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TABLE OF CONTENT

PART 1: MATHEMATICS

PART 2: STATISTICS

PART 3: COMPUTER SCIENCE & INFORMATION TECHNOLOGY

PART 4: OTHERS

THE IMPACT OF GEOMAGNETIC STORMS ON THE OCCURRENCES OF EARTHQUAKES FROM 1994 TO 2017 USING THE GENERALIZED LINEAR MIXED MODELS

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Abstract. This study is to investigate the impact of geoeffective solar events and geomagnetic storms on the occurrences of earthquakes from 1994 to 2017 in a statistical perspective where the data for the geomagnetic A_p index and shallow worldwide earthquakes were used. The A_p index is obtained from the Helmholtz-Centre Postdam – GFZ German Research Centre for Geosciences, and the earthquake events are from the United States Geological Survey (USGS) earthquake catalogue. We introduced the Generalised Linear Mixed Models (GLMM) to investigate a dynamic relationship between high geomagnetic storms with earthquake frequency across time. The GLMM is suitable for correlated and nonlinearly distributed data. It can be observed that there was an increase in earthquake frequency following the extreme value of the A_p index.

Keywords: Solar activity; geomagnetic storm; A_p index; earthquake; Generalised Linear Mixed Models (GLMM)

1. Introduction

In recent years many types of research have been done on the variation of earthquake activities related to solar events and geomagnetic interactions. The advanced research in sensors and understanding on how the Sun and Earth interact, encouraged the researchers to investigate this relationship further (Anagnostopoulos and Papandreou, 2012; Bijan, 2012a, 2012b; Herdiwijaya et al., 2015; M.H. Jusoh, 2013; Jusoh et al., 2015; Love and Thomas, 2013; Midya and Gole, 2014; Shestopalov and Kharin, 2014; Sukma and Abidin, 2016; Urata et al., 2018; Vargas and Kastle, 2012). Some research obtained a profound correlation between solar events and earthquakes, while others say that the earthquake triggered by solar events is irrelevant. Even though extraterrestrial force may not be as significant as the internal (movement of tectonic plates, faulting system, et cetera) effects, it should not be neglectable.

The correlation between solar activity and earthquake events remains unclear, as there are no testable correlations that can be used to objectively predict future earthquakes (Love and Thomas, 2013). The solar cycle only indicates the sunspots number but not necessarily a geoeffective solar event; therefore, if one wishes to study the solar-terrestrial relation, the solar cycle is not enough and must be use with other variables. Hence, the relationship between solar activity and earthquake occurrences should be investigated in a more specific way to understand the phenomenon.

The natural geomagnetic field of Earth may temporarily be disturbed by solar events, which caused a geomagnetic storm. These disturbances are usually triggered by the high-speed solar wind (HSSW) and the coronal mass ejections (CMEs). The weak-to-moderate geomagnetic disturbances are due to the HSSW, while CME drives the intense disturbances (Chen et al., 2014; Verbanac et al., 2011). In this study, the A_p index is used as an indicator of geoeffective solar events.

Ismail, N.H. et al. (2020) show that earthquakes activity might be affected by the geomagnetic storms using statistical analyses and emphasized that there are differences between days before and after the geostorm occurrence, hence, the solar influence upon earthquake occurrences cannot be neglected entirely. The motivation is to find the significant relationship between the four days before and after the geostorm with earthquakes activity using The Generalised Linear Mixed Models (GLMM) (Breslow and Clayton, 1993). The advantage of GLMM it can deal with correlated and nonlinearly data and able to proceed with diagnostic checking. Therefore, it is suitable to apply to our datasets, which we have 101 observations that change through days.

2. Data Selection and Methods

2.1. Data

We investigate the data of the geomagnetic index and the frequency of the earthquakes from 1994 to 2017. The planetary A_p index (in nano Tesla unit) is the most crucial index for forecasting geomagnetic conditions and is the only global magnetic index predicted by the space weather forecasting centers (Paouris and Mavromichalaki, 2017). This geomagnetic A_p index is provided by Helmholtz-Centre Postdam – GFZ German Research Centre for Geosciences provides a good indicator for the geoeffective solar activity. Figure 1 shows a total of 101 storms where the observation corresponds to the value of the Ap index from moderate to an extreme geomagnetic disturbance (Bartels, 1957) where the A_p is more than or equal to 57 nT ($A_p \geq 57$ nT). In this paper, we define these as *geostorms* and the geomagnetic data is obtained from the link ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/tab/. The gap between 2007 until 2011 is due to the A_p index is below the selected threshold value, which is $A_p \geq 57$ nT, and this also corresponds to an interval with minimum solar activity.

