Long-Short Term Memory (LSTM) Neural Network for Pre-earthquake Geomagnetic Anomaly Detection from Principal Component Time Series

LONG-SHORT TERM MEMORY (LSTM) NEURAL NETWORK FOR PRE-EARTHQUAKE GEOMAGNETIC ANOMALY DETECTION FROM PRINCIPAL COMPONENT TIME SERIES

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ABSTRACT

Pre-earthquake geomagnetic anomalous variations in Earth's ionosphere and lithosphere were examined in ~800 km radius for two major earthquake episodes in China – M6.0 in Arzak, occurred on 19th January 2020., and M6.3 occurred in Xizang on 22nd July 2020. The study has built on a previously conducted Empirical Orthogonal Function and Principal Component Analysis (EOF and PCA), utilizing ESA's satellite SWARM A, B, and C geomagnetic data [2]. Eight observed significant PC time series were selected for modelling using a LSTM neural network architecture on a short (~three-month) and long-term (~1-year_ time scales, each of them is split into training and testing subsets. Strong departure from normal behaviour was noted on 9th January 2020 in Arzak region, and on 14th July 2020 in Xizang, corresponding to results previously obtained through EOF and PCA. Several additional anomalous events were observed in a period of two weeks and one month prior to the earthquake events, which further investigations are under way.

INTRODUCTION

- Earthquakes: sudden release of pre-built stress along fault lines of tectonic plates in Earth's lithosphere
- Anomalous pre-cursory geomagnetic variations in Earth's lithosphere and ionosphere reported up to a month prior to a major earthquake event.
- Near-time earthquake prediction key: well- characterized spatial-temporal signature of the anomaly – not available yet!
- LSTM NNs have not yet been used in investigating pre-earthquake geomagnetic anomalies from PC time series

OBJECTIVE

- Examine the possibility of modelling and predicting a response of individual PC time series by means of LSTM NN
- Identifying potential pre-earthquake anomalies in the time series
- Evaluate outcome results in terms of individual response predictability and possibility of anomaly detection

METHODS

- Geomagnetic data from the ESA's SWARM A, B, C, collected at 1 Hz by the Vector Field Magnetometers
- Spatial-temporal EOF and PC components extracted in ~800 km radius of earthquake epicentres
- Earthquakes: Arzak, 19th January 2020, Xizang, 22nd July 2020 (Fig.1. and Table 1)
- LSTM NN modelling and predicting individual PC time series and potential pre-earthquake anomaly detection

