Exploring Spatiotemporal Trends of Earthquake Activity in the Iranian Plateau through Space-Time Cube Analysis

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KEY WORDS: Earthquake hazard, Earthquake prediction, Space-time analysis, Iranian plateau, Seismicity rate

ABSTRACT:

This study investigates the spatiotemporal trends of seismicity in the Iranian plateau over a 50-year period (1972–2021). To facilitate this analysis, the study region was divided into grids of 50 km, 75 km, and 100 km quadrangles. Earthquake data for each quadrangle were extracted, and quadrangles lacking sufficient data (i.e., fewer than five events over the study period) were excluded to ensure statistical validity. The Space-Time Cube (STC) model was employed to integrate spatial and temporal information, while the Mann–Kendall non-parametric test was used to detect monotonic trends in earthquake frequency within each quadrangle. A 95% confidence level ($p < 0.05$) was used as the threshold for identifying statistically significant trends. The resulting seismicity pattern maps categorized the quadrangles into three groups: no significant trend, increasing trend, and decreasing trend. Comparative analysis indicates that, across much of Iran, seismicity shows no significant temporal trend during the studied period. However, an increasing trend is evident in several quadrangles—predominantly in the Zagros fold-and-thrust belt, a region known for active convergence and crustal shortening. Conversely, decreasing trends are mainly observed in eastern and central Iran, including parts of the Lut and Central Iranian blocks, where recent major seismic activity appears to have declined. Sensitivity analysis using different spatial and temporal resolutions confirmed the robustness of these results. Overall, the findings suggest stable and spatially coherent seismicity trends, with localized zones of activity that correspond well with major tectonic structures. These insights provide a quantitative basis for linking long-term seismicity evolution with underlying geodynamic processes and contribute to improved regional seismic hazard assessment.

1. INTRODUCTION

The Iranian plateau, situated within the Alpine–Himalayan orogenic belt, is characterized by complex tectonic interactions among the Arabian, Eurasian, and Indian plates. These interactions give rise to high seismic activity, particularly along the Zagros, Alborz, and Makran zones. Understanding the spatial and temporal patterns of seismicity is crucial for linking observed earthquake behavior to the region's underlying tectonic mechanisms and for improving hazard mitigation strategies. Figure 1 illustrates the topography and approximate geographical extent of the Iranian Plateau, delineated as the study area in this research, within the context of the Middle East and its surrounding regions.

Seismic activity is a significant natural phenomenon that poses substantial risks to human life and infrastructure, particularly in tectonically active regions. The Iranian plateau (Figure 1), situated within the Alpine-Himalayan belt, experiences high levels of earthquake activity. In recent decades, this region has been affected by numerous destructive earthquakes, resulting in considerable human casualties and financial losses. Understanding the temporal and spatial patterns of seismicity is essential for characterizing earthquakes in the region, from both seismicity and tectonic viewpoints, and for elucidating the processes influencing earthquake occurrences. Moreover, such understanding is a critical step toward achieving improved earthquake prediction.

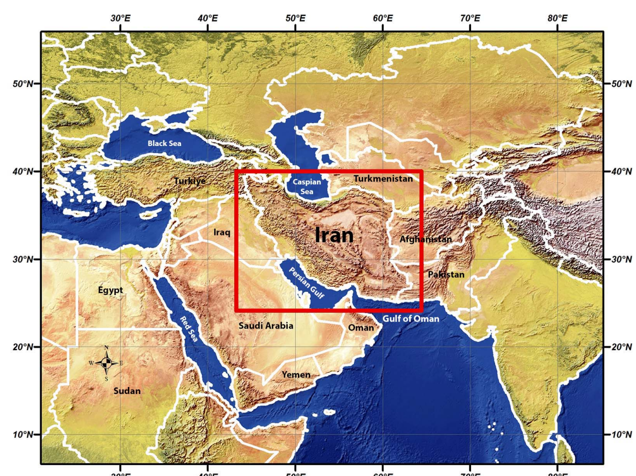

Figure 1. Generalized topographic map of the Middle East and surrounding regions, highlighting the Iranian Plateau (outlined in red rectangle) as the study region in this research.

Seismicity is not uniformly distributed across Iran; rather, it varies significantly due to the structural and tectonic differences among its regions. Many researchers have divided the Iranian plateau into distinct seismotectonic provinces (e.g., Nowroozi, 1976; Mirzaei et al., 1999), recognizing that each province or

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tectonic zone possesses unique seismotectonic characteristics. Over the past few decades, the study of seismicity across different parts of Iran, along with the tectonic differences that contribute to this variability, has been the focus of numerous investigations (e.g., Hashemi, 2013).

