



## Analysis of ionospheric response to Earthquake using GPS data: a case study of Chignik, North America and Southern-Sandwich, South America Earthquakes

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### Abstract

In this study, GPS-derived total electron content (TEC) data were utilized to monitor ionospheric behaviour 20 days before and 5 days after two significant earthquakes that occurred in Chignik, North America and Southern-Sandwich, South America on 10<sup>th</sup> November 2021 and 8<sup>th</sup> December 2021 respectively. Data were collected from GPS stations within the seismogenic zone. The sunspot number (SSN) and F10.7 indices were used to track solar activity during the events, while the planetary geomagnetic activity index (kp) and disturbance storm-time (Dst) indices were used to check geomagnetic activity. Results from the analysis revealed that TEC data contain both negative and positive ionospheric anomalies during the investigative period using a statistical analysis technique that involved moving median. Geomagnetic and solar indices indicated relative stillness during 88% of the anomalous days isolated for the earthquakes, hence anomalies were considered seismogenic.

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The result further suggests that a significant amount of disturbances is caused by seismogenic processes. As earthquake-induced anomalies were found within 20 days of the studied cases, it was also shown by the discovery of earthquake-induced TEC anomalies through temporal analysis that ionospheric fluctuations are crucial for earthquake forecasting. Therefore, this study suggests that there could be a connection between TEC anomalies in the ionospheric space and the occurrence of significant earthquakes. Thus, it is advised that TEC monitoring be seriously taken into account for short-term earthquake event forecasting, particularly in regions with unreliable seismic measurements.

**Keywords:** Earthquake; GPS-TEC; Seismogenic; Ionospheric; anomalies

### 1.0 Introduction

Earthquake is simply the shaking of the surface of the Earth resulting from a sudden release of energy in the Earth's lithosphere (Currie and Waters, 2014). It is regarded as the most impactful natural occurring event with respect to the Earth's surface and atmosphere as well as

global population. The occurrence of earthquakes has over the years proved to be hazardous to human lives and properties and wrecked economies. The agonies caused by earthquake have provoked scientists all over the world to conduct broad-based researches on various phenomena relating to this disastrous event with the sole aim of predicting them. Thus, for many decades, understanding earthquake corollaries and ways of mitigating them have continued to dominate discussions at many scientific and social fora (Thomas, 2021). While statistics has shown that most seismic events occur within the Circum-Pacific and Alpidic Belt; in recent times, earthquake occurrence has extended to unsuspected countries, regions and towns. This is a major concern as concrete resolutions for earthquake prediction and forecasting is still wrapped in huge uncertainty (Baselga, 2020).

Due to the complexity of earthquake-preparation processes, identifying true earthquake precursors from anomalous geophysical signals is still a global problem (Hafeez *et al.*, 2021). Many researchers have claimed to predict earthquakes/tsunamis by observing multiple indirect precursors such as recording behavior of animals, observing an increase in temperature, emission of radon gas, and observing the change in seismicity patterns of the region (Shi *et al.*, 2019). Others have tried direct prediction techniques encompassing methodologies consistent with measured parameters or/and seismic precursor parameters of earthquake preparation zones. However, it is very hard to generalize and standardize these prediction algorithms as the precursors are quite inconsistent with every event. With recent improvements in computational intelligence and increased harmonization of earth/atmospheric sciences and computer science, favorable and exciting results have been reported from studies applying systems consistent with different artificial intelligence

methodologies for predicting future earthquake/tsunamis from historic and instrumental data (Baselga, 2020).

Among different precursory phenomena studied on earthquake predictions, the ionospheric method are probably the youngest. The ionosphere is a part of the upper atmosphere where there are enough electrons and ions to effectively interact with electromagnetic fields (Heki and Enomoto, 2013). Due to its electromagnetic properties, the ionospheric plasma interacts with the Earth's magnetic field and to a considerable extent is controlled by it (Mendillo, 2006). The ionosphere is however spatially and temporally characterized by variations. This is caused by activities in its various layer. Seismic activity is one of the sources of the day-to-day ionospheric variability and is rapidly attracting the attention of earthquake researchers (Akhoondzadeh *et al.*, 2013; Akhoondzadeh, 2019; Thomas, 2021). This is related to the fact that the coupling between the anomalous generated electric field in the earthquake preparation zone and the one generated in ionosphere causes ion drift which can result in the modification of the ionosphere formation. If these modifications could be detected and reconstructed, they could be used to understand the behavior of the earthquake that caused it (Akhoondzadeh *et al.*, 2018; Akhoondzadeh, 2019).

