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Comparative Analysis of Variants of Geomagnetic Diurnal Variation Ratio Method for Earthquake Precursor Detection

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ABSTRACT

The application of electromagnetic signals in earthquake study has been applied by previous researchers through the monitoring of geomagnetic variations. The previous studies have revealed inconsistencies in the implementation of the diurnal variation ratio (DVR) method and the results were also found to be limited in specific events. This study sought to enhance the reliability of earthquake forecasting by implementing two different variants of the DVR method in investigating the magnetic responses prior to earthquakes (EQ). Global EQ events that occurred between 2000-2020 with magnitude above 5.0 were observed. The anomalies were detected as early as 60 days to 1 day prior to the EQ events for DVR using threshold value (Method 1), and 30 days to 15 days prior to the EQ events for DVR using the comparison with 1-year background geomagnetic data (Method 2). All geomagnetic N, E, and Z components showed anomalous behaviour during the quiet days but with temporal lags between the components. It can be concluded that Method 1 approach, yielded results with significantly more precursor presence than Method 2. The relationship of the geomagnetic variations with earthquake properties such as magnitude and focal depth showed higher rate of precursor presence in both the strong and mid-focus EQ. Future studies will be conducted to correlate geomagnetic variations with seismo-ionospheric response and physical ground movement prior to the events. The outcomes of this study will be able to provide insights of effective analysis for precursor study particularly in seismic hazard.

Keywords: Geomagnetic diurnal variations; earthquake precursor; SuperMAG database, diurnal variation ratio (DVR)

INTRODUCTION

The utilisation of geomagnetic emission has been applied extensively in earthquake precursor detection study. Various approaches have been established to observe the geomagnetic variations prior to earthquake, and in particular the diurnal variation ratio (DVR) method (Chen et al. 2010; Liu et al. 2006; Takla et al. 2018; Yusof et al. 2021). Although a considerable amount of literature has been published on DVR, these studies display inconsistencies in the application of the DVR method. Liu et al. (2006) showed that through the DVR technique, the geomagnetic anomalies were revealed one month before and during the earthquakes. The study was later complemented by Yusof et al. (2021) in their research where the DVR was implemented in a large-scale study. Similarly, they found that the geomagnetic anomalies appeared one month prior to the earthquakes. To deepen the understanding of DVR studies, Yusof et al. (2021) have also established an appropriate method to observe the commonly undetected precursors in horizontal components.

Although various DVR approaches in geomagnetic data have been employed in past studies, the most efficient approach has yet to be determined for the analysis of the magnetic response prior to the earthquakes. Furthermore, previous studies have been limited to specific events; thus, the aim of this study was to employ and assess the different DVR approaches used to analyse the magnetic response prior to the earthquakes while extending it into a global-scale study covering the years of 2000 to 2020. The use of the DVR method in detecting geomagnetic variation anomalies has been applied by previous researchers but using different approaches. In this study, we compared two variants of the DVR method to determine the efficiency of both (Chen et al. 2010; Liu et al. 2006; Yusof et al. 2021). The two variants of the DVR method are further explained under the respective sections in this paper. Statistical analysis was performed for both variants of the DVR method and was also used to determine the rate of precursor presence for both. The remaining part of the paper then discusses the two variants of the DVR method, the relationship of the precursor with earthquake properties, and the statistical rate of the precursor presence in both variants of the DVR method. The outcomes of this study will be able to provide an insight for effective analysis for precursor study particularly in seismic hazard and risk assessment.

