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Spatiotemporal analysis of fatal earthquakes between 1800 and 2015 at a global scale

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ABSTRACT

Earthquakes are catastrophic natural disasters and along with their aftereffects, they have caused significant fatalities, injuries and economic losses throughout history, and have changed the landscape physically. There is a need to understand the distribution and associated damage patterns of earthquakes to be better prepared and to ensure mitigation of damage in the future. This study analyses the spatial and spatiotemporal trends of earthquake occurrence and associated fatality at a global scale over the 215-year period between 1800 and 2015. Spatial and spatiotemporal analyses revealed that certain countries in Asia including Türkiye, China, India, Pakistan and Indonesia suffered the most both in terms of fatality and earthquake occurrence. There were significant spatiotemporal clusters of earthquake occurrence over this time period on the southern half of Asia, Türkiye and southwest Europe and northern Africa. The findings of the study provide a spatial and spatiotemporal characterization of fatal earthquakes and improve our understanding of these patterns at the global scale. Spatial analyses covering longer time intervals at regional and global scales should be undertaken in future studies to provide a more comprehensive understanding of earthquake occurrence and associated damage patterns.

1. Introduction

Throughout history, earthquakes and their associated aftershocks have resulted in a large number of injuries and deaths, as well as significant economic loss and changes in the physical landscape. Most earthquakes take place on major plate boundaries and in areas that are subject to stress from the movement of the plates (Shedlock & Pakiser, 1998). There is a need to understand the distribution of earthquakes and the associated damage resulting from them to be better prepared and to mitigate any damage in the future.

We have some understanding of spatial distributions and/or fatality associated with earthquakes at the country and regional levels particularly in certain seismically active regions. For example, Al-Ahmadi et al. (2014) analyzed spatial patterns of earthquake occurrence between 1900 and 2009 in the Red Sea to identify seismic clusters. Spatial analysis of earthquake occurrence and fatality in Türkiye for the period 1900 and 2015 was conducted by Gökkaya (2016). Province and region scale geostatistical analyses of earthquake occurrence in Türkiye were carried out by Akyürek & Arslan (2018) for the period 1900 and 2016 and Tağıl & Alevkayalı (2013) for the period 1900 and 2012, respectively. Seismic activity around the island of Cyprus for the period between 1900 and 2021 was spatially analyzed by Alevkayalı & Dindar (2022). Hashemi & Alesheikh (2011) analyzed the spatial and temporal trends of seismic activity since 1900 in Tehran, Iran. Annual mortality risk associated with earthquakes was modelled at the global scale by Li et al. (2015). Spatiotemporal characteristics of earthquakes have been addressed at the national and regional scales in a few studies. For example, Zohar et al. (2017) evaluated the spatial and temporal trends in earthquake occurrence and associated damage in Israel. Zheng-Xiang et al. (2005) analyzed shallow (focal depth ≤ 70 km) and strong (Ms≥ 6.0) earthquakes and fatality associated with them between 1901 and 2001 on mainland China. Benito et al. (2004) looked at the temporal and spatial trends of earthquakes in 2001 in El Salvador. Xu & Ouchi (1998) analyzed spatial and temporal characteristics of great earthquakes (Ms≥ 8.0) that occurred in Asia between 1934 and 1970. Utsu (1980) characterized the spatial and temporal distribution of earthquakes in Japan. In California, United States, Godano et al. (1999) tested a multifractal declustering method to predict spatiotemporal distribution of earthquakes between 1975 and 1995.

It is obvious from the abovementioned studies that a spatiotemporal analysis of earthquakes, i.e., how they are distributed through time and space, at a global scale

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is missing. Having information on the spatial and spatiotemporal patterns of earthquake occurrence and associated damage is important and necessary for a) filling the missing knowledge gap in terms of basic science, and b) better preparedness and damage mitigation for future earthquakes in terms of policy and practical aspect. In this study, the earthquakes that took place since 1800 which resulted in fatality at a global scale were examined. Specific objectives are to i) analyze the spatial patterns of earthquake occurrence and associated death at the country level, and ii) investigate the spatiotemporal patterns of earthquake occurrence. Findings are expected to improve our understanding of global trends of earthquake occurrence and associated fatality in a spatiotemporal context.

