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Seismology and Climatology: A Study of Seismological Impacts of Climate Change in Indonesia

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Abstract

Climate change has been a matter of discourse for the last several decades. Much research has been conducted regarding the causes and impacts of climate change around the world. The current research contributes to the knowledge of the influence of climate change on our environment, with emphasis on earthquake occurrences in the region of Indonesia. Using global temperature anomaly as a measure of climate change, and earthquake data in Indonesia for the period 1900-2022, the paper seeks to find a relationship (if any) between the two variables. Statistical methods used include normal distribution analysis, linear regression and correlation test. The results show peculiar patterns in the progression of earthquake occurrences as well as global temperature anomaly occurring in the same time periods. The findings also indicated that the magnitudes of earthquakes remained unaffected by global temperature anomalies over the years. Nonetheless, there appears to be a potential correlation between temperature anomalies and the frequency of earthquake occurrences. As per the results, an increase in temperature anomaly is associated with a higher frequency of earthquakes.

Keywords

Earthquakes, Climatology, Climate Change, Seismology, Correlation, Linear Regression, Indonesia

1. Introduction

Indonesia is recognized as a region vulnerable to earthquakes. This is because of its location at the intersection of three significant tectonic plates: the Indian-Australian, Eurasian, and Pacific plates. The Indian-Australian plate tends to shift northward, leading to a subduction zone beneath the Eurasian plates, while the Pacific plate moves in a westward direction [1]. Even though it is a known fact earthquakes are caused mainly as a result of geological influences, it is plausible that climatic factors also play a role in their occurrence. This study seeks to investigate a potential link between the recent changes in climate and the frequency of earthquakes in Indonesia. The purpose of this study is to not only investigate earthquake precursors but it also seeks to contribute to natural disaster risk assessment studies and disaster management planning.

Climate change has been known to have caused a great deal of natural disasters and extreme weather events, including; floods, droughts, and in other parts of the world, hurricanes. It's crucial to emphasize that climate change manifests various impacts worldwide and the impacts vary across different regions and climatic conditions. Due to its geography and topography, Indonesia has often been afflicted with shifts in rainfall and temperature [2]. The data that is analyzed is a collection of global temperature anomalies from 1900 to 2022, focusing on the time following the emergence of climate change impacts up to recent years. This will be compared with earthquake data of the same time period. Indonesia experiences some of the most powerful earthquakes.

When earthquakes surpass a magnitude of 9.0, they can cause destruction within a range of up to 1000 kilometers [3]. Despite occurring more frequently than average, considering the country's size, these earthquakes rarely lead to widespread devastation [3]. Numerous studies investigate potential abnormal heat patterns preceding major earthquakes [4] [5] [6] [7]. Some scholars deduce that abnormal heat patterns may be a result of the interaction of active tectonic plates beneath the surface of the earth. A similar research in Alaska [8], and conclude that global temperature anomalies have an effect of small and minor earthquakes.

Few research works have tackled the question of whether Indonesia is at a greater risk of earthquakes due to increasing temperature caused by global warming. The purpose of the current research is to make an attempt to answer this question by understanding the relationship between global temperature anomaly caused by climate change, and frequency of earthquake occurrences in Indonesia.

2. Materials and Methods

2.1. Data and Description of Variables

Global temperature anomaly data was collected from NOAA (National Oceanic and Atmospheric Administration) data-base [9]. The experimental data consist of global temperature anomaly data sets between the periods 1900 to 2022, and Indonesia seismic data for the period 1900-2022 have been collected from the earthquake database of the National Geophysical Data Centre (NCEI/WDS Global Significant Earthquake database) [10]. The specific time period represents the time period from the discovery of climate change effects to date. Temperature anomaly describes the difference between the long-term average temperature value and the recorded value. A positive temperature anomaly indicates that the temperature observed was warmer than the average value, while a negative anomaly indicates a cooler observed temperature [9].