Although previous studies (e.g., Nowroozi, 1976; Mirzaei et al., 1999; Hashemi, 2013) have delineated seismotectonic provinces and described regional seismicity, few have applied integrated spatiotemporal models capable of visualizing and quantifying trends over extended periods. The Space-Time Cube (STC) framework (Kwan & Lee, 2005) offers such an approach, enabling multidimensional visualization and analysis of earthquake occurrences across both space and time. This study applies the STC model to a half-century of seismic data for Iran, with the goal of identifying regions exhibiting significant changes in earthquake occurrence and exploring their potential tectonic implications.

A comprehensive understanding of the spatiotemporal patterns of seismicity in Iran is crucial for effective risk assessment, disaster preparedness, and mitigation strategies. This study aims to analyze the trends and patterns of seismicity in Iran using a Space-Time Cube (STC) model. This model facilitates a multidimensional representation of earthquake data over both time and space, allowing for a more nuanced analysis of events. The Space-Time Cube model is a robust analytical framework that integrates geographic information systems (GIS) with temporal data, enabling researchers to visualize and analyze the dynamics of seismic activity in a holistic manner (Kwan & Lee, 2005). By employing this approach, we can identify patterns that may not be evident when examining spatial or temporal data in isolation, thereby uncovering insights into how seismicity evolves over time and its correlation with geological and structural factors.

Previous studies have underscored the importance of spatiotemporal analysis in understanding seismicity. For instance, Zare et al. (2018) employed various statistical methods to analyze earthquake occurrences in Iran, revealing significant correlations between seismic activity and tectonic plate movements. Similarly, Mohammadi et al. (2020) utilized advanced GIS techniques to map seismic hazards in the region, highlighting the necessity for a more integrated approach to seismic data analysis. However, there remains a notable gap in research specifically applying the Space-Time Cube model to Iranian seismicity, which this research seeks to address.

In this study, we aim to provide a comprehensive overview of the spatiotemporal changes in seismicity patterns in Iran by meticulously examining earthquake data and analyzing its spatial and temporal dimensions. The significance of this research lies not only in its methodological contributions but also in its potential implications for earthquake preparedness and response strategies in Iran.

2. METHODOLOGY

The space-time cube model serves as a spatiotemporal data framework within Geographic Information Systems (GIS) by integrating spatial, temporal, and attribute information of geographic phenomena. This model facilitates the reconstruction of historical states, tracking of spatiotemporal changes, and prediction of development trends. By aggregating all sample points into spatiotemporal columns, the data are organized using the NetCDF (Network Common Data Form) structure. Within each column, calculations are performed on the data points, and specified attributes are aggregated to compute statistical summaries. The Mann-Kendall trend analysis assesses the trend of column values over time at each location, comparing the trend data bin values created at each location with previous unit values.

In this study, earthquake events were modeled as point processes within a three-dimensional space–time cube framework in ArcGIS Pro 10.7, using the NetCDF data structure to organize temporal and spatial attributes. Seismic data were obtained from the International Seismological Centre (ISC, 2024), covering 1972–2021. To ensure data completeness, only events with magnitudes ≥4.0 were included. Quadrangles with fewer than five recorded events were excluded to avoid statistical bias. The earthquake data from the ISC catalog undergoes a review process to ensure accuracy and reliability. However, inherent uncertainties exist in earthquake location and magnitude estimations. These uncertainties can influence the precise boundaries of seismicity trends identified in this study.

In this research, the STC method was selected due to its ability to integrate spatial and temporal dimensions simultaneously, offering enhanced detection of evolving seismic clusters compared to traditional spatial density or temporal frequency analyses. This model provides a novel approach to visualizing and analyzing these complex spatiotemporal patterns, offering a more integrated perspective than traditional methods. Also, the MK test was employed because it is robust against non-normal data and missing observations, providing a reliable assessment of long-term seismicity trends. Figure 2 illustrates a general outline of this model and its application in examining the spatiotemporal patterns of point processes.

In the Mann-Kendall trend test, the bin value for the first time period is compared to that of the second; if the first value is smaller, the result is +1; if larger, -1; and if equal, zero. The results for all pairs of time periods are summed, with an expected sum of zero indicating no trend over time. The observed sum is then compared to this expected sum, considering the variance of the values in the bin time series, the number of ties, and the number of time periods, to determine statistical significance. Each bin time series trend is recorded as a z-score and a p-value, where a small p-value indicates a statistically significant trend. The sign of the z-score determines whether the trend reflects an increase (positive z-score) or a decrease (negative z-score) in bin values (ESRI, 2025).