Recently, methodologies based on atmospheric anomalies (such as those in the earth's ionosphere) are increasingly being employed to study the behavior of earthquakes (Ulukavak *et al.*, 2020). Unfortunately, the relationship between earthquakes and variability in the earth's ionosphere is not straightforward as ionospheric variability itself can be attributed to several other factors such as geomagnetic storm and solar activities. To this end, it is important to distinguish between ionospheric disturbances connected with earthquake preparations and those from other disturbances as measures to

forecast earthquake and mitigate its losses (Komjathy *et al.*, 2012). In this work, satellite data from global positioning systems were used to compare the fluctuations in the ionosphere with regard to previous earthquake events in selected prone-locations. This research examines GPS - TEC data before and after two earthquakes for probable pre and post-seismo-ionospheric precursors. The study's ultimate goal is to increase scientific knowledge of the connection between ionospheric anomalies and earthquake occurrence with the primary goal of minimizing the human and economic loss experienced during such a disaster.

## 2.0 Data

One of the most widely accepted technique for ionosphere monitoring is measurement of Global Positioning System - Total Electron Content (GPS - TEC). This technique is based on the ionospheric effect on the propagation of the signal transmitted from the Global Positioning System and Global navigation satellite system. The space segment of the GPS consists of a constellation of 24 operating satellites in six circular orbits 20, 200 km above the Earth at an inclination angle of  $55^\circ$  with a 12-hr period. The satellite transmits two frequencies of signals ( $f_1=1,575.42$  MHz and  $f_2=1,227.60$  MHz). Since the ionosphere is a dispersive medium, scientists are able to evaluate the ionospheric effect with measurement of the modulations on the carrier (codes) and the carrier phases recorded by dual-frequency receivers. The ionospheric effect, which can be selected from the signal, is then transformed into TEC along the ray path between the satellite and the receiver. Total electron content is the total number of electrons integrated between two points along a tube of one meter squared cross section (technically between the receiver and the satellite). TEC is mostly associated with higher density in the F-layer than in the D and E layers which are the

different layers or regions in the ionosphere (Liu *et al.*, 2011; Currie and Waters, 2014). TEC data also provides opportunity to detect any acoustic, gravity, or both types of waves perturbations in the upper atmosphere.

The study locations are Chignick, U.S.A. as well as Southern-Sandwich, South America (Table 1). Fig. 1 shows a map of the epicenters of the investigated earthquakes. The earthquake data was downloaded from repositories of United States Geological Survey (<http://www.earthquake.usgs.-gov/earthquake-es>). 15 mins - interval TEC data for 26 days, which included 20 days before (Pre-seismic), during (Co-seismic) and 5 days after (Pascaseismic) the earthquake were retrieved from the network servers of International GNSS server (<ftp://data-out.unavco.org/pub/rinex>). Geomagnetic data, which include Planetary geomagnetic activity index (Kp) and disturbance storm-time index (Dst) indices as well as Solar index which include Sunspot number and F10.7 indexes (Solar Index) were downloaded from International Service of Geomagnetic Indices. The TEC data were retrieved from stations within the preparation zones of the respective earthquakes as given by Dobrovolsky *et al.* (1979). The two stations were selected from the network servers of International GNSS server (IGS). Geomagnetic data which included kp and Dst indices as well as Solar indices Sunspot number and F10.7 indices were downloaded from International Service of Geomagnetic Indices. The data were retrieved from the International Service of Geomagnetic Indices (ISGI) repository using the Space Physics Environmental Data Analysis Software (SPEDAS) version 3.1.