METHODOLOGY

For this study, the DVR method was applied to geomagnetic data to identify the earthquake precursor prior to the events. The method is among the best approaches for the observation of anomalies in geomagnetic variations (Chen et al. 2010), in addition to its advantages such as high data sampling rate for detailed quantitative analysis (Yusof et al. 2019). Through the SuperMAG database, a 1-min sampling (low-fidelity) period of geomagnetic daily variations data recorded globally between 2000 and 2020 were downloaded and analysed. Advances in geomagnetic data collection such as the SuperMAG database have facilitated the investigations of geomagnetic variations as earthquake precursors. Global earthquake events from 2000-2020 downloaded from USGS, as shown in Figure 1, were utilised in this study. The geomagnetic field data were measured based on the magnetic coordinate system where the N-direction indicates local magnetic northward, E-direction indicates local magnetic eastward while Z-direction indicates vertically downward direction. In this paper, all three NEZ-direction are mentioned as the NEZ-component (Gjerloev 2012).

Although the DVR method only requires low-resolution data, at least two magnetometer stations are needed to observe the anomalies, and both are termed as near and far stations. The epicentral distances for both stations are further defined in the sections on each method. The geomagnetic diurnal variation ratio, R of N, E, and Z-components for each station pair was computed as $R_N = \Delta N_{near} / \Delta N_{far}$, where the difference between the daily maximum and the daily minimum of both near and far stations were ratioed in each N, E, and Z component. There were some data gaps for certain stations during certain dates because of system malfunction and human activities. Thus, during those periods, no observations were made. Two approaches were adopted to evaluate the effectiveness of the DVR method in determining the earthquake precursors.

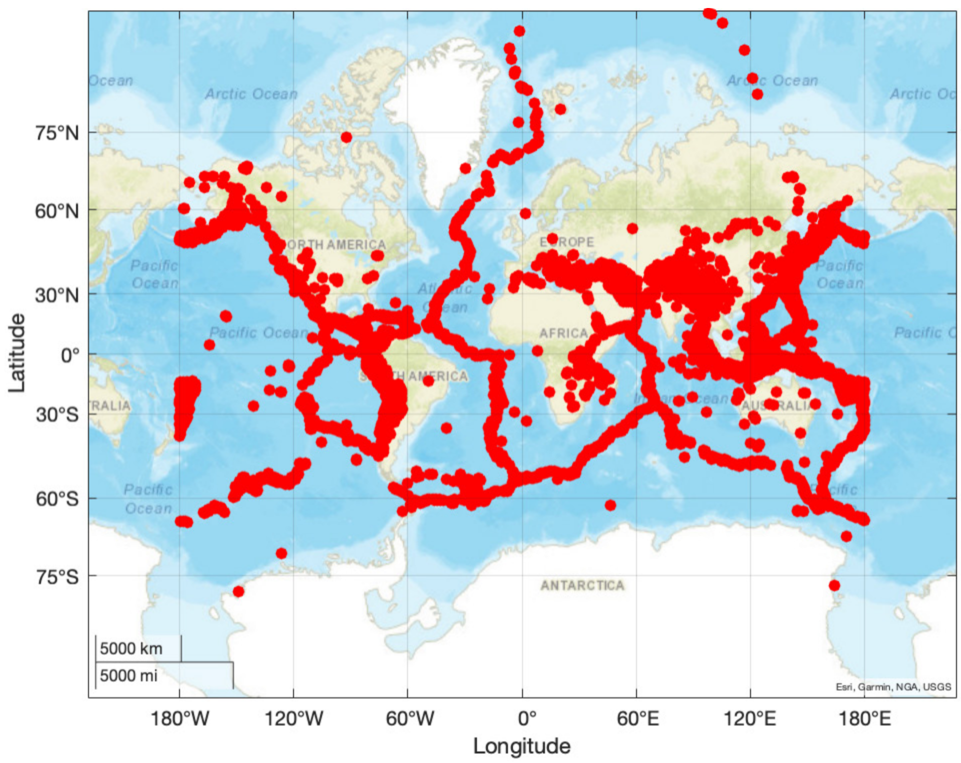

FIGURE 1. Global earthquakes of M5.0 and above during the period of 2000 to 2020. (USGS 2017)

