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Analysis of ionospheric TEC anomalies for global earthquakes during 2000-2019 with respect to earthquake magnitude (Mw ≥ 6.0)

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ABSTRACT

In this work, a relationship between ionospheric TEC anomalies and different earthquake magnitude groups before the main shocks was investigated. For this purpose, 2942 global earthquakes with Mw ≥ 6 from 2000 to 2019 and possible ionospheric TEC anomalies that occurred before earthquakes were examined by considering 13 different index values of space weather conditions (geomagnetic storm indices and solar activity indices). Anomalies of ionospheric TEC changes were defined for 15-days before and 4-days after the earthquakes by using 15-days moving median method with the length of 15 days. Earthquakes were first grouped according to their magnitudes, and then negative and positive TEC anomalies in quiet days before the earthquakes were detected. These anomalies were observed as ~5–13, ~5-10, ~5-15, ~3-13, ~7-15, ~1 and ~5-8 days ago for the earthquakes of 6.0 ≤ Mw < 6.5, 6.5 ≤ Mw < 7.0, 7.0 ≤ Mw < 7.5, 7.5 ≤ Mw < 8.0, 8.0 ≤ Mw < 8.5, 8.5 ≤ Mw < 9.0, and 9.0 ≤ Mw < 9.5, respectively. Mean of changes in TEC anomalies of these groups is 44.2 % TECU and we detected that the number of positive anomalies in each group is larger than the number of negative anomalies. Consequently, these analyses clearly show that the day-to-day changes in TEC anomalies may supply significant precursors prior to the global earthquakes (M ≥ 6) in the short-term earthquake prediction for main shocks.

1. Introduction

Earthquake prediction has been a very complex and important issue in seismology for more than a century. The phrase of *"short term prediction"* states the alarms from days to months, *"intermediate term prediction"* from a few months to several years, and *"long term prediction"* to from a few years to several decades. Current progress in literature reveals that acceptable and reliable models in earthquake prediction have not yet been available in the short-term in comparison with the intermediate or long term. That means the effective short term prediction is still a challenging issue (Sykes, 2002). The phrase of *"short term prediction"* states the alarms from days to months, *"intermediate term prediction"* from a few months to several years, and *"long term prediction"* to from a few years to several decades. However, the short-term earthquake prediction has a critical review and it may be difficult to detect the potential precursory anomalies for the short-term earthquake hazard (Huang et al., 2017). Thus, successful earthquake predictions in the short term for the near future earthquakes have been uncommon on a reliable and consistent basis.

It is well known that earthquakes do not occur randomly in space and time. Aftershocks, foreshocks, groundwater level and temperature, changes in animal behaviours, electromagnetic signals, precursory fault slip, chemical emissions, temporal variations of velocity, precursory quiescence or seismic activation are just a few of the indicators identified by seismologists (Holliday et al., 2005). In addition, many well-accepted seismological, geodetic and other geophysical precursors such as geomagnetic, geoelectric, geodetic and gravity precursors, ground fluid or hydro-seismology can be observed and monitored to develop the earthquake prediction practice (Geller, 2007; Huang et al., 2017). Since earth's crust is highly complex and earthquakes are generally to be chaotic, earthquake predictions can be thought on a statistical basis and these statistical behaviours of earthquake occurrences can be

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utilized to predict the next possible earthquakes (Rundle et al., 2003). Therefore, the main problem in the earthquake prediction studies is whether or not the statistical properties of earthquake occurrences can be used to predict future earthquakes. There are many different algorithms used for the earthquake prediction. However, these models have generally two approaches: the first group approaches are based on the empirical measurements of precursory seismicity changes whereas the second is based on the statistical models of earthquake activity. For this purpose, many researchers have made earthquake predictions for different regions of the world by developing different approaches such as *VAN* method (Varotsos and Alexopoulos, 1984), Region-Time-Length (*RTL*) algorithm (Huang et al., 2001; Sobolev and Tyupkin, 1997), *ZMAP* technique (Wiemer, 2011), *M8* and *CN* algorithms (Shcherbakov, 2003), *PI* and *RI* techniques (Nanjo et al., 2006; Tiampo et al., 2002). Although these approaches have some advantages or disadvantages compared to each other, and the best method does not exist. All the above mentioned methods allow users to measure, map and evaluate the possible earthquake hazard in the intermediate and long term for different seismicity regions of the world.

Since the 1900s, earthquake prediction studies have successfully been made and some of them are given here. For example, a successful prediction for February 4, 1975 ($Ms = 7.3$) earthquake was based on foreshocks and other geophysical parameters (Huang et al., 2017). Also, a successful prediction of the earthquake location was made for October 23, 2004, Niigata, Japan ($M = 6.8$) earthquake. As a global long-term forecast, the locations of December 23, 2004 ($M = 8.1$) Macquarie Island earthquake and of December 26, 2004 ($M = 9.0$) Sumatra earthquake were predicted successfully (Holliday et al., 2005). Öztürk (2011) made a statistical evaluation to detect the precursory seismic quiescence in and around the North Anatolian Fault Zone in Turkey and published successful prediction for future earthquakes such as September 22, 2011 ($M = 5.6$) Refahiye-Erzincan, July 30, 2013 ($M = 5.3$) Gökçeada-Çanakkale and December 3, 2015 Kığı-Bingöl ($M = 5.5$) earthquakes. It is clear that these examples of predictions include the intermediate or long terms evaluations of future earthquakes. However, examples of successful short-term predictions for the next earthquakes have been uncommon and short-term predictions may provide a successful probabilistic hazard assessment for earthquake risk.

