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Research Article

# Analysis of GPS TEC anomalies associated with Mw > 7 earthquakes in Japan

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**Abstract:**

The Global Positioning System (GPS) provides insights into the Earthquakes (EQs) ionospheric anomalies. Different space-and-ground parameters are used to observe EQ precursors. This paper uses the Total Electron Content (TEC) from nearby operating GPS stations to detect perturbation in the ionosphere before and after four EQs in Japan in 2011. In addition, the TEC variations in relation to the depth and magnitude of the EQs are noticed. The analysis shows significant variations in TEC to depth and magnitude in association with each main shock. TEC value abruption starts on 8 March and continues for 6 days in March. In April, TEC abnormalities start 5 days before and after the man shock. The geomagnetic Kp index is higher than four from March 10 to 12. The anomalies in this study are clearly associated with geomagnetic storms, as the Kp index is active. Moreover, the Dst index is below the negative 50 (nT) in the seismic period of March and April. The ionosphere parameters will define the severity of seismic activity in future.

**Keywords:** GPS stations, Ionospheric anomalies, Earthquake precursor, Depth of Earthquake, Magnitude of Earthquake, Space parameters, Ground parameters, Seismic activity.

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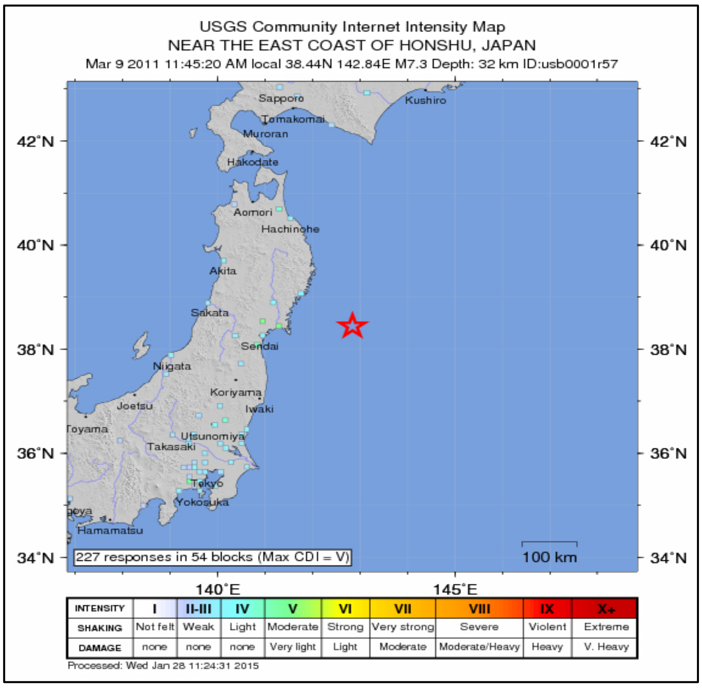
## 1. Introduction

Destructive natural hazards are known to cause severe changes to the infrastructure of a region. Among these hazards, Earthquakes (EQs) are a hazardous type of natural hazard that not only influences the environment but causes extreme causalities and considerable infrastructural damage each year on a global scale. Scientists are striving to explore novel methods so that they can predict this severe hazard and save human lives in the near future. Seismic events are supposed to release a lot of trace gases during their preparation phases just a number of days before the main shock that initiates some chemical transitions in the lower atmosphere and may bring changes in the ionosphere, while some reports have evidenced that, too (Jin & Jin, 2014). Several studies have previously reported possible seismo ionosphere anomalies that may indicate the forthcoming EQ and can be used as potential seismic precursors (Yao *et al.*, 2012; Fuying *et al.*, 2011; Adil *et al.*, 2021a; b). On the other hand, some studies have opposed the hypothesis of LAIC coupling and dedicated these so-called "ionospheric precursors" as an influence of space weather phenomenon (Masci *et al.*, 2015). However, the debate is not over, and many promising studies are coming that suggest that this marvellous phenomenon should be explored.