DVR METHOD 1: ANOMALIES BASED ON THRESHOLD VALUES

In this method, the near stations were defined as stations with epicentral distance of less than 190 km, while far stations were defined as stations with an epicentral distance of more than 600 km and less than 1000 km (Yusof et al. 2021). Two global geomagnetic indices, namely the ap (mid-latitude observatories) and Dst (low latitude observatories) were also observed during the study period to discriminate between the anomalies and the solar-terrestrial disturbances. The datasets were acquired from the NASA OMNIWeb Service. This is crucial as any anomalies observed during the so-called disturbed periods should be excluded from the analysis as they are considered as non-seismogenic geomagnetic variation anomalies which were not caused by local underground processes (Xu et al. 2013; Yusof et al. 2021). Disturbed periods were identified when the daily values of ap >27 nT or Dst < -30 nT; the results were not observed to eliminate the external influences. As a precautionary step to remove any external factors, the one-day period after the geomagnetic storm was also considered disturbed and was not observed.

The geomagnetic Z-component could also be affected by ionospheric currents, thus the 15-day moving mean were observed and the periods which exhibited the anomalous behaviour were considered as anomalies, as the influence of ionospheric currents could only persist for a few days. Hence, the geomagnetic diurnal variations ratio, R was identified as anomalous when it exceeded the threshold value obtained from the formula $\mu_R \pm k\sigma_R$ ($k = 2$), where the parameters μ_R and σ_R are the mean and the standard deviation of R, respectively (Yusof et al. 2021).

DVR METHOD 2: ANOMALIES BASED ON 1-YEAR BACKGROUND COMPARISON

Following Chen et al. (2010) and Liu et al. (2006), the DVR for the 1-year observation period was computed to construct a background distribution for each station. The similar process was also applied for every five adjacent 15-days observation period in relationship to the earthquake events occurring within 50 km to the near station to obtain a monitored distribution for each station. The far stations were defined as stations with epicentral distance more than 50 km and less than 300 km. To examine the relationship between the ratios and the earthquake occurrences, the monitored distributions for the five time periods were further compared to the associated background distribution. It should be noted that in this study, the use of the method did not take into consideration the effect of solar-terrestrial disturbances. Statistical significance of the results was analysed using t-tests that use the correlation between an experimental variable and control variable and is equivalent to the Pearson correlation coefficient to see if there was any significant difference in the monitored distribution compared to the background distribution. Additionally, this method was improved from Liu et al. (2006) by comparing the three components of geomagnetic variations as mentioned in the Introduction.

RESULTS AND DISCUSSION

DVR METHOD 1: ANOMALIES BASED ON THRESHOLD VALUE

Figure 2 presents the DVR of N, E, and Z components for 60 days before until 60 days after the M5.5 Earthquake of 15th June 2014, near the East Coast of Honshu, Japan. As shown in Figure 2, the diurnal variation ratio for each station pairs of Kakioka (KAK) and Kuju (KUJ), KAK and Memambetsu (MMB), and KAK and Rikubetsu (RIK) was calculated for each component, and labelled as R_N, R_E, and $R_{Z,}$ respectively. The top panel shows the hourly values of ap and Dst with the upper and lower dashed line marking the threshold value which is used to indicate the occurrence of the geomagnetic storm when the value exceeded the threshold line; the observation during the day was therefore excluded. Additionally, the vertical red line indicates the earthquake occurrence day, and the observation period was conducted 60 days before and after the earthquakes. The 15-day moving mean of each component is shown as bar charts for the anomalous period only.

For the M5.5 earthquake event which occurred on 15th June 2014 at 18:19:14 (UTC) near the east coast of Honshu, Japan where the geographic coordinate of its epicentre was 36.604°N 141.724°E, results revealed that the anomalous period ranged from 60 days to 1 day prior to the event. The anomalies could be observed through the N-, E-, and Z- components. Both N and Z components exhibited the anomalies as early as 2 months prior to the event. However, the E component only showed significant fluctuations of the geomagnetic diurnal variation starting a week before the event.

