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Evidence of Correlation between High Frequency Geomagnetic Variations and Seismicity in the Caribbean

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Abstract

An analysis between the hourly distribution of earthquakes in three areas of the Caribbean and the high-frequency variations of the geomagnetic field is presented. The number of earthquakes selected for each zone is between 10,000 and 43,000, which guarantees a statistically significant distribution. The hourly distributions of seismicity in all areas show a bay-shape distribution with a significant increase in the number of earthquakes at night, from 11 PM to 5 AM. For example, in eastern Cuba 36.7% of earthquakes occur at that time, representing 11.7% over 25% in the absence of any time preference. Geomagnetic disturbances were compiled from several years to be able to make a statistically significant hourly distribution of their occurrence, being determined by sudden changes in the magnetic field at a short period of 1 minute. In this sense, geomagnetic data were processed between the years 2011-2016, recorded by the geostationary satellite GOES13 and the magnetic ground station SJG in San Juan, Puerto Rico. The result shows a significant correlation between hourly earthquakes distribution and high-frequency geomagnetic variations. The time-varying conductivity response of Earth's interior also correlates with seismicity. The theory behind this correlation could be related to the piezoelectric phenomena and the electromagnetic force induced when the magnetic field is disturbed.

Keywords

Caribbean Seismicity, Conductivity Response, Geomagnetic Storms, Hourly Earthquakes Frequency, Electromagnetic Induction, Eddy Currents, Geomagnetic Field

1. Introduction

The correlation between magnetic field anomalies and the occurrence of earthquakes has always been a topic of great interest in the scientific community. Previous studies have tried to demonstrate the occurrence of electromagnetic induction caused by the propagation of seismic waves when the movement of the particles that propagate through the interior of the crust alters the Earth's magnetic field, generating an electric current [1] [2]. This causes an electromagnetic disturbance accompanying the seismic waves and an electromagnetic signal that propagates independently and arrives first those seismic waves. Sorokin *et al.*, [3] present an electrodynamic model based on the perturbation of the conductivity current in the global atmosphere-ionosphere electric circuit due to the injection of charged aerosols into the atmosphere during the preparation and development of an earthquake. Base on the same principle, geomagnetic anomalies have been found before and after strong earthquakes [4]. On the other hand, through satellite magnetic measurements and ground magnetic stations, an increase in seismicity has been found in areas of negative anomalies of the Earth's magnetic field [5].

For most seismologists, the occurrence of earthquakes should not have a preferential hour during the day or a specific date during the year. This means that when making an hourly distribution of earthquakes occurrence over a long period of time, no particular shape should appear in the distribution curve, it should be approximately flat. However, on many occasions, distributions with certain hour preferences have been seen, mainly in seismic swarm zones or earthquakes aftershocks [6], where the distribution normally includes a high number of events in a relatively small area. On the other hand, with the use of global earthquakes, a correlation has been found between solid earth tides and earthquakes activity [7] [8], although previous studies contradict this approach [9]. A strong correlation has also been found between hourly distribution of seismicity and variations in the magnetic field in volcanic areas [10].

This study reveals a significant correlation between the hourly earthquakes distribution and high-frequency geomagnetic variations in the Caribbean caused mainly by solar activity. Here, although a possible theory is given, the subject stays open for a better understanding of the physical process behind the results.

2. Observational Data

Three areas in the Caribbean, which include Eastern Cuba, Colombia and Puerto Rico are shown in **Figure 1**. The selection is based on the criteria that the area is relatively small, no greater than one-third of a time zone (5 degrees in longitude), and the number of selected earthquakes is statistically significant, usually greater than 10,000 events. Also it was included shallow and deep earthquakes in oceanic and continental areas. The seismic events in each zone have magnitudes greater than 1.5 from 1970 to 2019 (**Figure 2**), with the exception of eastern Cuba that only includes earthquakes from 1998 to 2019.