2. Materials and methods

2.1. Data

The earthquake data were acquired from National Centers for Environmental Information, Significant Earthquakes Database (NOAA, 2021). Only those earthquakes which caused death directly from the earthquake (i.e., excluding the earthquakes with fatality that only was caused by secondary effects like tsunamis and landslides) between 1800 and 2015 were considered. Shapefiles with global administrative units at the country level were downloaded from the Global Administrative Areas website and then converted to Equidistant Azimuthal projection (GADM, 2021). This distance preserving projection allowed accurate spatial statistical calculations. Next, earthquake location point shapefile was joined to the global countries polygon shapefile by summing number of earthquakes and fatality. Finally, histogram of earthquake magnitude was generated to obtain descriptive characteristics.

2.2. Spatial analysis

Average nearest neighbor (ANN) analysis was used to test whether earthquake distribution had a clustered pattern. In this analysis, the distances between each feature centroid and its nearest neighbor's centroid are measured and then all these nearest neighbor distances are averaged. The ANN ratio is calculated by dividing the observed average distance by the expected average distance according to the formulae below:

$$ANN = \frac{\overline{D}_O}{\overline{D}_E} \tag{1}$$

where $\overline{D}_O$ is the observed mean distance between each feature and its nearest neighbour:

$$\overline{D}_O = \frac{\sum_{i=1}^{n} d_i}{n} \tag{2}$$

and $\overline{D}_E$ is the expected mean distance for the features given in a random pattern:

$$\overline{D}_E = \frac{0{,}5}{\sqrt{n/A}} \tag{3}$$

here d_i represents the distance between feature i and its nearest neighbouring feature,

n corresponds to the total number of features, and A is the area of a minimum enclosing rectangle around all features, or a user-specified area value.

If the average distance is less than the average for a hypothetical random distribution (i.e., when the ANN ratio is less than 1), the distribution pattern is considered clustered. If the average distance is greater than the average for a hypothetical random distribution (i.e., when the ANN ratio is greater than 1), the distribution pattern is considered dispersed (Rogerson, 2015).

Statistically significant clusters and outliers of earthquake occurrence and fatality at the country level were identified using the Anselin Local Moran's I statistic (Anselin, 1995). The Local Moran's I coefficient for the i observation is defined with the formula:

$$I_i = \frac{(x_i - \bar{x}) \sum_{j=1}^{n} w_{ij}(x_j - \bar{x})}{\sigma^2} \tag{4}$$

where n is the number of spatial objects (the number of points or polygons), x_i are the values of the variable for the compared objects, $\bar{x}$ it is the mean value of the variable for all objects, w_{ij} is the spatial weight between feature i and j, and σ^2 is the variance, which is calculated as follows:

$$\sigma^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \tag{5}$$

This statistic was preferred over hot spot analysis because it also allows for the identification of outliers. A positive I value indicates that a feature is surrounded by features that have similarly high or low values, i.e., it belongs to a cluster. A negative value for I indicates that a feature is surrounded by features with dissimilar values, i.e., an outlier. Z-scores and p-values were then calculated, which are used to determine significance. A p-value of 0.05 was used as the significance threshold. In addition, a fixed distance band spatial relationship with a Euclidean distance (i.e., straight line distance) and a 4971835 m threshold distance was used in the analysis. The threshold distance (i.e., the distance at which the spatial autocorrelation is maximized) was determined using an incremental spatial autocorrelation function.