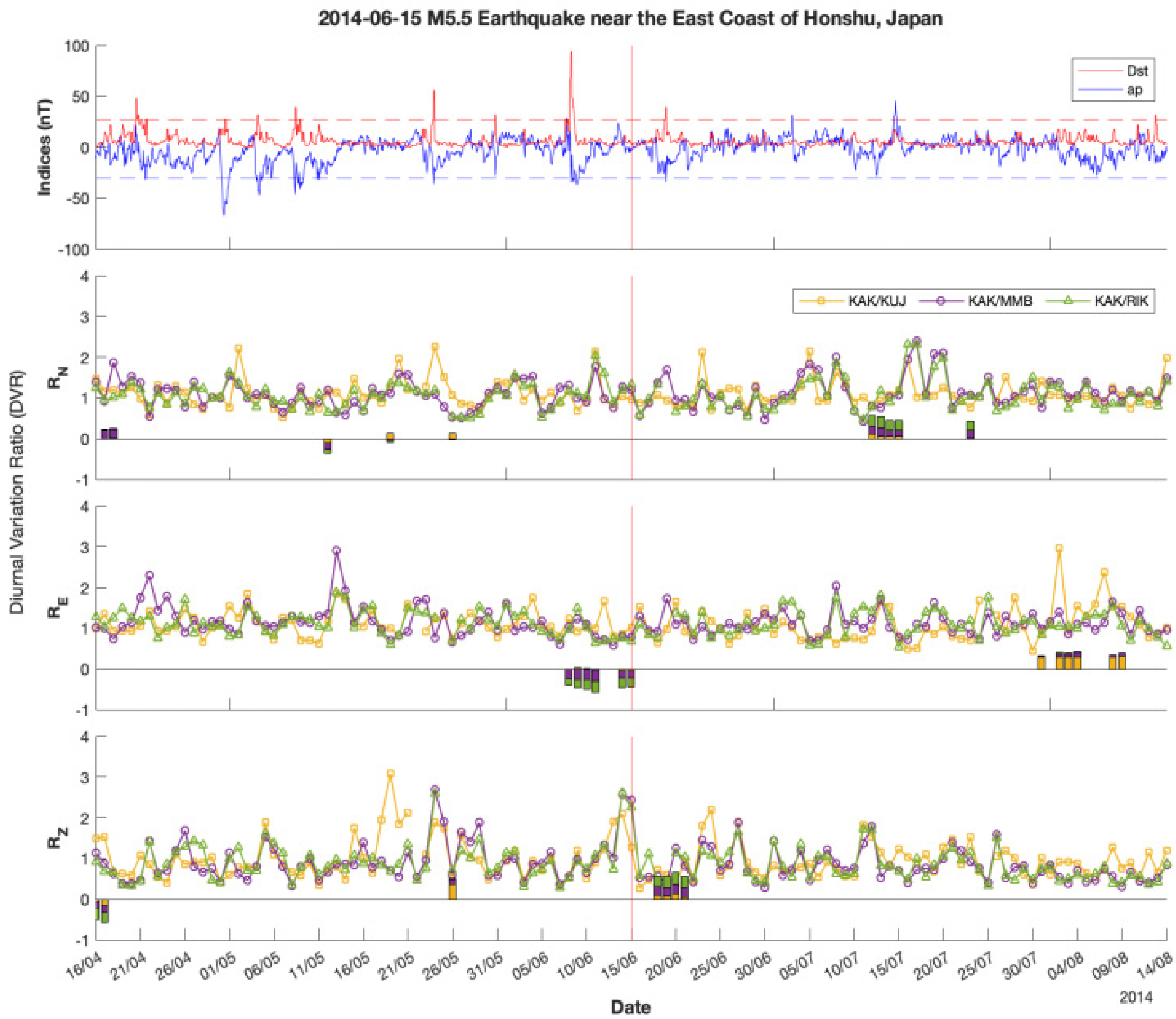

FIGURE 2. Geomagnetic DVR shows anomalies for the M5.5 earthquake of 15th June 2014 which occurred near the East Coast of Honshu, Japan.