The Mann-Kendall test is specifically designed to analyze data collected over time for consistent increasing or decreasing trends. Its primary objective is to statistically assess whether there is a monotonic upward or downward trend in the variable of interest over time. A monotonic trend indicates that the variable consistently increases or decreases, although the trend may not necessarily be linear. Unlike parametric linear regression analysis, which requires normally distributed residuals and tests whether the slope of the estimated regression line differs from zero, the Mann-Kendall test is non-parametric and does not impose such distributional assumptions. It evaluates whether a dataset is increasing or decreasing over time and whether that trend is statistically significant, without assessing the magnitude of change.

In this study, the Mann-Kendall statistical test was employed to examine the time trend of the seismic data, evaluating whether this trend was statistically significant and determining its direction (for further details on the theoretical foundations of this statistical method, refer to DelSole and Tippett, 2022). Data analysis and result presentation were conducted using Minitab (version 21.4.2) and ArcGIS (version 10.7). The application of this analytical method in the study of natural processes that exhibit spatial and temporal variability, particularly in the context of seismicity, has garnered significant attention from researchers globally in recent decades (e.g., Teng et al., 2020; Vijay and Nanda, 2021; Bantidi and Nishimura, 2022; Ye et al., 2022).

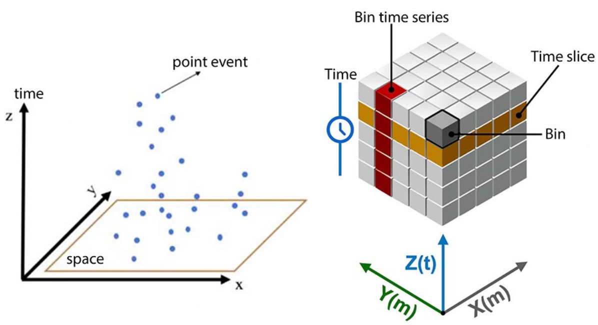

Figure 2. Graphical representations of point event analyses utilizing the Space-Time Cube model (adapted from ESRI, 2025).

3. DATA ANALYSIS AND RESULTS

The data used in this study were obtained from the ISC (2024) database. This database contains reviewed seismicity records for the region covering the period from 1972 to 2021. It includes information on earthquake location (latitude and longitude), depth, magnitude, and origin time. To ensure data homogeneity, events with magnitudes less than 4.0 were excluded from the analysis. Figure 3 presents the seismicity map of Iran, highlighting the epicenters of earthquakes with magnitudes equal to or greater than 0.4 that occurred during the specified period. The ISC data undergoes rigorous review processes to ensure accuracy. However, inherent uncertainties exist in earthquake location and magnitude estimations. These uncertainties can arise from factors such as the distribution of seismic stations, the complexity of the Earth's subsurface, and limitations in data processing techniques. While a detailed uncertainty assessment is beyond the scope of this extended abstract, it's important to acknowledge that these uncertainties can influence the results of the spatiotemporal analysis.

For the analysis of seismicity trends, the space-time cube method was employed. The study region was divided into square cells or quadrangles with dimensions of 50 km, 75 km, and 100 km. Additionally, the 50-year data period (1972-2021) was segmented into time slices of one and two years. Following the exclusion of quadrangles lacking sufficient data, the frequency of earthquakes in each cell was analyzed using the Mann-Kendall statistical method. Accordingly, each cell's temporal series of earthquake counts was analyzed using the Mann–Kendall test, a rank-based, non-parametric method suitable for non-normally distributed time series. Trends were classified as:

Increasing trend: positive z-score, $p < 0.05$

Decreasing trend: negative z-score, $p < 0.05$

No significant trend: $p \geq 0.05$

Sensitivity analyses were performed for three spatial resolutions (50 km, 75 km, 100 km) and two temporal intervals (1-year and 2-year slices). The Minitab 21.4.2 software was used to validate trend calculations.

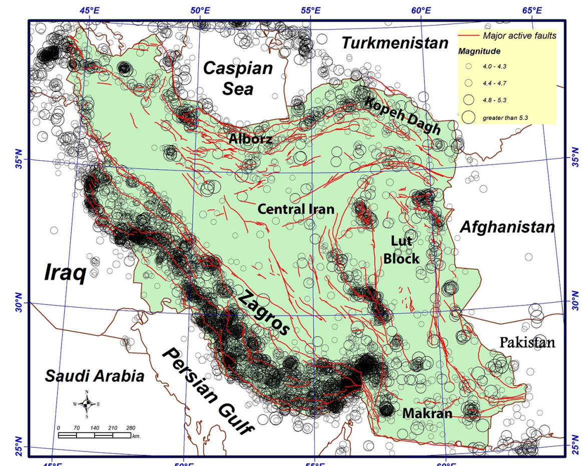

Figure 3. Seismicity map of Iran illustrating the epicenters of earthquakes that occurred in the region from 1972 to 2021 (data derived from the ISC data catalog).