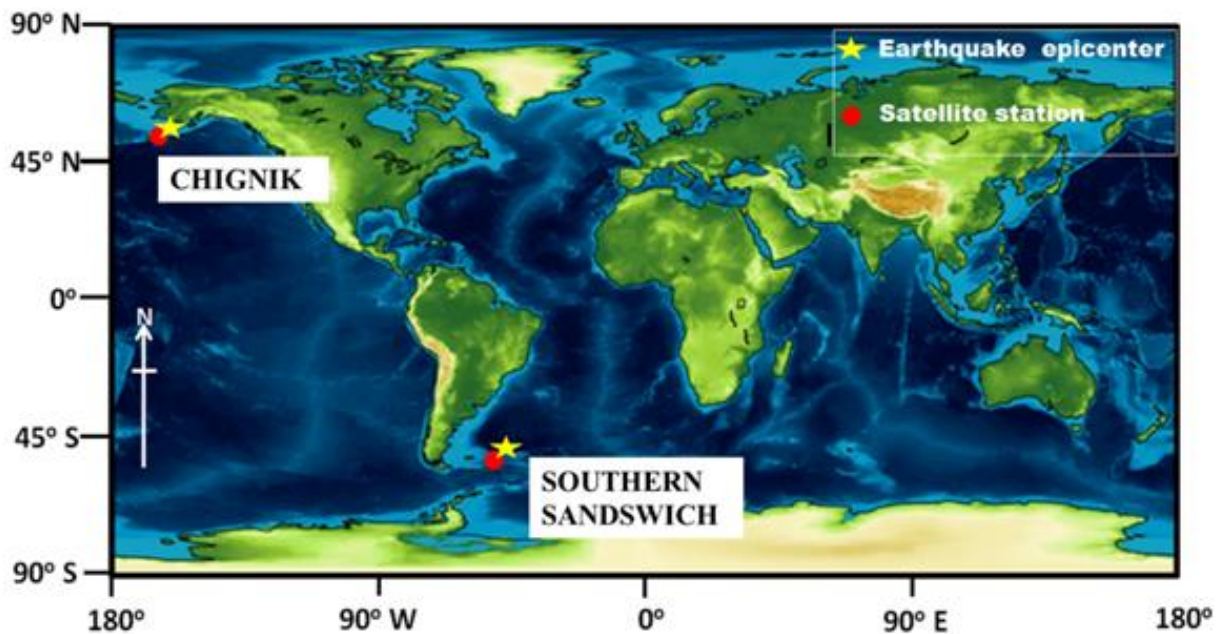
## 3.0 Methodology

In this study, GPS-TEC data were utilized to monitor ionospheric behavior 20 days before and 5 days after two significant earthquakes that occurred in Chignik, North America and

Southern - Sandwich, South America December 2021 respectively.  
Earthquakes on 10<sup>th</sup> November 2021 and 8<sup>th</sup>

**Table 1:** Details of the studied earthquakes events

EQ Mag.	EQ Location	Country	Event Date	Radius of Preparation Zone (km)	Geo-coordinates of epicenter			Distance of Earthquake to Epicenter (km)
					Lat. (°)	Long. (°)	Depth (km)	
7.0	Chignik	USA	10/11/2021	1023.293	56.295°N	156.581°W	51.6	383.371
8.1	Southern Sandwich	South America	8/12/2021	3040.885	58.375°S	25.264°W	22.8	827.063



**Fig. 1:** Map showing the epicenters of the two investigated earthquakes. The yellow stars represent the epicenters while the red circles are the GPS stations.

Solar and geomagnetic indices collected from the relevant magnetometers were analyzed comparatively with the GPS -TEC measurements to ascertain the true source of the ionospheric anomaly if present. For this study, satellite data obtained respectively from global positioning systems were employed to comparatively study the variations in the ionosphere with respect to the historical event of earthquakes in the selected locations.

All the raw data went through stages of data processing before it was used for analysis. The data obtained from the two stations were not originally the total electron content data required for this research, but rather, geometry-

free linear combination of the code (P) and carrier-phase ( $\Phi$ ) measurements. These combinations were in RINEX compressed .Z formats.