DVR METHOD 2: ANOMALIES BASED ON 1-YEAR BACKGROUND COMPARISON

The purpose of a t-test is to compare the mean values between two groups. Hence, in this study, t-tests were used to determine whether the geomagnetic variation ratio for the observation period before the EQ is significantly different from the geomagnetic variation ratio of the 1-year background distribution. The monitored distribution at the near station during the five consecutive periods within the EQ occurrence time was compared to its associated 1-year background distribution.

TABLE 1. t-tests results of DVR using the 1-year background geomagnetic data.

Component	Observation Period (Days in relationship to the EQ Period)	P-value		
		Ishinomaki EQ of 29th August 2012 (ONW/KAK)	Ishinomaki EQ of 29th August 2012 (ONW/MIZ)	Ishinomaki EQ of 05th May 2012 (ONW/KAK)
N	−30 to −15	0.02	0.99	0.82
	−15 to −1	0.62	0.04	0.70
	EQ Period	0.09	0.23	0.18
	+1 to +15	0.84	0.46	0.01
	+15 to +30	0.11	0.20	0.02

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E	−30 to −15	0.47	0.13	0.03
	−15 to −1	0.15	0.13	0.47
	EQ Period	0.10	0.54	0.21
	+1 to +15	0.33	0.18	0.02
	+15 to +30	0.07	0.87	0.63
Z	−30 to −15	0.36	0.01	0.22
	−15 to −1	0.05	0.09	0.74
	EQ Period	0.21	0.27	0.26
	+1 to +15	0.11	0.29	0.34
	+15 to +30	0.56	0.82	0.86

Table 1 shows two earthquake events with significant differences between the monitored and background period distributions. The Ishinomaki EQ that occurred on 5th May 2012 showed anomalies of DVR for station ONW/KAK 30 days before the earthquake only in the E component, whereas the Ishinomaki EQ that occurred on 29th August 2012 showed anomalies of DVR for both the ONW/KAK and ONW/MIZ stations. A paired sample t-test was performed to compare the significant difference between the monitored and background distribution. There was a significant difference in DVR between the observation period of 30 to 15 days before the EQ Period in the N-component for Ishinomaki EQ of 29th August 2012 for stations ONW and KAK in the N-component, during the 15 days before the EQ Period in the N-component, during the 30-15 days before the EQ Period in the Z-component for Ishinomaki EQ of 29th August 2012 for stations ONW and MIZ, during the 30 to 15 days before the EQ Period in the E-component for Ishinomaki EQ of 5th May 2012 for stations ONW and KAK and the 1-year background distribution in relation to the near station for each earthquake events. Figure 3 presents the results of DVR for ONW and MIZ stations for Ishinomaki EQ of 29th August 2012. The monitored distribution observation period before the EQ showed significant deviation from their backgrounds in both the N- (25-07-2012 until 08-08-2012) and Z-components (08-08-2012 until 22-08-2012).

