以雙向長短期記憶網路重建臺灣地震前電離層 TEC 異常辨識流程與模型再現性分析

Reconstruction of a Bi-LSTM Framework for Detecting Pre-Earthquake Ionospheric TEC Anomalies in Taiwan and Analysis of Model Reproducibility

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摘 要

本研究以 Tsai et al.(2022)之雙向長短期記憶網路(Bidirectional Long Short-Term Memory, Bi-LSTM)架構為基礎，重建臺灣規模 6.0 以上地震前之電離層全電子含量(Total Electron Content, TEC)異常辨識流程，並探討資料前處理與模型參數設定對異常判別結果之影響。本研究所用 TEC 取自 CODE 全球電離層圖(Global Ionosphere Map, GIM)中最接近臺灣之位址(120°E、22.5°N)之單一網格資料；描配地磁擾動指數(Dst)、太陽輻射通量 F10.7、太陽黑子數及 Lyman-α 輻射作為模型輸入變數，其中每日太陽活動參數根據太陽高度角轉換為逐小時值。案例選取遵循原研究者補充資料所列之正例、負例與訓練期，利用過去 168 小時之多變量觀測資料預測次一小時之 TEC 值，透過比較相鄰兩個 15 日階段之均方根誤差(RMSE)與平均絕對誤差(MAE)計算相對誤差指標，再經由多個獨立訓練模型配合多數決機制辨識潛在之地震相關電離層異常。本研究著重於建立一套可追溯且可重複執行之資料處理與模型驗證流程，系統性比較 TEC 正規化範圍、地方時對齊方式、網路架構、訓練策略及隨機種子等參數設定對相對誤差分布與分類敏感度之影響。最後，將本研究獲取之案例判別結果、相對誤差特徵及異常辨識成效與原研究發表之數據進行交叉對照，進一步釐清資料前處理細節與深度學習模型再現性對於地震電離層前兆辨識之影響程度。本研究成果有望作為後續運用長期電離層觀測資料執行地震異常分析，以及檢驗人工智慧模型可靠性與可重現性之方法學基礎。

關鍵字：電離層全電子含量、雙向長短期記憶網路、地震前兆、相對誤差分析、深度學習再現性、TEC 異常辨識

Abstract

This study reconstructs the bidirectional long short-term memory (Bi-LSTM) framework proposed by Tsai et al. (2022) for identifying ionospheric total electron content (TEC) anomalies preceding earthquakes of magnitude 6.0 or greater in Taiwan. The study also examines the influence of data preprocessing and model configuration on anomaly classification. TEC is extracted from the CODE Global Ionosphere Map at the single grid point nearest Taiwan, located at 120°E and 22.5°N. The model inputs further include the disturbance storm time index (Dst), F10.7 solar radio flux, sunspot number, and Lyman-α emission. Daily solar activity parameters are converted into hourly features according to the solar elevation angle. Positive, negative, and training periods are defined according to the Supporting Information of the original study. Multivariate observations from the preceding 168 hours are used to predict TEC for the following hour. Root-mean-square error and mean absolute error are calculated for two adjacent 15-day stages, and their normalized differences are used as relative-error indicators. Multiple trained models are subsequently combined through majority voting to identify ionospheric variations potentially associated with earthquake preparation. The main objective is to establish a traceable and reproducible workflow for data reconstruction, TEC prediction, relative-error calculation, and model evaluation. Particular attention is given to the effects of TEC normalization scope, local-time alignment, model architecture, training protocol, and random-seed variability on the relative-error distributions and classification sensitivity. Comparisons with the reference cases and reported results of the original study are used to evaluate the reproducibility of the Bi-LSTM framework. This work provides a methodological basis for future investigations of earthquake-related ionospheric anomalies and for assessing the reliability and reproducibility of artificial-intelligence models applied to long-term ionospheric observations.

Key words: total electron content, Bi-LSTM, earthquake precursor, relative error, model reproducibility