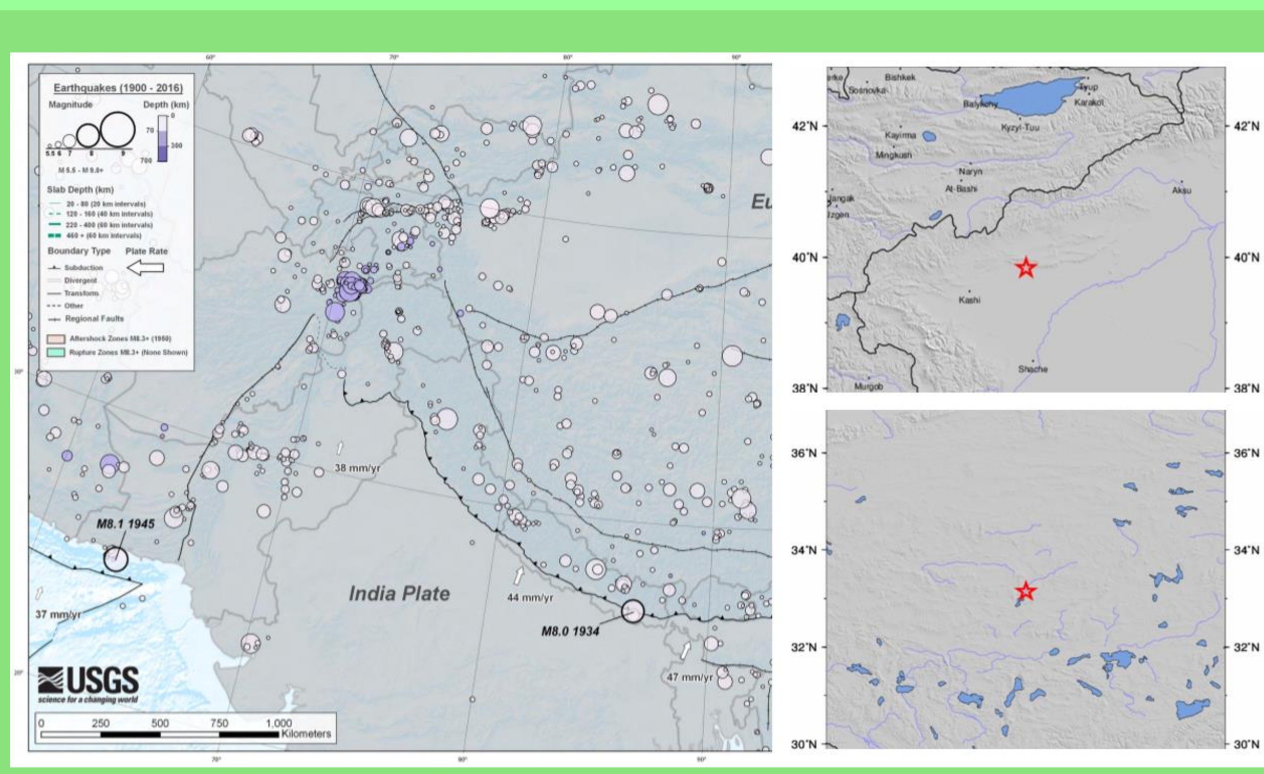

Fig. 1. Seismotectonic setting in >1000 km radius of earthquake epicentres, showing fault line locations (left). .Arzak earthquake epicentre (top right), and Xizang (bottom right) earthquake epicentres. Source: USGS.gov

Table 1. Major earthquakes in the area of China, used for the study. Source: USGS.gov

Earthquake Time and Location	Magnitude and Epicentre	Depth	Short-term analysis	Long-term analysis
19.01.2020, 13:27:56 UTC, 86 km ENE of Arzak, China	M 6.0, 39.831°N 77.106°E	6.3 km	28th October 2019 to 24th January 2020	1st January 2019 to 24th January 2020
22.07.2020 20:07:19 UTC, Western Xizang, China	M 6.3, 33.144°N 86.864°E	10.0 km	4th May to 27th July 2020	20th July 2019 to 27th July 2020

Table 2. LSTM NN layer, number of hidden units and training epochs used for each individual PC time series

LSTM layer configuration			
Location and time span	Data Source (SWARM A, B, C)	Hidden units	Training Epochs
Short-term: Arzak	A: PC 1, 7	20	300
	B: PC 4, 8		
	C: PC 1 - 4		
Short-term: Xizang	C: PC 4 - 8		
Short-term: Arzak	A: PC 2 - 8	30	300
	B: PC 1 - 3, 5 - 7		
	C: PC 5 - 8		
Short-term: Xizang	A: PC 1, 3, 4 - 8		
	B: PC 1 - 8		
	C: PC 1 - 3		
Long-term: Arzak	A: PC 1 - 2, 5 - 8	30	500
Long-term: Xizang	A: PC 4 - 6		
Long-term: Arzak	B: PC 1 - 8		
	C: PC 1 - 8		
Long-term: Xizang	A: PC 7, 8		
	B: PC 1 - 8		
	C: PC 1 - 8		
Long-term: Arzak	A: PC 4	50	300
Short-term: Xizang	A: PC 1 - 3		