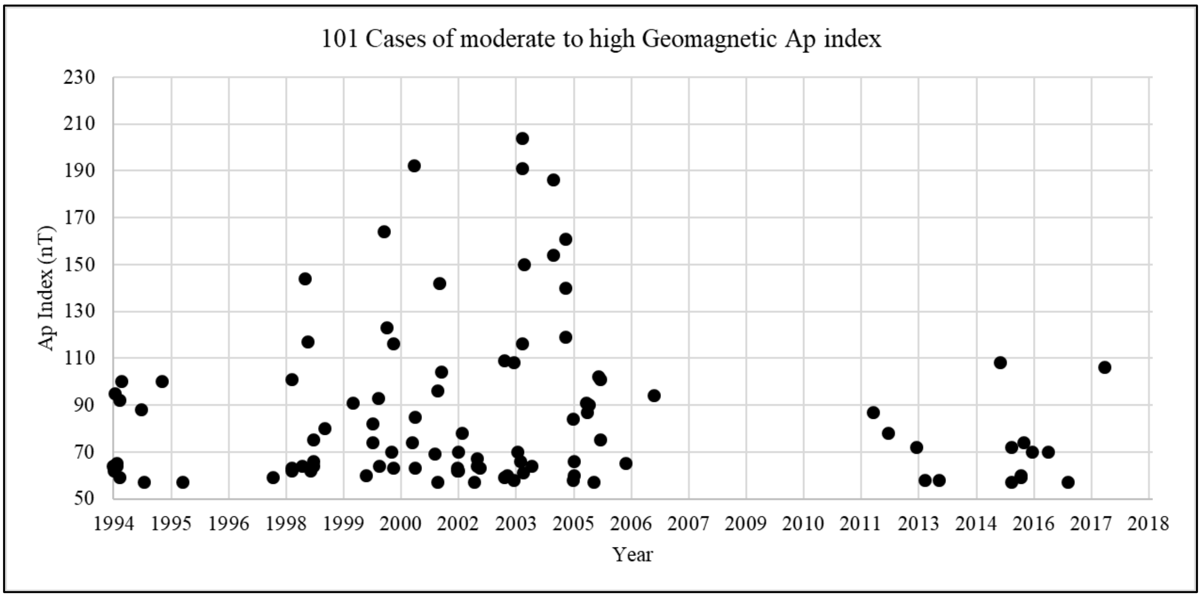

Figure 1: 101 cases with moderate to high geomagnetic Ap index (Ap ≥ 57 nT)

We filtered the data from the worldwide earthquakes with magnitude, $M \geq 4.5$, and depth of foci, $d \leq 70$ kilometers from the United States Geological Survey (USGS) earthquake catalogue. The USGS dataset for earthquakes with $M < 4.5$ occurring around the world other than the US region can be hard to detect if there are not enough data, and it would take several months to complete the dataset. Therefore, we considered the dataset with $M \geq 4.5$, although the data with $M<4.5$ are available. The specific focus here is on shallow crustal earthquakes and closer to the atmosphere, which responsible for the vast bulk of earthquake damage; subduction-related events are not discussed to any extent. The outermost layer of the Earth, has a maximum depth of approximately 70 km, with an assumption that the effects of the electromagnetic interaction between the Sun and Earth only affect the crust while the deeper earthquakes are more reliant on the internal geophysical influences (Jusoh et al., 2015). The earthquake data were presented in Figure 2, which consists of 101 cases of the geostorms. Figure 3 shows the distribution of the earthquake dataset with the magnitude dataset.