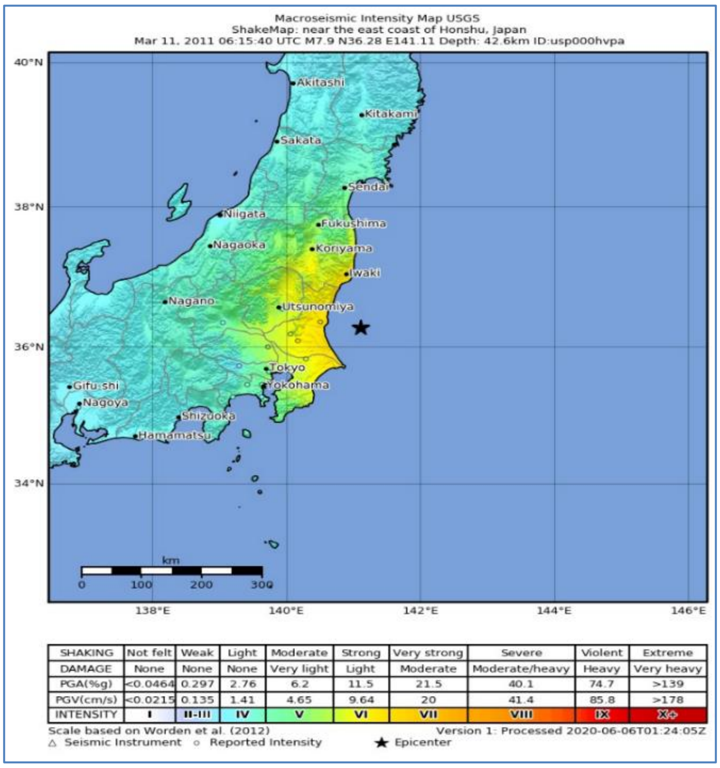
Many studies have some promising findings regarding ionosphere precursors, such as observing anomalous GPS Total Electron Content (TEC). The statistical significance of the electron density variations before the seismic activities has been found very evident in almost every study, indicating a positive gesture towards the possible EQ forecasts in the near future with the increasing cluster of satellites (Denisenko & Zeng, 2020; Rahman, 2020; Shah, 2020). Similarly, some studies have described the possible mechanisms of triggering these ionospheric anomalies. Pulinets *et al.* (2015) proposed the Radon gas release during the seismic preparation zone that further generates the vertical seismogenic electric field through the air ionisation in the atmosphere that brings irregularities in the electron concentrations of the ionosphere; this hypothesis is later confirmed in an analysis conducted by Adil *et al.* (2021c).

Figure 1: Epicentral point of the EQ on 9 March 2011



In March 2011, there were a series of EQs in Japan of different magnitudes, and one of them was the deadliest of Mw 9.0, which killed about 19,000 people, and the economic loss was about 200 billion US dollars. This paper considers different aspects of the four large magnitude EQs in March-April 2011 on the eastern coast of Japan. The ionosphere, which can be affected by solar activity and geomagnetic activity, metrological events, and a less severe seismic activity of Mw 7.3 on 9 March, near the east coast of Honshu, Japan, could be the Precursor for the next devastating shock of Mw 9.0 on 11 March 2011. For this TEC, Dst and Kp index are analysed with the depth and magnitude of the seismic main shocks. In previous reports, the disturbances were shown in many aspects of the troposphere and ionosphere. The IONOLAB TEC data shows insight into the variations associated with depth and magnitude.