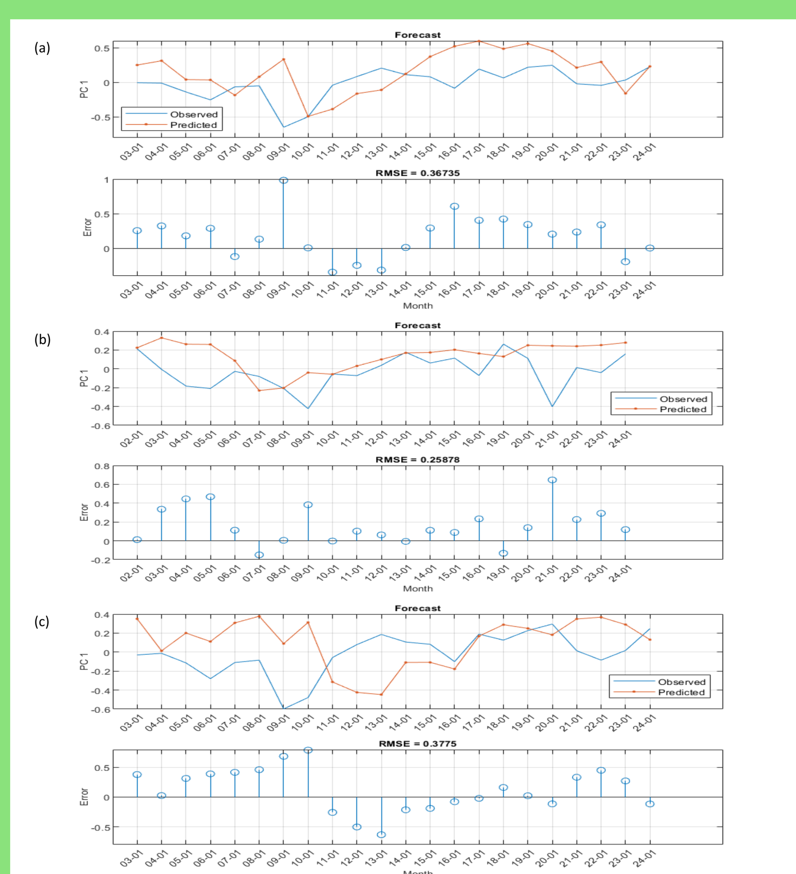

Fig. 2. Short term LSTM NN analysis for PC 1 time series, for Arzak earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

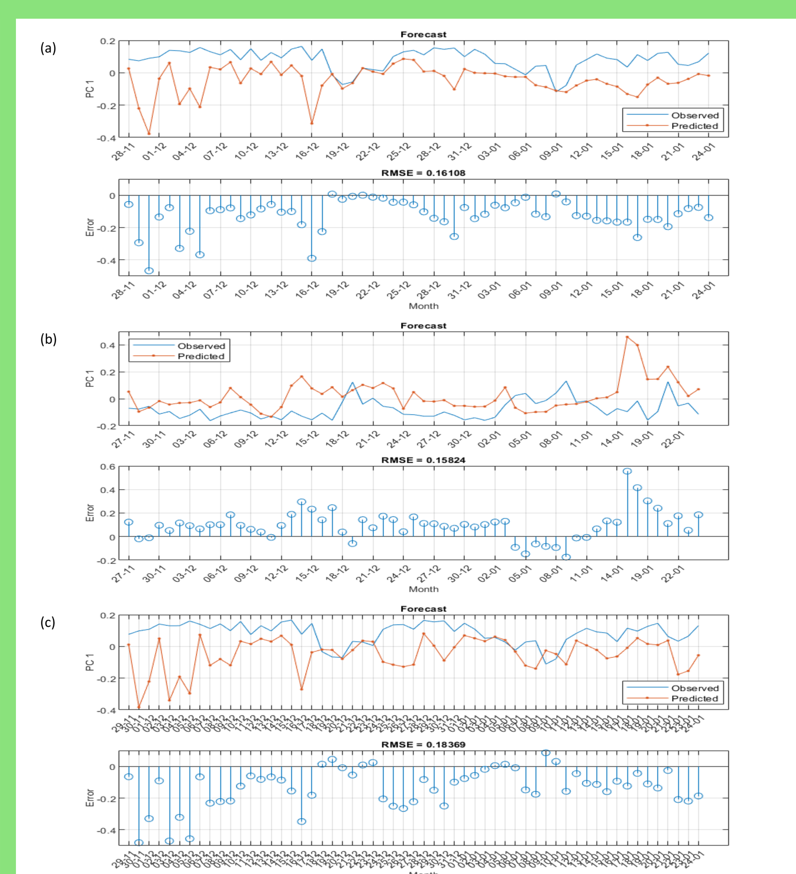

Fig. 3. Long term LSTM NN analysis for PC 1 time series, for Arzak earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