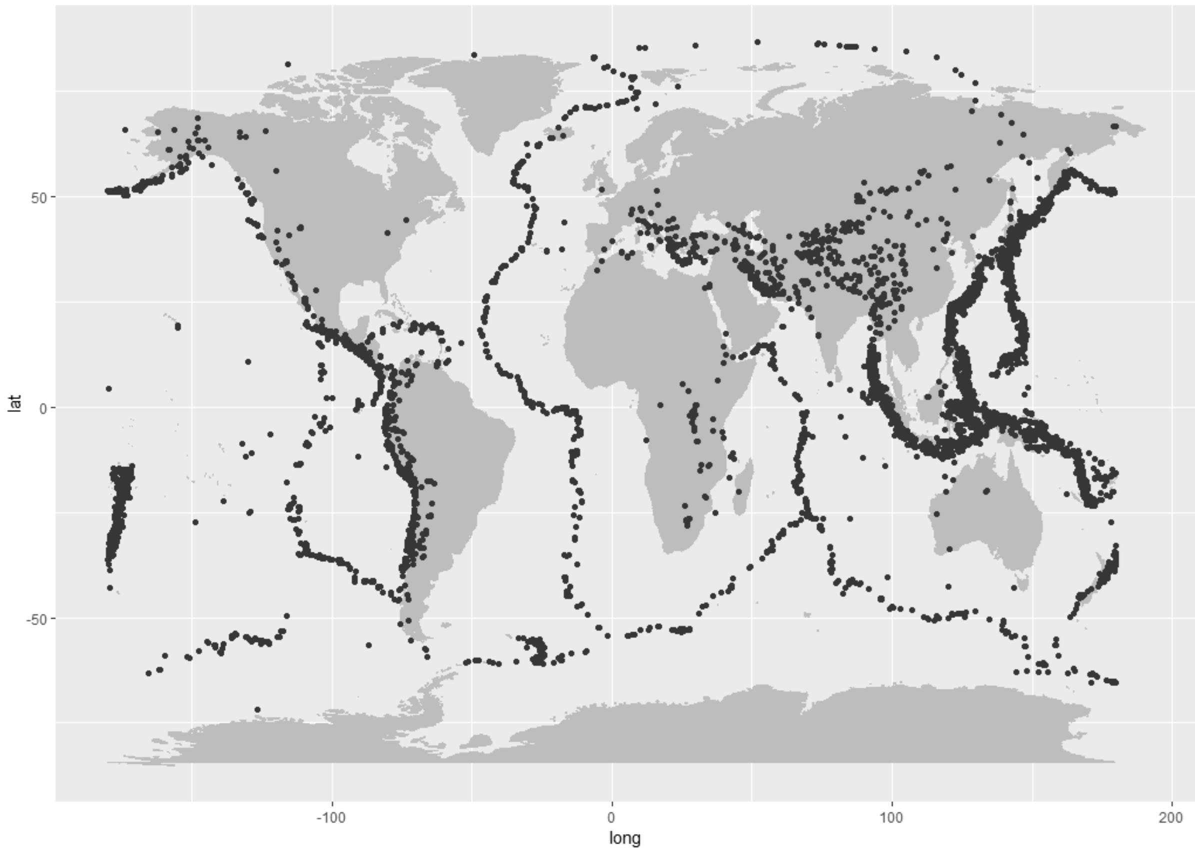

Figure 2: Worldwide earthquake data (M ≥ 4.5 and depth of foci, d ≤ 70 km)

The earthquake frequencies are counted for each of the days of the geostorm occurrences. In this study, we only focused on four days before and four days after the event. We defined Day-0 as the day of the geostorm with the condition, $A_p \geq 57$ nT. Hence, there are nine consecutive days, i.e., Day-4, Day-3, Day-2, Day-1, Day-0, Day+1, Day+2, Day+3, Day+4, and a total of 10743 earthquakes occurrences were recorded for all the 101 observations of high A_p index.