2.3. Spatiotemporal analysis

Earthquake occurrence data between 1800 and 2015 were analyzed using space-time scan statistics to understand the spatiotemporal patterns of the data. The open source SaTScan software with the retrospective space-time analysis with a space-time permutation probability model was employed to identify clusters. In this analysis, the space-time permutation only requires case data with spatial location and time information. A cluster in a geographical area is identified if during a specific time period, that area has a higher proportion of its cases in that time period compared to the remaining geographical areas. This is done by comparing the number of observed cases in a cluster to what would have been expected if the spatial and temporal locations of all cases were independent of each other so that there is no space-time interaction. The analysis uses a cylindrical window, in which the circular or elliptical base corresponds to space and the height represents the time period of potential clusters. Then, the cylindrical window is moved in space and time, ensuring that each possible time period is considered for each possible geographical location and size. As a result, an infinite number of overlapping cylinders of different size and shape (each of which represents a possible cluster), jointly covering the entire study region are obtained. The significance of identified space-time clusters is determined by the p-value, which is calculated with the Monte Carlo replication. SaTScan performs simulations to generate a number of random replications of the dataset. The null hypothesis is that there are no clusters and it's rejected if the maximum likelihood ratio calculated for the most likely cluster in the dataset is greater than the maximum likelihood ratios calculated for the most likely clusters in the random dataset (Kulldorff, 2015).

In the space-time permutation model, the likelihood ratio function approximates a Poisson distribution. The Poisson generalized likelihood ratio (GLR) is used to test the null hypothesis (Kulldorff et al. 2005). The Poisson GLR is obtained by the following formula:

$$\left(\frac{c}{E[c]}\right)^{c}\left(\frac{C-c}{C-E[c]}\right)^{C-c} I() \tag{6}$$

where C is the total number of cases, c is the observed number of cases within the window, $E[c]$ is the expected number of cases within the window under the null-hypothesis, $C-E[c]$ is the expected number of cases outside the window, and $I()$ is an indicator function set to 1 when SaTScan scans for clusters with either high or low rates.

Among the many windows evaluated, the one with the maximum GLR constitutes the space–time cluster of cases that is the least likely to be a chance occurrence (Kulldorf et al. 2005). A more in-depth statistical discussion of the space-time permutation model can be found in Kulldorf et al. 2005.

One of the outputs of SaTScan analysis is a shapefile showing the identified clusters. The attribute table of this shapefile includes information about the cluster centroids, cluster radius, start and end date of time interval of the cluster, the number of earthquakes in that cluster and the associated p value. This cluster shapefile was overlaid the countries and earthquake occurrence layers to generate the spatiotemporal cluster map.

3. Results and discussion

3.1. Descriptive statistics

There were 1558 earthquakes resulting in fatality between 1800 and 2015. Magnitude of these earthquakes displayed a normal distribution with an average of 6.4 with 5.8 and 7.1 representing the 25th and 75th percentiles, respectively (Figure 1). The total death toll associated with the earthquakes over this time period was 2731370. Haiti was by far the country that suffered the most in terms of fatality per earthquake with only four earthquakes resulting in approximately 321000 deaths. Turkmenistan and Armenia followed Haiti which had 36803 and 13945 fatalities per earthquake, respectively (Appendix 1).

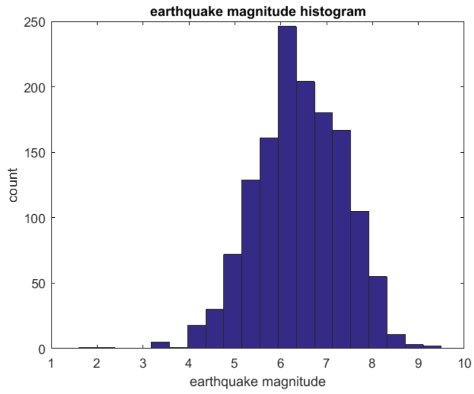

Figure 1. Histogram showing the magnitudes of the earthquakes between 1800 and 2015

3.2. Spatial patterns

Earthquake distribution was very significantly (p≈ 0) clustered and concentrated around plate boundary lines in Asia, Europe, Oceania, Africa and North, Central and South America (Figure 2).