Figure 2: Epicentre of the EQ on 11 March 2011



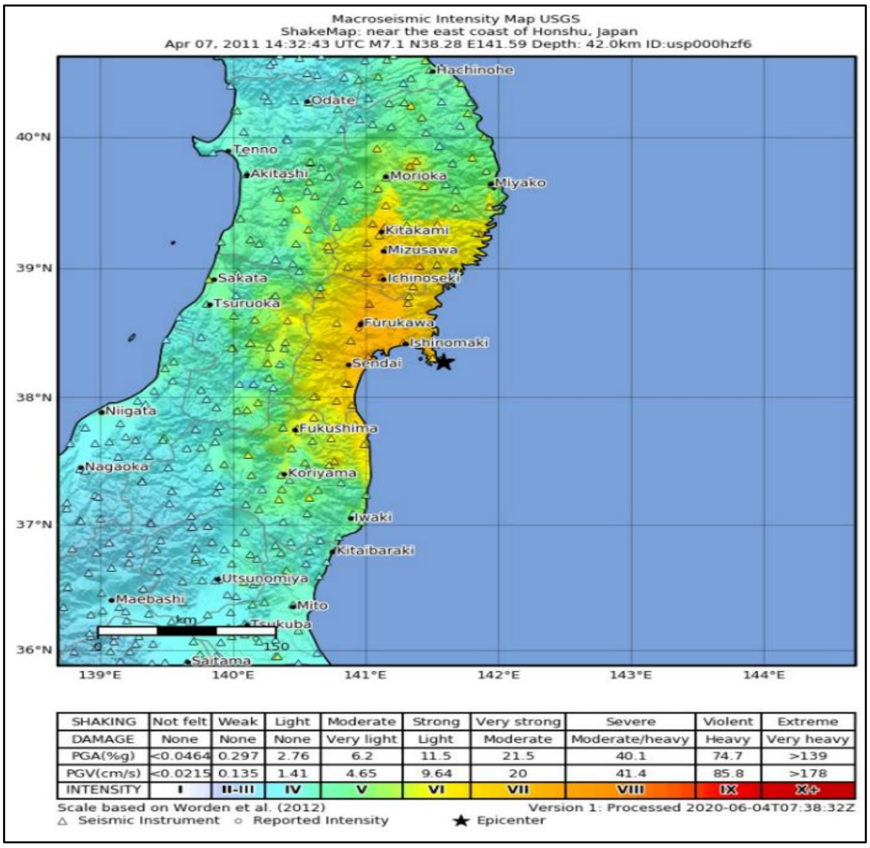

## 2. Case study

The series of EQs occurred due to the faulting between the Pacific and American plates. The studied EQs are largely located in the sea, where the occurrence of the seismo ionospheric anomalies is most likely associated with Tsunami (Pulinets *et al.*, 2015). A detailed description is provided in Table-1.

Table-1: Details of the Earthquakes (EQs)

| Earthquake | Parameters | | |
|---|---|---|---|
| | Magnitude | Depth (km) | Geographical location |
| 9 March- 2:45 UTC | 7.3 | 32 | 38.4°N 142.8°E |
| 11 March- 06:15 UTC | 7.9 | 42.6 | 36.2°N 141.1°E |
| 11 March- 06:25 UTC | 7.7 | 18.6 | 38.0°N 144.5°E |
| 7 April- 14:32 UTC | 7.1 | 42 | 38.2°N 141.5°E |

Figure 3: Epicentre of the EQ on April 7 2011




### 2.1. Data collection and methodology

The data depth and magnitude of all the EQs are taken from the United States Geological Survey (USGS) website. The IONOLAB provides the TEC data from three stations, which has hundreds of stations across the Globe. The “spaceweatherlive.com” provided the Kp index for the month of March and April. The Kyoto website provides the Dst index. To show anomalies in the acquired data, MATLAB codes were used for making graphs.

## 3. Results

We have investigated the ionospheric response to the sequential EQs in the Japan region that can be regarded as possible seismic precursors. The cumulative TEC graphs for all the measured values in the selected IGS stations are shown in Figure 4, where the abrupt variations before and after the main shocks are statistically observed along the series of EQs in March and April associated with the main shock. However, the Dst and Kp are not quiet during these days. On the other hand, the individual graphs for each analysed IGS station along with the seismic events are represented as KSMV in Figure 5, AIRA in Figure 6, and MATKA in Figure 7. In each of these analyses, we can observe a characteristic ascendancy peak preceding each seismic event that attains its maximum phase within 5 days before the impending shocks, but it is associated with the geomagnetic storm, as Kp and Dst remain active. This specific variation can be observed in each analysed station in Japan. To get a further zoomed look, we designate the daily TEC values for these stations, represented in Figure 8. One can see that the TEC values began to climb in the first two weeks of March 2011. The TEC values gradually ascend from March 1 and reach the maximum till the two gigantic seismic events on March 15, 2011, and subsequently turn back to normal. This unique feature is described for seismic events in the reports of Pulinets *et al.* (2015) and Shah *et al.* (2020). In this paper, these variations are clearly associated with geomagnetic storms.