2.2. Statistical Methods

2.2.1. Generalised linear mixed model (GLMM)

Generalised Linear Mixed model (GLMM) is an extension of Generalised Linear model (GLM) and a special case for Linear Mixed model (LMM) while the GLMM is for the data which is non-linearly distributed. The LMM is the combination of linear regression and time series model (Frees, 2004). It is different from linear regression and time series, where it takes the dynamic information into consideration and including the linear predictors into the model. In real life not all data have normally distributed where we must reconsider the linear behaviour of the responses and the parameters. The GLMM allows us to apply the LMM into the data with non-normal behaviour such as Poisson distribution to handle the dataset with the count response variable.

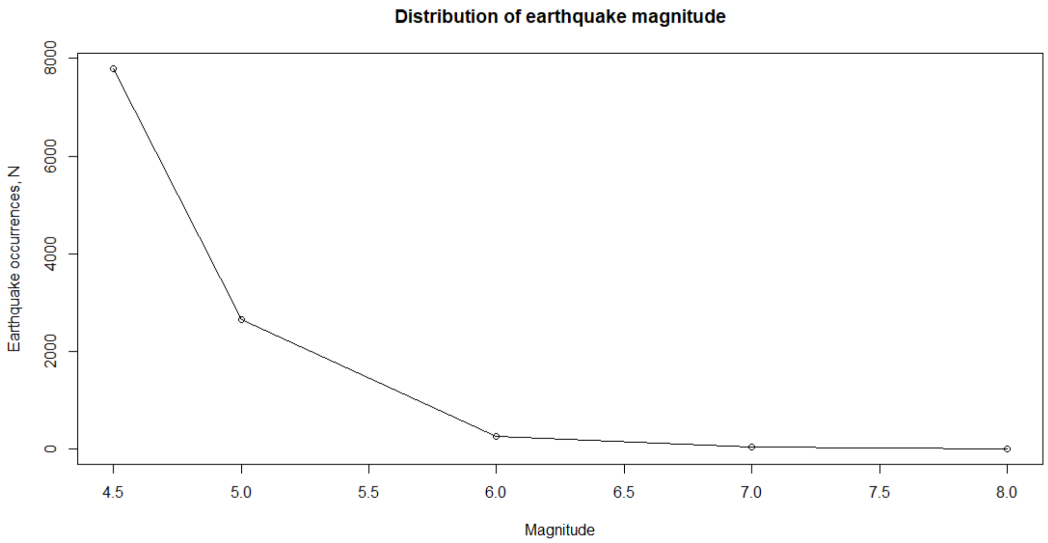

Figure 3: Distribution of earthquake magnitude

The GLMM contains the fixed effect and the random effect terms. The random effects defined as the character of the variation induced in the response by the different levels of non-repeatable covariates (Bates, 2005). Supposed that the data has n observations with response variable y_i, then the Generalised linear mixed model is defined as (Lin, 1997).

$$g(\mu_i^b) = \eta_i^b = x_i^T \boldsymbol{\alpha} + z_i^T \boldsymbol{b} \tag{1}$$

In Equation (1), the term $g(.)$ is referred as a canonical link function, where x_i is $p \times 1$ covariate vector that associated with fixed effects, α and z_i is $q \times 1$ covariate vector that associated with random effects, b. The response y_i is assumed to be independent with means $E(y_i|b) = \mu_i^b$ on conditional of $q \times 1$ unobservable random effects, b. The Equation (1) can be simply written in a matrix form as

$$g(\mu^b) = \eta^b = \boldsymbol{X\alpha} + \boldsymbol{Zb} \tag{2}$$

where $\boldsymbol{X}$ and $\boldsymbol{Z}$ contain rows of x_i and z_i respectively (Lin, 1997).

$$L(\theta; y) = \int f(y|b,\theta)p(b|\theta)db \tag{3}$$

In GLMM, we estimate using the maximum likelihood estimation together with Laplace approximation to maximize the integral as in Equation (3) (Raudenbush et al., 2000). The maximization of Equation (3) with respect to θ shows the response, y depends on parameter b, while b depends on the parameter θ. In the previous study, the Laplace approximation is one of the methods that are more accurate to maximize the integral compared to other methods such as the Penalised Quasi-likelihood (PQL) and the Gauss-Hermite Quadrature (Bolker et al., 2009; Raudenbush et al., 2000).