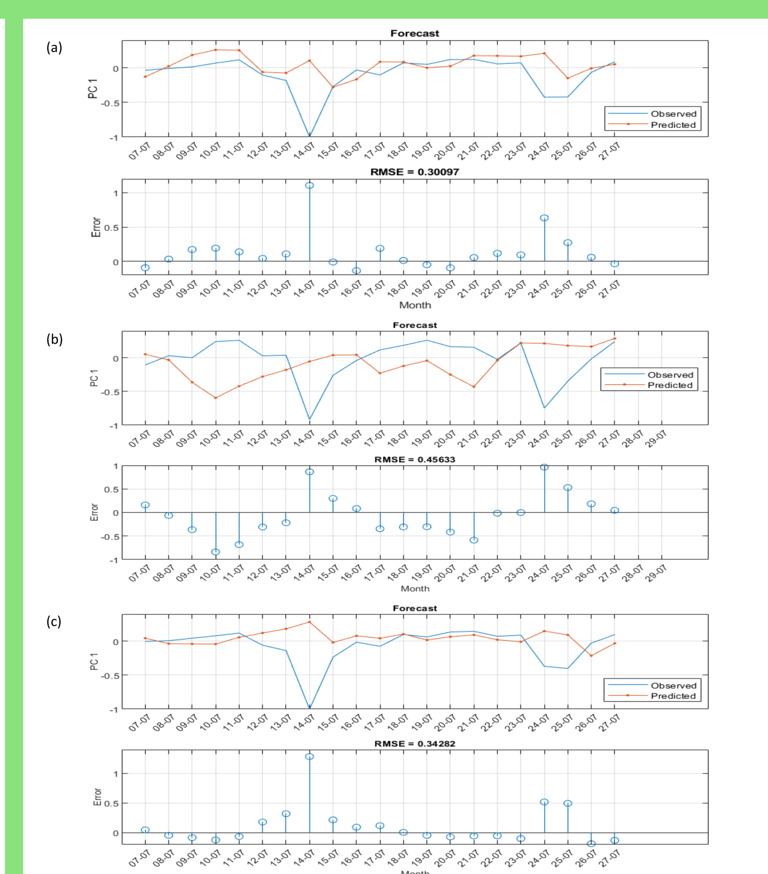

Fig. 4. Short term LSTM NN analysis for PC 1 time series, for Xizang earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

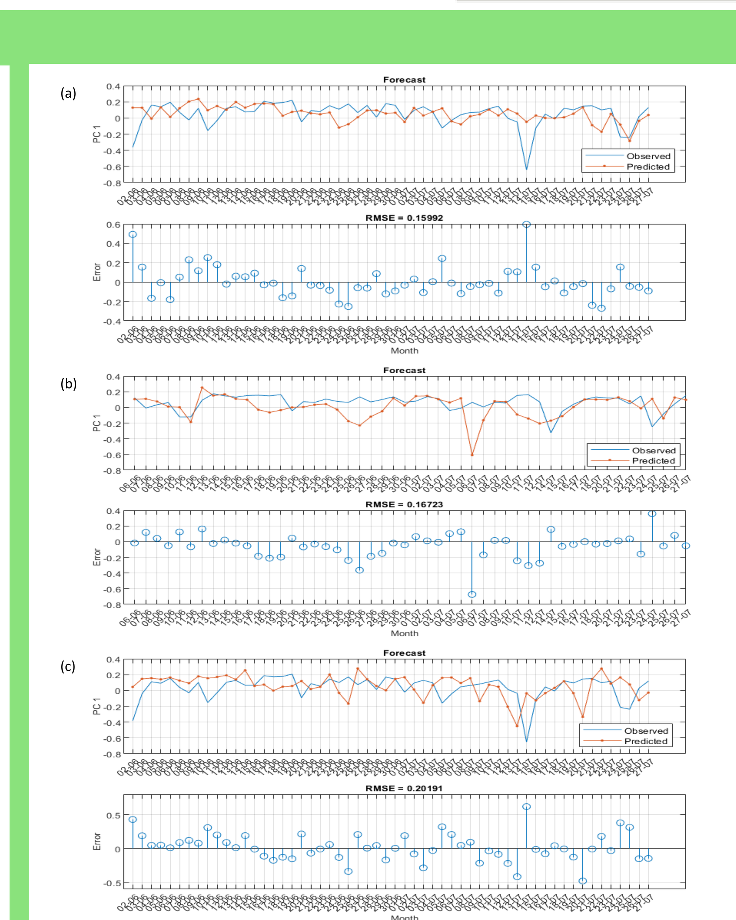

Fig. 5. Long term LSTM NN analysis for PC 1 time series, for Xizang earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