By deducting the measurements from the P1 code, the geometry-free linear combination for pseudo-range measurements, P4, was calculated. To obtain unbiased Slant Total Electron Content, differential code biases (DCBs) should typically be determined, it should be added (STEC). Although there have been recommendations, a set method for including these DCBs in TEC computation has not yet been established. In order to achieve

this, the approach of removing DCBs from STEC calculations was adopted. Equation 1

$$STEC_n^m(y) = \frac{1}{A} \left( \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right) [P_{4,m}^m(y) - DCB^m + DCB_u] \quad (1)$$

where  $f_1$  and  $f_2$  are the carrier frequencies of  $L_1$  and  $L_2$  signals of GPS satellites.

$STEC_n^m$  indicates the Slant Total Electron Content (STEC) on the slant signal path from the receiver,  $n$  and satellite,  $m$ .  $A$  stands for the amplitude while  $DCB^m$  and  $DCB_u$  are the differential code biases (DCBs) defined for pseudo-range measurements,  $y$  denotes the time sample ranges from 1 to total number of time samples in a record.

VTEC was obtained using a thin shell approximation (Klobuchar, 1987) of the single layer ionosphere model related in equation 2;

$$M(z_m(y)) = \frac{STEC_n^m(y)}{VTEC_n^m(y)} \quad (2)$$

where the mapping function  $z_m(y)$  is defined as the satellite zenith angle at the receiver position. The mapping function  $M(z)$  is defined as follows in equation 3:

$$M(z) = \frac{1}{\cos z^1} = \frac{1}{\sqrt{1 - \sin^2 z^1}} = \frac{1}{\sqrt{1 - \left( \frac{R}{R+H} \sin(\alpha z) \right)^2}} \quad (3)$$

$$\sin z^1 = \frac{R}{R+H} \sin(\alpha z)$$

where,  $z^1$  is the zenith angle at the ionospheric pierce point (IPP) where the line-of-sight between the satellite and ground receiver intersects the thin shell.  $R$  is the earth's radius (6,378.137 km),  $\alpha=0.9886$  is a scaling factor from the modified single layer mapping function (Schaer 1999) and  $H$  is the ionospheric shell height 350 km (Mannucci *et al.*, 1993).

The calibrated VTEC values are determined using equation 4 for each continuous arc. The hourly VTEC values were then estimated with the calibrated VTEC values at IPP over each GNSS station by fitting the approximation of second-order polynomial surfaces to IPP points for a 24-hour run (Durmaz and Karslioglu 2014).

$$VTEC = (v_{IPP}, S_{IPP}) = a_0 + a_1 v_{IPP} + a_2 S_{IPP} + \dots + a_3 v_{IPP}^2 + a_4 S_{IPP} + a_5 v_{IPP}^2 \quad (4)$$

where  $v_{IPP}$  and  $S_{IPP}$  are the spherical coordinates of the IPP in the sun-fixed reference frame;  $a_0, a_1, a_2, a_3, a_4$  and  $a_5$  are the polynomial surface coefficients. The topside hourly VTEC values at each station were calculated by substituting the sun-fixed spherical coordinates of each station alongside the estimated polynomial surface coefficients. Missing VTEC values above the stations were completed by interpolation. Furthermore, the

differential Total Electron Content was calculated as the daily TEC minus the average for one month for the observed UT hour (equation 5).

$$dTEC = TEC - \frac{\overline{TEC}}{N} \quad (5)$$

where  $\overline{TEC}$  is the mean TEC over one month and  $N$  is the number of days in the month.

For the analysis stage and investigation of TEC anomaly, the moving median (MM) method was employed. The MM method employs quartile based statistical analysis method (Liu *et al.*, 2009). Here, the MM values of GPS-TEC were calculated in advance by using a quartile-based statistical analysis method. The lower quartile (LQ) and upper quartile (UQ) were also calculated. The lower bound (LB) and upper bound (UB) are calculated as shown in equation 6 and 7 respectively.