Figure 4: TEC variations from 1 March to 14 April for the stations at the top of the panels

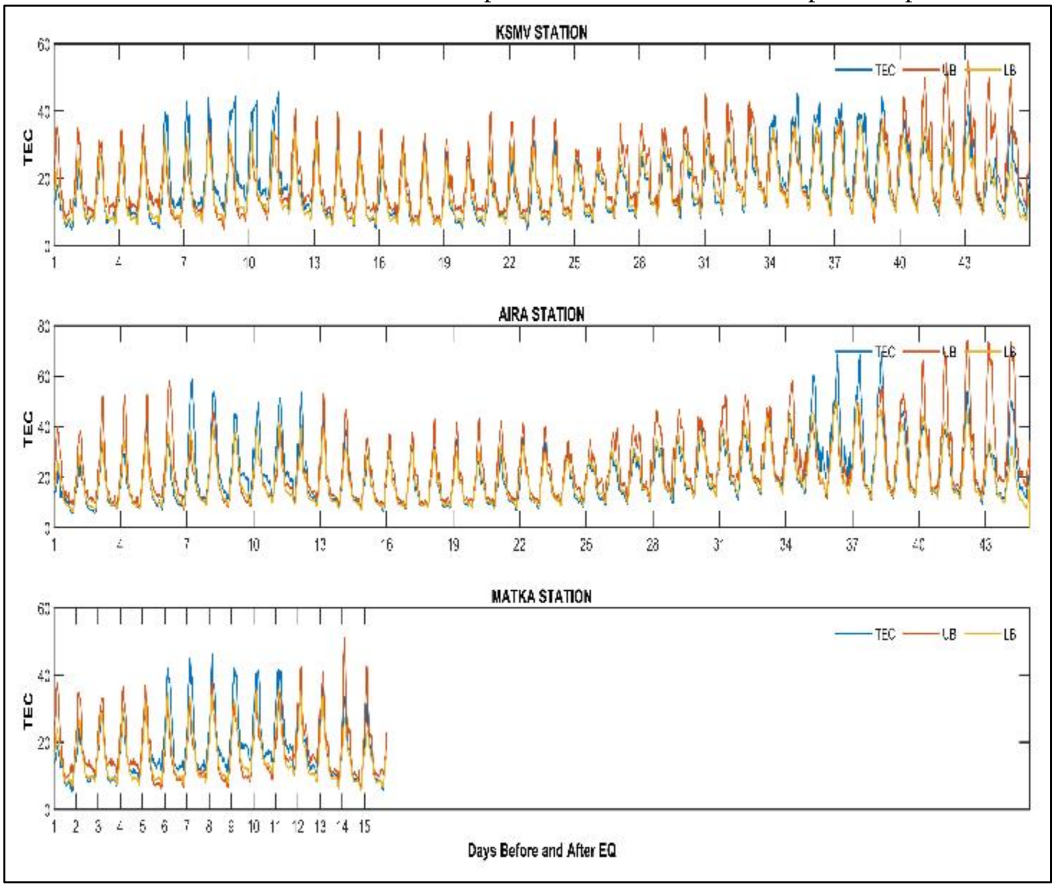



Figure 5: KSMV station observations for the EQ depth and magnitude analysis

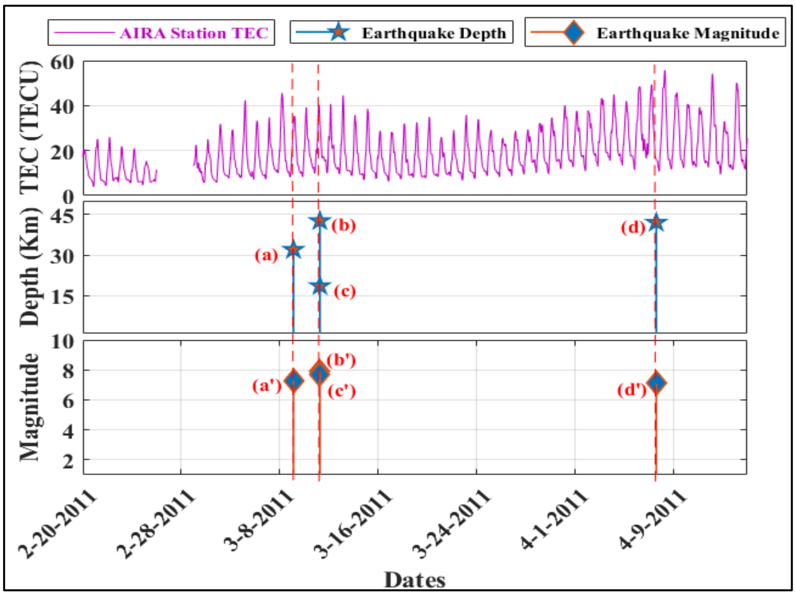


Figure 6: AIRA station observations of the EQ depth and magnitude analysis

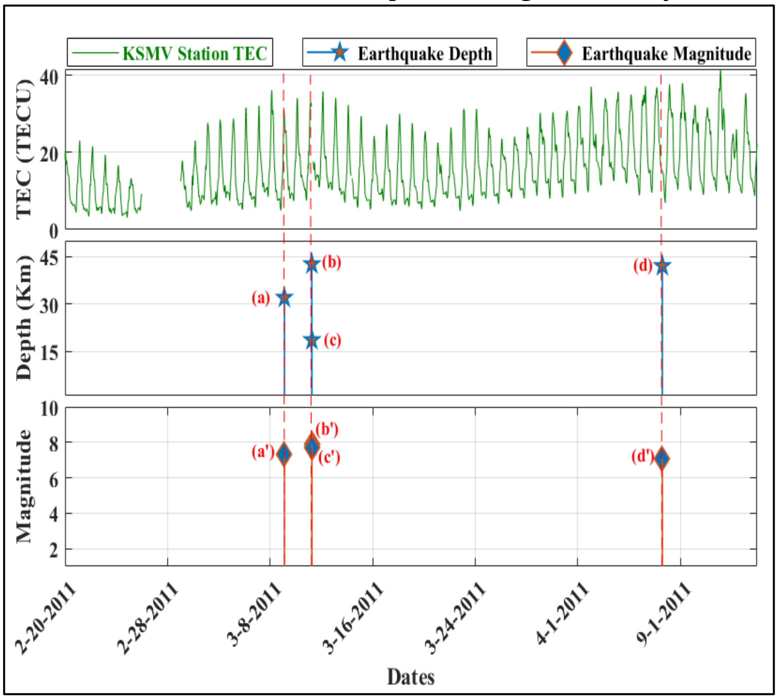
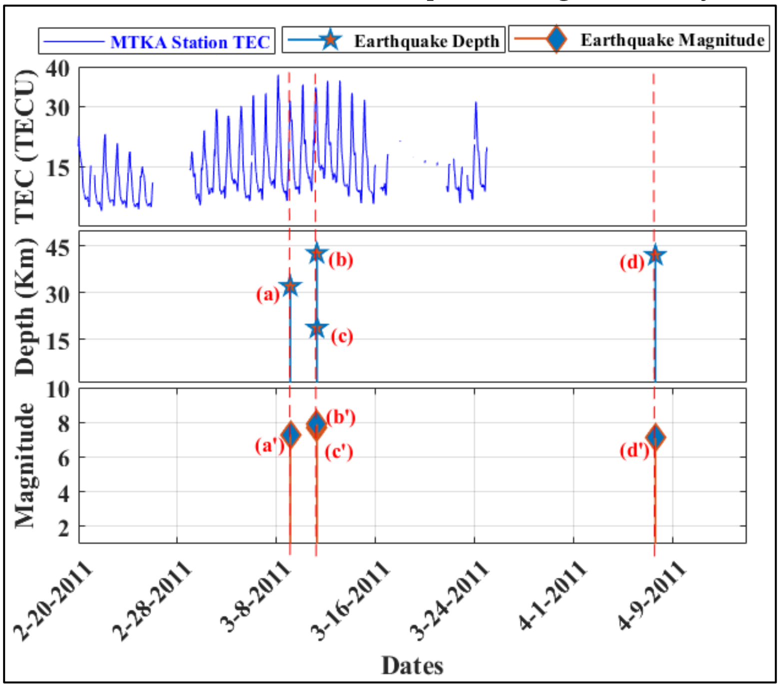



Figure 7: MATKA station observations of the EQ depth and magnitude analysis




Similarly, the trend also sounds to be repeating in the case of the April 11 event, where the TEC values again ascend in a characteristic manner from April 1 and attain their maximum peak on the main shock day before turning back to normal. The geomagnetic conditions are closely monitored during the period, and the periodicity in Dst and Kp does not perfectly correlate with the TEC values (Figure 9), as we can observe in the case of seismic events to TEC values. In this sense, we can say that the observed variations are for somehow decoding a trend of seismically induced TEC variations that can open the doors to EQ forecasting.