2.2. Formatting of Mathematical Components

Research methods can be summarized as follows:

1) Conduct normal distribution analysis.

2) Conduct stability analysis.

3) Calculate linear closeness using linear regression equations.

4) Use a correlation test to determine the relationship between climate and earthquakes.

2.2.1. Normal Distribution Analysis

Normal Distribution will involve the calculation of the mean, mode, median, standard deviation and probability distribution in order to obtain a graphical representation of the data.

$$f\left(x \mid \mu,\sigma^2\right)=\frac{1}{\sigma\sqrt{2\pi}}\mathrm{e}^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

2.2.2. Stability Analysis

Stability analysis is used to describe how well the data can be managed and involves the determination of critical values based on the standard deviation. Critical values for a two-tailed test at a significance level α can be calculated using the inverse cumulative distribution function of the standard normal distribution (Z-distribution). In this paper, with a 95% confidence level ($\alpha = 0.05$), the critical values are:

Critical value for the right tail:

$$Z_{\alpha/2} = \Phi^{-1}\left(1-\alpha/2\right)z \tag{2}$$

Critical value for the left tail:

$$Z_{\alpha/2} = \Phi^{-1}\left(\alpha/2\right) \tag{3}$$

where Φ^{-1} represents the inverse cumulative distribution function of the standard normal distribution.

2.2.3. Linear Regression

Linear regression is used to determine the general trend of the data set. Consider a linear regression model for a set of data points $\left(x_i, y_i\right)$ where $i = 1,2,\cdots,n$: The simple linear regression equation:

$$y = mx + c \tag{4}$$

where m is the slope and c is the y-intercept. The slope m (coefficient) is calculated using:

$$m=\frac{n\sum(x_iy_i)-\sum x_i\sum y_i}{n\sum x_i^2-\left(\sum x_i\right)^2} \tag{5}$$

The y-intercept c is calculated using:

$$c=\frac{\sum y_i-m\sum x_i}{n} \tag{6}$$

The predicted value $\hat{y}$ based on a given x can be calculated as:

$$\hat{y}=mx+c \tag{7}$$

The coefficients m and c can also be computed using matrices:

$$\begin{bmatrix} m \\ c \end{bmatrix}=\left(X^{\mathrm{T}}X\right)^{-1}X^{\mathrm{T}}Y \tag{8}$$

where,

$$X=\begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ \vdots & \vdots \\ 1 & x_n \end{bmatrix} \tag{9}$$

and,

$$Y=\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{10}$$

2.2.4. Correlation Test

A correlation test used to express statistically how the two variables—Global Temperature Anomaly and Earthquake occurrence in Indonesia for the specified time period. The process involves calculating the Pearson correlation coefficient and determining P-values. Scatter-plots are used to help visualize the result.

Consider two variables X and Y for which we want to calculate Pearson's correlation coefficient (r) and its associated P-value. Let $X=\{x_1,x_2,\cdots,x_n\}$ and $Y=\{y_1,y_2,\cdots,y_n\}$ be the sets of values for each variable. The Pearson correlation coefficient (r) is given by:

$$r=\frac{n\sum xy-\sum x\sum y}{\sqrt{\left(n\sum x^2-\left(\sum x\right)^2\right)\left(n\sum y^2-\left(\sum y\right)^2\right)}} \tag{11}$$

To calculate the P-value associated with r, we can use statistical methods, such as:

Let r be the calculated correlation coefficient and df be the degrees of freedom.

$$\text{p-value}=P\left(|R|>|r|\right) \tag{12}$$

where $R\sim t(df)$.

3. Results

In order to obtain a more in-depth understanding of the data, the various statistical—normal distribution analysis, stability analysis and linear regression analysis were carried out on both data sets for the period 1900-2022 *i.e.* Global Temperature Anomaly data set and the data set of Earthquake Occurrences in Indonesia. All calculations were made using python and the results are summarized in the following tables and images.

