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Research Article

Risk zone analysis using chaos theory from earthquake data

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ABSTRACT

Earthquakes are natural disasters that cause harm to humanity. To minimise this harm, earthquake prediction studies are conducted, but in order to carry out these prediction studies, it is essential to understand the characteristics of earthquakes and analyse them accurately. This study examines the characteristics of earthquakes in the light of chaos theory. Two consecutive major earthquakes that occurred in Turkey in 1999 and the regions where they occurred were considered for this purpose. Earthquake catalogue data recorded in the last 30 years prior to the major earthquakes in these regions were used. The chaotic characteristics, such as the time between the two earthquakes, the magnitude of earthquakes, the depth of earthquakes, and the distance of each earthquake from the location where the major earthquake occurred, was analysed through frequency analysis, phase portraits, and the Lyapunov exponent method. The results indicate that all four characteristics are chaotic, with positive Lyapunov values for both regions.

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INTRODUCTION

Earthquakes, a natural disaster that causes significant loss of life and property, especially in regions known as the Earth's seismic hotspots, are a major concern. Turkey, primarily located within the second-degree earthquake belt, has experienced numerous devastating earthquakes in the past century, resulting in a substantial loss of human life and extensive economic damage. One of the most devastating earthquakes in this period occurred on August 17, 1999, claiming the lives of more than 18,000 individuals [1]. According to some sources, another earthquake is reported to have claimed the lives of over 50,000 people on February 6, 2023 [2]. These disasters have become evident that earthquake prediction efforts are of paramount importance in taking preventive measures and minimising losses.

Accurate understanding of earthquake geology and characteristics is crucial for earthquake prediction. Earthquakes are a result of thermal and tectonic movements occurring in the Earth's inner layers, which lead to the formation of tectonic plates. These plates are dynamic structures, accumulating energy at their contact points. When this stored energy exceeds a certain threshold, earthquakes occur. The magnitude of earthquakes is indicative of the size of the fractured surface and the released energy [3]. Considering that seismic waves are mechanical waves,

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it can be inferred that regions adjacent to the epicentre of a major earthquake are at risk, as energy is transferred from one point to another. The time gap between two significant earthquakes can vary from several years to a few months or even a few hours [4].

While it has long been assumed that everything in the universe is interconnected through cause-and-effect relationships, the randomness of earthquake occurrences was once widely accepted. However, due to its complex and interrelated nature, the chaotic behaviour of earthquakes has come under scrutiny [5].

In a study conducted in 1994, the fractal dimension of the strange attractor was determined to investigate whether the earthquakes that occurred in the Koyna region of India between February 1967 and December 1981 were an example of deterministic chaos. The results showed that the phase space portrait was on the strange attractor. By applying the Wolf technique, it was observed that the Lyapunov exponents were positive, indicating chaotic behaviour [6].

In another study in Japan in 1994, data from over 14,470 earthquakes with a magnitude greater than 2.6 were analysed. Lyapunov exponents were applied to a time series derived from the time difference between seismic events, and the results indicated positivity [7].

Another study looked at data from two groups to see how many earthquakes happened at distances of 220 and 440 km in the Shillong region of India from 1964 to 1992 in 1996. This study examined the applicability of deterministic chaos in earthquake formation and suggested that earthquakes occurring at long distances could be considered as precursor earthquakes. The Lyapunov results were positive for both data groups [8].

In a study from 2001, earthquake time-magnitude series were created using earthquakes with a magnitude greater than 2.0 that occurred in four different regions of Greece over the last 20 years. The maximum Lyapunov exponents were calculated, and the results were positive for all regions, indicating the chaotic nature of seismic events [9].

Another study in 2009 applied chaotic analysis to seismic time series and made seismic predictions using RBF. The study used earthquake magnitude data from the Guangxi region over the last 30 years. The seismic time series chaos analysis showed that the maximum Lyapunov exponent was positive [10].

In a study in 2009 that investigated the nonlinear characteristics of fault movements near the fault, data from different locations and times in China and the United States were used. The maximum Lyapunov exponent for the acceleration-time series of fault movements was found to be positive, indicating chaotic behaviour [11].

In another study in 2010, chaotic analysis was applied to seismic time series data. The study used earthquake magnitude-time series data from the Guan Shi region in China between 1980 and 2010. The maximum Lyapunov exponent was found to be positive for all seismic time series, suggesting their chaotic characteristics [12].

In a 2012 study, 24 ground motion records from the Chi Chi earthquake were analysed to determine whether earthquake ground motions are random or chaotic signals in Taiwan. The results showed that the correlation dimension of ground motion was a fractal dimension, and the Lyapunov exponent was greater than zero [13].

In another study conducted in 2012, monthly earthquake time series data with a magnitude greater than 4.0 were analysed, segmented by fault zones, for the period between 1997 and 2011 in Bali. The analysis showed that the maximum Lyapunov exponent was positive for all regions [14].

Finally, in a study conducted in 2012, earthquake magnitude data from the Pacific region between 1899 and 2009 were used to investigate and characterise earthquake formation using chaos theory. The results showed that the Lyapunov exponent was positive for all subregions, indicating the chaotic nature of earthquakes [15].

Unlike other studies, this research evaluates various parameters, including earthquake magnitude, depth, the time interval between consecutive earthquakes, and the distance of each earthquake's location from the epicentre of a major earthquake. Thus, the study expands the framework of seismic data analysis in light of chaos theory, and it evaluates the risk of earthquakes in neighbouring regions and the risk of consecutive earthquakes.

BACKGROUND

Chaotic Systems

It is well known that events in the universe are based on a cause-and-effect relationship, which is deterministic. Events occurring within this deterministic structure are highly sensitive to initial conditions, leading to what is known as chaos [16]. In 1887, Henri Poincaré discussed chaos with the three-body problem and introduced the concept of phase space and geometric modelling. Prior to this, Newton argued that the future motion of objects could be known if the conditions were known. However, Poincaré contended that they could not be measured accurately due to the sensitivity of initial conditions [17]. Orbits drawn with two different initial conditions that are very close to each other can exponentially diverge from each other over time [16].

In 1962, Edward Lorenz, who was studying weather prediction events, introduced the "butterfly effect," suggesting that small and often neglected factors could lead to significant events [18]. In 1989, Benoit B. Mandelbrot introduced the concept of fractals [19]. Fractals are defined as structures that contain a hidden formula within themselves and repeat endlessly. They represent the geometry of nature and are an embodiment of chaotic dynamic systems. Another concept related to chaos, strange attractors, was explained by David Ruelle. In a strange attractor, there are an infinite number of points, and these points correspond to different states of the chaotic system [17].

To unravel chaos in nonlinear time series, qualitative, quantitative, and hybrid methods are available. Qualitative methods include power spectral analysis, principal component analysis, nearest neighbour-organised wrong, and the Poincaré method. Quantitative methods cover correlation dimension, Kolmogorov entropy, maximum Lyapunov exponent, and other techniques [13].

While it used to be solely associated with mathematics, chaos theory has gained importance and expanded its applications in various fields such as chemistry, biology, optics, electronics, and fluid dynamics over the last 30 years. Chaos theory has been applied in areas including the solar system, meteorology, biology, neuroscience (in fields like the heart and brain), and beyond. It has also found applications in fields like digital marketing, finance, and crisis management. Chaos theory provides an opportunity to analyse and predict complex systems that may seem random but have underlying structure, such as earthquakes [13].

Lyapunov Exponent

One of the primary challenges in chaos theory is how to measure it. The Lyapunov exponent is one of the best methods for this purpose and serves to characterise the qualitative and quantitative aspects of dynamic behaviour. If a system has one or more positive Lyapunov exponents, it can be said to be chaotic. The Lyapunov exponent represents the average exponential rate of separation and convergence of nearby trajectories in phase space. In its application, it tracks the long-term growth rate of small-volume elements in a dynamical system [20].

The technique known as the "Wolf technique," which was introduced by Alan Wolf and his colleagues, was applied in their pioneering work to the Belousov-Zhabotinskii chemical reaction and the Couette-Taylor hydrodynamic flow [20]. In addition to the Wolf technique, the calculation of Lyapunov exponents also involves the use of Jacobians and small data methods [13]. In this study, the Wolf technique was employed.

DATA

Study Area

There are three major earthquake zones: the Pacific, Alp-Himalaya, and Atlantic in the world [21]. Turkey is located in the Alp-Himalaya earthquake zone and is predominantly a second-degree earthquake risk country. Within the country, there are several active fault lines, both large and small, including the North Anatolian, West Anatolian, and East Anatolian fault lines. The North Anatolian fault line, for instance, is approximately 1500 kilometres long [22], and over the past century, it has been the site of numerous significant earthquakes, resulting in many casualties.

Within the scope of this study, the recent earthquakes on the North Anatolian fault line, such as the 7.4 magnitude Gölcük earthquake on August 17, 1999, and the 7.2 magnitude Düzce earthquake on November 12, 1999, have been analysed. Figure 1 illustrates the earthquakes that have occurred in the relevant region over the past century.

To assess the first earthquake, the Golcuk earthquake, a narrower region, specifically the Marmara region, was selected. The second earthquake, the Duzce earthquake, was chosen as the 2nd region, encompassing a broader area that includes the Marmara region and the surrounding provinces, as it is related to the Golcuk earthquake. The latitude and longitude information for these regions is presented in Table 1.