The main goal of this study is to present a novel methodology of the short-term earthquake prediction and to make a contribution to an effective prediction for large/destructive earthquakes. Although earthquake catalogues as the complete and long observations including about 50–100 years are generally used for the prediction, some environmental changes mentioned above can provide significant signs before the occurrences of earthquakes. One of the most encouraging methods among these precursory chances can be given as the monitoring ionospheric Total Electron Content (TEC) variations in TEC unit (1 TECU = 10^{16} electron/m^2). In recent years, a lot of research has been done on this subject (Table 1). In our statistical-based novel method, we have included variables belongs to environmental changes, the electromagnetic emissions from ground in a wide signal spectrum, atmospheric and ionospheric events and local magnetic field changes, fluctuations in the ionospheric TEC anomalies for the short-term earthquake prediction. Thus, this study will provide preliminary and remarkable information about such an effort by supplying a new perspective.

2. Data and methods

In this research, 2942 earthquakes with Mw ≥ 6.0 occurred in different regions of the world between 2000 and 2019 freely available in the earthquake database and fault catalogues in the USGS earthquakes web interface were obtained (http://earthquake.usgs.gov/earthquakes/search/) (Fig. 1). The classification of earthquakes according to their magnitude and the number of earthquakes in each group were given in Table 2. Table 2 shows that 69 %, 30 % and 1% of total earthquakes have occurred between $6.0 \leq Mw < 6.5$, $6.5 \leq Mw < 8.0$ and $8.0 \leq Mw < 9.5$, respectively. All maps, graphics, calculations and some statistical procedures were performed in MATLAB® (2017b) environment.

2.1. The relation between earthquakes and ionospheric anomalies

It is quite difficult to define directly the environmental structure of the preparatory stage occurred prior to the earthquakes and therefore, it is more accurate to describe the potential effects indirectly by observing the environmental variations. Conversely, these changes might be due to geological, geophysical or atmospheric circumtances, but earthquake occurrences and the effects that trigger these variations have not yet been exactly described (Fidani, 2010; Guo and Wang, 2008; Pulinets et al., 2006; Tronin et al., 2004). During large events, the crust of the earth sometimes shows strong emissions, frequently weak, and it has occasionally short lifespan. Signals includes electromagnetic emissions over a wide frequency range, ionospheric or atmospheric events, regional variations in magnetic field. The peroxy bonds are broken and then electrically charged carriers are released in order to compose positive holes. Positive holes can carry free volumes from trapped volumes without difficulty and they are very mobile. The electric current generated by the positive current transition produces low-frequency electromagnetic radiation and magnetic field changes in a system which works like a battery. Positive holes arrive the earth and then, ionized molecules actualizes between the ground and air interface. Rising and ionizing air can be seen as a potential reason of irregularities in the ionosphere (Freund, 2011; Ulukavak and Yalçinkaya, 2017b). The relationship between earthquake activity and electron density changes has not still been fully figured out today (Namgaladze et al., 2009; Pulinets, 1998). The first theory is related to the electron emission, i.e. piezoelectric effect that is due to the trapped rocks. In a laboratory environment, the upper surface of the granite block was exposed to the pressure and then, ionization of the molecules was shown in the air contacted side of the granite block (Freund et al., 2009). Electrons (e-) and the positively charged carrier holes (h•) flow through the pressured rock volume to the non-pressured side of the granite and then a current occures between the pressure applied side and end of the rock block. This difference behaves as an current over the battery. The pressed side acts as a negative pole of the battery cell and is also loaded with positively charged molecules. The charge carrier h• allows the positive holes to be held on the surface. The proven and confined Rocks-Earth surface variations in the lithosphere-atmosphere-ionosphere system will be formed by the spatial expansion of this experiment and this system cause the ionization in the rocks with the stress accumulated in the fault ruptures before the strong events. Also, this system spreads the ionized air to the ionosphere layer and increase the electron density in the ionosphere (Kuo et al., 2011; St-Laurent et al., 2006; Ulukavak and Yalçinkaya, 2017b). By considering this theory, earthquakes were classified according to their magnitudes with ionospheric TEC anomalies.

Positive and negative ionospheric anomalies occur before earthquakes. It is considered that positive ionospheric anomalies are caused by the increase of electron oscillations in the ionosphere due to the p-holes whereas negative ionospheric anomalies arise from mostly in the Sub-Ionospheric Points (SIP) far away from earthquake epicentre (Heki, 2011). These negative anomalies return to normal again by disappearing together with Co-seismic Ionospheric Disturbances (CID) emerged with earthquakes.

From previous studies in the literature, it has been revealed that earthquakes which occurred land and oceanic regions cause ionospheric TEC anomalies in advance earthquake (He and Heki, 2017; Sunardi et al., 2018; Tao et al., 2017; Xia et al., 2011; Zhu et al., 2018). Li and Parrot (2013) showed that the earthquakes occurred under the oceans provide more anomalies than those of earthquakes occurred on lands by analysing the ion density changes received from DEMETER

Table 1
Literature studies for the detection of seismo-ionospheric TEC anomalies.

No	Years	Number of EQ	Magnitude of EQ	Space Weather Conditions	Depth of EQ (km)	EQ Precursor (Day)	Reference
1	1999-2002	20	M ≥ 6	–	–	~1-5	Liu et al. (2004)
2	1994-1999	184	M≥5	–	–	~5	Liu et al. (2006)
3	1999-2006	5	M ≥ 6	Kp	–	~1-6	Afraimovich and Astafyeva (2008)
4	1998-2008	17	M ≥ 6	Dst	–	~3-5	Liu et al. (2009)
5	2008	1	M = 8	Dst, Kp F10.7, AE	–	~5–13	Jhuang et al. (2010)
6	2004-2008	4	M > 6	Dst	–	~3-6	Liu et al. (2011)
7	1998-2010	52	M ≥ 6	Dst, Kp F10.7	≤40	~1-5	Kon et al. (2011)
8	2010	7	M≥7	Dst, Kp F10.7	–	~8-11	Yao et al. (2012)
9	2002-2010	736	M ≥ 6	Dst	≤40	~1-21	Le et al. (2011)
10	2007-2009	50	M≥7	Kp	≥20	~10	Fuying et al. (2011)
11	2008-2012	3	M≥7	Dst, Kp F10.7	≤30	~5-6	Zhu et al. (2013a)
12	2003-2012	144	M≥7	Dst	–	~4-7	Zhu et al. (2014)
13	1998–2012	–	M ≥ 6	–	≤40	~1-5	Hattori et al. (2014)
14	1998-2014	1492	M≥5	Dst, Kp F10.7	≤150	~5	Shah and Jin (2015)
15	2010	2	M ≥ 6	Dst, Kp EUV 01-50 Bz, Ey	–	~3-4	Aggarwal (2015)
16	2010	1	M > 7	Dst, Kp F10.7	–	~1-5	Ulukavak and Yalcinkaya (2017a)
17	2003-2014	133	M≥7	Dst, Kp F10.7	≤60	~1-6	Zhu et al. (2016)
18	2000-2014	1279	M ≥ 6	Kp, Dst	≤40	X	Thomas et al. (2017)
19	2006-2015	100	M≥7	Dst, Kp F10.7	–	~8	Li et al. (2018)
20	2003-2016	63	M≥5	Dst, Kp F10.7	–	~0-10	Şentürk and Çepni (2018)
21	2003-2014	1339	M ≥ 6	Dst	≤60	~1-5	Zhu et al. (2018)
22	2015-2017	3	M≥7	Dst, Kp F10.7, AE	–	~10	Tariq et al. (2019)

