have always been a permanent threat to humanity. Understanding the complex nature of EQs and detecting pre-seismic EQs precursors has been a promising long-lasting endeavour that has immense potential for scientific advancement and societal development. The phenomenon of seismo-ionospheric coupling prior to any mega-EQ, using the Total electron content (TEC) data derived from the Global Navigation Satellite System (GNSS), is now being extensively studied as a major EQ precursor.

In the preliminary stages before the mainshock, the stress-activated peroxy bonds Freund et al. (2018) are broken which give rise to a positive ion cluster in the near vicinity of the ground atmosphere within the EQ preparation zone and generate an anomalously strong electric field. This field reaches the upper level of the ionosphere without any decay and induces large-scale negative anomalies in TEC in the F2 region of the ionosphere. After ruling out possible contributions due to the solar-terrestrial environment, the negative anomalies of seismogenic origin are plotted in the GIM latitude-longitude-time (LLT) map to locate the probable EQ epicentre.

The GNSS-derived TEC values are extracted from the CODE server which has data upload-delay of 3-5 days. This data-lag might provide scope for a prominent perturbation to go unnoticed before the earthquake, hence a machine-learning based approach is proposed for real-time forecasting and assessment of TEC ionospheric-anomalies with a quantitative comparison between the models.

FIGURE 1: Results for Indonesia Earthquake



D

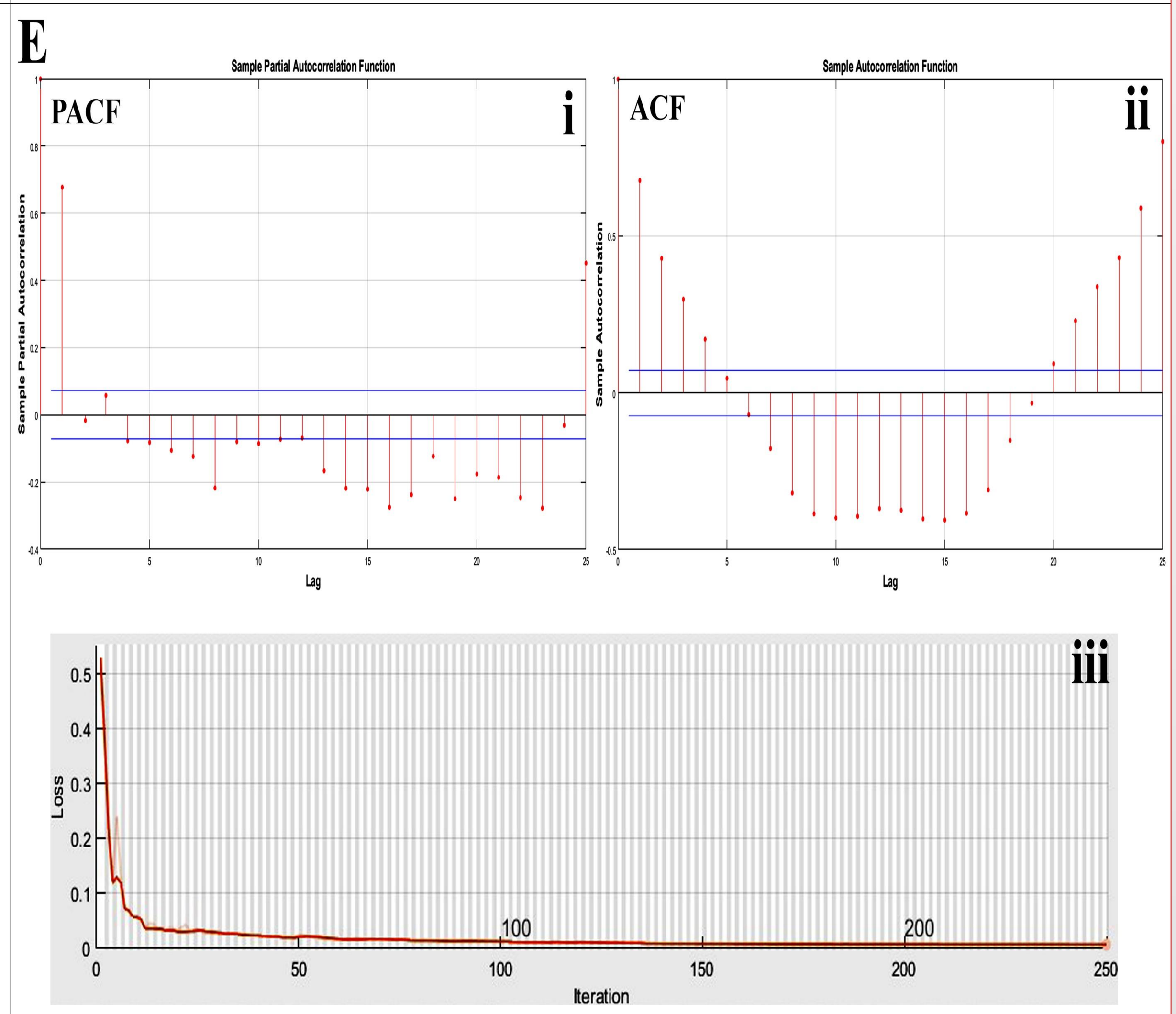
Indonesia EQ, 6.8Mw, 06 May 2020, 13:53 UTC Depth: 107 Km, Epicentre: 6.776°S 129.785°E				
Model	ARIMA		LSTM	
Error	RMSE	MAPE	RMSE	MAPE
Non-Anomalous Day 30th April 2020	2.19	19.73	2.15	10.67
Anomalous Day ★ 01st May 2020	3.29	26.87	3.41	16.81
Overall Error (Validation set)	2.53	8.06	2.6517	12.18