$$LB = MM - 1.5(MM - LQ) \quad (6)$$

$$UB = MM + 1.5(UQ - MM) \quad (7)$$

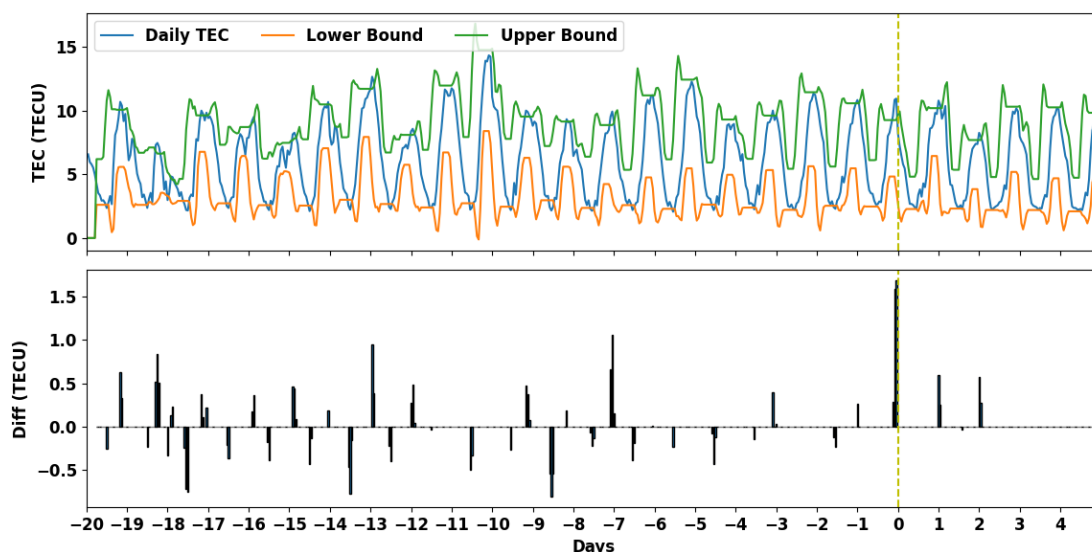
#### 4.0 Results and Discussion

Vertical Total Electron Content (VTEC) for Chignik and Sandwich, as well as solar and geomagnetic activity during the events period, were monitored using the sunspot number and F10.7 indices, while geomagnetic activity was monitored using the kp and Dst indices. Positive anomalous TEC perturbations were observed on days -19, -18, -13, -7, 0 and 5 for the Chignik earthquake, while negative anomalies were observed on days -17, -13, -11, and -8 (Fig. 2). These anomalous perturbations are considered to be seismogenic, as they were found to be devoid of activity when compared to the geomagnetic (kp and Dst) and solar

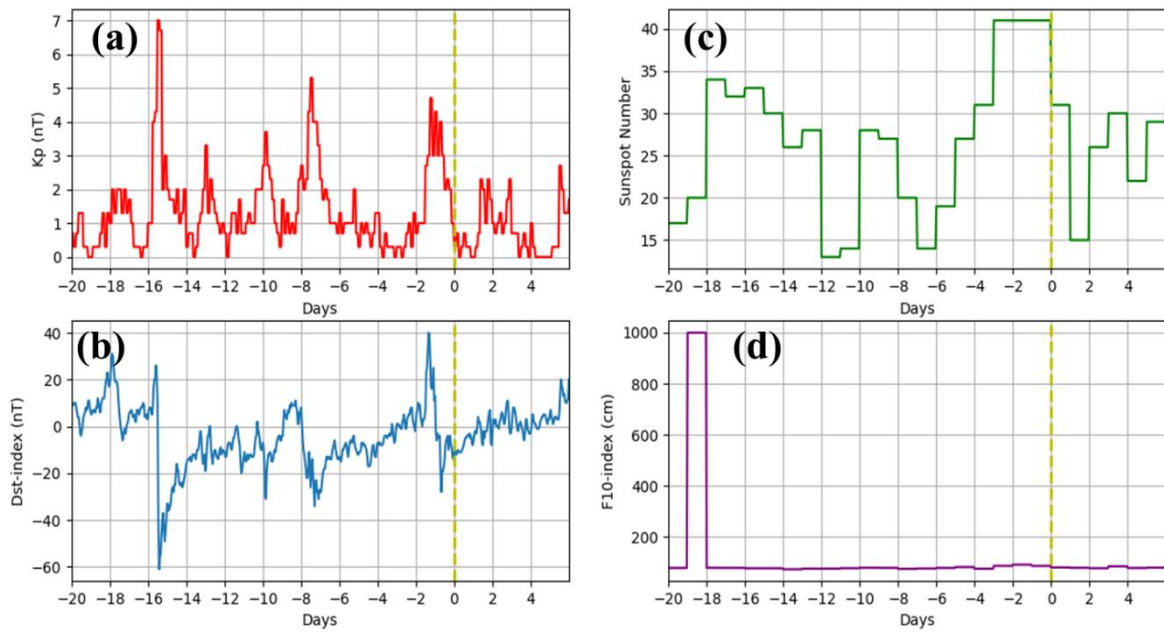
indices (F10.7 cm and sunspot number) (Fig. 3).