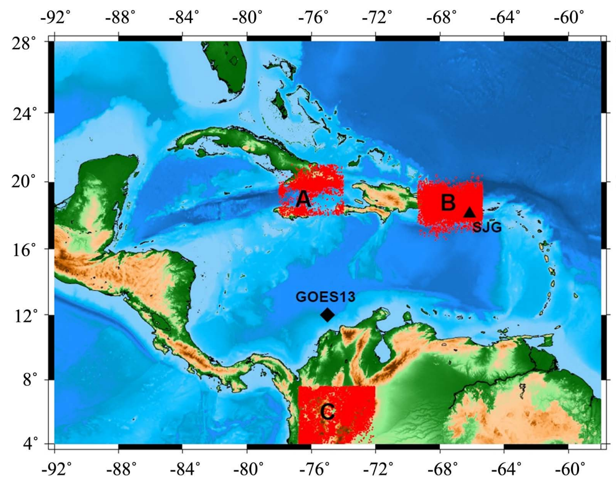

Figure 1. Map with the selected areas. Red dots represent the epicenters of all earthquakes with magnitudes greater than 1.5 from 1970 to 2019. Black triangle locates the magnetic ground station of San Juan (SJG), Puerto Rico. Black rhombus locates the zenith in longitude (75 W) of the GOES13 geostationary satellite, but zenith in latitude is actually located at the equator.

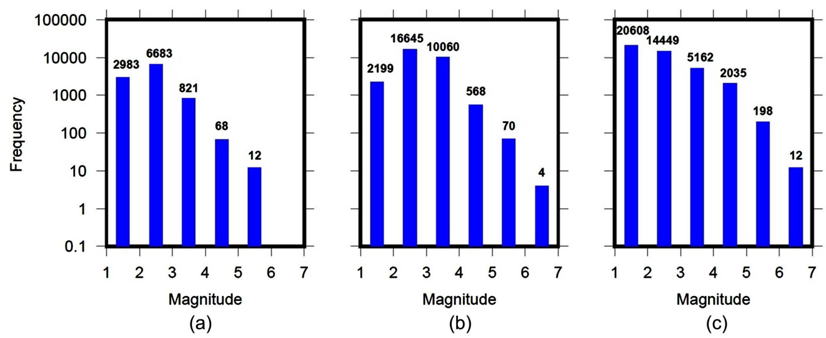

Figure 2. Magnitude-frequency relationship for each area. (a) Cuba 5/1998-12/2019; (b) P. Rico 1/1970-12/2019; (c) Colombia 1/1970-12/2019.

The hourly earthquakes distribution for each zone is shown in **Figure 3**. The zone of Colombia (C) shows an additional distribution that includes only earthquakes with depths greater than 100 km to see if there is some influence of deep earthquakes in the distribution shape. It can be seen the bay-shape hourly distributions in all areas, having an approximately flat shape in the first 5 hours and then begin to decrease until they reach the minimum one or two hours after noon and then increase until midnight. This implies a significant increase in the number of seismic events between 11 PM to 5 AM. For example, in eastern Cuba 36.7% of earthquakes occur at that time, representing 11.7% over 25% in the absence of any time preference.

Figure 4 reveals the natural source of the distribution shape of the hourly earthquakes frequency in all areas. The distributions keep the same shape when the selected time is divided in two periods (zone C) and the range of magnitudes is increased (zones A and B). That excludes the influence of any anthropogenic source or magnitude detection threshold in the shape of the distribution.

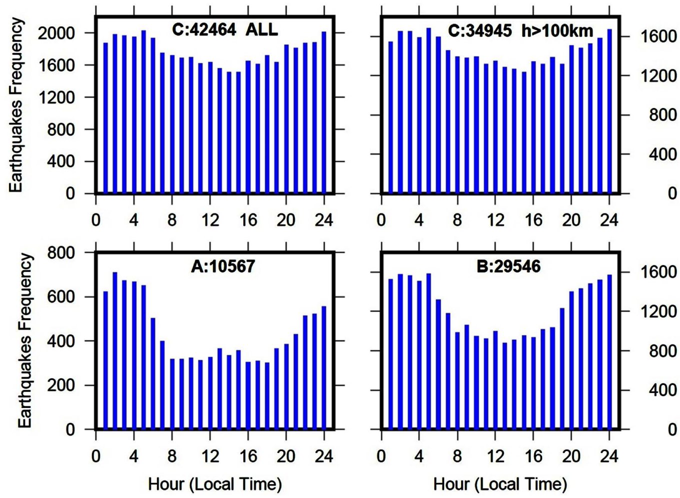

Figure 3. Hourly distribution of the number of seismic events in each zone. Each graph presents the total number of earthquakes in the hourly earthquakes frequency. Zone C also shows events with depth (h) greater than 100 km.