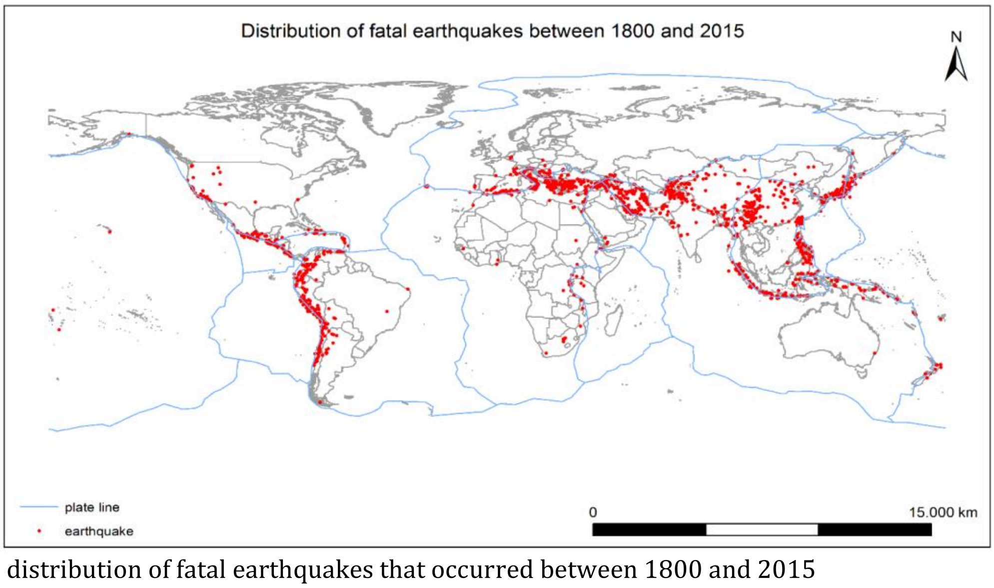

Figure 2. Global distribution of fatal earthquakes that occurred between 1800 and 2015

Only nine countries were significant clusters or outliers of fatality resulting from the earthquakes between 1800 and 2015. In these countries, 2170820 people died, which accounts for 79% of the total death toll over 215 years (Table 1).

Table 1. Countries that are significant clusters of fatality resulting from the earthquakes between 1800 and 2015

Country	Total fatality	p value	Cluster type
China	732126	≈ 0*	HH
Japan	224831	≈ 0*	HH
Pakistan	157996	≈ 0*	HH
Iran	249573	≈ 0*	HH
Haiti	321006	≈ 0*	HL
Turkmenistan	110411	≈ 0*	HH
Italy	149611	4.1×10^{-3}	HL
India	61470	0,01	HH
Türkiye	163796	0,05	HL

**High-high (HH) clusters refer to those countries with high fatality values which also are surrounded by countries with high fatality values while high-low (HL) outliers refer to those countries with high fatality values which are surrounded by countries with low fatality values. p values smaller than the order of 10-3 are expressed as ≈* 0

All the countries were located in Asia with the exception of Italy and Haiti. Japan, China, India, Pakistan, Iran and Turkmenistan were high-high clusters, indicating that the countries around them also had high fatalities. On the other hand, Italy, Türkiye and Haiti were high-low outliers, surrounded by countries with low fatalities (Figure 3). Some of these countries identified in this study as high-high clusters like India, China, Pakistan, Iran, and Turkmenistan also were found to have high annual earthquake mortality risk by Li et al. (2015).