3.1. Results on Global Temperature Anomaly Data

The following are the statistical results in the Global Temperature anomaly for the period 1900-2022 and they collectively offer a summary of the distribution, central tendency, and variability of data, allowing better understanding of the characteristics of the data:

Number of samples in Anomaly: 123

Mean Global Temperature Anomaly: 0.16341463414634147

Mode of Global Temperature Anomaly: 0.1

Median of Global Temperature Anomaly: 0.02

Standard deviation of Global Temperature Anomaly: 0.45355034652535176

A standard deviation of 0.5 with a mean of 0.2 indicates that the data is relatively tightly clustered around the mean of 0.2. Almost all of the data would falls within the range of approximately −0.8 to 1.2. The mode which is the most frequent value is 0.1, and the mid most value is 0.02.

Critical value for the right tail: 1.0523569785116922

Critical value for the left tail: −0.7255277102190094

Slope (Coefficient): 0.010538623260373269

Intercept: −20.502825579445638

3.2. Results on Highest Earthquake Magnitudes in Indonesia for the Period 1900-2022

The collective summary of the distribution, central tendency, and variability of data is as follows: Number of samples in Mag: 279

Mean: 6.640860215053763

Mode: 6.5

Median: 6.6

Standard deviation of Mag: 0.9344220572681842. A standard deviation of 0.9 with a mean of 6.6 indicates a high level of variation in the data around the mean. Majority of the data falls within the range of 3.9 to 9.3. The mode which is the most frequent value is 6.5, and the mid most value is 6.6.

Pearson's correlation coefficient: 0.2519665863046944

P-value: 0.00493231758965154

3.3. Correlation Test

Correlation Coefficient: −0.39

P-value: 0.0000

The correlation is statistically significant.

4. Discussion

4.1. Analysis of Global Temperature Anomaly Data

The line graph (**Figure 1**) of the Global Temperature Anomaly Data for the period 1900-2022 indicates an upward trend, with fluctuations throughout the time period. The highest temperature anomaly recorded is during the period 2020-2022, about 1.25 times higher than what is considered the normal global temperature. Between 2000 and 2010 there exists a sharp decrease in temperature anomaly. The lowest temperature anomaly recorded was between 1910 and 1920, less than −0.5 degrees of what is considered normal global temperature. While a temperature anomaly greater than 0 indicates a positive deviation from the average, or expected temperature range, a value less than 0 signifies a negative deviation from average temperature range. The overall upward trend indicates that global temperatures are likely to increase over the next few centuries.

The Normal Distribution Analysis (**Figure 2**) reveals a bell-shaped graph which implies that the data follows a normal distribution, exhibiting specific characteristics of a well-defined central tendency, and predictable patterns of variability. It's also notable that the left tail drops quickly compared to the right tail. The calculated mean was 0.163 (rounded off) while the median was 0.02. This indicates the data is not perfectly symmetric. The distribution is slightly positively skewed indicating that there may exist some positive outliers that caused a shift in the mean.

The linear regression equation is given by:

$$Y = -20.503 + 0.012X + \varepsilon \quad (13)$$

where, Intercept: −20.502825579445638.