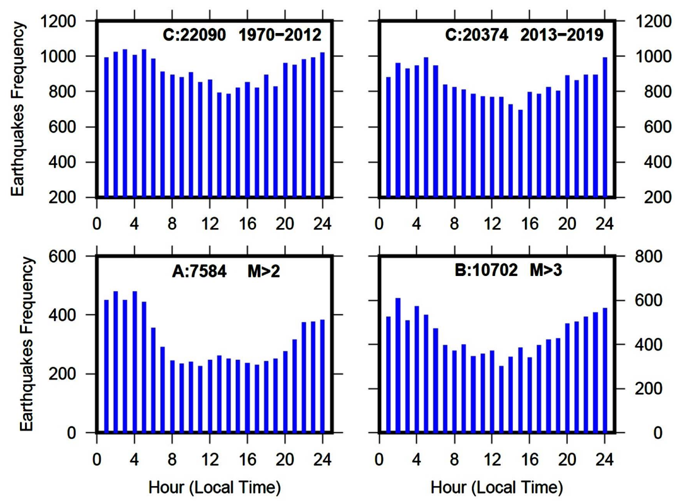

Figure 4. Hourly earthquakes frequency with two time-span for zone C and greater magnitudes (M) selection for zones A and B.

The magnetic measurements include 6 years of continuous data collected by the GOES13 geostationary satellite with zenith at 75 degrees west longitude (36,000 km altitude), and the ground magnetic station located in San Juan, Puerto Rico (SJG), both with sampling frequency of 1 min. The strength of diurnal geomagnetic field measured by both instruments is modulated by the sunrise and sunset (Figure 5). The maximum geomagnetic value is reached at noon, however the total electron content (TEC) in the ionosphere reach the maximum value 4 hours later. A difference in the curves between the satellite and the ground station is also observed. The magnetic field measured at high altitude is completely symmetrical before and after noon, but at the Earth's surface it shows a steeper drop after noon. The difference could be the result of a local ground effect response, but that issue needs to be investigated worldwide.

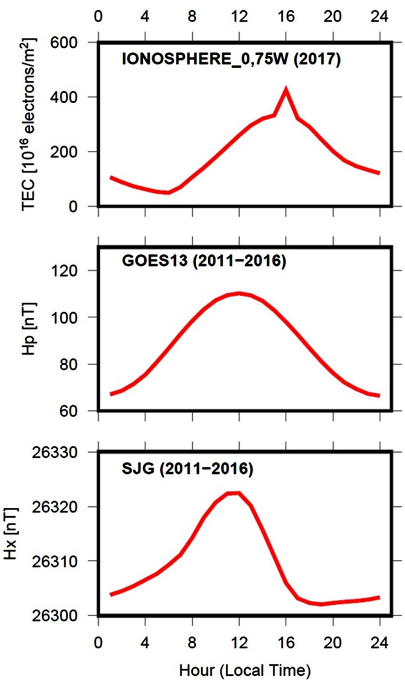

Figure 5. Diurnal average of magnetic field recorded by Puerto Rico ground magnetic station (SJG) and geostationary satellite GOES13. The curves represent the hourly average of magnetic field compiled from 6 years of data (2011-2016). On the top, the average of diurnal behavior of the total electrons content (TEC) in the ionosphere above the same area during 2017 is also observed.

An example of how magnetic disturbances are recorded on the earth is shown in Figure 6. It can be seen 6 days of magnetic field records and TEC values in the ionosphere during September 2017. The first two days (5th and 6th) show relative calm, but on day 7th the earth is hit by a geomagnetic storm (the most intense in 2017) lasting more than 24 hours and caused by a coronal mass ejection (CME) with about 700 km/s solar wind speed.

Figure 7 shows a time window of 16 hours, framed by blue vertical lines in Figure 6. In this case, the rate of change (geomagnetic gradient) of GOES13 and SJG time series is represented as the change between successive samples of the magnetic field. Note that the greatest disturbance of the magnetic field began at 23:00 UTC on day 7th and the maximum disturbance of TEC in the Ionosphere is reflected 4 hours later at 03:00 UTC next day.