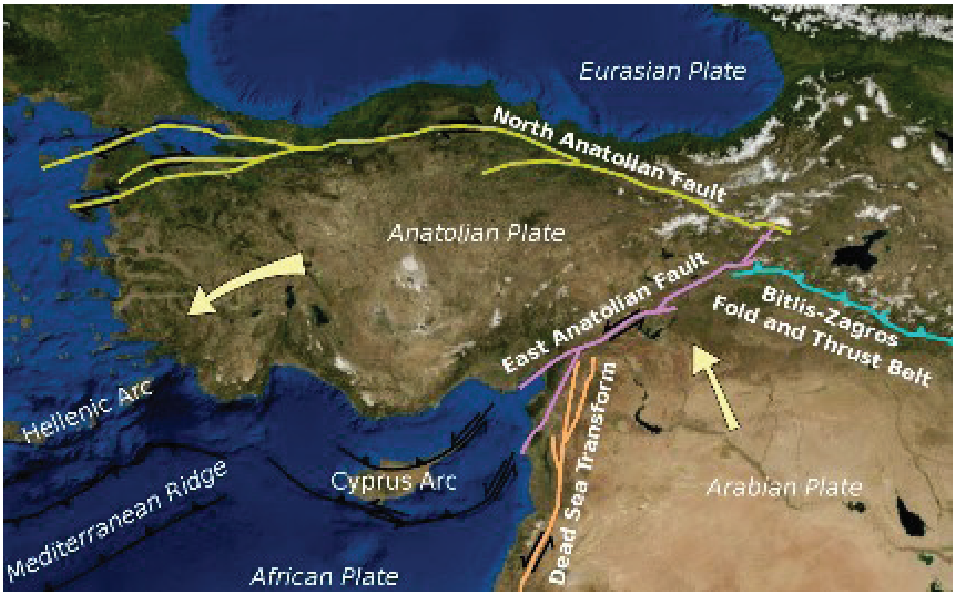

Figure 1. Anatolian Plate Vectoral [23].

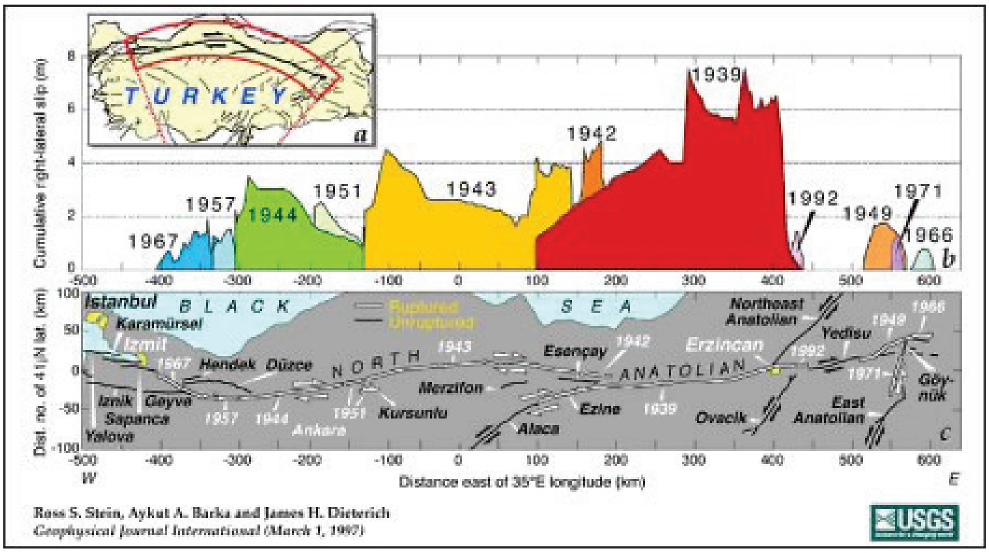

Figure 2. The North Anatolian Fault and slip magnitudes of earthquakes in the 20th century [24].

Data Acquisition

In this study, earthquake data from the years 1970 to 1999 within the Marmara region and the surroundings of Düzce province were utilised. The earthquake data was obtained from B.U. KOERI Regional Earthquake-Tsunami Monitoring Center. The seismic catalogue data in the system includes earthquake code, date and time of occurrence, latitude, longitude, depth, magnitude (xM MD ML Mw Ms Mb), earthquake type, and location information [25].

When retrieving the data, latitude and longitude were entered in accordance with the reasons described in the previous section. The largest value within the parameters of time-dependent magnitude (Md), local magnitude (Ml), surface wave magnitude (Ms), body wave magnitude (Mb), and moment magnitude (Mw) was selected as the earthquake magnitude, denoted as xM.

Since chaos analysis takes into account the potential significant impact of even small earthquakes, earthquakes with a magnitude greater than 1.0 were included in the analysis. Upon initial examination, it was found that there were no earthquakes smaller than 2.0 in the dataset. The depth parameter was limited to 80 km, as deep earthquakes have much less impact on the surface.

When analysing the 30-year earthquake data, a total of 10 earthquake time series were obtained as follows: three 10-year time series (1970-1980, 1980-1990), and two 5-year time series for each of the following periods (1990-1995, 1995-1999). The number of earthquakes in the time series created for each region over the years can be seen in Table 2.

Table 1. Parameters Used for Data Retrieval

	Region 1 (Marmara Region)	Region 2 (Marmara Region and the Surrounding Area of Duzce Province)
Latitude	40.68 - 41.55	40.00 - 42.00
Longitude	26.04 - 30.13	26.00 - 34.00
Magnitude	1.0 - 9.0	1.0 - 9.0
Depth (km)	0 - 80	0 - 80
Time	1970-1999	1970-1999

Table 2. Earthquake Time Series - Number of Data

	Region 1 (Marmara Region)	Region 2 (Marmara Region and the Surrounding Area of Duzce Province)
1970-1980	285	1078
1980-1990	973	3298
1990-1999	2583	6083
1990-1995	1334	3075
1995-1999	1249	3008

Four characteristics have been identified for analysis in the obtained time series. These include earthquake magnitude, depth, the period between two consecutive earthquakes, and the distance between each earthquake and the significant earthquake that occurred. For region 1, the distance between each earthquake and the Golcuk earthquake was calculated, while for all earthquakes in region 2, distances to both the Golcuk and Duzce earthquakes were calculated and analysed separately as distance 1 and distance 2. Information on magnitude and depth was directly taken from the catalogue data, while period and distance information was calculated.

METHOD

Time and Frequency Analysis

Time and frequency analysis were conducted using the MATLAB program. Frequency graphs were generated from the period, magnitude, depth, and distance information of 10-year and 5-year time series for both the 1st and 2nd regions. Phase portraits of the period, magnitude, depth, and distance characteristics were obtained for different time series in each region. Additionally, histogram graphs for these characteristics were created for the time series. All graphs can be found in the Results and Discussion section.

Lyapunov Exponent

The Lyapunov exponent was calculated using the MATLAB program. For both the 1st and 2nd regions, the Lyapunov exponents were computed for the period, magnitude, depth, and distance information of 10-year and 5-year time series. The calculations resulted in the generation of attractor and Lyapunov graphs, which can be found in the Results and Discussion section.

RESULTS AND DISCUSSION

Time Analysis

Time analysis with 10-year intervals was conducted for all selected variables in both regions. Additionally, the last 10-year period was divided into two 5-year intervals. The time analysis of these 5-year time series was performed to investigate whether there were any changes that could lead to a major earthquake.

As a result, in Figures 3, 4, 7, and 8, a uniformization over time in terms of period and depth was observed in both regions, indicating a convergence towards a regular distribution. On the other hand, Figures 5, 6, 9, 10, and 11 did not reveal any significant changes in the magnitude and distance of the earthquake.

Frequency Analysis

The Fast Fourier Transform, like in time analysis, was calculated for all selected variables in both regions with 10-year intervals, and the last 10-year period was divided into two 5-year intervals. The Fast Fourier Transform was computed for a total of 10 separate time series to investigate whether there were any changes that could lead to a major earthquake.

As observed in Figures 12-20, in both regions, as the time of occurrence of a major earthquake approach for all features, the DC component becomes dominant. While there is still a considerable time before the earthquake occurs, other components are stronger, but over time, they tend to be drawn towards the DC component. The convergence towards a regular distribution observed in time analysis confirms the strengthening of the DC component in FFT.

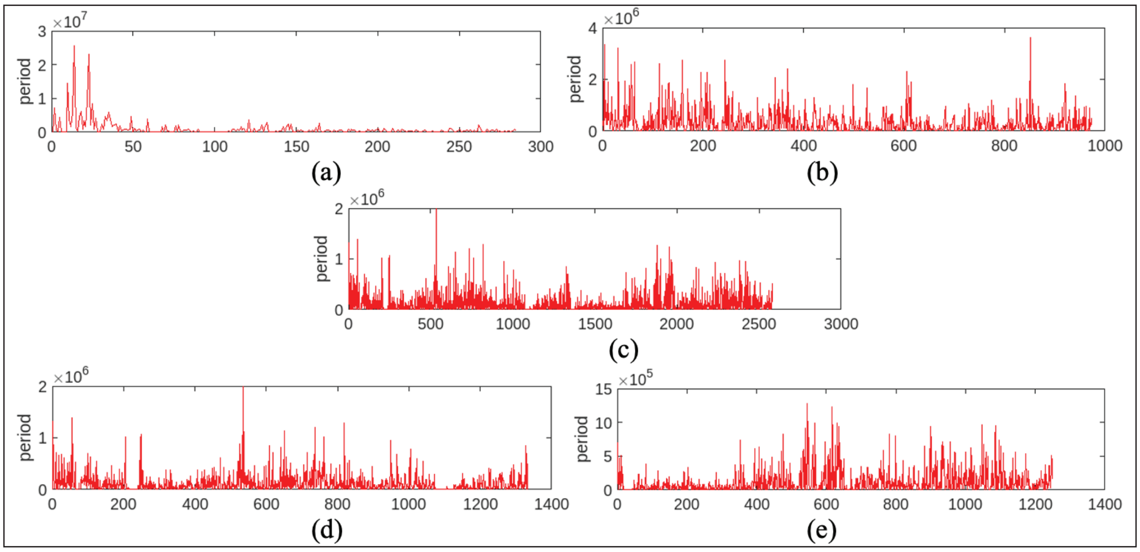

Figure 3. Region 1 Period Frequency Graph a) 1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