Similarly, for the Southern Sandwich earthquake, positive anomalous TEC perturbations were observed at -2, -4, -11, -13, -14 and -19 days whereas negative anomalies were very low and negligible (Fig.4). These anomalies were considered seismogenic as all the geomagnetic and solar indices indicated relative quietness during the anomalous days (Fig. 5). For all the cases experimented, earthquake-induced anomalies were observed within 20 days of the respective event.

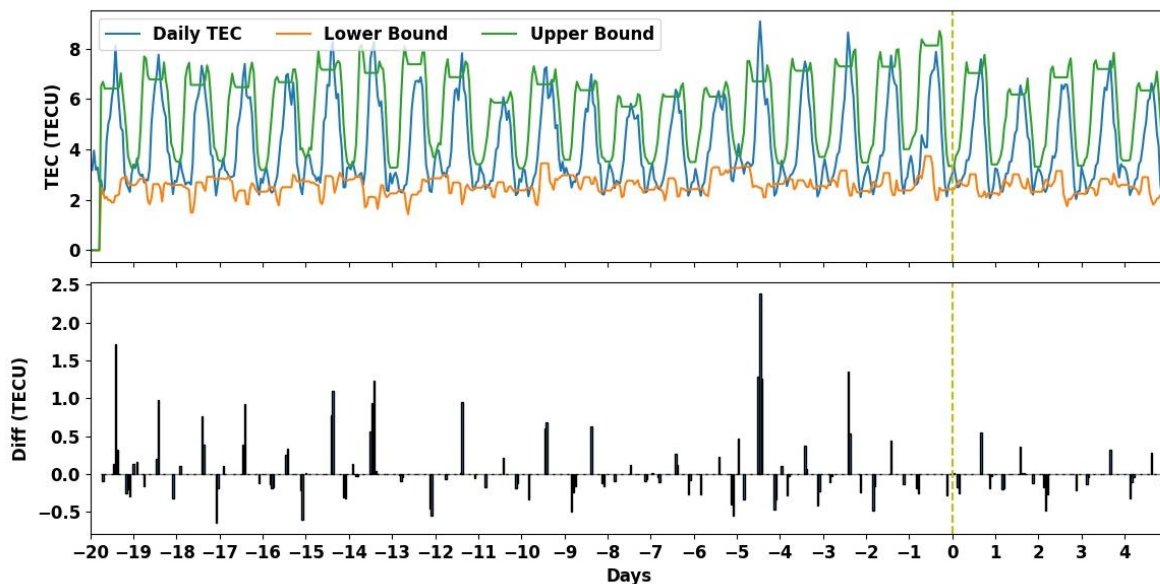
While this study is pioneering for analysis of ionospheric response to earthquakes using GPS data, these findings are consistent with those from other investigations conducted and reported in the literature for events of similar magnitude (Pulinets *et al.*, 2007; He and Heki, 2017; Ibanga *et al.*, 2018; Shah *et al.*, 2019; Shah *et al.*, 2020; Bolaji *et al.*, 2021; Tariq *et al.*, 2021). This research revealed that ionospheric anomalies caused by earthquakes can be monitored during geomagnetic quiet storm circumstances.