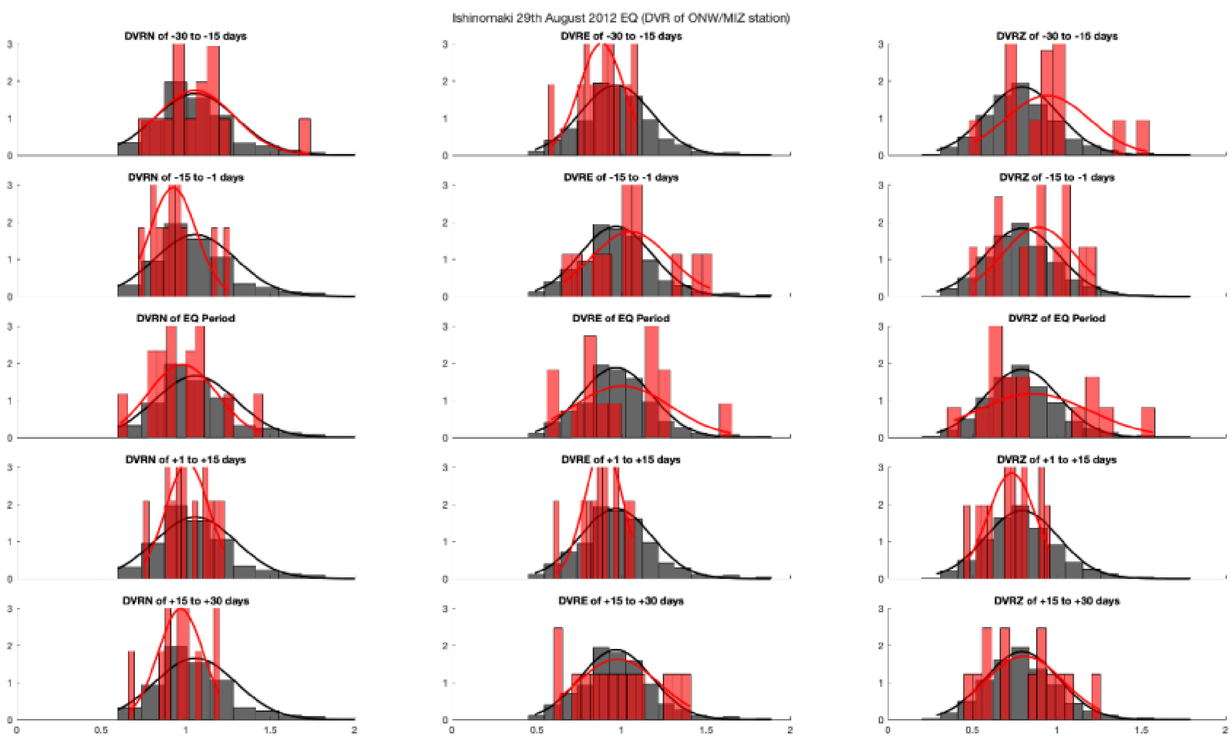

FIGURE 3. DVR using the 1-year Background Geomagnetic Data for Onagawa (ONW) and Mizusawa (MIZ) for the EQ of 29th August 2012, 44 km E of Ishinomaki, Japan.

STATISTICAL COMPARATIVE ANALYSIS OF BOTH METHODS

Earthquakes can be classified based on their properties: (a) magnitudes, to define the severity of earthquakes, i.e., moderate (M5.0 – 5.9), strong (M6.0-M6.9), major (M7.0-7.9), and great (M8.0 and higher), as reported in the U.S. Geological Survey (2010); and (b) depths as defined by Hayakawa (2015), i.e., shallow-focus (earthquake occurring at a depth of less than 70 km), intermediate depth or mid-focus (earthquake with a focal depth between 70-300 km), and deep-focus (earthquake occurring at a greater depth ranging from 300-700 km).

Figure 4 shows the distribution of global earthquakes with and without precursors from 2000 – 2020 with different magnitudes and depths. From the scatter plots, it can be observed that DVR using Method 1 reported the precursor presence significantly more than DVR using Method 2 for both magnitude and depth properties. Precursor presence for moderate earthquake yielded result of 26.34% using Method 1 while 15% was reported using Method 2. For strong earthquakes, the former also gave better results with 41.25% for precursor present earthquakes, while no earthquakes with precursors were found for DVR using Method 2.