3. Geomagnetic Data Processing

In order to compare high frequency geomagnetic disturbances with hourly earthquakes distribution it was necessary to define "anomalous geomagnetic variations". Figure 8 shows 6 years average of diurnal geomagnetic gradients with a sampling frequency of 1 min. From this figure is possible to set a threshold value in which a sudden perturbation will overcome a normal gradient of the geomagnetic field. In this sense it was defined as geomagnetic perturbation when the geomagnetic gradients in absolute value exceeds 0.5 nT for SJG ground

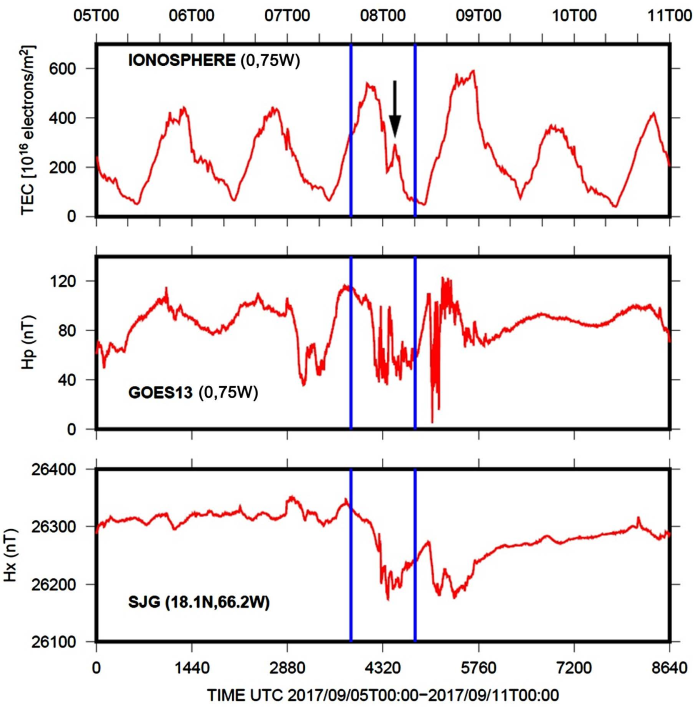

Figure 6. Record of geomagnetic storm caused by a Coronal Mass Ejection (CME) between September 7 and 8, 2017. The sampling rate of SJG ground magnetic station and GOES13 satellite is 1 min. TEC values in the ionosphere are calculated every 15 min. Black arrow points to the maximum anomaly in the Ionosphere.

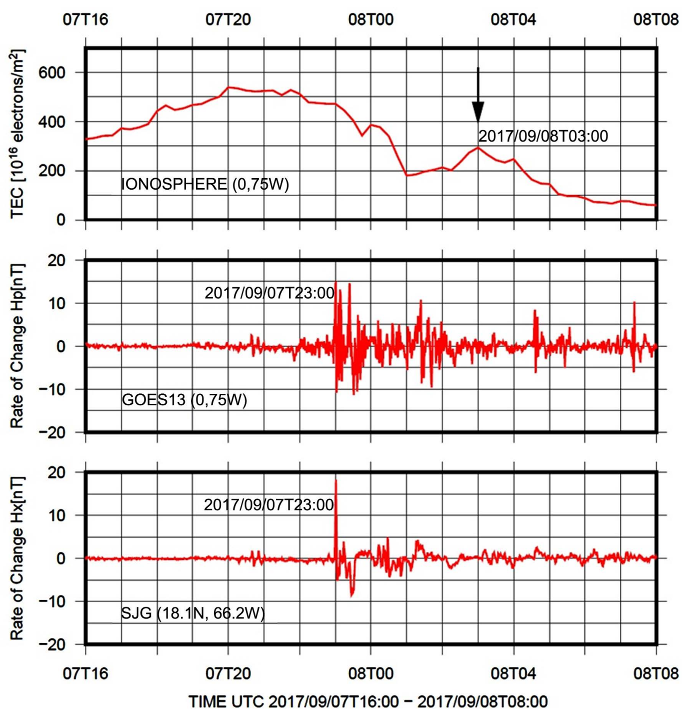

Figure 7. Time window from 16 hours during September 7 and 8, 2017. GOES13 and SJG show the rate of change of the magnetic field. The arrival time of the maximum magnetic disturbance and the maximum TEC disturbance in the ionosphere are indicated. Black arrow points to the maximum anomaly in the ionosphere.

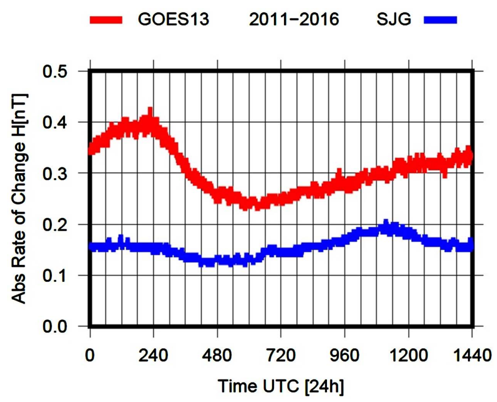

Figure 8. Daily average of 1 min sampling absolute rate of change of geomagnetic field recorded from 2011 to 2016 by GOES13 and SJG.

magnetic station and 1 nT for GOES13 satellite. The number of magnetic disturbances was obtained by counting the anomalous geomagnetic gradients and grouping them into one-hour periods to make an hourly distribution. The horizontal north component was selected because this account for the stronger geomagnetic values in the study region.