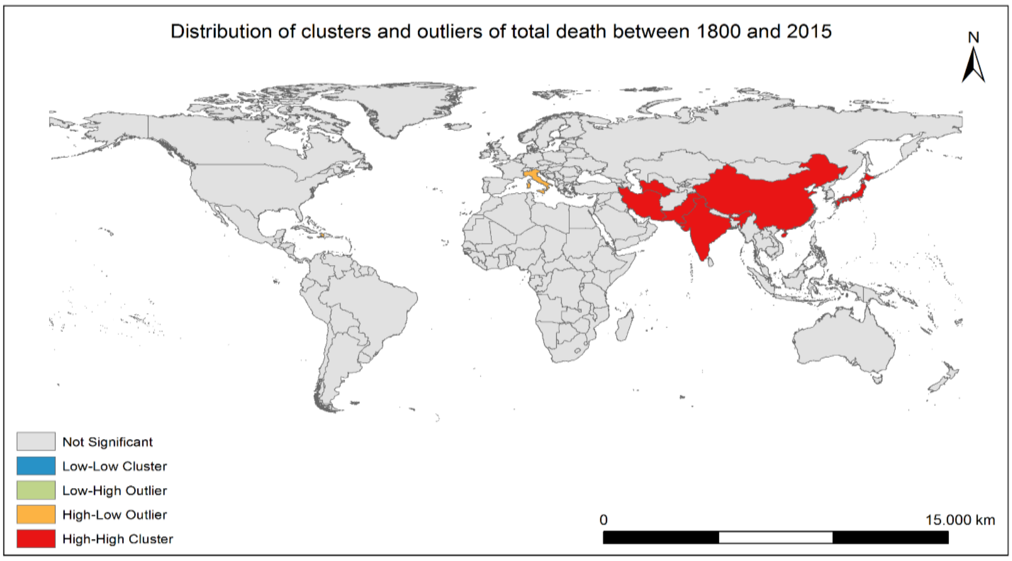

Figure 3. Distribution of countries that are clusters and outliers of total death resulting from the earthquakes between 1800 and 2015

Fourteen countries were significant clusters or outliers of earthquake occurrence over the 215 year period. Total number of earthquakes in these countries, 1056, made up 68% of the total occurrence (Table 2).

Table 2. Countries that are significant clusters of earthquake occurrence between 1800 and 2015

Country	Total fatality	p value	Cluster type
China	174	≈ 0*	HH
Iran	149	≈ 0*	HH
Japan	81	≈ 0*	HH
Türkiye	129	≈ 0*	HL
Taiwan	57	≈ 0*	HH
Italy	69	1.3×10^{-3}	HL
Pakistan	31	1.8×10^{-3}	HH
Afghanistan	32	4.5×10^{-3}	HH
India	31	0,01	HH
Indonesia	101	0,03	HL
Peru	61	0,04	HL
Greece	61	0,04	HL
Mexico	51	0,06	HL
Algeria	29	0,08	HL

**High-high (HH) clusters refer to those countries with high values of earthquake occurrence which also are surrounded by countries with high values of earthquake occurrence while high-low (HL) outliers refer to those countries with high values of earthquake occurrence which are surrounded by countries with low values of earthquake occurrence. p values smaller than the order of 10-3 are expressed as ≈ 0*

Most of the countries that had high fatality also were clusters or outliers of earthquake occurrence. Additional countries that had significant clusters of earthquakes but not significant clusters of fatality included: Algeria in Africa; Mexico and Peru in the Americas; Taiwan, Indonesia, Afghanistan in Asia; and Greece in Europe. Unlike the fatality patterns, Turkmenistan and Haiti did not show significant clusters of earthquake occurrence. This is reflected in their very high fatality rates (Appendix 1). Indonesia, Türkiye, Greece, Italy, Algeria, Peru and Mexico were significant outliers surrounded by countries that had a small number of earthquakes. Similar to the pattern in fatality, most of the countries identified in Asia were surrounded by countries that also had a high number of earthquake occurrence (Figure 4).