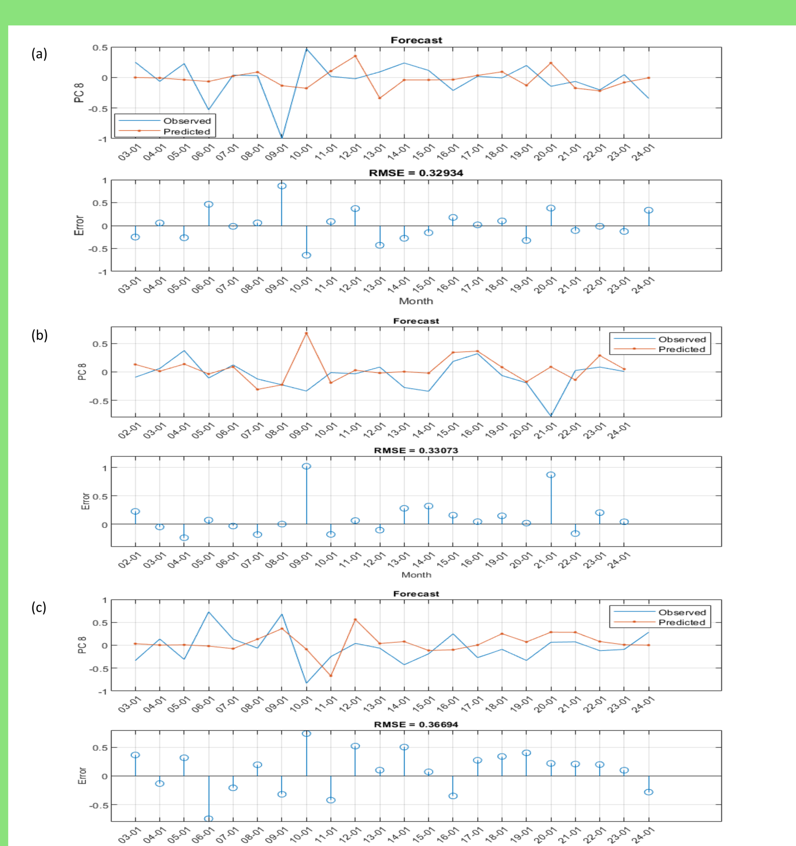

Fig. 6. Short term LSTM NN analysis for PC 8 time series, for Arzak earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

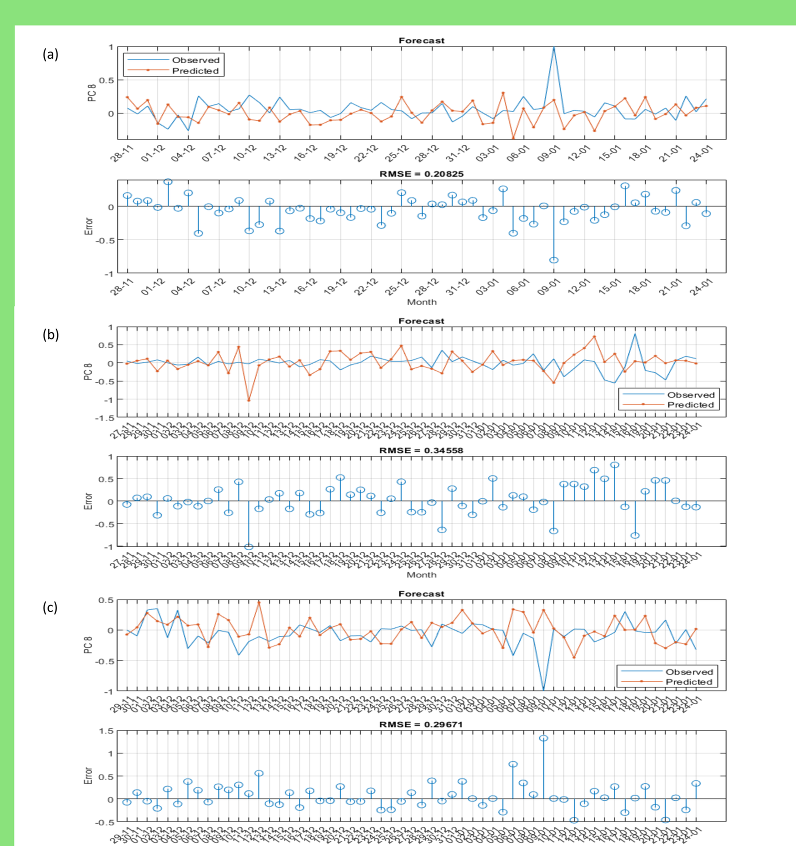

Fig. 7. Long term LSTM NN analysis for PC 8 time series, for Arzak earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