Figure 4 displays maps depicting the spatiotemporal trend patterns of seismicity in the Iranian plateau for time slices of one-year interval, across different quadrangle dimensions (50 km, 75 km, and 100 km). In contrast, Figure 5 presents similar maps but for time slices of two-year interval. In these maps, quadrangles are classified into three categories based on their seismicity trends: cells that do not exhibit a significant trend in seismicity frequency over time; cells indicating a decreasing seismicity trend, categorized by varying degrees of statistical validity; and cells demonstrating an increasing trend pattern, also separated based on statistical significance.

The model employed in this study allows for the generation of multiple maps representing the spatiotemporal patterns of seismicity by selecting quadrangles of varying dimensions and time slices with different intervals. While these maps do not display identical patterns, they collectively provide a comprehensive overview of the spatiotemporal seismicity trends in the region.

An examination of the maps in Figures 4 and 5 reveals that, despite minor local variations, the overall pattern remains consistent across resolutions, confirming the robustness of the STC–Mann–Kendall approach. Most of Iran exhibits no significant temporal trend, suggesting stable long-term seismic activity. However, distinct regional differences are evident: The Zagros region (particularly its central and southern parts) shows increasing trends, consistent with ongoing active shortening and crustal deformation along the Arabian–Eurasian plate boundary. Parts of central and eastern Iran, including the Lut block, display decreasing trends, possibly reflecting seismic quiescence following prior high-activity periods.

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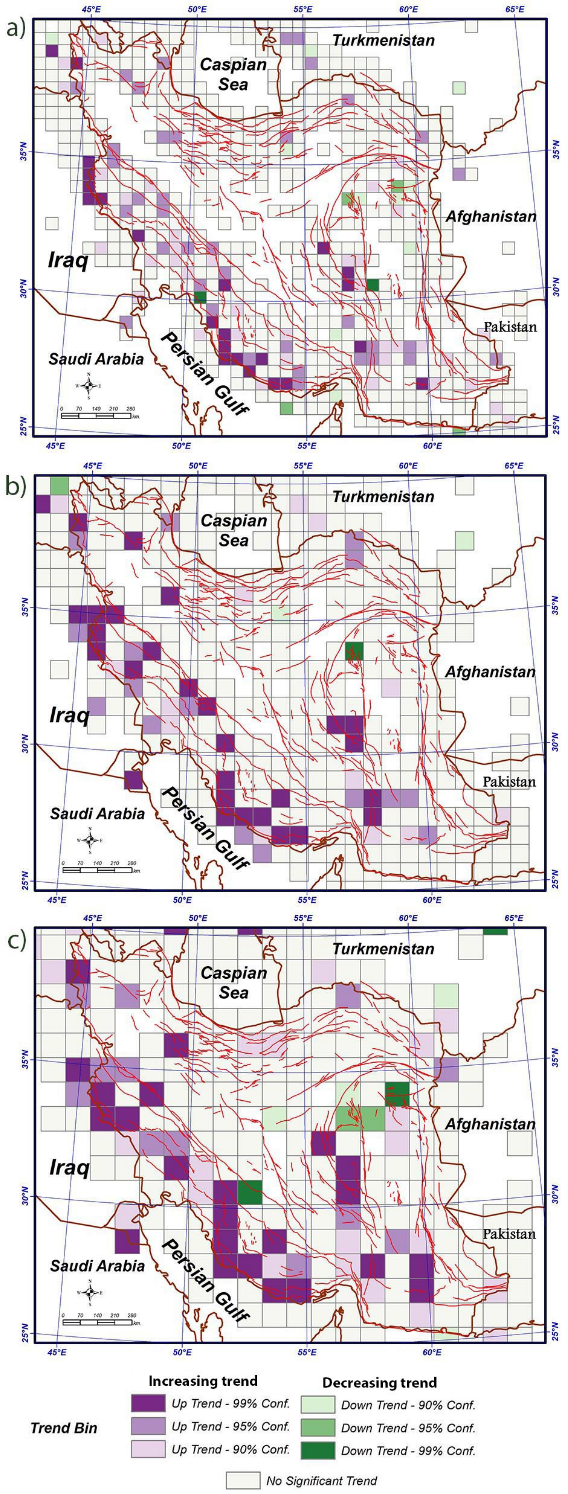

Figure 4. Maps depicting the spatiotemporal trend patterns of seismicity in Iran from 1972 to 2021, prepared for a time slice of one year and employing different cell dimensions: a) 50 km, b) 75 km, and c) 100 km.