4. Results and Discussion

Figure 9 shows the correlation between the hourly distribution of the number of seismic events in two seismic zones and the number of geomagnetic disturbances recorded by the geostationary satellite GOES13 and the magnetic ground station SJG.

In order to understand this correlation, it is necessary to mention the dynamic of the global electric circuit between earth and ionosphere. According to this concept, worldwide thunderstorm activity is in effect a d.c. generator (vertical dipole) causing current to flow through the circuit and maintaining the Earth's electric field [11]. Conduction currents can flow in the atmosphere because it is ionized. Changes to the global electric circuit are associated with changes in conductivity linked with the time-varying presence of energetic charged particles, mainly influenced by solar wind [12]. As is known by Faraday's Law, when a magnetic field is disturbed, an electric current is generated (eddy current), whose intensity depends on the frequency of the perturbations. The currents generated by solar winds in the ionosphere cause magnetic field fluctuation on the Earth's surface, inducing electrical currents, which penetrate into the earth and, in the presence of Earth's magnetic field, generate electromagnetic force, known as Lorentz force [13]. According to Urata *et al.*, [13] the Lorentz force tilts the subtle force balance in the earth crust towards triggering the release of stress strain energy, initiating an earthquake in a similar way as a mountain climber's step can trigger the avalanches.

The diurnal fluctuation of Earth's magnetic field (**Figure 5**) is a low-frequency disturbance with a period of 24 hours, which implies that the crust is always exposed to an electric current with low intensity. Following Eccles *et al.*, [14] a

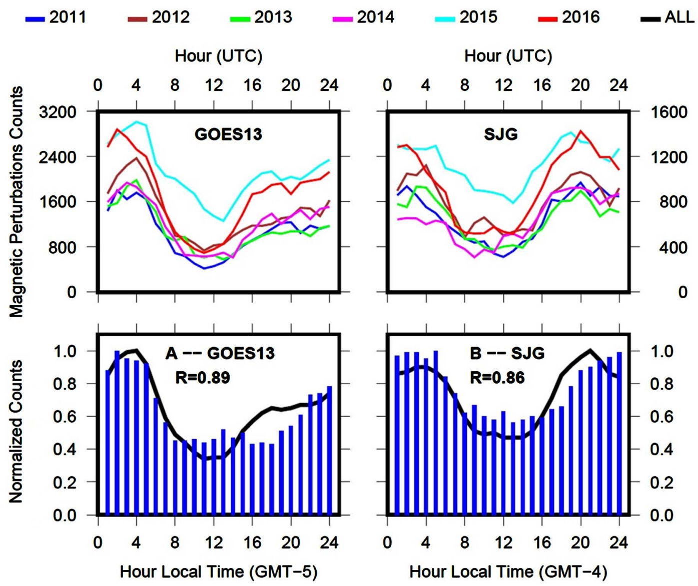

Figure 9. Comparison between hourly earthquakes frequency and hourly magnetic disturbances from 6 years data. Zone A is compared with data recorded by the GOES13 satellite, having its zenith in the same time zone. Zone B is compared with data recorded by SJG ground magnetic station located in the same area. Upper graph plots every year separately and lower graph plots the average shifted 5 hour before local time. R indicates correlation coefficient.

piezoelectric crystal can be defined as one that becomes electrically charged on deformation, or as one that becomes deformed when an electric field is applied. In this sense, rocks when receiving an electric current can react depending on the piezoelectric properties of their minerals composition. When a high-frequency magnetic disturbance occurs, an electric current is induced more intense than the one which normally circulates through the Earth's crust. Furthermore it is probable that some areas may experience elastic deformation due to the piezoelectric phenomena. If the area includes a tectonic fault close to its rupture point, an earthquake could be triggered.