satellite.

On the other hand, it has been considered that ionospheric anomalies before the earthquakes happen with different physical mechanism according to earthquake occurrences on land and under the oceans. This physical mechanism by which possible earthquake-induced ionospheric TEC anomalies on lands occur with p-holes can be

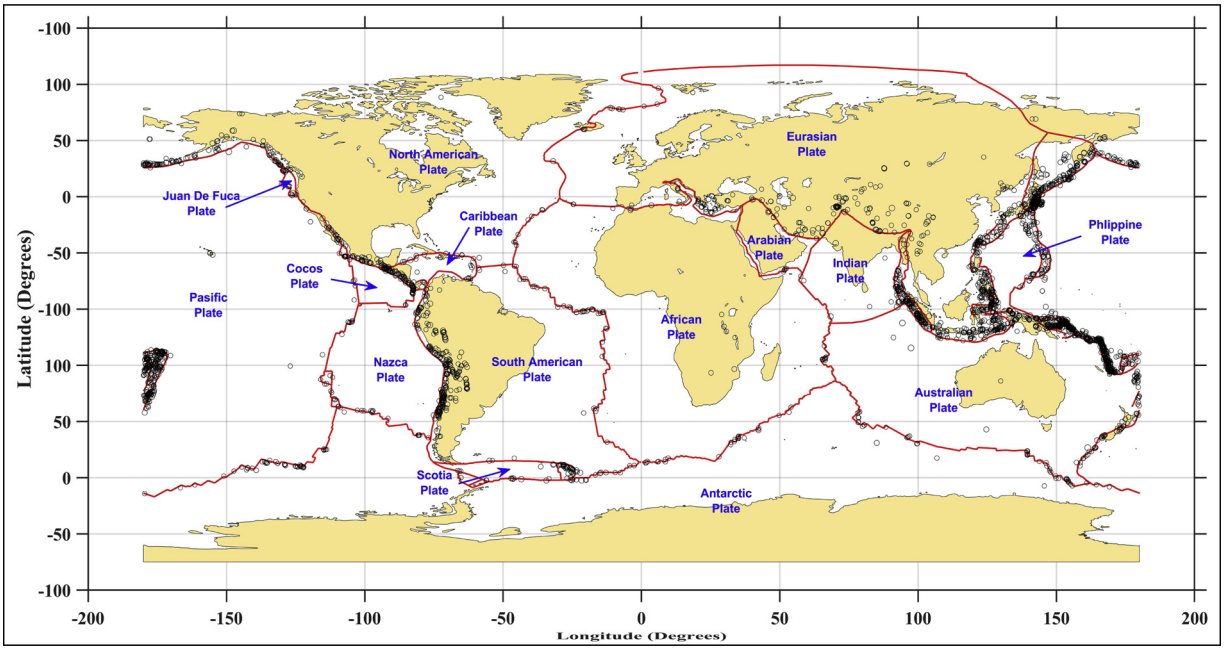

Fig. 1. Global epicenter distributions of 2942 earthquakes with Mw ≥ 6. Red lines show the plate boundaries (created using MATLAB® 2017b) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
The groups and numbers of earthquakes in which occurred between 2000 and 2019 according to their magnitudes.

Magnitude Groups	Number of Earthquakes	Number of Earthquakes Anomaly Detected
6.0 ≤ Mw < 6.5	2026	811
6.5 ≤ Mw < 7.0	622	273
7.0 ≤ Mw < 7.5	184	76
7.5 ≤ Mw < 8.0	87	33
8.0 ≤ Mw < 8.5	18	8
8.5 ≤ Mw < 9.0	3	1
9.0 ≤ Mw < 9.5	2	1

related to the studies made by Freund et al. (2009) and Freund (2011). Pulinets et al. (2015) explained that, the ionization before earthquake interact with the geophysical processes for the Lithosphere-Atmosphere-Ionosphere-Magnetosphere System in a number of physical and chemical process. The process in the appearance of ionospheric TEC anomalies due to earthquakes under the ocean can be related to physical mechanisms such as Ouzounov et al. (2011), detected possible earthquake precursors before the March 11, 2011 Tokyo earthquake wich occurred under the ocean with infrared sensor data in satellites observing temperature changes in the earth's atmosphere. Pulinets and Davidenko (2018), investigated many earthquakes that occurred under the ocean and showed that radon release before earthquake increases the ionization level in the ionosphere. Pulinets et al. (2018), showed that radon activity before the earthquakes are related to Very Low Frequency (VLF), Electric Field (EF) and Acoustic Gravity Waves (AGW) in geochemical-thermal interface and in geochemical-electromagnetic interface and, they also yielded the schematic structure of these physical mechanisms by studying the earthquakes that occurred both on lands and under the ocean. In this context, ionospheric precursors of the earthquakes that occurred under the ocean can also be associated with the realization process of both geochemical-thermal and geochemical-electromagnetic physical mechanisms.