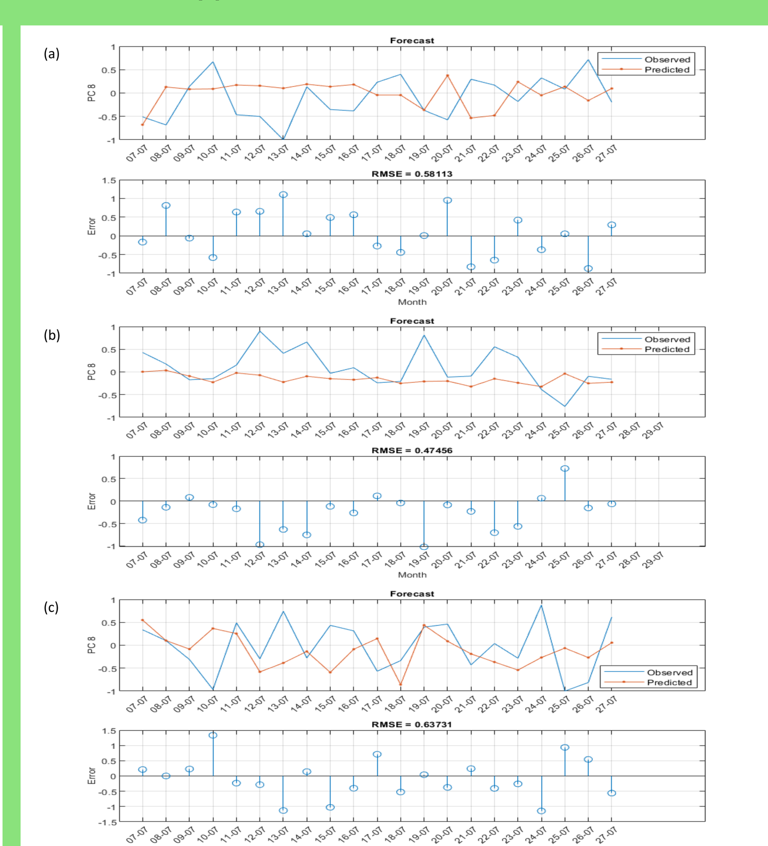

Fig. 8. Short term LSTM NN analysis for PC 8 time series, for Xizang earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

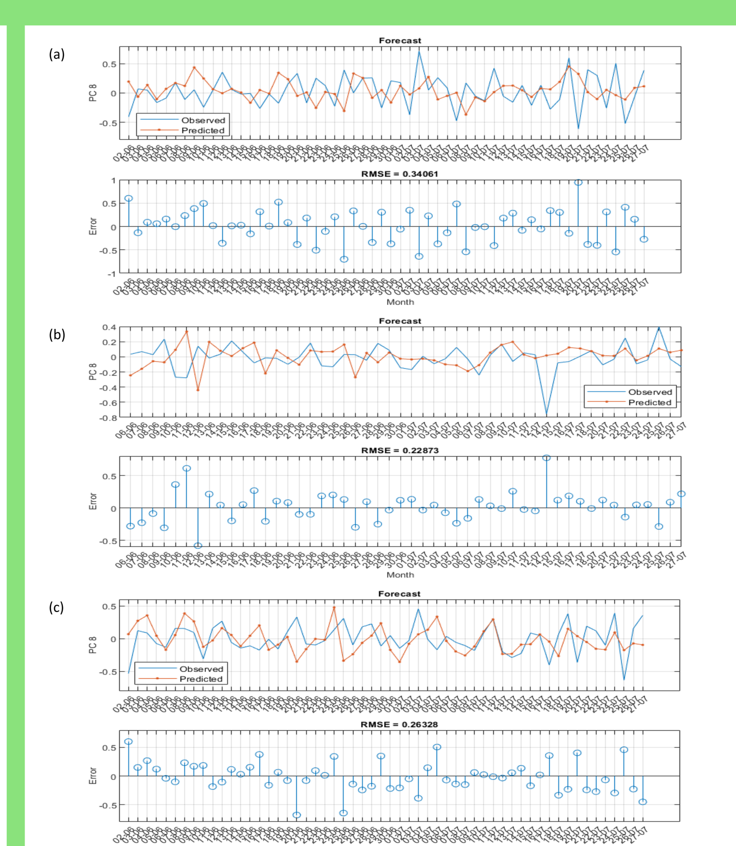

Fig. 9. Long term LSTM NN analysis for PC 8 time series, for Xizang earthquake for SWARM A (a), SWARM B (b), and SWARM C (c)