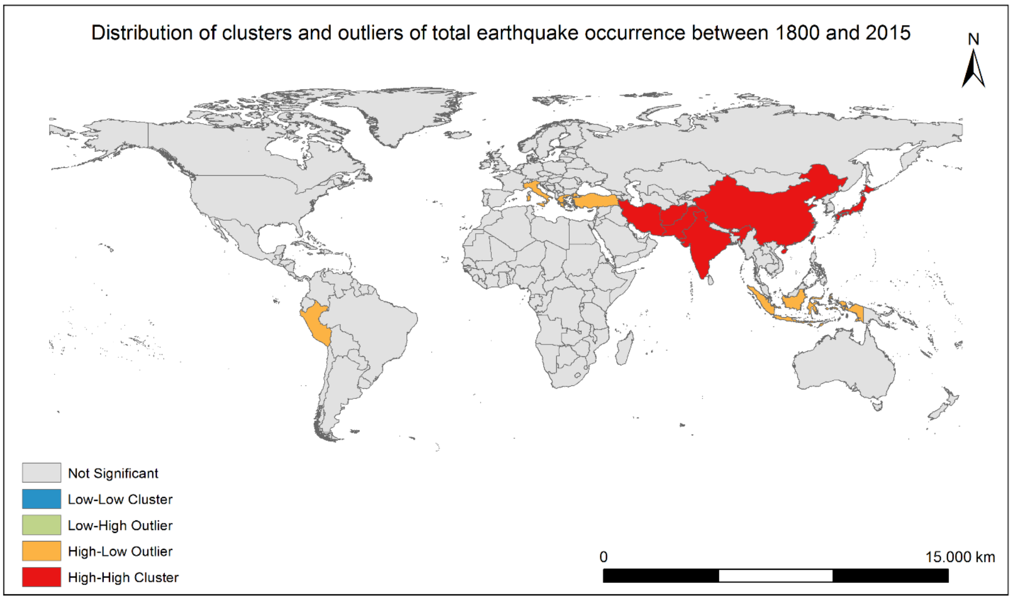

Figure 4. Distribution of countries that are clusters and outliers of total earthquake occurrence between 1800 and 2015

3.3. Spatiotemporal analysis of earthquake occurrence

Spatiotemporal analysis identified 12 clusters, most of which were centered over Asia. Three of them were over Türkiye and one of them was over Iran. There was one in Central America over Guatemala and El Salvador, and two in South America, one between Argentina and Chile border and the other one at the tip of the continent. However, only four of these 12 clusters were significant. They are indicated in blue circles in Figure 5.

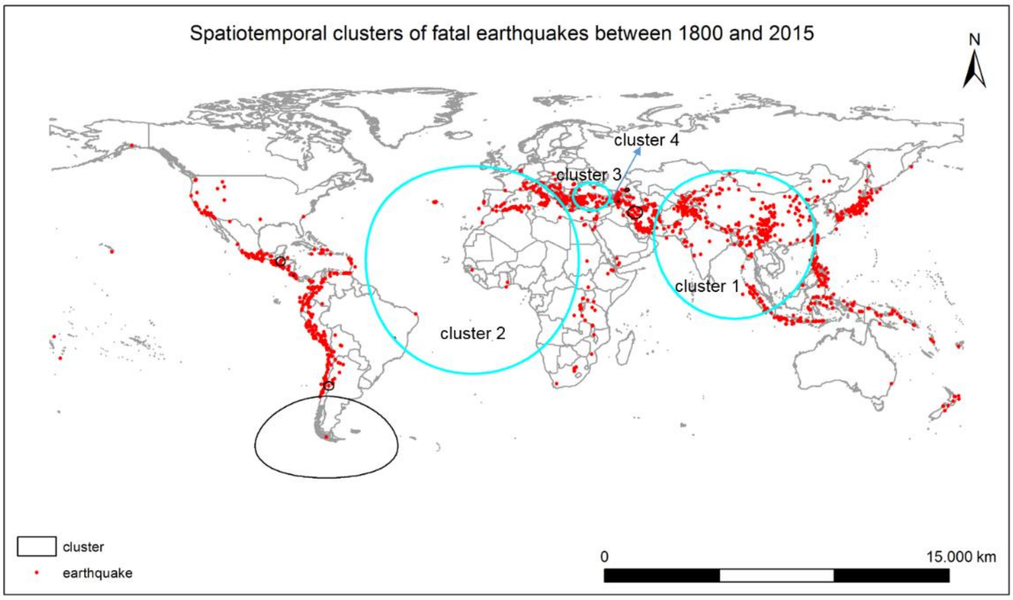

Figure 5. Spatiotemporal clusters of fatal earthquakes between 1800 and 2015. The clusters highlighted in blue are significant spatiotemporal clusters

Cluster 1 centered over the southern half of Asia included 374 earthquakes that occurred between 1996 and 2015 over a 20 year period resulting in 815697 deaths, or 30% of the total death toll over the 215 year period. The locations of the earthquakes were scattered across the countries identified as high clusters of earthquake occurrence and/or fatality such as India, China, Afghanistan, Pakistan, Tajikistan, Nepal and Indonesia. The other significant geographically large cluster, (cluster 2) covered Western Europe, western portion of Africa and eastern section of Brazil and the Azores in the Atlantic. There were 141 earthquakes in this cluster which corresponded to a 75 year period between 1817 and 1891 resulting in 184295 deaths, i.e., 7% of the total death toll over the 215 year period. Almost all of the earthquakes occurred in the Mediterranean basin including Italy, western Greece, northern Libya and southern Spain. Cluster 3 was mostly over Türkiye and the Black Sea. This cluster corresponded to an eight year period between 1938 and 1945 during which 80 earthquakes occurred, all of which were in Türkiye. The last significant cluster, cluster 4, was located in eastern Türkiye corresponding to a one year period in 1966 during which four earthquakes occurred (Table 3). The high frequency of earthquake occurrence in Türkiye also was observed through spatiotemporal analysis by Gökkaya (2016). Two significant clusters were identified over a 112 year period extending from 1900 to 2012.