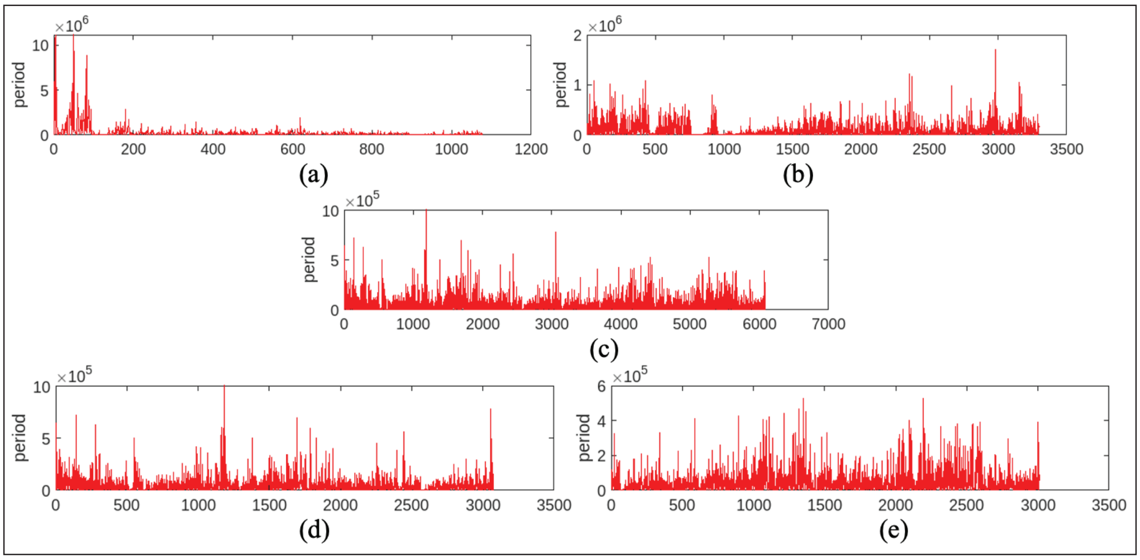

Figure 4. Region 2 Period Frequency Graph a)1970-1980, b) 1980-1990 , c)1990-1999, d) 1990-1995, e) 1995-1999.

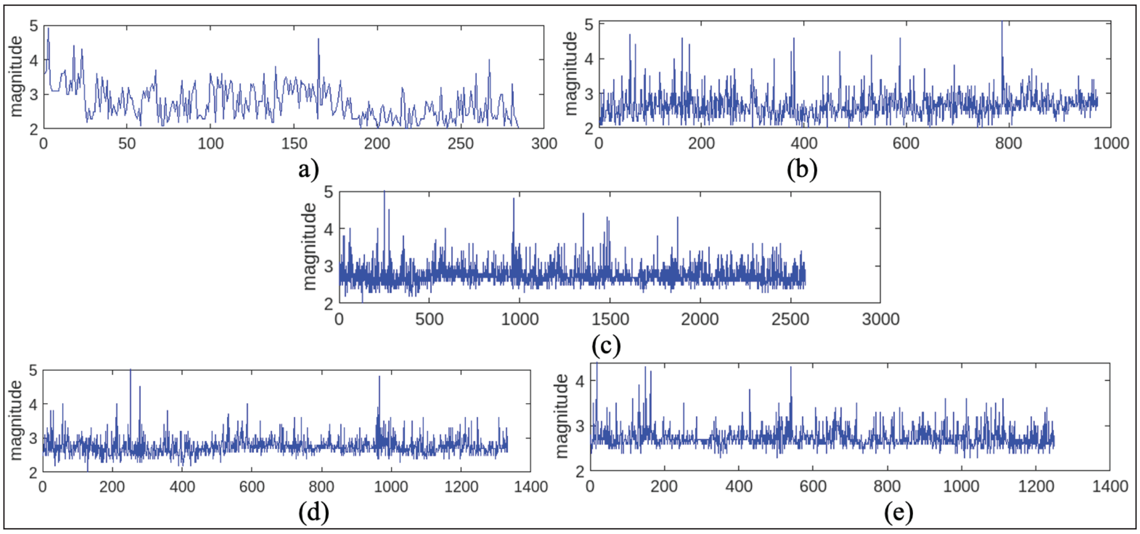

Figure 5. Region 1 Magnitude Frequency Graph a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

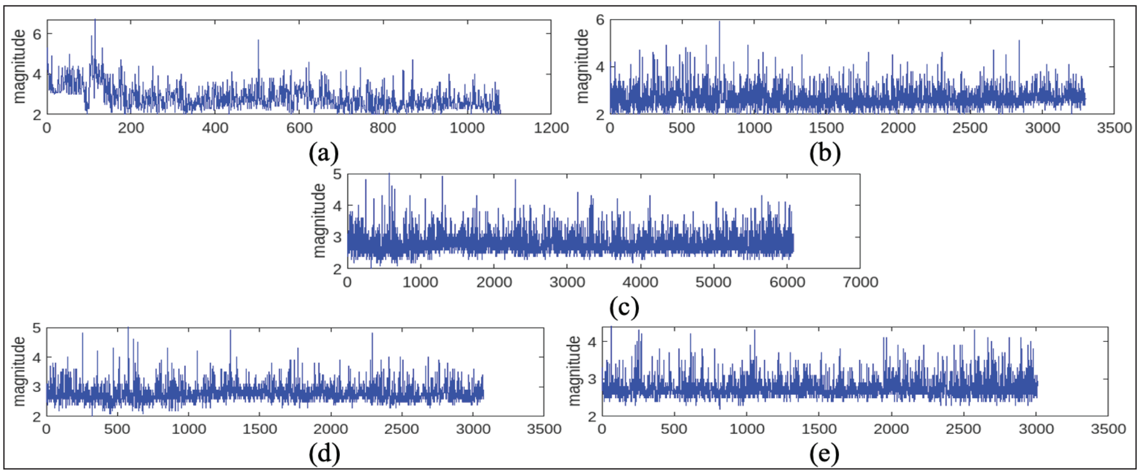

Figure 6. Region 2 Magnitude Frequency Graph a)1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

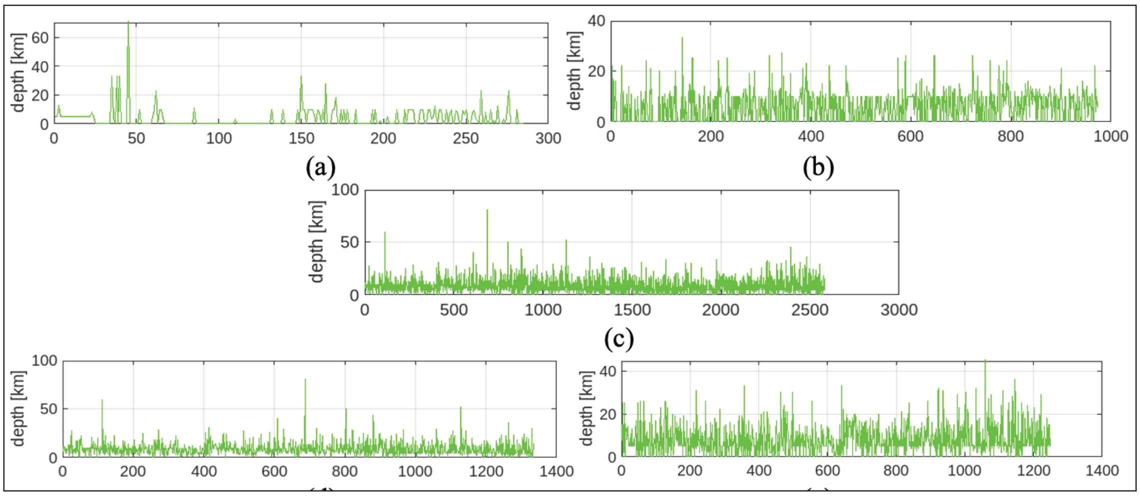

Figure 7. Region 1 Depth Frequency Graph a) 1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

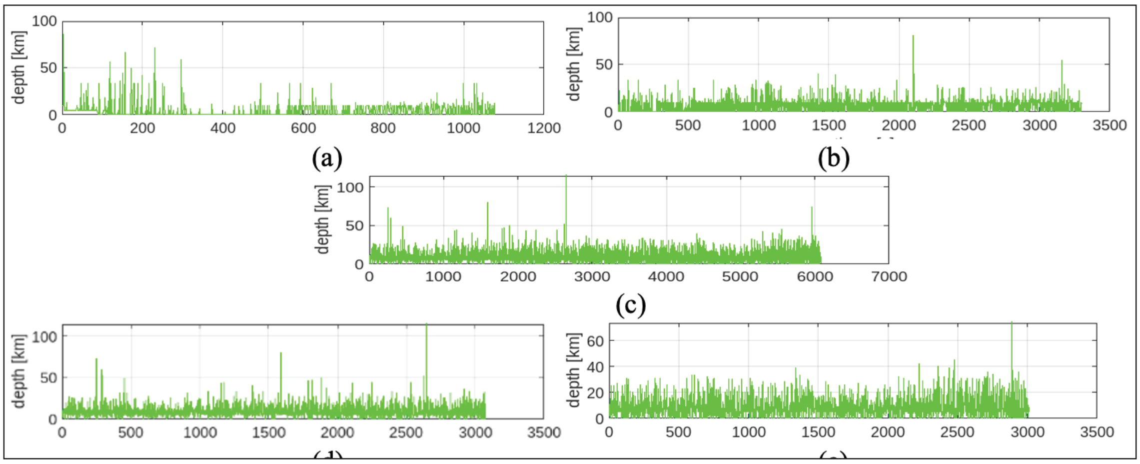

Figure 8. Region 2 Depth Frequency Graph a) 1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