TEC values are proportional to the electric current intensity flowing in the ionosphere-earth global electric circuit. Furthermore, the penetrating electric current into the Earth's crust are more intense at least 4 hours later that the time when the electromagnetic force is induced by solar wind influence (**Figure 7**). That can explain the 5 hours shifted correlation in **Figure 9**. If the assumption for correlation between current electric intensity and seismicity is correct, then must also exist some correlation between time-varying conductivity response of Earth's interior and earthquakes occurrence. Fujii and Schultz, [15] defined the conductivity response (C-response), which connects the magnetic vertical component with the gradients of the horizontal components of electromagnetic fluctuations, as

$$C(\omega) = \frac{-B_r(\omega)}{\nabla_h B_h(\omega)} \tag{1}$$

where, B_r and B_h are the radial and horizontal components of the geomagnetic field, respectively, and ω denotes the angular frequency. Here, the interest is oriented to the time-varying C-response, but Equation (1) is expressed in frequency domain. In this case, a simplified time domain version of C-response expressed in absolute values could be defined as

$$C(i) = \frac{|B_Z(i)|}{|B_{Hx}(i) - B_{Hx}(i-1)| + |B_{Hy}(i) - B_{Hy}(i-1)|} \tag{2}$$

where, B_Z is the vertical component, B_{Hx} is the horizontal north component, B_{Hy} the horizontal east component, and i denotes the sample in the discrete-time data. The diurnal C-response is calculated by applying Equation (2) in the geomagnetic time series (1 min sampling) to obtain the hourly averages distribution (**Figure 10**).

The bay-shape diurnal C-response is consistent through the years and correlates with the hourly earthquakes frequency. Diurnal C-response values in **Figure 10** are expressed as differences with the maximum value of the distribution for better comparison. Bigger C-response values are supposed to correspond to stronger electric currents flowing into the earth.

Although all zones, which include shallow and deep earthquakes on oceanic and continental areas, have a similar bay-shape earthquakes frequency distribution, small differences between the oceanic zones (A and B) and the continental zone (C) can be noted. It is observed that the areas of Cuba and Puerto Rico have more pronounced drop in the number of events from 8 AM to 4 PM when compared to the area of Colombia. It is likely that could be an additional stress due to the oceanic loading tides [16] [17], or an electrokinetic effect due to the formation of an electrical double layer at the solid-liquid interface [18] [19]. In the last case, could be an increase of the electric current intensity due to the existence of a liquid layer, the ocean.

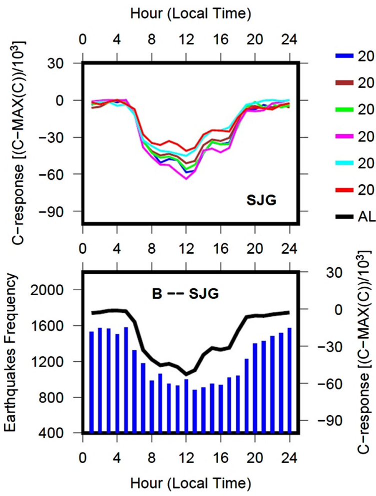

Figure 10. Comparison between hourly earthquakes frequency in seismic zone B and time-varying C-response from 6 years data recorded by SJG station. Upper graph plots every year separately and lower graph plots the average.

It is often difficult to distinguish whether locally recorded magnetic perturbations have the source within the crust or are caused by external events like solar activity. The loading and rupture of water-saturated crustal rocks, together with fluid/gas movements, stress redistribution and change in material properties, has long been expected to generate associated magnetic and electric field perturbations [20]. However, in this study, using high altitude satellite measurements (36,000 km) excludes the option that magnetic disturbances have their origin in the interior of the earth.

5. Conclusion

The results show a strong correlation between high-frequency geomagnetic disturbances and earthquake occurrence, having a delay of approximately 5 hours after the electromagnetic force is induced. The diurnal earthquakes frequency describes a bay-shape distribution modeled mainly by time-varying electric current flowing into the earth. Earthquake frequency has the greater values along the first 5 hours of the day, then gradually decreases until one or two hours after noon, and begins to increase again until midnight. The number of samples analyzed for both, the magnetic field variations and the number of earthquakes, guarantees statistically significant hourly distributions. The results obtained suggest that high-frequency magnetic disturbances can be considered as a trigger mechanism of earthquakes, regardless of the magnitude that those may have. Besides, the time-varying conductivity response of Earth's interior also correlates with diurnal earthquake frequency. Finally, geomagnetic storms are useful to forecast an increase in the probability of earthquake occurrence within few hours after affecting the earth.

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Conflicts of Interest

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

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