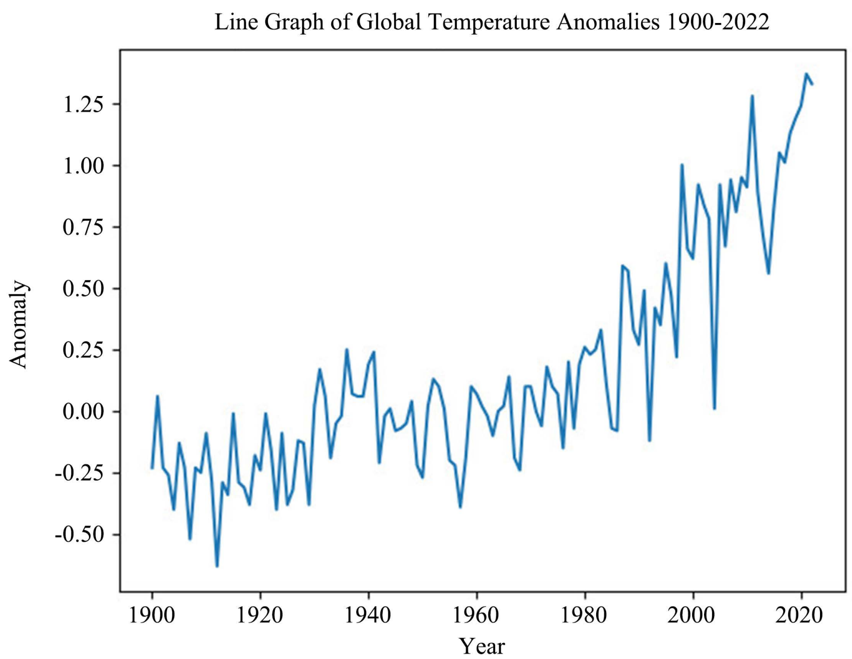

Figure 1. Global temperature anomaly from 1900-2022.

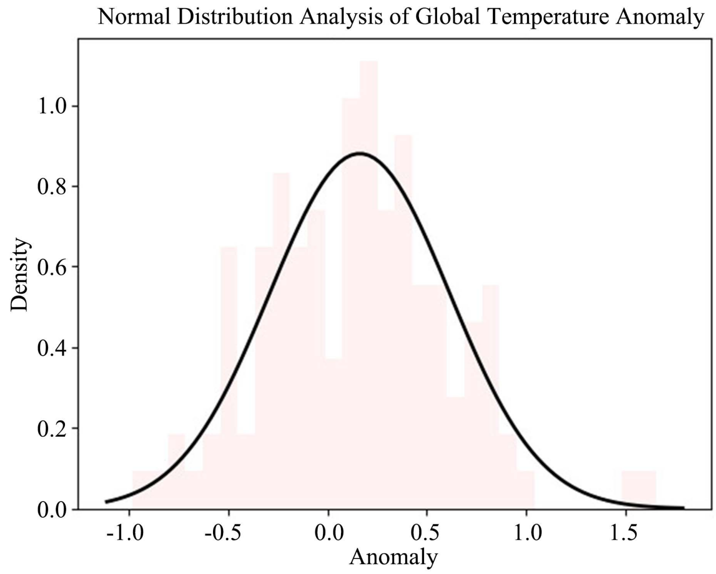

Figure 2. Normal distribution analysis of global temperature anomaly 1900-2022.

Slope: 0.010538623260373269. A positive slope means that as X increases, Y is expected to increase. That is, as the years increase, temperature anomaly is expected to increase. However, large negative intercept suggests that even when the independent variable X is zero, the expected value of Y is substantially lower (**Figure 3**).

The R-squared value of 0.6862183120507789 lies closer to 1 than 0, which indicates that the independent variable has a strong explanatory power on the dependent variable. Aside from potential bias caused by outliers, no other potential sources of bias were detected.

4.2. Analysis of Earthquake Data

According to the Scatter Plot (**Figure 4**), the cluster of points increases as years progress. This indicates an increase in earthquake occurrences in Indonesia over-time. The main cluster appears around magnitudes of 5 - 8, between the period 1980 and 2022. The largest Earthquake magnitude recorded, with a magnitude above 9 occurred after the year 2000. This coincides with the sharp temperature anomaly increase in the same time period.

The Normal distribution analysis (**Figure 5**) reveals a bell-shaped curve which indicates a level of symmetry. The mean of 6.64 and median of 6.6 indicate that data is nearly symmetric. A level of skewness can be observed as slightly positive, indicating the presence of positive outliers.

The standard deviation was 0.943 which indicates that most of the earthquakes were close to the mean in magnitude (6.64) Magnitudes between 6.0 and 6.9 are considered strong and could cause damage to infrastructure and could also be life threatening if they occur in highly populated areas. Kurtosis of −0.6279336419464818 which means the data have fewer extreme values (**Figure 6**).