3. Results

For our dataset, we considered variable, Day ($\pm$4 days and Day-0) as the random effect. Each geostorm is considered as one observation since it has information about the frequency of the earthquakes for nine days, where we have 101 geostorms altogether from 1994 until 2017. For this dataset, there is no fixed effect included in the model.

The observations are varied through time (Days), which means a dynamic dataset. Hence, a mixed models is found suitable due to multiple observations across time (Day). Since there is a dynamic behaviour in the dataset, we choose the Generalised Linear Mixed model due to correlated in time and count response variable. We built two models with no fixed effect, where Model 1 only focused on Day as the random effect, while Model 2 has cross-random effects, which were Day and observation to overcome the over dispersion issue.

In this study, we considered the number of earthquakes that occurred as the response variable. Since we have the count response, we found Poisson distribution is suitable in GLMM and Laplace approximation for estimation. The Laplace approximation has an advantage, which gives more accurate results than the Penalized quasi-likelihood (Bolker et al., 2009). The GLMM assumes that the linear predictor consists of two portions, which consist of fixed and random effects. In this case, we have no fixed effect only intercept, which makes the output, only gives the estimated intercepts to explain the importance of the effects (McCulloch and Neuhaus, 2005).

Table 1: The comparisons of fixed, random effects and the Akaike Information Criterion (AIC) between Model 1 and Model 2

	Fixed effect	**Random effects**		**AIC**
	Intercept	**Variable**	**Standard Deviation**	
Model 1	2.47	Days	0.05	7994.3
Model 2	2.38	Days	0.05	6294.1
		Obs	0.40	

We used the Akaike information criterion (AIC) values to choose the best model where the lower the AIC indicates a better model. Table 1 shows the AIC for Model 1 is higher than Model 2, which is 7994.3, while Model 2 is only 6294.1. Hence, Model 2 is selected to be the best model for this data.

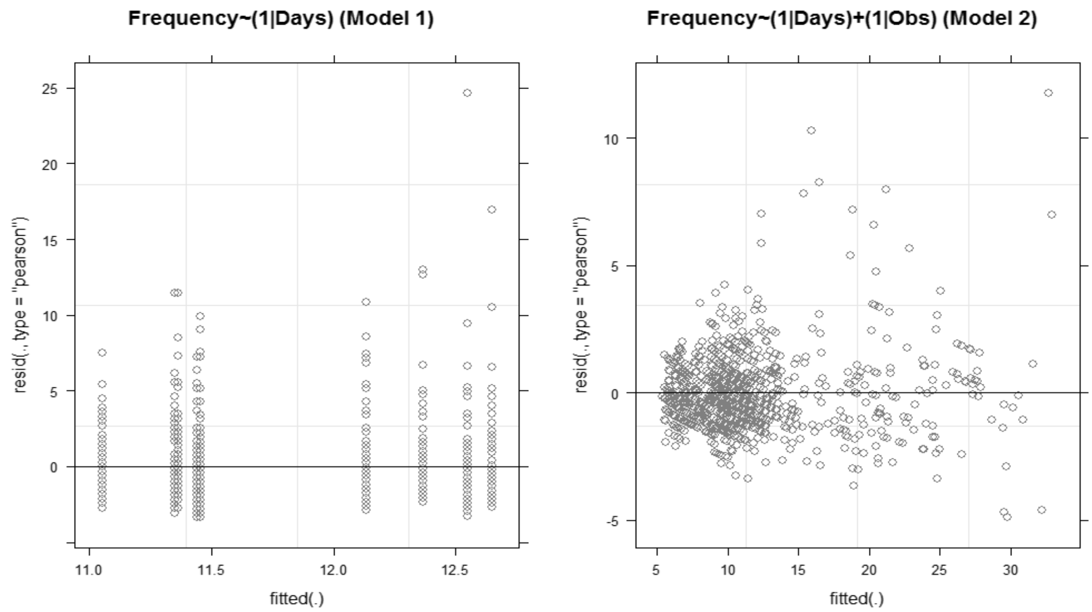

Figure 4: Residual plots for Model 1 and Model 2

Figure 4 shows the residual plots for Model 1 and Model 2. Model 1 is the random effect fitted by Day, and clearly shows that the fitted model is a single link between variables, meanwhile, most of the points in Model 2 were scattered around zero, which indicate Model 2 is better than Model 1. Hence, we found Model 2 is the best fit compared to Model 1. In GLMM, we assumed the error is normally distributed and from the comparison of histogram in Figure 5 shows that the distribution errors in Model 2 is more symmetric than Model 1, which slightly skewed to the right.