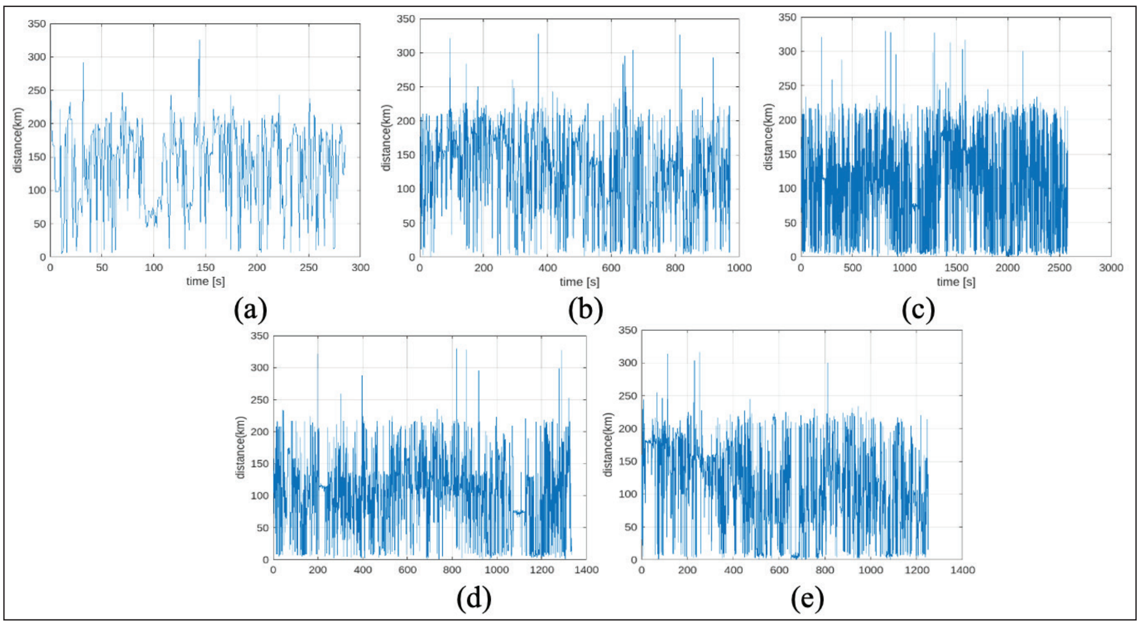

Figure 9. Region 1 Distance Frequency Graph a) 1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

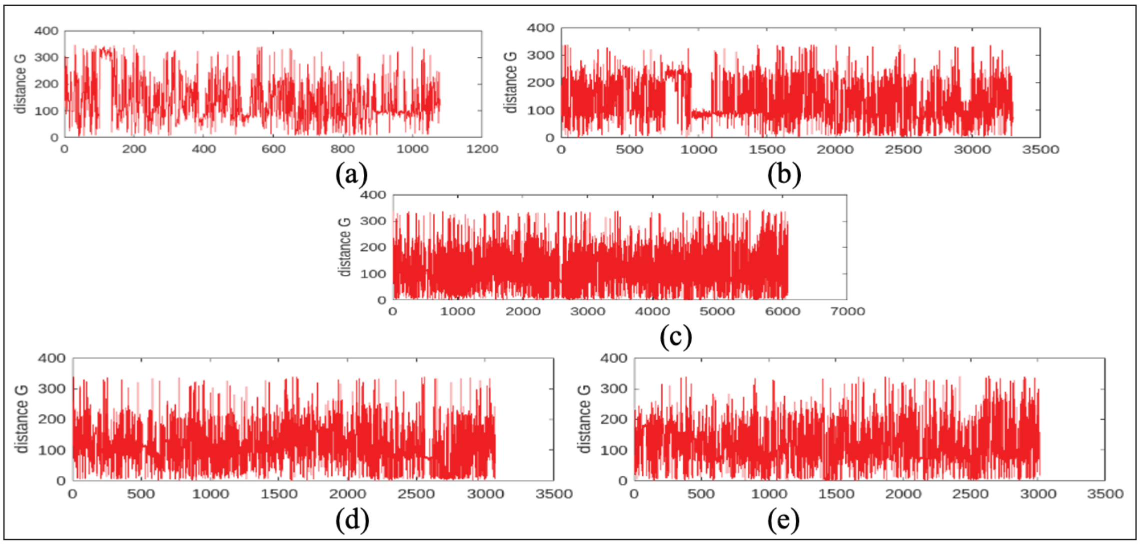

Figure 10. Region 2 Distance 1 Frequency Graph a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

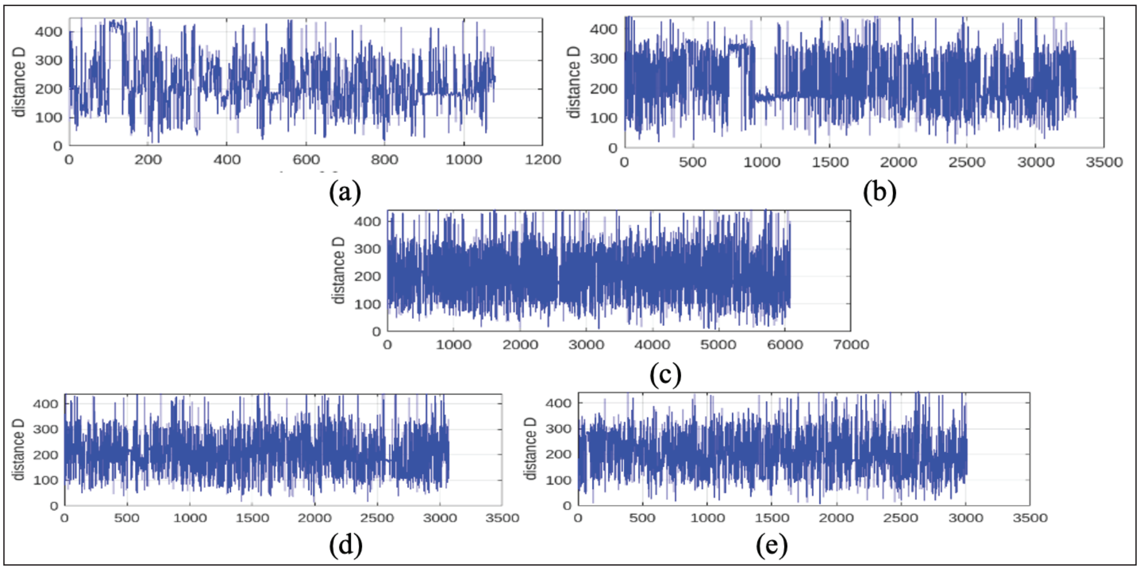

Figure 11. Region 2 Distance 2 Frequency Graph a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

Phase Portraits

In the phase portraits drawn for magnitude-period and magnitude-distance, the attractor trajectories resemble chaotic orbits, as seen in Figures 21 and 22. In general, as time progresses, the measured or calculated quantities of the variables tend to increase, but it can be observed that structures resembling chaotic trajectories remain unchanged. This pattern was observed for each variable.

Histogram

In the histograms, it is generally observed that as the major earthquake approaches, the number of occurrences of variables increases. In Figure 23, it can be seen that the periods become shorter, indicating that earthquakes occur more frequently for both regions.

In Figure 24, it can be noted that as a major earthquake approaches, the earthquake magnitudes increase, and the magnitude histogram tends to resemble a normal distribution.

Lyapunov Exponent

The Lyapunov exponent method was applied to four different characteristics of both the 10-year and 5-year time series taken into account for both regions. Instead of the final value obtained from the Lyapunov exponents, the convergence to a single value was examined, and the results were recorded as a series of data. These data series, which include varying sample sizes, were later graphically represented. In Figure 27, the Lyapunov change graph obtained for the period and magnitude features in the first region is shown for five different time intervals.

In the graph obtained for magnitude, a decrease is observed after the 15th sample, which corresponds to the last 10 years of data and the years 1990-1995 and

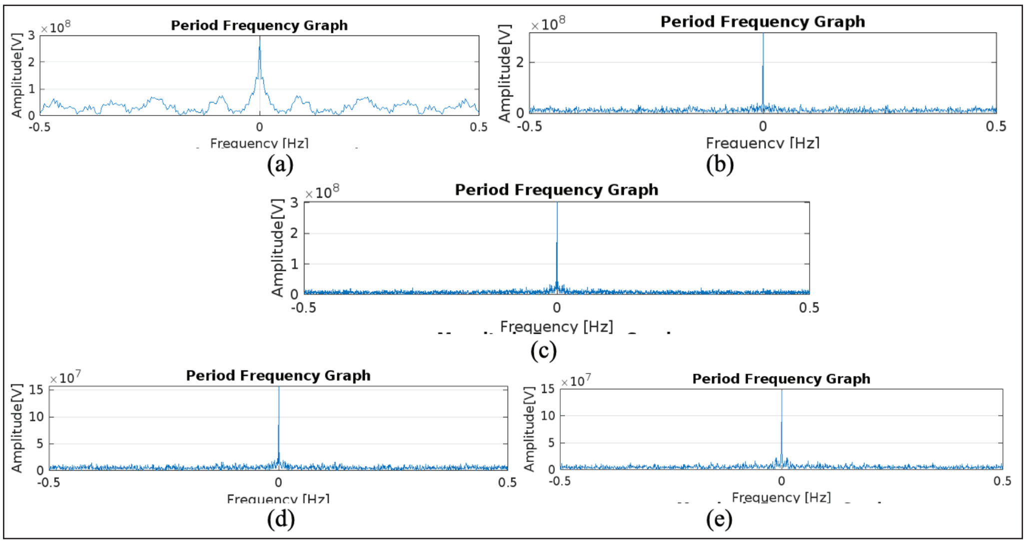

Figure 12. Region 1 Period Frequency Graph a) 1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