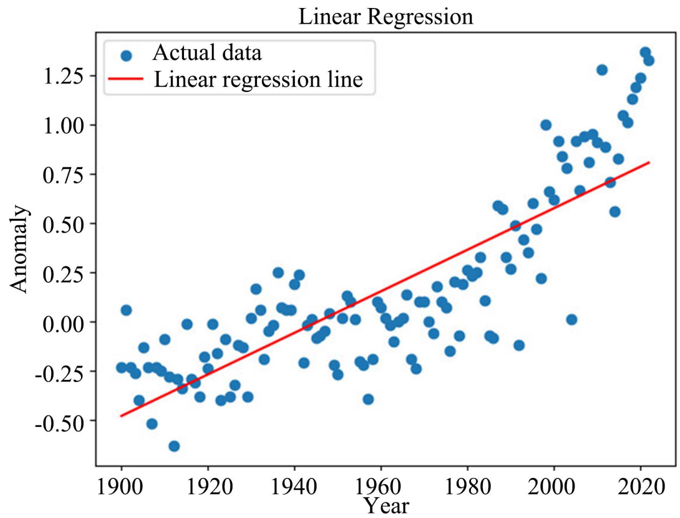

Figure 3. Linear regression analysis of global temperature anomaly.

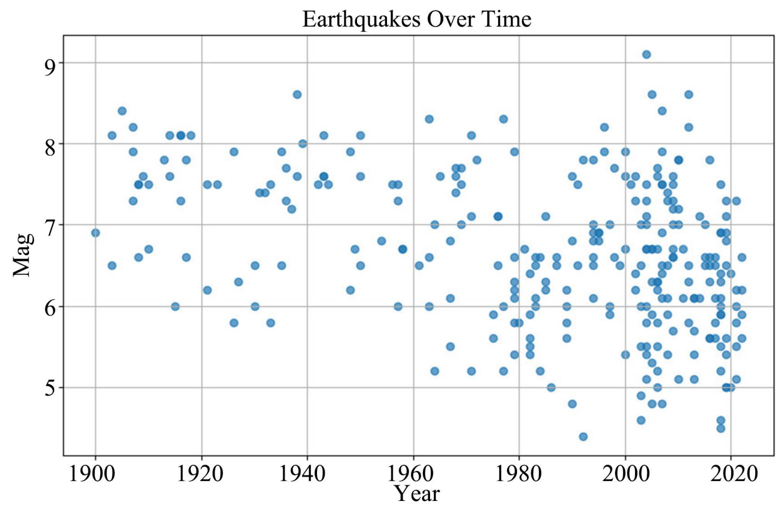

Figure 4. Scatter plot of earthquakes in Indonesia from 1900-2022.

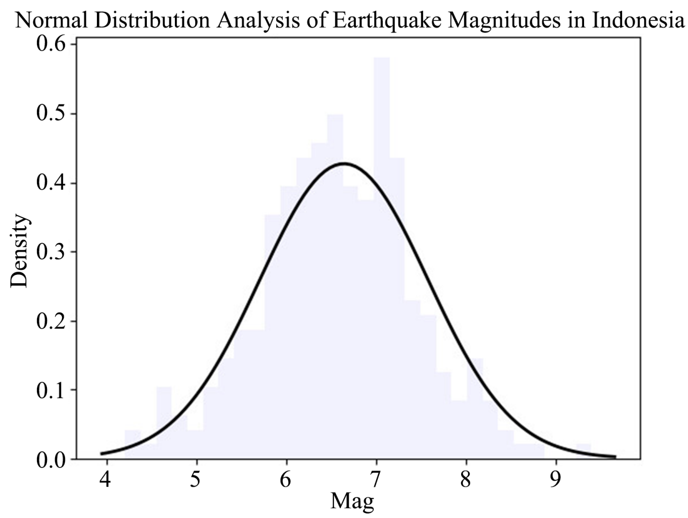

Figure 5. Normal distribution analysis of earthquake data in Indonesia 1900-2022.