2.2. Obtaining TEC variations and space weather conditions data

In this study, global ionosphere maps including TEC (GIM-TEC) variations with time resolution in 2 h (two hours) and with a spatial resolution in 2.5 and 5 degrees in latitude and longitude provided by International GNSS Service (IGS) were used for the statistical analyses and therefore spatial variations of seismo-ionospheric disturbances of pre-earthquake ionospheric anomalies were investigated (Hernández-Pajares et al., 2009). We extracted the TEC data from Global Positioning System (GPS) ionex data during 2000–2019 years for global earthquakes of Mw ≥ 6.0 and investigated the seismo-ionospheric variations in TEC prior to the earthquake by using the TEC data of the grid points around the epicenter to interpolate the epicenter TEC data. TEC is expressed in TEC unit (TECU) where 1 TECU = 10^{16}electron/m^2.

Various effects such as solar activity, geomagnetic activity, human-induced effects or meteorological events are mainly affective on the ionospheric parameters (Aggarwal, 2015) especially in the Polar and Equatorial regions. The solar terrestrial conditions should be noticed to exclude anomalies that may have been caused by geomagnetic or solar activities when investigating the relationship between earthquake and ionospheric anomalies (Pulinets and Legen'ka, 2003). In addition, the ionosphere presents normal day-to-day, seasonal and diurnal changes making it difficult to describe possible pre-earthquake ionospheric anomalies as causes variations in the ionospheric parameters, such as GPS-TEC, on a regional scale (Afraimovich and Astafyeva, 2008). In order to distinguish the possible effects of earthquakes on the ionosphere layer from the sun and geomagnetic changes, detailed analysis for changes in space weather conditions requires index values (e.g., solar activity: Proton flux [Pf] at six different energy levels, Solar Flux [F10.7], Extreme Ultraviolet [$EUV_{01\text{-}50nm}$] and Extreme Ultraviolet [$EUV_{26\text{-}34nm}$]; geomagnetic storm indices: Disturbance storm-time [Dst], Planetary Geomagnetic Aktivity Index [Kp], z component of Magnetic Field Index [Bz], Proton density [P_d]) of different solar and geomagnetic space weather conditions. In most earthquake precursory studies Kp, Dst and F10.7 indices were used to eliminate the active space weather conditions (Cahyadi and Heki, 2013; Ho et al., 2013; Li et al., 2018; Shah and Jin, 2015; Zhao et al., 2010). In this study, thirteen different geomagnetic and solar index variations (i.e., Dst, Kp, Bz, P_d, Pf with six threshold values, F10.7, $EUV_{01\text{-}50nm}$ and $EUV_{26\text{-}34nm}$) were considered for space weather condition variations. We obtained the geomagnetic storm indices (Dst, Kp), magnetic field variations (Bz), solar activity indices (F10.7, $EUV_{01\text{-}50nm}$ and $EUV_{26\text{-}34nm}$), proton density (P_d) and proton flux variations with six different threshold values (Pfs) from Goddard Space Flight Center (GSFC) OMNI Web interface via https://omniweb.gsfc.nasa.gov/form/dx1.html and EUV Flux variations were obtained from the University of Southern California Space Sciences Center achieve from http://www.usc.edu/dept/space_science/semdatafolder/semdownload.htm. The reason why we use this variety of solar and geomagnetic indices is to make more detailed analysis on anomalies that can be detected except earthquakes and to interpret the possible ionospheric anomalies due to earthquakes according to more accurate results.

2.3. Analysis of the GIM-TEC variations and space weather conditions

In this study, the data on F10.7 cm (Atıcı and Sağır, 2017; Bruevich et al., 2014; Vitinsky et al., 1986), $EUV_{01\text{-}50nm}$ and $EUV_{26\text{-}34nm}$ (Judge et al., 2011; Tsurutani et al., 2005), Kp (Astafyeva and Heki, 2011; Zolesi and Cander, 2014) and Dst (Contadakis et al., 2012; Hattori et al., 2011; Kamide et al., 1998), Bz (Dashora et al., 2009; Pulinets and Legen'ka, 2003), P_d (King and Papitashvili, 2005) and Pfs (John and Kurian, 2009; Schwenn, 2004) changes were investigated according to the limit values, and quiet and active days which were not affected by space weather conditions were detected. As an example, September 12, 2006 La Rioja- Argentina earthquake (Mw = 6.0) was given in Figs. 2, 3 and 4.

As seen in Fig. 2, according to the limit values of geomagnetic storm indices, active days before the earthquake are due to the magnetic field (Bz = +5.5 nT) change in August 30, 2006; due to the magnetic field (Bz = -7.2 nT) and proton density (P_d = 17.2 N_p/cm^3) changes which in August 31, 2006; due to the magnetic field (Bz = -5.7 nT) and geomagnetic storm (Kp = 4.3) changes in September 1, 2006; due to the magnetic field (Bz = -6.5 nT), proton density (P_d = 18.4 N_p/cm^3) and geomagnetic storm (Kp = 5.7) changes in September 4, 2006. In Fig. 2, although Kp index cannot reach the limit value of 4.0 in August 31, the fact that Bz index changes (limit value = +5 nT) which is used as related to the earth magnetic field change and proton density change (limit value = 15N_p/cm^3) values exceed the limit values clearly show the necessity of the using more space weather condition index.