Figure 8: Mean TEC variations from all the stations

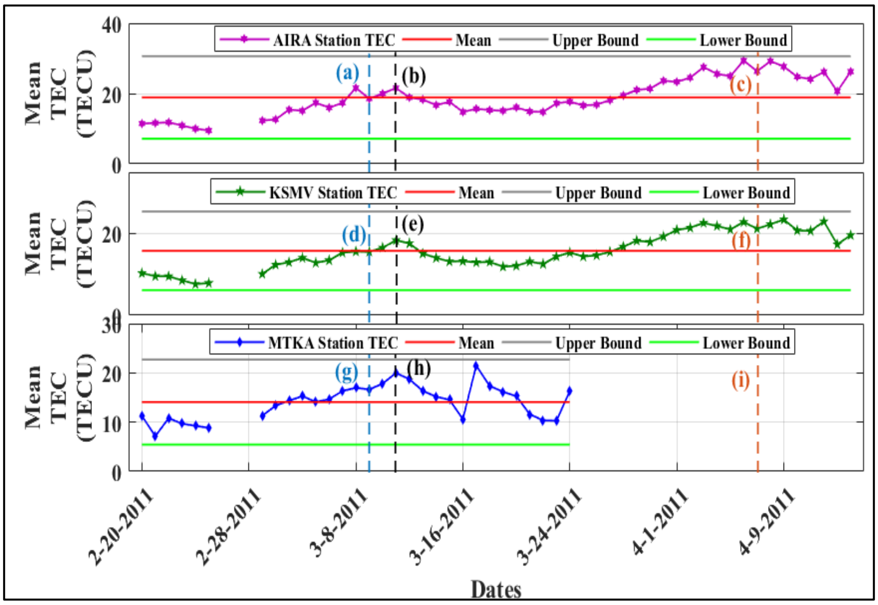
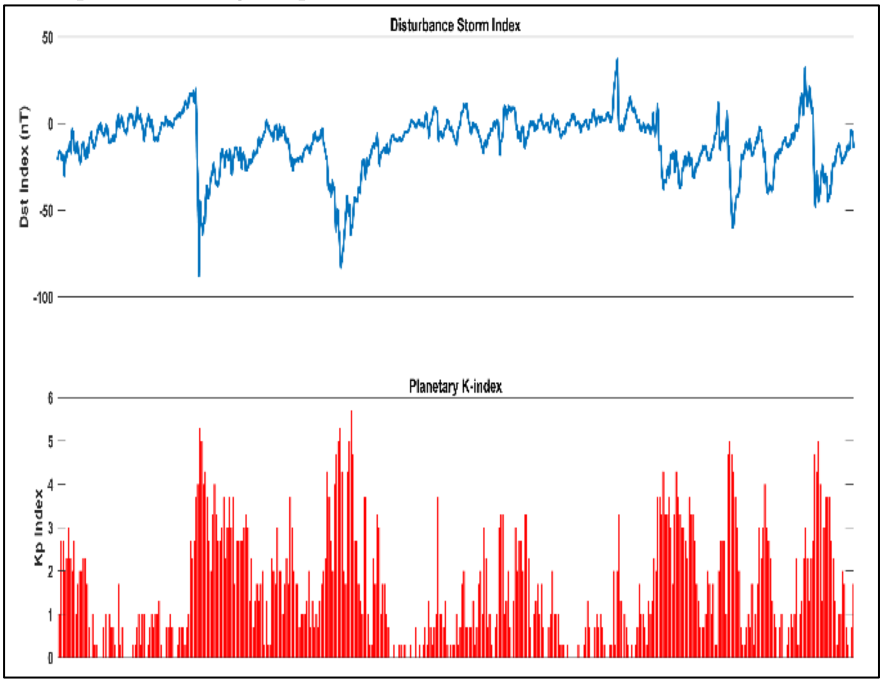



Figure 9: Dst and Kp index during the period




## 4. Discussion

In this study, the increase in the ionosphere could not be due to the high concentrations of the Earth's degassing during the seismic events as the solar storm and geomagnetic activity are high during these days. We can observe a very unique trend in the TEC values, where the TEC concentrations are used to enhance 5 days before the event and eventually enhanced till the main shock before going to normal. Similar observations were recorded by Kiyani *et al.* (2018), where they found significant variations in the TEC values before a giant M 8 Fiji EQ in 2018. In another analysis, large TEC enhancements were recorded before the M 7 Papua New Guinea

EQ, where the authors claimed that the seismic TEC anomalies could also be observed during high geomagnetic activities (Ulukavak & Inyurt, 2020). As storm values are active before and after the main shocks. In this case, the polarisation occurs before and after the main shock. Sometimes, it shows the dense TEC vertical to the epicentre, and sometimes, it drifts. In this case, it drifts toward the south of the epicentre of the seismic region (Figure 10 & Figure 11). A slight variation is not noticed when the magnitude and depth of the EQ relation are found. The other factors confirm the abnormality, such as the Dst and Kp index in the same period. The proposed mechanism from Pulinets *et al.* (2015) urges us to conduct more statistical analysis to validate the TEC anomalies as possible seismic precursors.