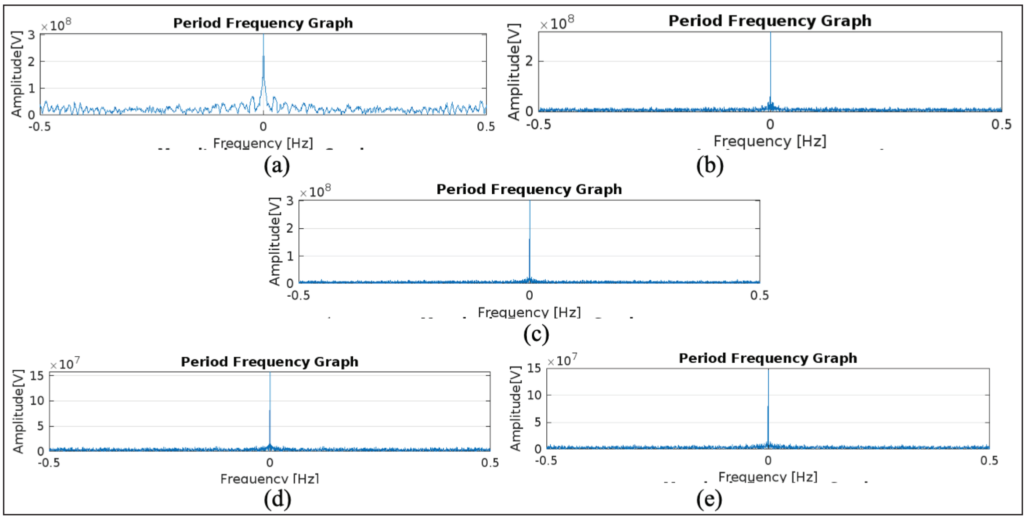

Figure 13. Region 2 Period Frequency Graph a)1970-1980, b) 1980-1990 , c)1990-1999, d) 1990-1995, e) 1995-1999.

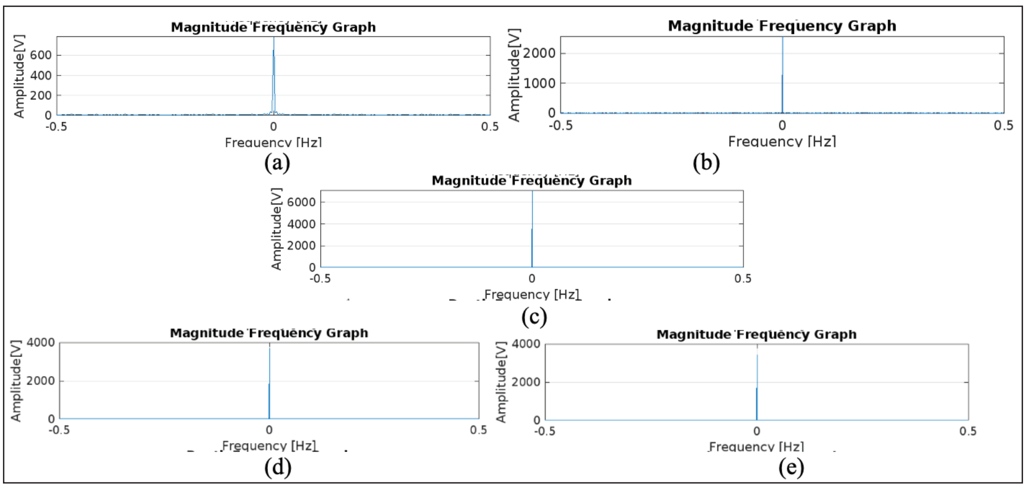

Figure 14. Region 1 Magnitude Frequency Graph a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

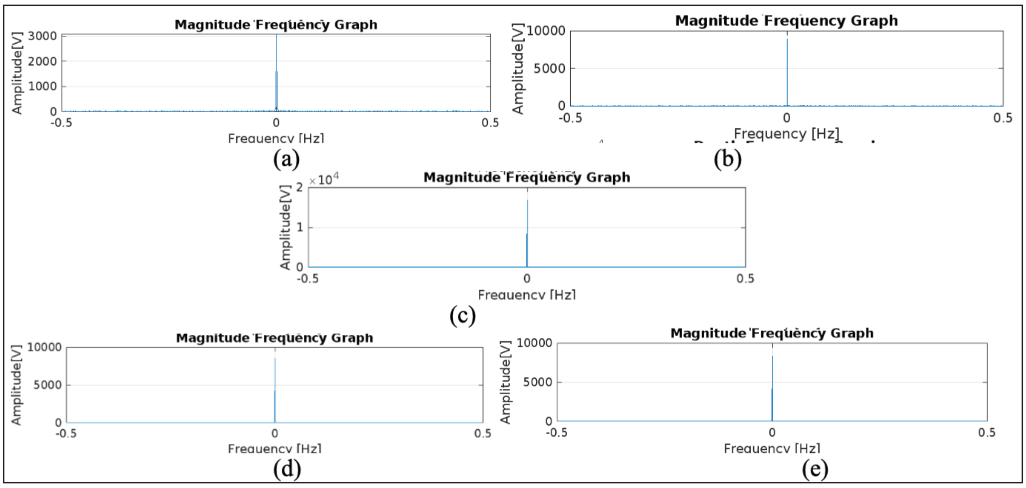

Figure 15. Region 2 Magnitude Frequency Graph a)1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

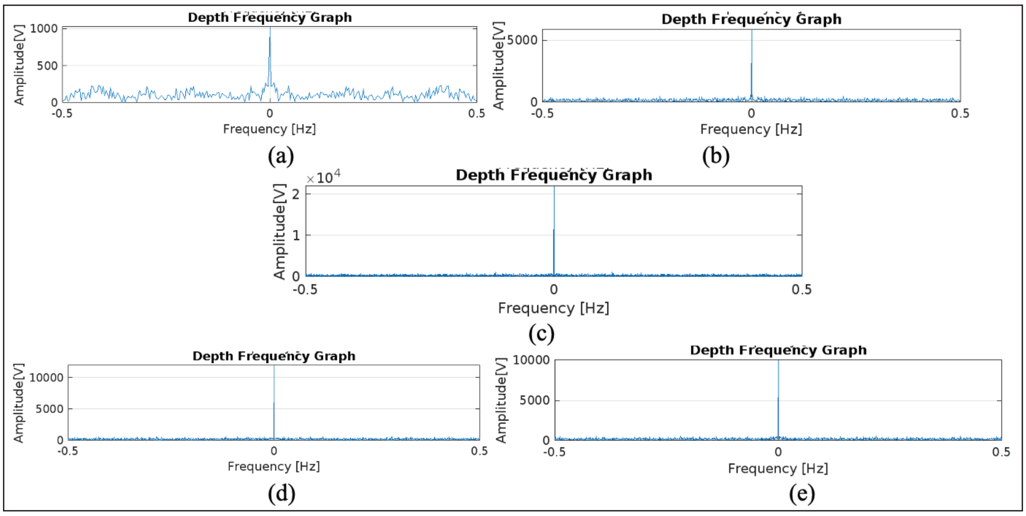

Figure 16. Region 1 Depth Frequency Graph a) 1970-1980, b) 1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

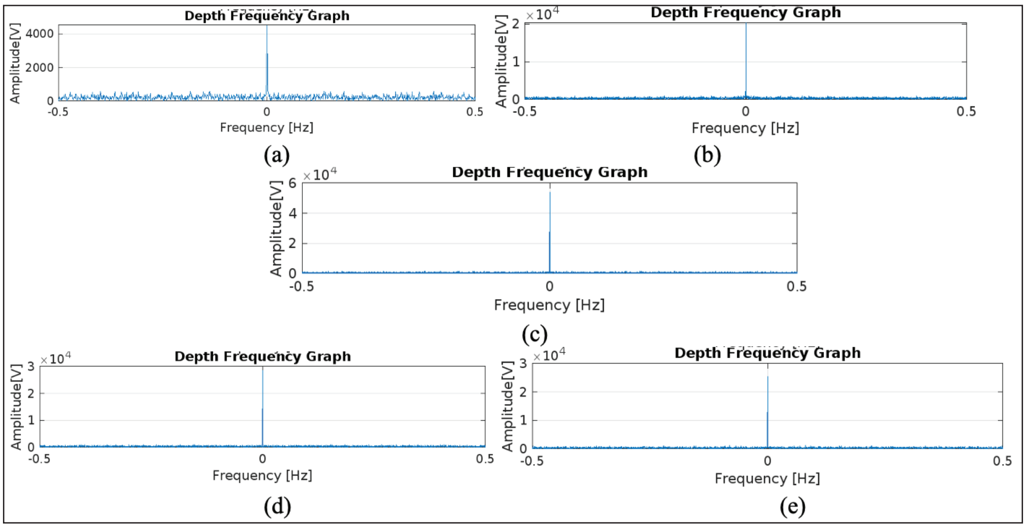

Figure 17. Region 2 Depth Frequency Graph a) 1970-1980, b) 1980-1990 , c)1990-1999, d) 1990-1995, e) 1995-1999.

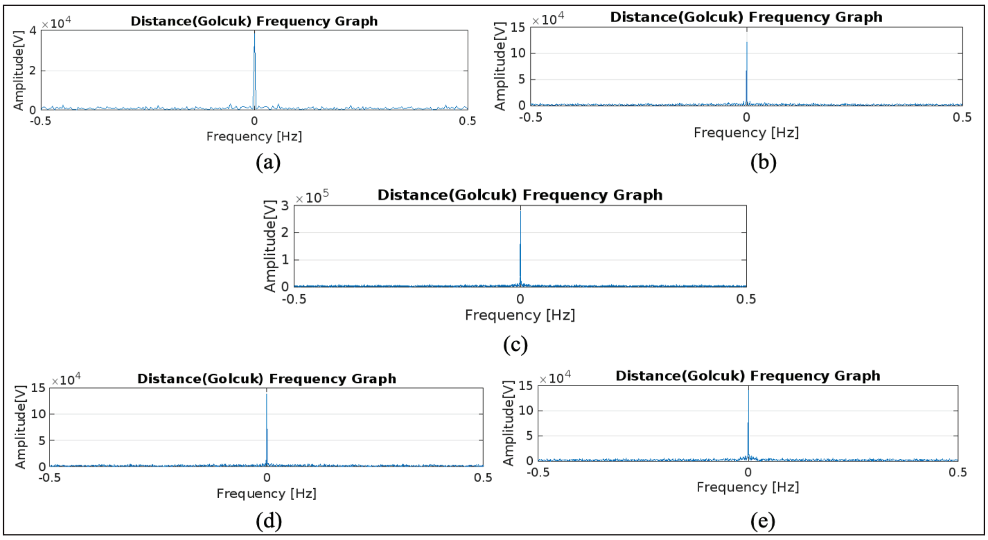

Figure 18. Region 1 Distance Frequency Graph a) 1970-1980, b) 1980-1990, c) 1990-1999, d) 1990-1995, e) 1995-1999.