As seen in Fig. 3, although F10.7, the solar activity index, on September 8, 2006 is lower than the limit values of 150 sfu, the fact that the indices of $EUV_{01\text{-}50nm}$ and $EUV_{26\text{-}34nm}$ show the evidence actively which indicates the importance of using more indices of space weather conditions in the analysis. As seen in Figs. 3 and 4, according to the limit values of solar activity indices, active days before the earthquake are due to the excessive ultraviolet flux ($EUV_{0.1\text{-}50nm}$ = 1.29 × 10^{10} cm^2/s and $EUV_{26\text{-}34nm}$ = 2.48 × 10^{10} cm^2/s) changes which takes place on September 8, 2006; due to the excessive ultraviolet flux ($EUV_{26\text{-}34nm}$ = 2.47 × 10^{10} cm^2/s) and proton density (P_d = 19.3 N_p/cm^3) changes that occurs on September 10, 2006. When the days of active space weather condition after the earthquake are examined, it can be clearly seen that active days are due to only the excessive ultraviolet flux ($EUV_{0.1\text{-}50nm}$ = 1.26 × 10^{10} cm^2/s and $EUV_{26\text{-}34nm}$ = 2.42 × 10^{10} cm^2/s) changes which takes place on September 13, 2006. By examining Figs. 2, 3 and 4 together, we detected quiet and active

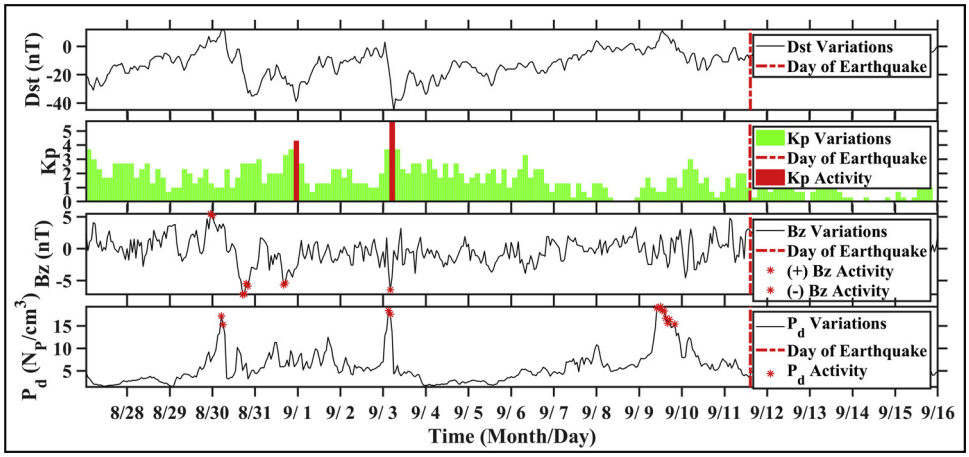

Fig. 2. Active days detected with geomagnetic storm indices (Disturbance storm-time [Dst], Planetary Geomagnetic Aktivity Index [Kp], z component of Magnetic Field Index [Bz], Proton density [P_d]) for September 12, 2006 La Rioja, Argentina earthquake.

days according to all space weather conditions (Fig. 5). As shown in Fig. 5, when we analyse the space weather conditions before the earthquake in September 12, 2006 La Rioja-Argentina, earthquake day and the days of 1., 3., 5., 6., 7., 9., 10., 14. and 15., the days of 2., 3. and 4. before the earthquake were detected as quiet days, whereas the remaining days were considered as active days.

15-days moving median (MM) method is a quartile based statistical analysis technique and the investigation of seismo-ionospheric TEC anomalies can be done by using this application (Liu et al., 2009). Therefore, the MM values of GPS-TEC were firstly computed by using this method. In adidtion, we calculated the lower quartile (LQ) and upper quartile (UQ). The GPS-TEC values were assumed in the normal distribution the expected MM and LQ or UQ are m (mean) and ± 1.34 σ (standard deviation) (Samuel et al., 2005). The lower bound [LB = MM-1.5(MM-LQ)] and upper bound [UB = MM + 1.5(UQ-MM)] were estimated, respectively. Anomalies are identified when GPS-TEC variations are out of the range limited with the LB and UB (Liu et al., 2009). For instance, in order to generate MM, UB and LB for the 16th day, the TEC values for the first 15 days were utilized. Similarly, 15 days of TEC data between the 2nd and 16th day were used to generate bounds for the 17th day. If more than one-third of the data (e.g., eight hours are anomalous in a day) are greater or lesser than UBs and LBs in a day, this day was taken as anomalous (Liu et al., 2009; Ulukavak and Yalcinkaya, 2017a). For this work analyses for TEC changes obtained from GIM-TEC maps of all earthquakes for 15-days before and 4-days after the main shock was prepared and ionospheric TEC changes in September 12, 2006 La Rioja-Argentina earthquake was given as the example (Fig. 6).

In this study, according to 15-days moving median statistical analysis method, day was accepted as possible earthquake precursor, in case the ratio of TEC anomaly numbers which takes place in the day of quiet space weather conditions to the total number of data in a day are greater than 4/12. The anomaly values calculated in Fig. 6 depict that some anomalies were observed before the earthquake occurrences such as 1–4 TECU positive anomaly on August 28, 2006; 0.3–1.8 TECU positive anomaly on September 1, 2006; 0.6 TECU positive anomaly on September 2, 2006; 0.4–3.3 TECU positive anomaly on September 4, 2006; 0.2-0.8 TECU positive anomaly on September 5, 2006; 0.3 TECU positive anomaly on September 6, 2006; 0.7 TECU positive anomaly on September 7, 2006; 0.8 TECU positive anomaly on September 8, 2006; 0.4 TECU positive anomaly on September 9, 2006; 2.9–4.5 TECU positive anomaly on September 10, 2006. On the other hand, the anomalies calculated after the earthquake, two anomaly changes can be seen as 3.4 TECU positive anomaly on September 13, 2006 and 0.2 TECU positive anomaly on September 15, 2006.