Meanwhile, in terms of depths, approximately 25% of earthquakes with precursors were detected for shallow-focus earthquakes for DVR using Method 1 and 17% for DVR using Method 2. The mid-focus showed higher presence of precursor with approximately 76% for DVR using Method 1 but no precursor was detected for DVR using Method 2.

One unanticipated finding was that the intermediate depth EQ produced higher rate of precursor presence compared to the shallow depth EQ as hypothetically, the shallow depth EQ should give higher precursor presence. A possible explanation for this might be related to the generation mechanism of the geomagnetic diurnal variation anomalies. The well-established theory by Hayakawa (2015) in explaining the seismo-electromagnetic phenomena of the electrification process that occurs prior to the EQ could further support the idea. The intermediate- and deep-focus EQ occur in depths below the earth surface defined as the subduction zone which is also known as the Wadati-Benioff zone. It occurs in the asthenosphere layer with the mineralogical composition of olivine (Reynard et al. 2010). The different composition from the environment of shallow depth EQ could possibly influence the electrification process, hence affecting the rate of precursor presence.

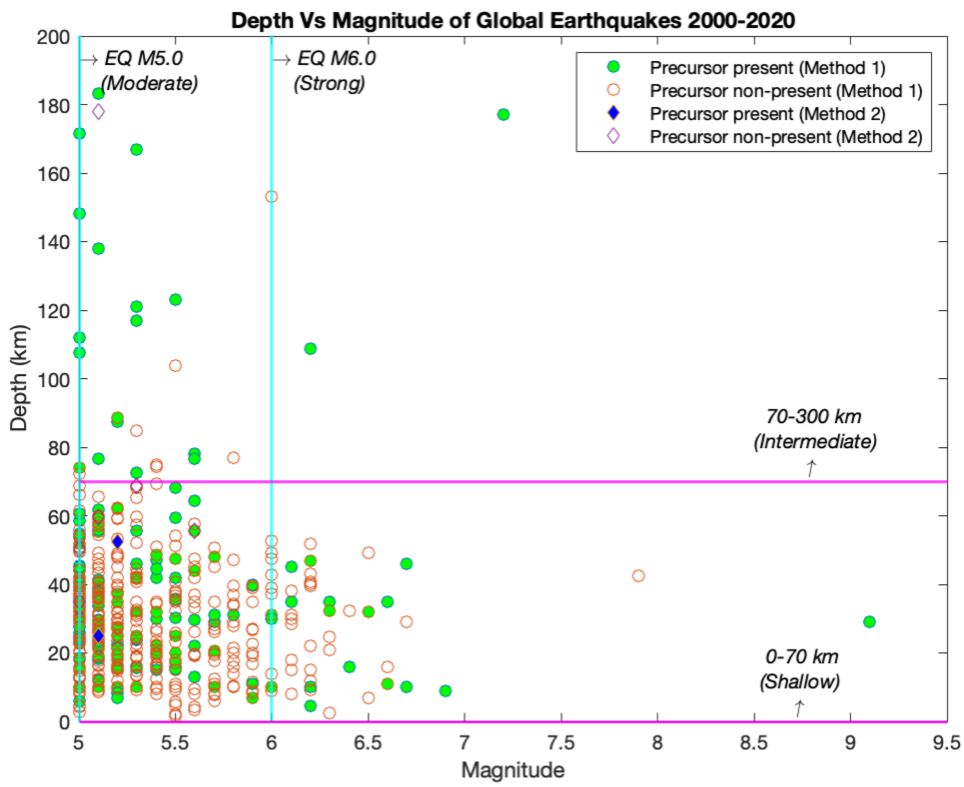

FIGURE 4. Depth vs Magnitude for global earthquakes.