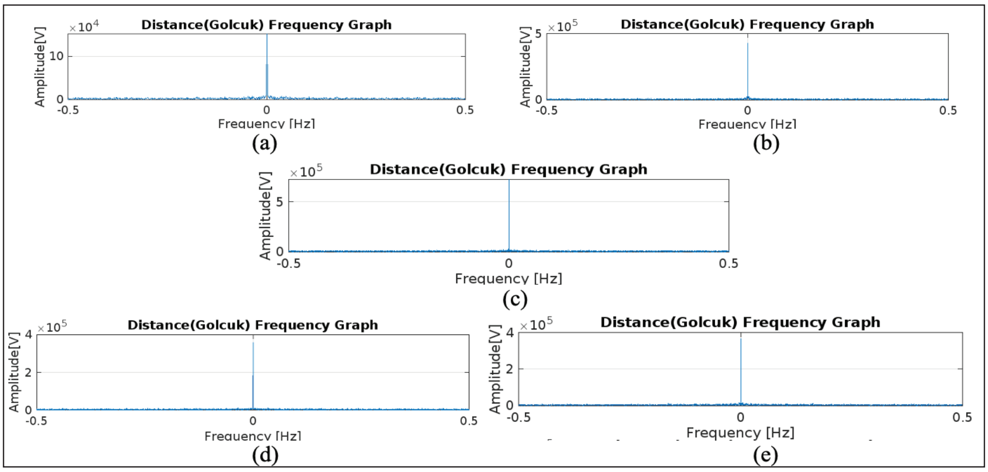

Figure 19. Region 2 Distance 1 Frequency Graph a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

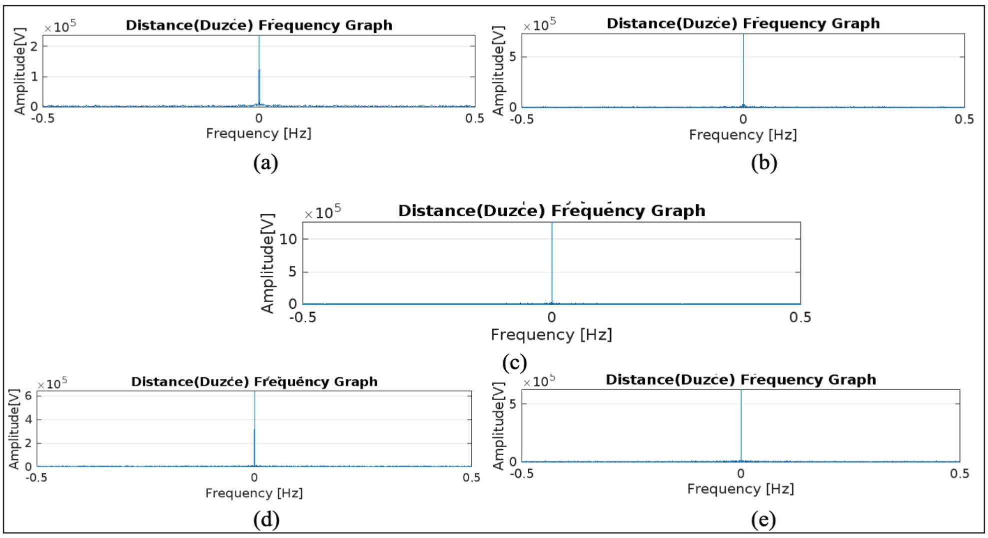

Figure 20. Region 2 Distance 2 Frequency Graph a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

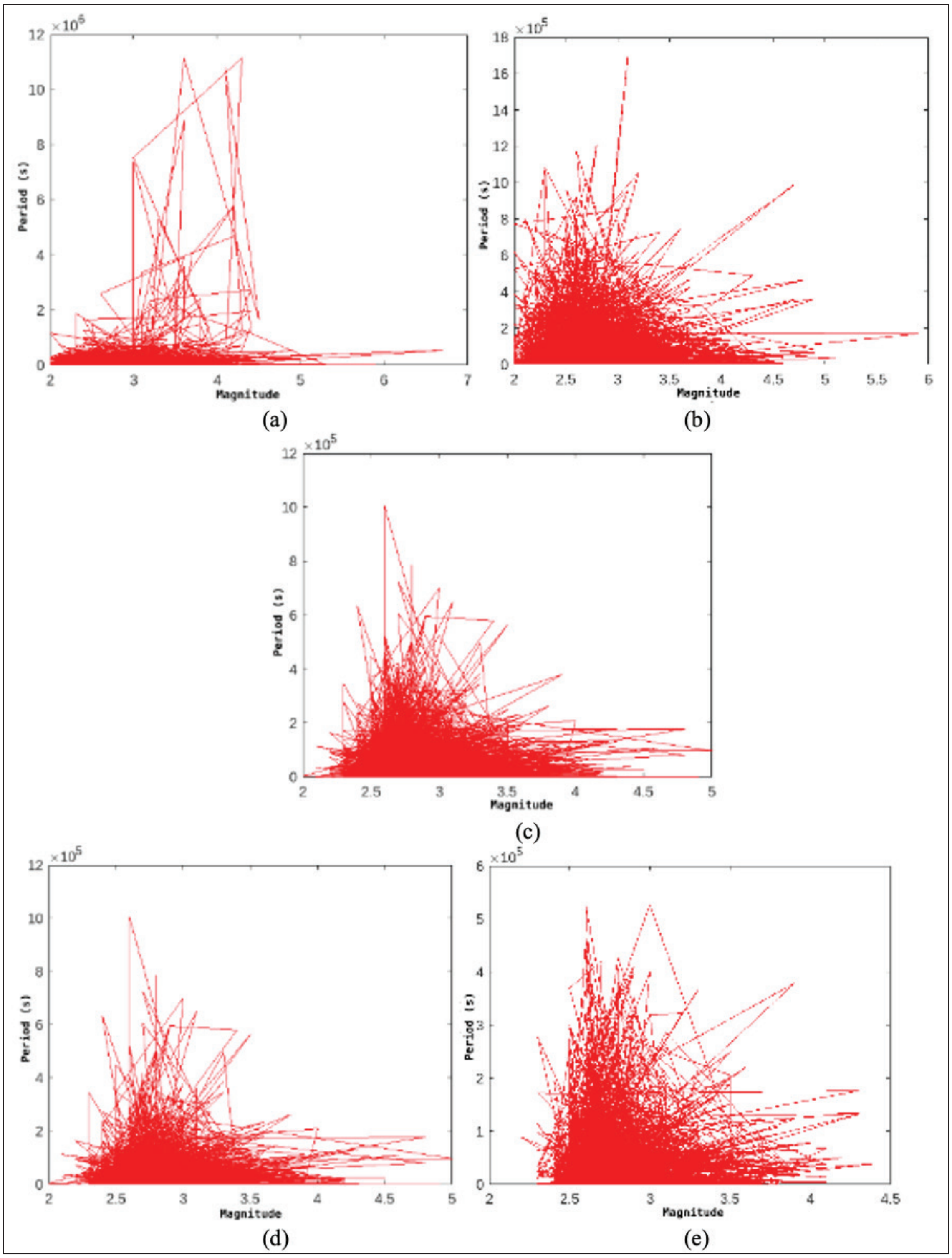

Figure 21. Region 2 Magnitude-Period Phase Portraits a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