Both Figs. 5 and 6 shows that quiet (August 28, 2006, September 2 and 5, 2006) and active (September 1, 4, 8, 9 and 13, 2006) days on that the possible earthquake precursor occur were determined. In this

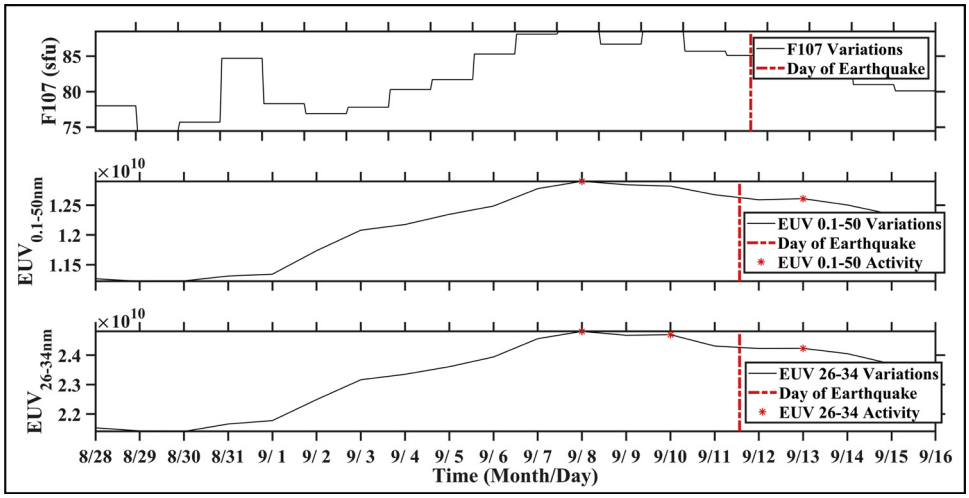

Fig. 3. Active days detected with solar activity indices (Solar Flux [F10.7], Extreme Ultraviolet [$EUV_{01\text{-}50nm}$] and Extreme Ultraviolet [$EUV_{26\text{-}34nm}$]) for September 12, 2006 La Rioja, Argentina earthquake.

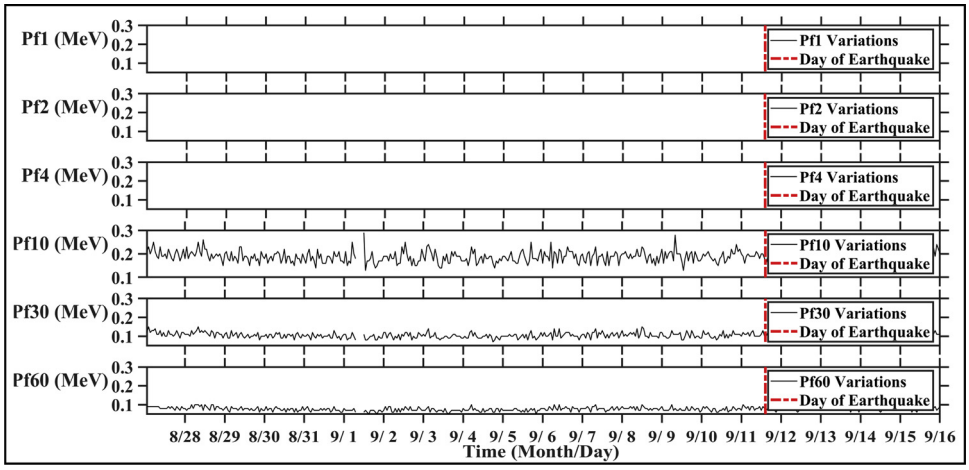

Fig. 4. Active days detected with solar activity indices (Proton flux [Pf] at six different energy levels) for September 12, 2006 La Rioja, Argentina earthquake.

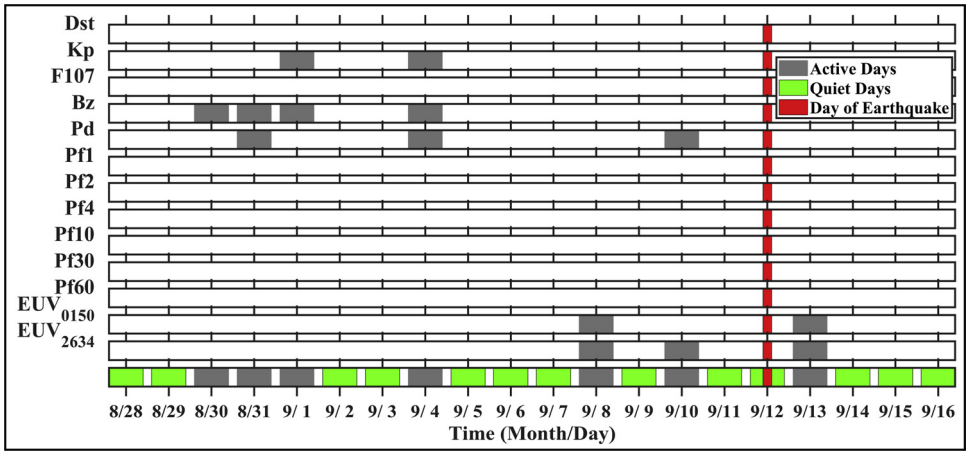

Fig. 5. A general representation of geomagnetic and solar activities.

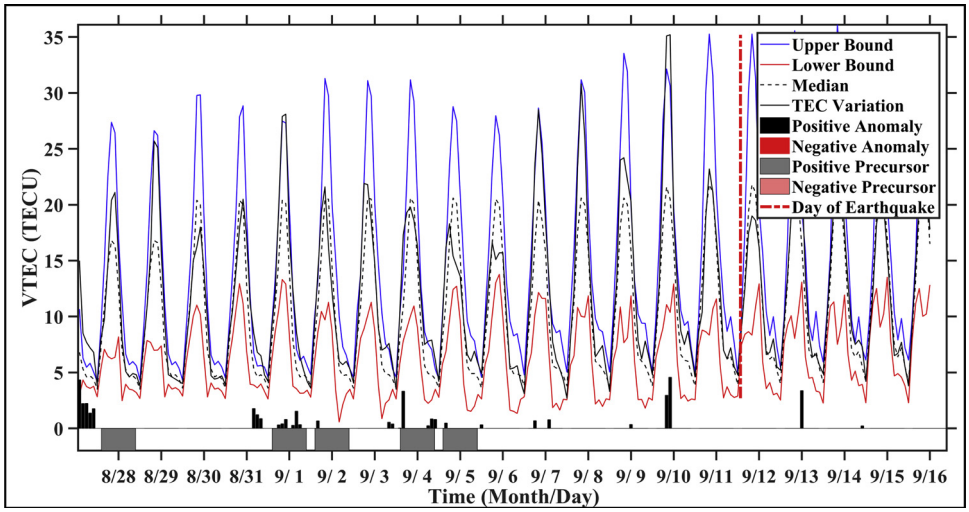

Fig. 6. Ionospheric TEC changes for September 12, 2006 La Rioja, Argentina earthquake.