Figure 10: Total Electron Content (TEC) drift

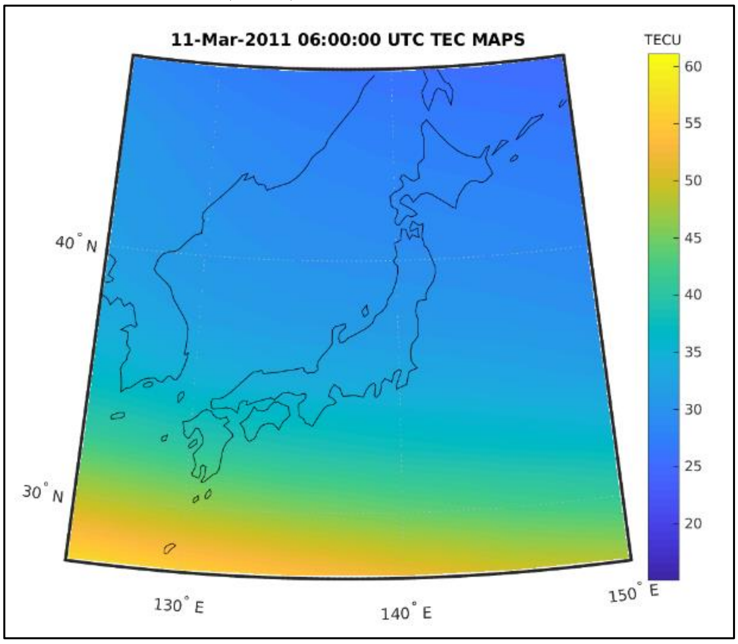
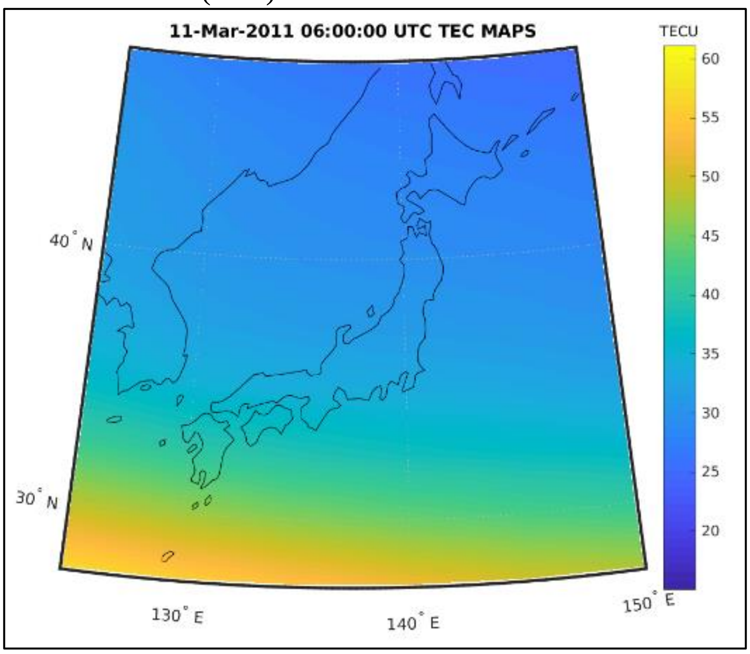



Figure 11: Total Electron content (TEC) drift



## 5. Conclusion

The analysis of several parameter data shows that the ionospheric anomalies are due to geomagnetic storms. Though the evidence is strong enough for Earthquake (EQ) but, it is hard to depend on seismic precursors during active geomagnetic storm days. The future prediction of time, epicentre and magnitudes. However, there are rough variations associated with each EQ. The abrupt behaviour of seismic activity has random connections with its environment. In addition, finding its calculated relation with each parameter of the environment is complex due to the unavailability of reliable data and in-depth analysis. More focus is required on data collection and processing.

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