The study then focused on the regional study to better compare the efficiency of both approaches as the geomagnetic data were acquired based on the magnetometer location. Figure 5 presents the distribution of regional earthquakes occurring in Japan with and without precursors from 2000-2020 with different magnitudes and depths. In this regional study, the statistics of precursor presence for DVR using Method 2 in terms of depth and magnitude were the same as mentioned in the global study, while precursor presence for DVR using Method 1 for moderate earthquakes was 22.90% compared to 30.65% for strong earthquakes. In relation to the focal depth of the earthquakes, 21.28% precursor presence was found for the shallow-focus EQ while 67.86% precursor presence was found for the mid-focus EQ. The results showed almost a similar trend as in the global study. It can be concluded that Method 1 yielded more significant results compared to Method 2.

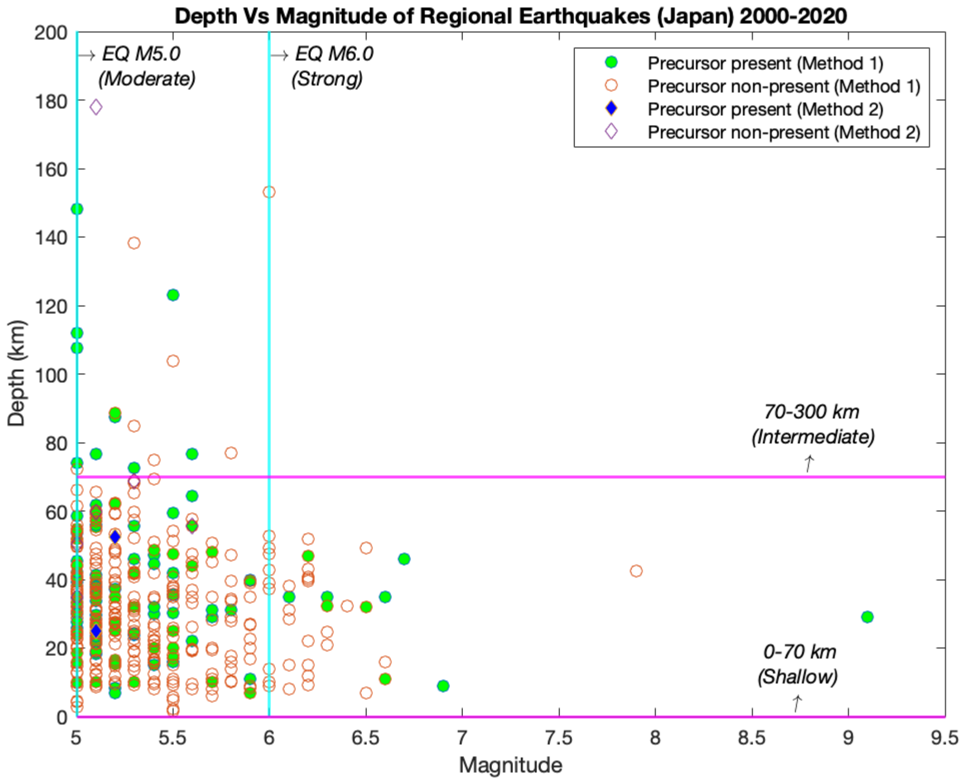

FIGURE 5. Depth vs Magnitude for regional earthquakes in Japan

CONCLUSION

The present study was designed to assess and review different approaches of DVR in investigating the magnetic responses prior to earthquakes. The two DVR variants implemented by previous studies were compared and analysed to determine the efficiency of both techniques. One of the more significant findings to emerge from this study is that Method 1 yielded more significant results compared to Method 2. The anomalies appeared as early as 60 days before the EQ event for Method 1 while Method 2 revealed the anomalies as early as 30 days in all components. The evidence from this study suggests that both methods could produce significant results in detecting earthquake precursors prior to the earthquake events. To further investigate the seismo-ionospheric effect in the Z-component, multi-observation approach using different kinds of sensors such as GPS is recommended. Additionally, the correlation of the anomalous period with physical ground movement can be investigated to further enhance the reliability of earthquake precursors.

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DECLARATION OF COMPETING INTEREST

None

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