context, positive ionospheric TEC precursors shown on the 7., 10. and 15. quiet days before the main shock can be considered as possible earthquake precursors since they occur in the quiet space weather conditions. Detailed analysis of active/quiet space weather conditions made for September 12, 2006 La Rioja-Argentina earthquake, detection of anomalies seen in ionospheric TEC changes and evaluation and interpretation of these two analyses were achieved for 2942 global earthquakes.

3. Results and discussions

In the scope of this study, the quiet days were detected by analyzing

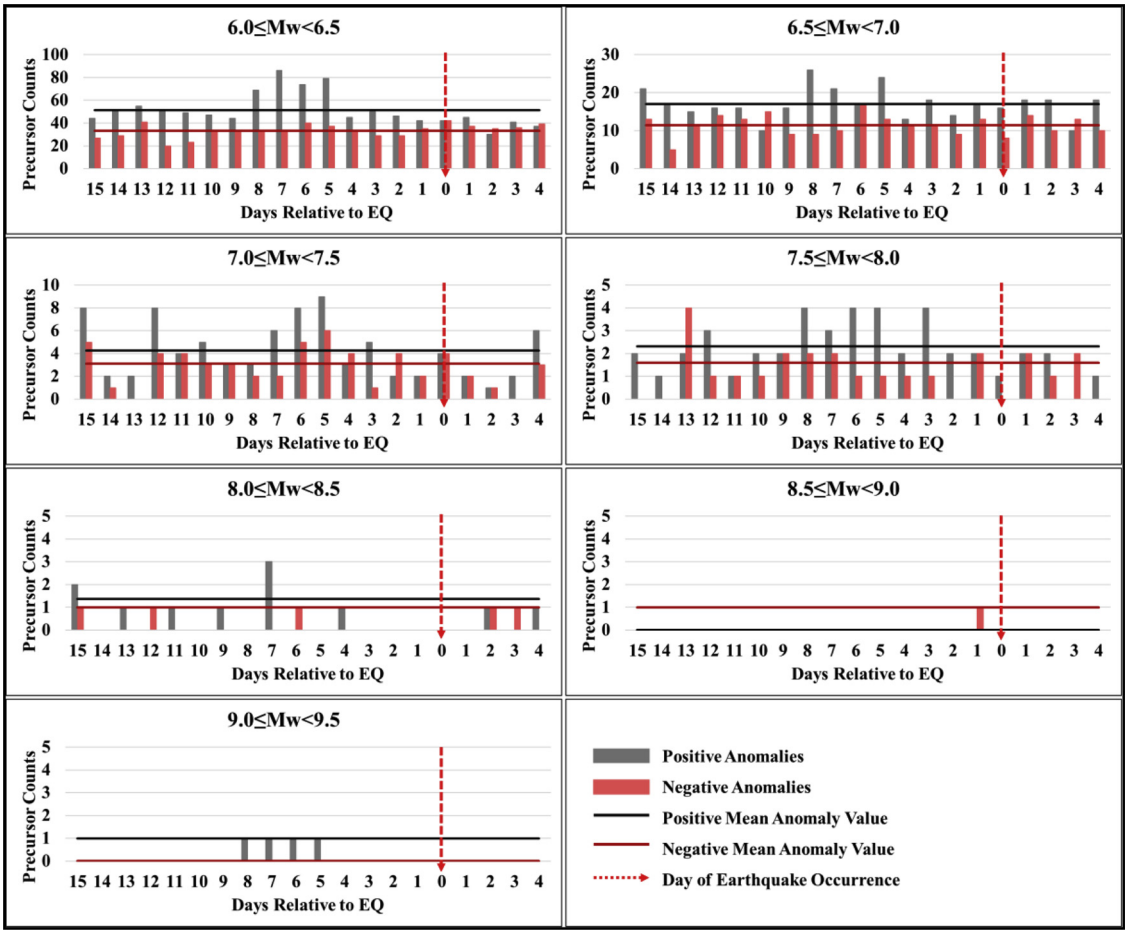

Fig. 7. Possible abnormal TEC days and earthquake numbers appeared in quiet days before the earthquakes of 6.0 ≤ Mw < 9.5.