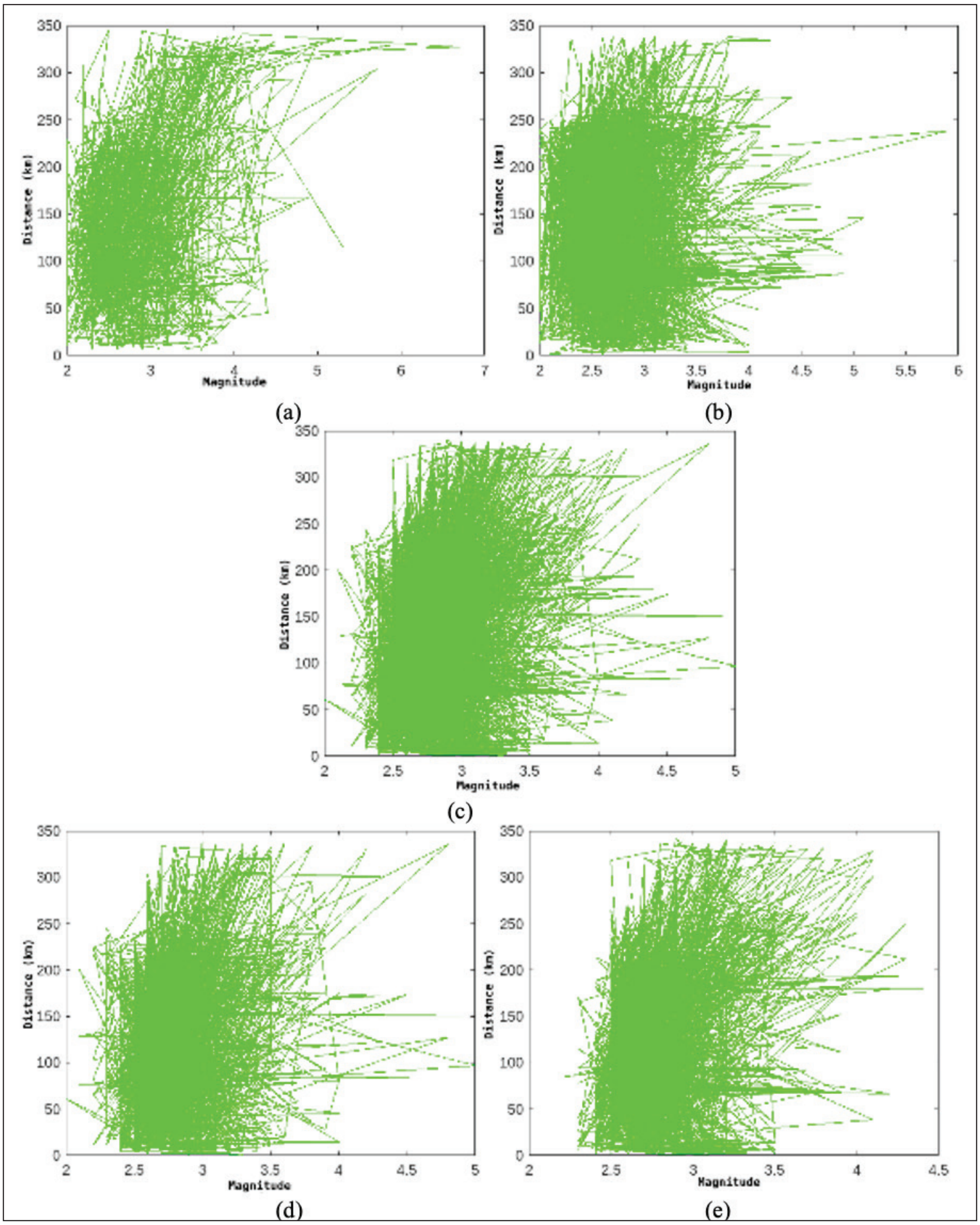

Figure 22. Region 2 Magnitude-Distance Phase Portraits a)1970-1980, b)1980-1990, c)1990-1999, d) 1990-1995, e) 1995-1999.

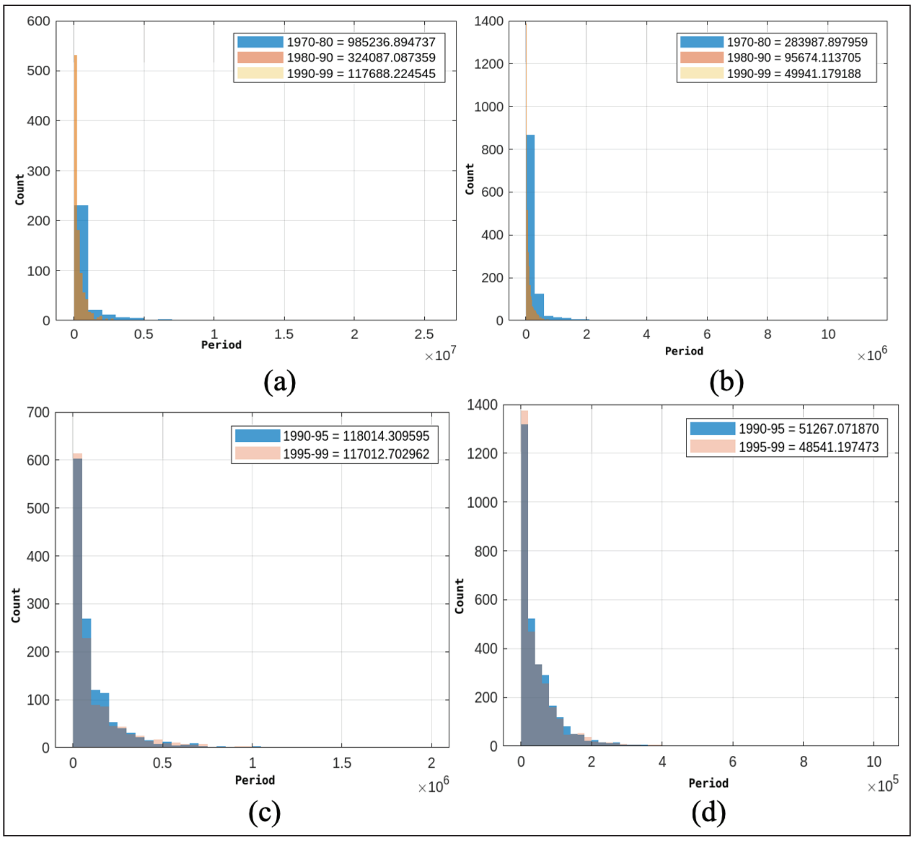

Figure 23.. Period Histograms a) Region 1 1970-1999, b) Region 2 1970-1999, c) Region 1 1990-1999, d) Region 2 1990-1999.

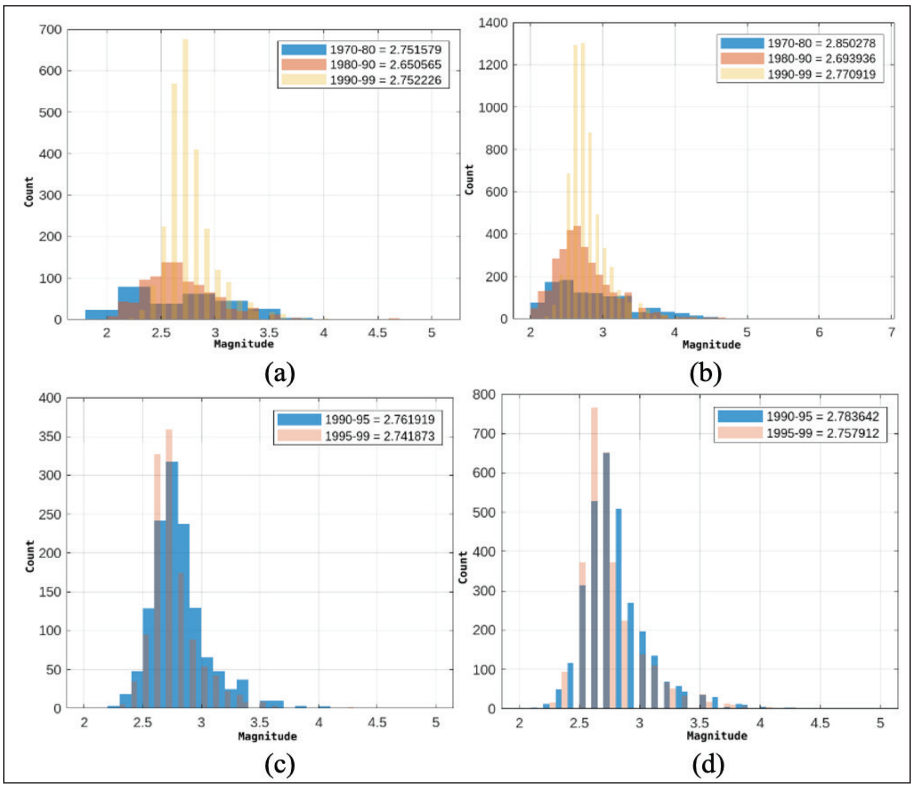

Figure 24. Magnitude Histograms a) Region 1 1970-1999, b) Region 2 1970-1999, c) Region 1 1990-1999, d) Region 2 1990-1999.

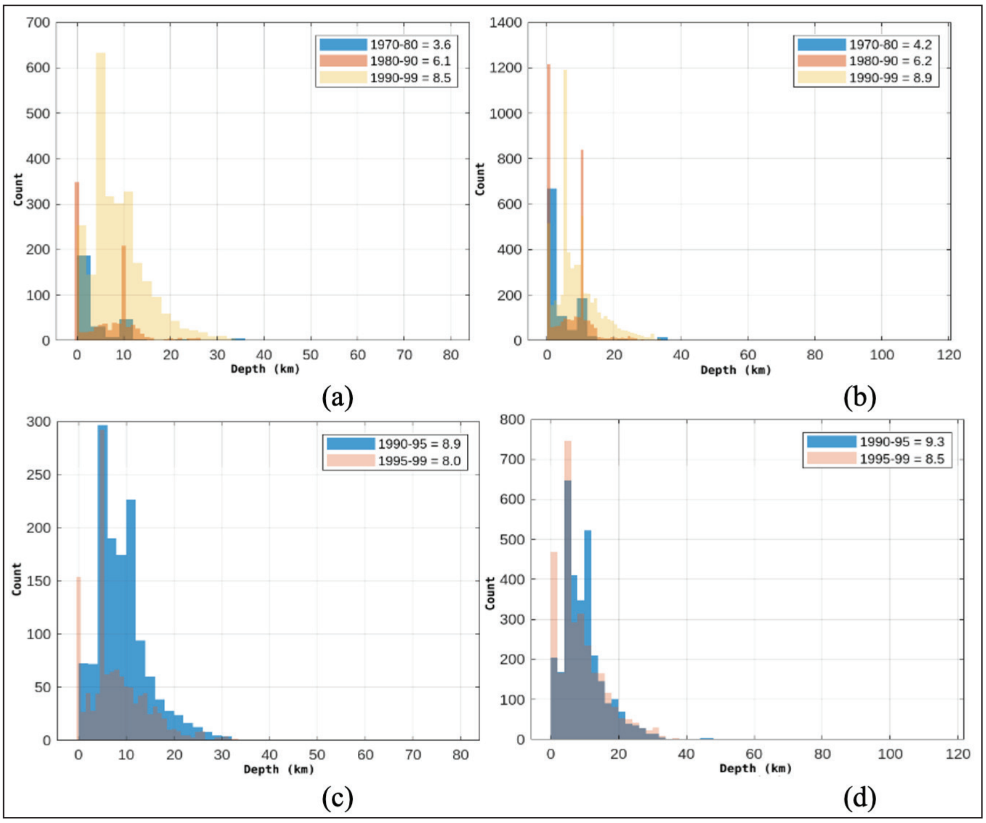

Figure 25. Depth Histograms a) Region 1 1970-1999, b) Region 2 1970-1999, c) Region 1 1990-1999, d) Region 2 1990-1999.