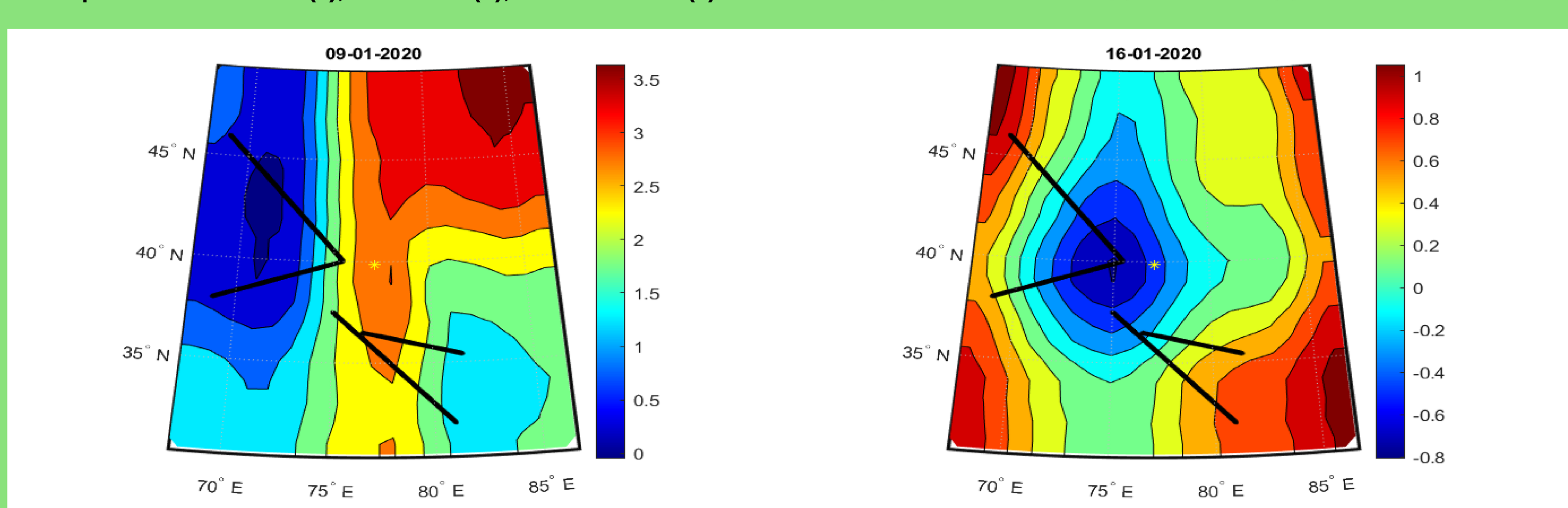

Fig. 10. Geomagnetic residual reconstructed around Arzak earthquake epicenter from the first 8 modes, SWARM A, on 9th January and 16th January 2020.