4. Discussions and conclusions

The solar-terrestrial relation involves many complicated processes and systems. Therefore, the results obtained must be interpreted with caution. We have shown that based on 101 geostorms, the earthquake frequency at Day 0 increased gradually until Day+2 before drastically decreasing in Day+3 and Day+4. Table 2 described the pattern between before and after the geomagnetic storm, which means that the geostorm can cause a difference in the frequency of earthquake, (Ismail et al., 2020).

To further investigate the behaviour of earthquakes around a geostorm, we proceed with the GLMM. We build two models, and after careful comparisons, the AIC of the model shows that Model 2 is a better model. Model 2 shows that the earthquake activity and geostorm observations are important. These findings suggest that geostorm is an important variable to investigate the earthquake occurrences and the frequency of earthquakes might be affected by the occurrences of the geomagnetic storm.

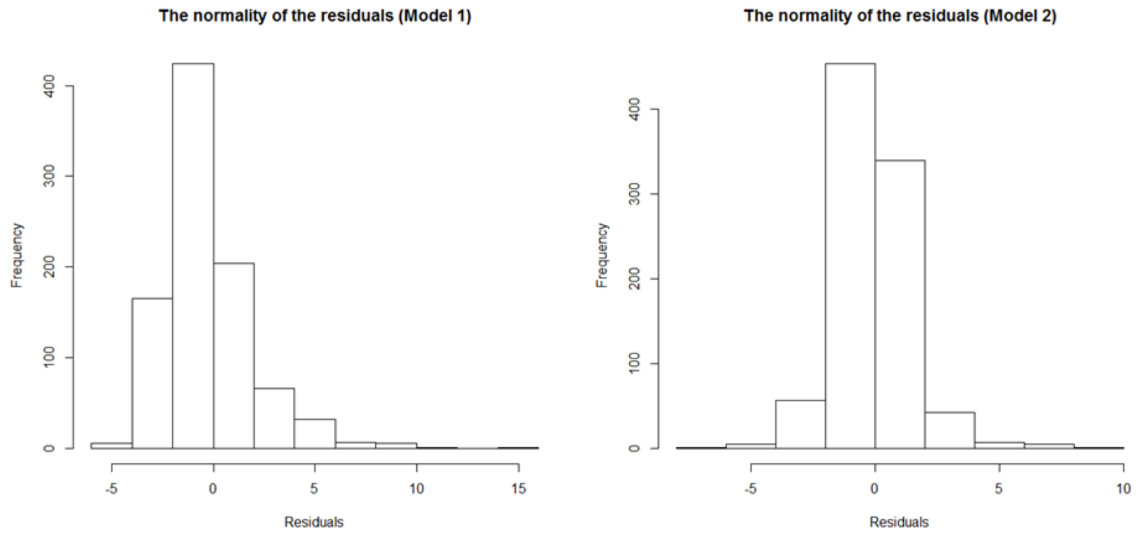

Figure 5: Normality of the Residuals for Model 1 and Model 2

Table 2: Description of clusters in the dendrogram

Variable	Cluster	Descriptions
Day 0, Day+1, Day+2, Day+3, Day+4	1	The earthquake happened at the onset and after geostorm
Day-1, Day-2, Day-3, Day-4	2	The earthquake happened before geostorm

These results are supported by previous findings (Anagnostopoulos and Papandreou, 2012; Odintsov et al., 2006; Urata et al., 2018) which found that the disturbance in geomagnetic field is often strongly related to triggering of earthquake occurrences. Hence, from these findings, we cannot neglect the effects of solar events and geomagnetic storms on the occurrences of earthquakes. This research is still far from using the geomagnetic disturbance as an earthquake prediction mechanism. However, one can expect a variation of seismic activities when the earth's magnetic field experience major disturbance from the Sun itself.

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