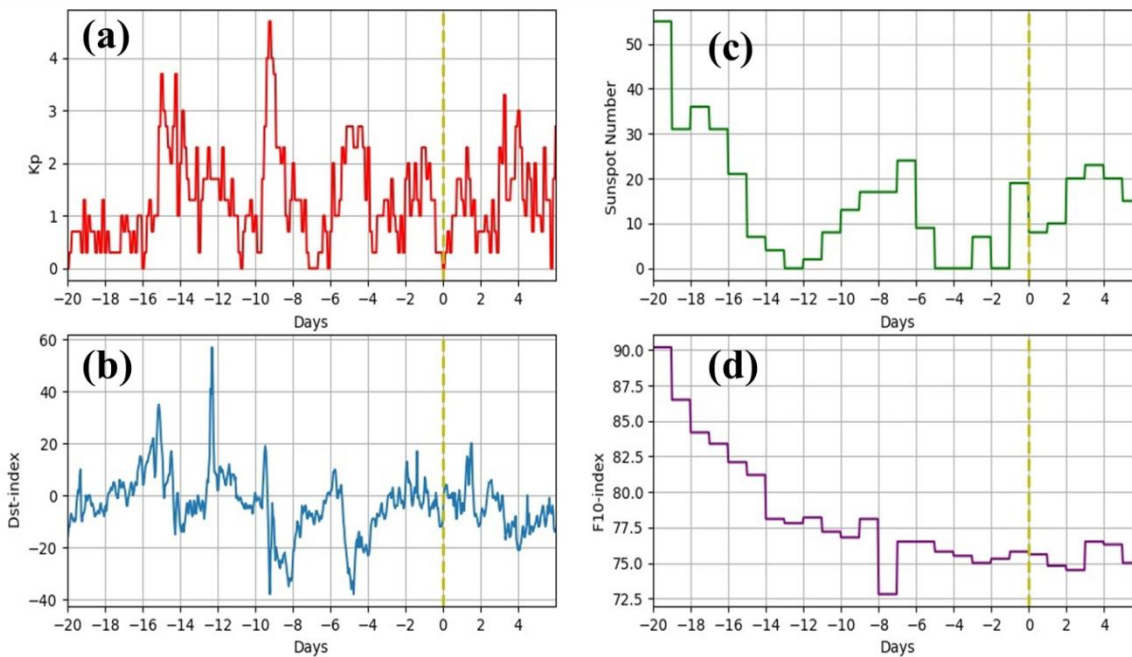
**Fig. 2:** Temporal TEC before and after the M 7.0, Chignik earthquake of 10/11/2021



**Fig. 3:** Variations of Geomagnetic and Solar indices within the study period against days relative to the Chignik earthquake of 10/11/2021 (a) Geomagnetic Index (kp) (b) Disturbance Storm Time (Dst) (c) Sunspot Number Index (d) Solar Activity (F10.7)



**Fig. 4:** Temporal TEC before and after the M7.3, Southern Sandwich earthquake of 8/12/2021 -2, -4, -11, -13, -14, -19



**Fig. 5:** (a) Geomagnetic Index (Kp) (b) Disturbance Storm Time (Dst) (c) Sunspot Number Index (d) Solar Activity (F10.7) intervals before and after the solar and Geomagnetic Indices at intervals before and after the Southern Sandwich earthquake of 8/12/2021

## 5.0 Conclusion

Two large earthquakes (magnitude  $\geq 7.0$ ) that occurred between January and December 2021 were investigated for GPS-TEC obtained from nearby operating stations. The data were collected at 60 minutes interval for 20 days before and 5 days after the events. Using the kp, dst, sunspot number, and F10.7 cm indices, ambiguities related to other ionospheric events, such as solar and geomagnetic disturbances, were also checked. The findings showed that most anomalous days were characterized by low activity in the indices, pointing to a seismogenic origin for a considerable proportion of the perturbations. The finding of earthquake-induced TEC anomalies through temporal analysis demonstrated the value of ionospheric variations for earthquake forecasting as anomalies were discovered within 20 days of all the events. Notwithstanding, it is crucial to note that ionospheric variability is extremely ambiguous even in the midst of quiet geomagnetic and solar conditions. As a result, measured parameters that occasionally show variations in

these circumstances could still be linked to other unidentified factors. It is recommended that appropriate governments and geophysical organizations of those countries pay very close attention to how natural disasters affect the lower atmosphere in order to forecast them and if at all possible, prevent them. Additionally, further research is needed especially in the area of long-term impact precursory potential of GPS-TEC.

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