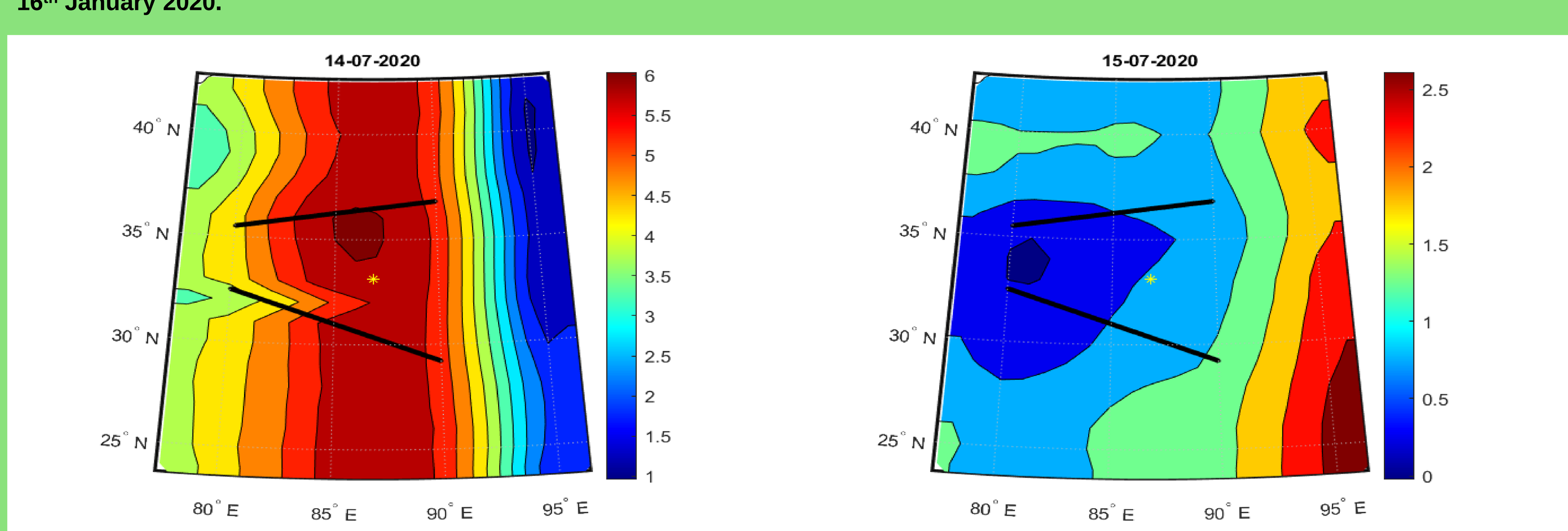

Fig. 11. Geomagnetic residual reconstructed around Xizang earthquake epicenter from the first 8 modes, SWARM A, on 14th July and 15th July 2020.

RESULTS

Arzak Earthquake:

- Short-term: Potential pre-earthquake anomaly was observed on 9th January 2020, in PC 1, 2, 4, 6, and 8 for SWARM A and in PC 1, 2, 3, 6, and 7 for SWARM C data (Illustrated for PCs1 and PCs8 in Fig. 2. and Fig. 6.). For SWARM B data, no anomalies were observed
- Long-term: PC 8 exhibits a strong anomalous response on 9th January 2020, in both SWARM A and C (Illustrated in Fig.7.) while PC 1 doesn't show the same (Fig.3.). For SWARM B, the anomalous signature is visible on 16th January (Illustrated in Fig. 7.)

Xizang Earthquake:

- Short-term: Strongest anomalous response for SWARM A, B and C is found on 14th July in PC1 (Illustrated for PC1 and PC8 in Fig.4. and Fig.8.). For PC8, the potential anomaly was observed on 8th and 13th July in SWARM A, 12th, 13th, and 14th July in SWARM B, and 10th, 13th, and 15th July 2020 for SWARM C
- Long-term: PC1 exhibited an anomalous response on 14th July for SWARM A and C and July 6th for SWARM B (Fig.5.) SWARM B showed little long-term anomalous behavior, and the variation on 14th July is only found in PC 8 (Fig.9.). SWARM A and C showed no significant anomalies in PC8.

DISCUSSION

- The strength of the anomalous signature was decided based on an error margin of 0.5, between the predicted PC response from LSTM NN analysis and its real values
- Arzak case: In addition to the anomaly of 9th January, previously also observed in EOF and PC analysis [2], a strong potential pre-earthquake anomaly was revealed by using LSTM NN modelling on 16th January 2022. Geomagnetic residual constructed from the first 8 PCs is shown for both 9th and 16th January in Fig.10.
- Xizang case: The most distinctive anomaly is visible on 14th July, which agrees with previous PC and EOF analysis. Several other potential dates have been outlined in Results. Geomagnetic residual reconstructed from the first 8 PCs is shown for July 14th and July 15th,2020.
- LSTM NN analysis revealed several other potential anomalous events, in addition to a simple EOF and PC procedure. This requires further investigation, related to quantifying the strength of the anomalous response.

LSTM NN modelling

A basic LSTM NN consists of an input layer, an LSTM layer, and output layer. The LSTM layer, configured of a hidden state and a cell state, in which long-term dependencies between data points are learned [1]:

Pre-processing	LSTM NN modelling of individual PC time series	LSTM NN parameters
• EOF and PC component extraction [2], and determining the significant number of components – 8 for both Arzak and Xizang earthquakes	• Focused on investigate standard/normal system response and anomalous deviations • Has not been applied for detecting pre-earthquake geomagnetic anomalies from the PC time series, yet	• The loss was estimated with root mean square error (rmse) during training process. Learning rate of 0.05, learning rate drop period of 125, gradient threshold of 0.5, and learning rate drop factor of 0.2 were used to train the NN for all PCs, the number of epochs and hidden units varied (Table 2)

CONCLUSIONS

- LSTM NN analysis of individual PC time series identified potential pre-earthquake geomagnetic anomalies
- The measure of strength of a particular anomalous event needs re-evaluation
- Some detected anomalies may come from other sources or related to data processing
- Longer timeline for analysis (~3 years) is currently underway

MAJOR REFERENCES

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