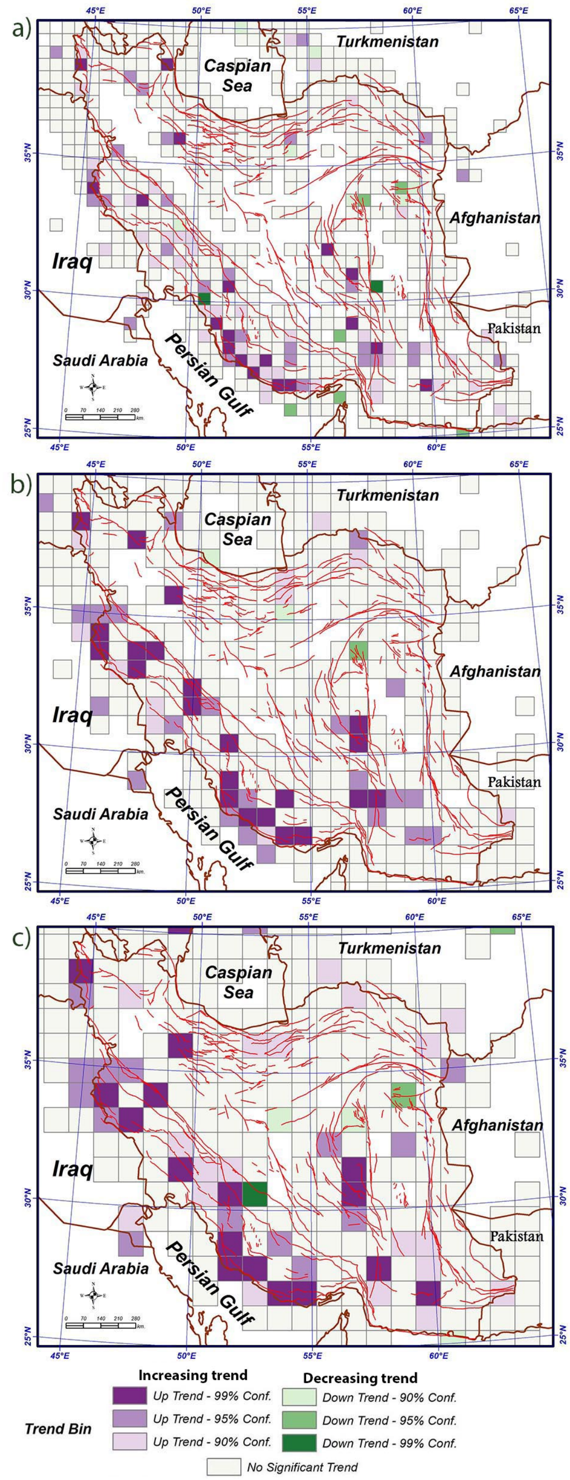

Figure 5. Maps depicting the spatiotemporal trend patterns of seismicity in Iran from 1972 to 2021, prepared for a time slice of two years and employing different cell dimensions: a) 50 km, b) 75 km, and c) 100 km.

4. CONCLUSIONS

In summary, the findings of this study can be listed as follows:

a) The spatiotemporal analysis of seismicity in Iran, as illustrated in the maps presented in Figures 4 and 5, shows that most regions across Iran exhibit no statistically significant spatiotemporal trend, suggesting long-term seismic stability. However, areas within the Zagros Fold and Thrust Belt display increasing seismicity, consistent with the region's active fault systems and compressional tectonics. Conversely, parts of eastern and central Iran show decreasing trends, possibly reflecting strain release or lower activity of local faults. The results are broadly consistent with earlier Iranian seismicity research (e.g., Hashemi, 2013; Zare et al., 2018), confirming that the STC–MK combination provides a scientifically valid and efficient framework for national-scale seismic trend analysis.

b) Comparative analyses reveal that smaller grid sizes (50 km) produce more localized and precise spatial representations, while time interval variations exert minor influence on overall trend patterns—demonstrating the robustness and reliability of the findings.

c) The analysis was limited to linear trend detection. Future research should incorporate non-linear models, optimize spatial and temporal parameters, and integrate geological fault data, population density, land use/cover, and infrastructure information for assessing potential earthquake impacts and validating these findings against previous studies.

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