It's also interesting that there were no significant spatiotemporal clusters in Central or Southern America despite the large number of earthquakes and clusters being identified there.

Table 3. Characteristics of the clusters identified by the spatiotemporal analysis

Cluster	Start date	End date	Number of earthquakes	p value
1	01.01.1996	31.12.2015	374	≈ 0*
2	01.01.1817	31.12.1891	141	≈ 0*
3	01.01.1938	31.12.1945	80	≈ 0*
4	01.01.1966	31.12.1966	4	0.03
5	01.01.1957	31.12.1963	21	0.34
6	01.01.1985	31.12.1985	8	0.35
7	01.01.1949	31.12.1949	3	0.36
8	01.01.1976	31.12.1977	3	0.44
9	01.01.1873	31.12.1874	13	0.75
10	01.01.1871	31.12.1872	1	0.99
11	01.01.1910	31.12.1910	2	0.99
12	01.01.1830	31.12.1830	2	0.99

**p values smaller than the order of 10-3 are expressed as ≈ 0*

The earthquake dataset utilized in this study is by no means exhaustive. The current study only considers those earthquakes in which death was attributed to the immediate earthquake in the vicinity of the epicenter. Therefore, some major earthquakes that caused significant fatality due to tsunamis far from the epicenter such as the Papua New Guinea earthquake that took place on July 17, 1998 were not considered. However, this is not likely to change the spatial and spatiotemporal patterns identified in this study because there are only a few earthquakes that were not included in the study. A very significant portion of the earthquakes that caused fatality are aligned on and/or in the vicinity of the major plate boundaries.

There are numerous seismic, geologic and site-specific factors like the earthquake magnitude, seismic wave attenuation, geological structure of the affected area, type and quality of construction, the closeness of the earthquake epicenter location to urbanized and industrialized centers, population density, and time of earthquake occurrence which all impact the damage and fatality caused by an earthquake. These factors were not considered in the current study, which focuses on the spatial and spatiotemporal analysis of global earthquake occurrence and associated fatality.

This study was conducted at the country scale but global geospatial analyses at finer geographic units like states and provinces would provide more detailed information on the occurrence and fatality patterns of earthquakes.

4. Conclusions

The global distribution of fatal earthquakes is significantly clustered around plate boundaries. Asia was impacted the most by earthquakes over the 215 year period between 1800 and 2015. In particular certain countries in Asia like Türkiye, China, India, Pakistan and Indonesia suffered the most both in terms of fatality and earthquake occurrence as shown by spatial and spatiotemporal analyses. There were significant spatiotemporal clusters of earthquake occurrence over this time period on southern half of Asia, Türkiye and southwest Europe and northern Africa. The findings of the study provide a spatial and spatiotemporal characterization of fatal earthquakes and improve our understanding of these patterns at the global scale. The information gained from the study will be useful to better plan for future earthquakes and mitigate the associated damage. Spatial analyses covering longer time intervals at regional and global scales should be undertaken in future studies to provide a more comprehensive understanding of earthquake occurrence and associated damage patterns as well as examining the relationship between fatality and factors contributing to it.

Author Contributions

A single author carried out the study.