1995-1999. This decrease implies a reduction in chaos and suggests that a major earthquake is approaching. The low Lyapunov value in the data from the last 5 years, especially for the years 1995-1999, is noteworthy. The years 1970-1980 had a small number of earthquakes, and the chaos in the magnitude values was high. Looking at the years 1980-1990, it is observed that chaos is higher compared to the last 10 years.

In the graph obtained for the period, it can be said that the evaluation is challenging for the years 1970-1980 due to the small amount of data. For the years 1980-1990, the Lyapunov value is lower, implying that the earthquake interval is less chaotic than the last 10 years. In the last ten years before the major earthquake, it was observed that the complexity of the time difference between consecutive earthquakes increased compared to other years. This suggests that predicting when an earthquake will occur before a major earthquake can become unpredictable.

The largest Lyapunov exponents for both regions, five-time intervals, and four different characteristics have been recorded in Table 3 and Table 4. These tables allow for the examination of the chaotic nature and the variation with respect to the time series and regions.

CONCLUSION

This study analysed earthquake data using four main characteristics: earthquake magnitude, depth, the time interval between two consecutive earthquakes, and the distance between earthquakes and significant earthquakes that occurred.

The analysis results indicate that as a large earthquake approaches, there is a significant decrease in the chaos of earthquake magnitude. Based on this, it is believed that considering the parameter of earthquake magnitude will increase the likelihood of success in prediction studies. When the earthquake period is examined, it is generally observed to increase as the earthquake approaches, but it is believed to reach saturation. No distinctive feature as pronounced as earthquake magnitude and period has been found in the examined depth and distance parameters.

Since the region and year selection is specific as in other studies in the literature, earthquake analysis studies cannot be compared in this respect. However, studies in the literature generally focus on the chaos of the earthquake and analyse it based on its magnitude. In this study, on the other hand, four different parameters of the earthquake were considered, evaluated separately, and analysed, aiming to achieve a more diverse and comprehensive perspective.

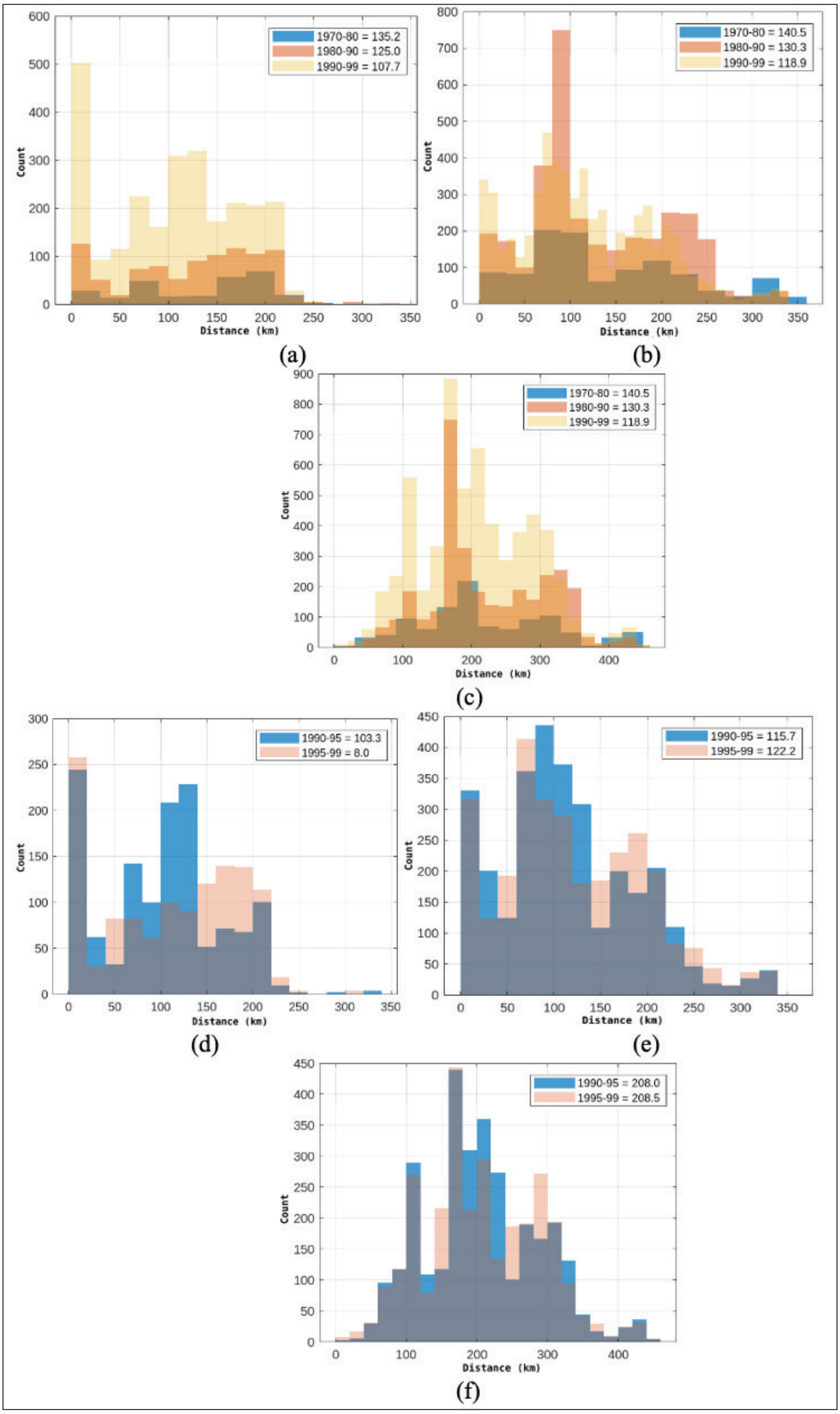

Figure 26. Distance Histograms a) Distance 1 for Region 1 1970-1999, b) Distance 1 for Region 2 1970-1999, c) Distance 2 for Region 2 1990-1999, d) Distance 1 for Region 1 1990-1999, e) Distance 1 for Region 2 1990-1999, f) Distance 2 for Region 2 1990-1999.

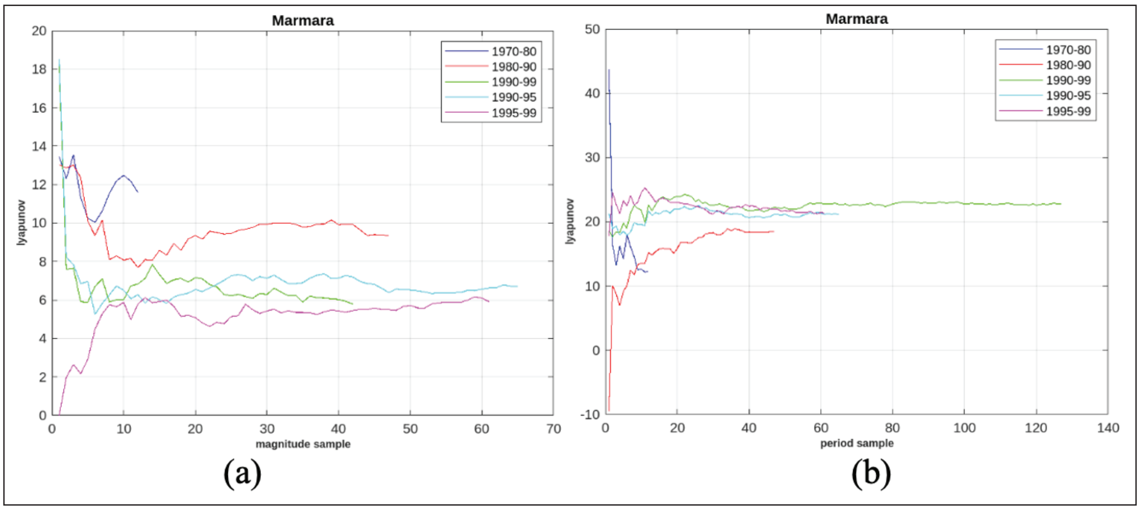

Figure 27. Earthquake Sample-Maximum Lyapunov Exponent a) Magnitude, b) Period.

Table 3. Maximum Lyapunov Exponent for Region 1

	period	magnitude	depth	distance (Golcuk)
1970-1980	12.3505	11.586	11.2072	13.8149
1980-1990	18.4613	9.333	15.8291	17.2275
1990-1999	22.7811	5.7860	17.6084	20.7139
1990-1995	21.0719	6.7222	15.4252	19.4666
1995-1999	21.3586	5.908	16.0193	19.3204

Table 4. Maximum Lyapunov Exponent for Region 2

	period	magnitude	depth	distance (Golcuk)	distance (Duzce)
1970-1980	17.024	11.345	17.1672	17.5122	17.3641
1980-1990	21.9841	10.1227	17.3073	20.4834	20.5179
1990-1999	23.6318	8.3172	17.9624	22.1843	22.1843
1990-1995	22.2651	7.0714	17.1739	20.2456	19.5648
1995-1999	22.7333	7.6290	17.5525	20.7375	20.0788

Using these varying characteristics, as shown in this study, in earthquake prediction efforts could enhance success and provide guidance to researchers.

CREDIT AUTHOR STATEMENT

Zeynep Calim: Methodology,Literature Review, Software, Writing. Zehra Gulru Cam Taskiran: Software Validation. Tulay Yildirim: Conceptualism Mentorship.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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