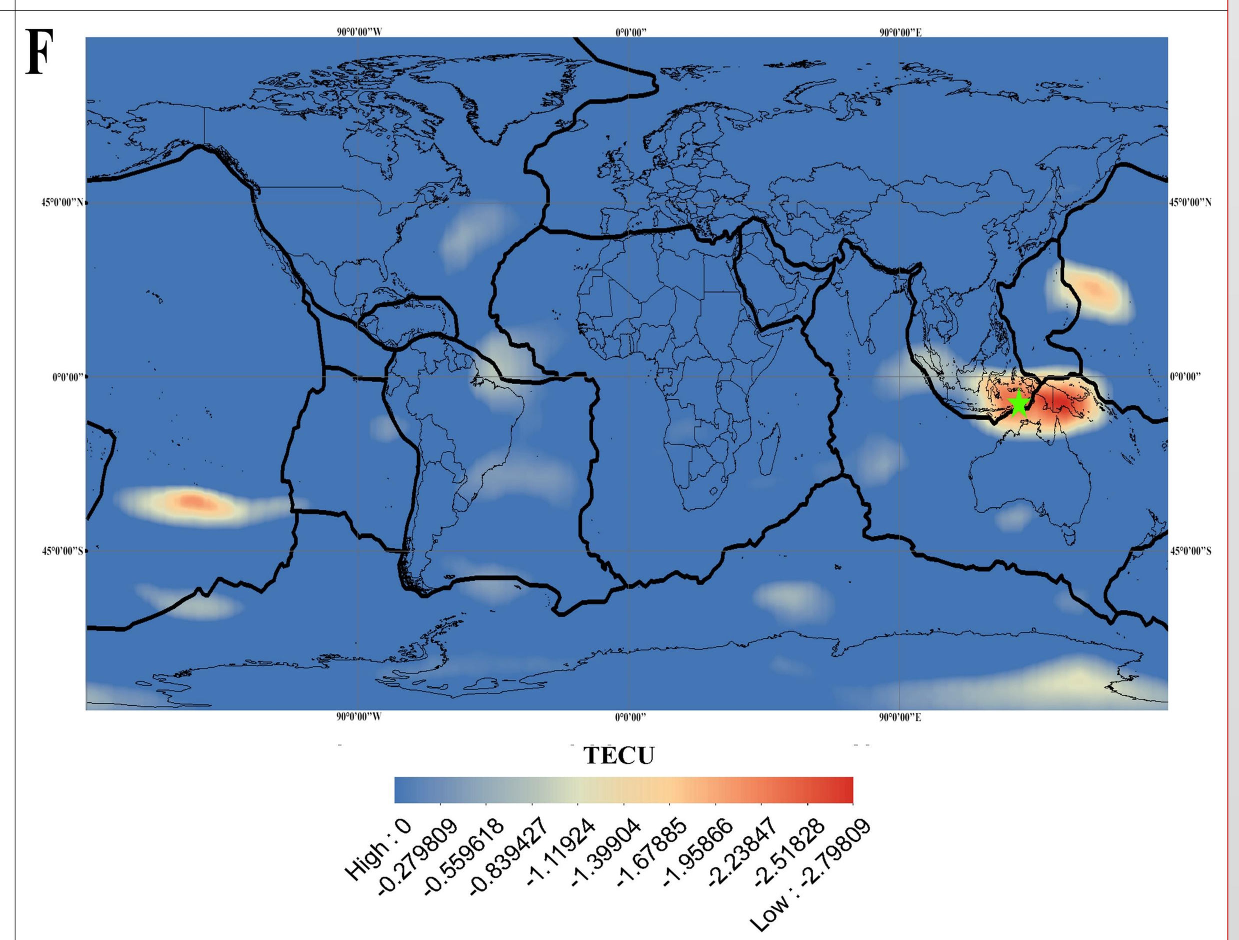
i

Augmented Dickey-Fuller test on Indonesia EQ		
Observation	Value	Comments
p-value	0.026226	p < 0.05
Test Statistic (TS)	-2.2116	TS < cValue i.e. Stationary
Critical Value (1%)	-1.9414	

ii

E(Anm Day) > E(Non Anm Day)
E(Anm Day) > E(Forecasted Overall)
E = Error, Anm = Anomolous





A Global Ionospheric Latitude-Longitude Time (GIM-LLT) map showing forecasted significant TEC anomaly in red near Indonesia on 01 May 2020 at 04:00 UTC.
Resolution 2.5° X 5.0°

METHODOLOGY

The training and test TEC dataset was divided into 8:2 ratio. After the data processing the hyper model parameters were optimized for the training dataset following which the TEC anomalies were validated by comparing the forecasted and actual TEC values on the test dataset. For ARIMA analysis, we start with the ADF test to check for stationarity of TEC data and after observing the test-statistics critical values and p-value we reject the null hypothesis. On calculating the ACF and PACF plots we select model parameters values in accordance with the lowest AIC value. While, for the LSTM model, we start with standardizing the training data to have zero mean and unit variance.

The model is fit using the 'Adam' version of stochastic gradient descent, optimized using the 'mse' loss-function and run through 250 epochs using the rectified linear activation-function (ReLU) for better performance.

RESULTS

Both the models were successfully able to detect and predict significant evidence for pre-seismic ionospheric TEC anomalies on 01 May 2020, 20 May 2019 and 11 April 2015 respectively before the occurrences of Indonesia, Peru and Nepal EQs. The time series analysis of forecasted TEC data revealed that the RMSE and MAPE error on the anomalous day was found to be significantly higher than the preceding non-anomalous day error and the overall forecasted error

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[2] Saqib et al, Ionospheric anomolaies detection using ARIMA as an earthquake precursor, May 2021

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