Statement of Conflicts of Interest

The author declares no conflicts of interest.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

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Appendix

Appendix 1. The number of earthquakes and associated fatality by country between 1800 and 2015

Country	Continent	Total number of earthquakes	Total fatality	Fatality per earthquake
Afghanistan	Asia	32	12964	405
Armenia	Asia	2	27890	13945
Azerbaijan	Asia	4	218	54
Bangladesh	Asia	4	11	2
Bhutan	Asia	1	11	11
China	Asia	174	732126	4207
Georgia	Asia	6	548	91
India	Asia	31	61470	1982
Indonesia	Asia	101	34788	344
Iran	Asia	149	249573	1674
Iraq	Asia	2	120	60
Israel	Asia	2	8000	4000
Japan	Asia	81	224831	2775
Kazakhstan	Asia	4	463	115
Kyrgyzstan	Asia	5	267	53
Malaysia	Asia	2	19	9
Mongolia	Asia	1	30	30
Myanmar	Asia	12	1181	98
Nepal	Asia	6	20288	3381
Pakistan	Asia	31	157996	5096
Palestine	Asia	2	288	144
Philippines	Asia	41	5397	131
Russia	Asia	9	2470	274
South Korea	Asia	1	9	9
Syria	Asia	1	148	148
Taiwan	Asia	57	14485	254
Tajikistan	Asia	10	4089	408
Türkiye	Asia	129	163796	1269

Continuation of appendix 1

Country	Continent	Total number of earthquakes	Total fatality	Fatality per earthquake
Turkmenistan	Asia	3	110411	36803
Uzbekistan	Asia	4	16894	4223
Yemen	Asia	3	4011	1337
Albania	Europe	16	3432	214
Belgium	Europe	2	3	1
Bosnia and Herzegovina	Europe	5	47	9
Bulgaria	Europe	4	138	34
Croatia	Europe	3	8	2
Cyprus	Europe	2	42	21
Czech Republic	Europe	1	2	2
France	Europe	8	5064	633
Greece	Europe	61	13608	223
Hungary	Europe	1	2	2
Italy	Europe	69	149611	2168
Kosovo	Europe	1	1	1
Macedonia	Europe	3	1100	366
Montenegro	Europe	2	132	66
Portugal	Europe	7	138	19
Romania	Europe	5	2659	531
Serbia	Europe	3	6	2
Slovenia	Europe	3	9	3
Spain	Europe	5	2924	584
Switzerland	Europe	1	1	1
Ukraine	Europe	1	11	11
Algeria	Africa	29	16308	562
Burundi	Africa	1	3	3
Democratic Republic of the Congo	Africa	5	75	15
Djibouti	Africa	1	2	2
Egypt	Africa	5	766	153
Ethiopia	Africa	2	70	35
Ghana	Africa	2	25	12
Guinea	Africa	1	443	443
Kenya	Africa	1	1	1
Libya	Africa	1	300	300
Malawi	Africa	3	13	4
Morocco	Africa	3	13828	4609
Mozambique	Africa	1	4	4
Rwanda	Africa	1	1	1
South Africa	Africa	8	48	6
South Sudan	Africa	1	31	31
Sudan	Africa	1	2	2
Tanzania	Africa	4	11	2
Tunisia	Africa	1	13	13
Uganda	Africa	3	152	50
Barbados	N. America	1	3000	3000
Costa Rica	N. America	14	2653	189
Cuba	N. America	1	8	8
Dominican Republic	N. America	2	8	4
El Salvador	N. America	12	6029	502
Guatemala	N. America	15	28082	1872
Haiti	N. America	4	321006	80251
Honduras	N. America	2	10	5
Jamaica	N. America	1	1000	1000
Martinique	N. America	2	391	195
Mexico	N. America	51	12143	238
Nicaragua	N. America	4	13457	3364

Continuation of appendix 1

Country	Continent	Total number of earthquakes	Total fatality	Fatality per earthquake
Panama	N. America	2	13	6
United States	N. America	38	1362	35
Argentina	S. America	9	22519	2502
Bolivia	S. America	4	115	28
Brazil	S. America	2	2	1
Chile	S. America	45	63246	1405
Colombia	S. America	36	5653	157
Ecuador	S. America	16	82310	5144
Peru	S. America	61	70412	1154
Trinidad and Tobago	S. America	1	1	1
Venezuela	S. America	15	28349	1889
Australia	Australia	1	12	12
Fiji	Australia	1	2	2
New Zealand	Australia	10	465	46
Papua New Guinea	Australia	15	3183	212
Solomon Islands	Australia	3	106	35
Tonga	Australia	1	1	1
Vanuatu	Australia	2	6	3
Total		**1558**	**2731370**	

**Only those countries with earthquake occurrence are listed*