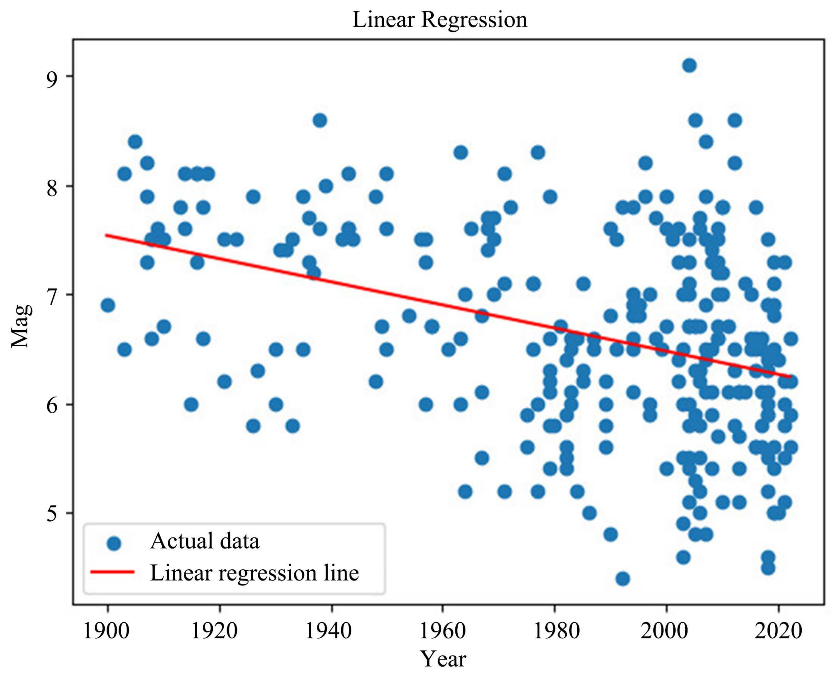

Figure 6. Linear regression analysis of earthquake occurrence in Indonesia 1900-2022.

The linear regression equation is given by:

$$Y = 27.674 - 0.011X + \varepsilon \tag{14}$$

where the intercept = 27.67431054034266 and the slope = −0.010599392828576283. A negative slope indicates a downward trend of earthquake magnitudes over time.

R-squared value of 0.14565349637741237 which means that only about 20 percent of the fluctuations in earthquake magnitudes are accounted for by the variables in the model. The other 80 percent is not explained by the model.

4.3. Correlation Test

The Correlation coefficient of −0.39 indicates a negative relationship between the two variables. As global temperature anomaly increases, the earthquake magnitudes in Indonesia tend to decrease, and vice versa. A P-value of 0 indicates that the observed result is extremely unlikely under the assumption that the null hypothesis is true. Therefore, the result is considered statistically significant.

5. Conclusions

The purpose of this research was to investigate the relationship between climate change (measured through increase in global temperature) and earthquake occurrences in Indonesia. Based on the results, it is evident that the relationship between temperature anomaly and earthquake occurrences is not a straightforward one. The results indicate that increase in global temperatures over the past century may have had an impact on the frequency of earthquakes. This conclusion was drawn from the observation that the highest global temperature recorded coincided with the most earthquakes occurrences in Indonesia. Another likelihood is that there perhaps exists a third factory responsible for both scenarios (high temperature and high earthquake frequency) to occur at the same time. The available evidence does not definitively indicate whether Indonesia faces a heightened risk of earthquakes due to rising temperatures attributed to global warming. Further research can be conducted to investigate this, as well as to understand different ways in which thermal stress could have geological impacts that lead to earthquakes.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviation

NOAA: National Oceanic and Atmospheric Administration
NCEI: National Centers for Environmental Information