the space weather condition indices according to Figs. 2, 3, 4 and 5 for 15-days before and 4-days after of all the earthquakes. Then, ionospheric TEC changes of earthquake epicenter obtained from GIM-TEC were analyzed by using 15-days moving median statistical analysis method and possible ionospheric TEC anomalies before the earthquake were determined (Fig. 6). Afterwards, by analyzing the results of space weather conditions and the anomalies obtained from ionospheric TEC changes together, possible ionospheric TEC precursors corresponding to quiet space weather conditions were identified. The earthquakes with anomalies, the numbers of positive and negative ionospheric TEC anomalies before and after the earthquakes obtained by grouping according to the earthquake magnitudes specified in Table 2 were calculated by adding according to days the anomalies were observed (Fig. 7). As seen Fig. 7, ionospheric TEC anomalies observed before the earthquake were detected at 5, 6, 7 and 8 days ago in the positive anomalies and 0, 5, 6 and 13 days ago in the negative anomalies for obtained the earthquakes of 6.0 ≤ Mw < 6.5; at 5, 7, 8 and 15 days ago in the positive anomalies and 1, 5, 6 and 10 days ago in the negative anomalies for obtained the earthquakes of 6.5 ≤ Mw < 7.0; at 5, 6, 12 and 15 days ago in the positive anomalies and 0, 2, 5, 6, 12 and 15 days ago in the negative anomalies for obtained the earthquakes of 7.0 ≤ Mw < 7.5; at 3, 5, 6, 8 and 12 days ago in the positive anomalies and 1, 5, 7, 8, 9 and 13 days ago in the negative anomalies for obtained the earthquakes of 7.5 ≤ Mw < 8.0; at 7 and 15 days ago in the positive anomalies and 6, 12 and 15 days ago in the negative anomalies for obtained the earthquakes of 8.0 ≤ Mw < 8.5. In addition, a negative anomaly was observed at 1 day ago for a single earthquake of 8.5 ≤ Mw < 9.0 and a positive anomaly was detected at 5, 6, 7 and 8 days ago for a single earthquake of 9.0 ≤ Mw < 9.5. According to the results of study by Le et al. (2011), seismo-ionospheric anomalies closer to the earthquake occurrence time (7 days ago) is obtained as the magnitude of earthquakes occurring at shallow depths (≤40km) increases (M ≥ 6). The results of Le et al. (2011) confirm the statistical analysis of the present study (Fig. 7). In addition, when we looked at the results of study by Shah and Jin (2015), it is seen that seismo-ionospheric precursory anomaly of ~5 days earlier detected for 1492 shallow (≤50km) earthquakes with magnitude larger than 5.0 between 1998 and 2014 supports the occurrence range (~5-8) of seismo-ionspheric precursors obtained for the earthquakes of 6.0 ≤ Mw < 6.5 in this study.

There are a lot of studies in the literature on this subject and many of them have investigated the possible ionospheric TEC changes which appeared prior to the earthquakes by using one or two earthquakes. The findings of these studies were generally performed to identify the possible ionospheric TEC precursors that preceded the earthquake (Afraimovich and Astafyeva, 2008; Aggarwal, 2015; Liu et al., 2011; Tariq et al., 2019; Zhu et al., 2013b). Previous literature studies show also that the anomalies that appeared prior to earthquakes with magnitude larger than 7.0 (Fuying et al., 2011; Tariq et al., 2019; Yao et al., 2012; Zhu et al., 2014, 2013b) compared to earthquakes with magnitude larger than 6.0 (Hattori et al., 2014; Kon et al., 2011; Liu et al., 2011; Şentürk and Çepni, 2018) moves away from the earthquake occurrence day. Jhuang et al. (2010) stated in their study that seismo-ionospheric anomalies of an earthquake with Mw = 8.0 appear approximately 5–13 days ago before the earthquake.

A summary of several recent studies made in recent years on the detection of possible ionospheric TEC anomalies that occurred prior to the main shock was presented in Table 1. As seen in Table 1, the relationship between possible ionospheric TEC anomalies and earthquake was investigated before 1492 events at most. In addition, three different

indices (Dst, Kp, F10.7) values of space weather conditions were generally used in these researches and it was not clearly explained in these studies how many of the anomalies detected before the earthquakes occurrences were observed on quiet days in terms of space weather conditions. In this study, possible ionospheric TEC anomalies before 2942 earthquakes with magnitudes equal to and larger than 6 occurred between 2000–2019 were identified and, it was aimed to make an examination according to 13 different index values of space weather conditions (geomagnetic storm indices: Dst, Kp, Bz, P_d; solar activity: F10.7, $EUV_{01\text{-}50}$ and $EUV_{26\text{-}34}$, Pf at six different energy levels). For this purpose, quiet days were detected with more number of indexes of space weather conditions and the number of days before the main shocks that the possible ionospheric TEC anomalies occur was presented in a more reliable way. Also, the relationship between earthquake magnitudes and possible ionospheric TEC anomalies before the earthquakes was examined and discussed in this study. As a result of the analyses in the present study, positive and negative anomalies that appeared before the earthquakes were observed much earlier (~5-15 days ago) than the earthquake occurrence day (Fig. 7). These results reveal that a possible indicator of more stress and the energy that will emerge in the earthquake occurrence time will start to accumulate earlier (Rikitake 1987).

In the present study, the ratio of positive and negative anomaly numbers that appeared before the earthquake was calculated for different earthquake magnitude groups (Fig. 8). As seen in Fig. 8, changes in the groups of ionospheric TEC anomalies classified according to earthquake magnitudes can be given as follow: positive anomaly ratio for the earthquakes of $6.0 \leq Mw < 6.5$ is 61 % and negative anomaly ratio is 39 %; 60 % positive anomaly ratio and 40 % negative anomaly ratio for the earthquakes of $6.5 \leq Mw < 7.0$; 60 % positive anomaly ratio and 40 % negative anomaly ratio for the earthquakes of $7.0 \leq Mw < 7.5$; 65 % positive anomaly ratio and 35 % negative anomaly ratio for the earthquakes of $7.5 \leq Mw < 8.0$; 69 % positive anomaly ratio and 31 % negative anomaly ratio for the earthquakes of $8.0 \leq Mw < 8.5$. In addition, a negative anomaly ratio of 100 % for the earthquakes of $8.5 \leq Mw < 9.0$ and a positive anomaly ratio of 100 % for the earthquakes of $9.0 \leq Mw < 9.5$ were calculated because of single earthquake in these groups. The positive anomaly is generally calculated as larger than negative anomaly for different magnitude groups (Fig. 8).

Positive and negative mean ionospheric TEC anomaly values were calculated according to different earthquake magnitude groups and mean value of TEC anomaly changes determined in each group was calculated as 44 % TECU; positive anomaly for the earthquakes of $6.0 \leq Mw < 6.5$ is 45.4 % TECU and negative anomaly is 42.8 % TECU; 45.8 % TECU positive anomaly and 40.5 % TECU negative anomaly for the earthquakes of $6.5 \leq Mw < 7.0$; 47.3 % TECU positive anomaly and 42.7 % TECU negative anomaly for the earthquakes of $7.0 \leq Mw < 7.5$; 42.1 % TECU positive anomaly and 41.8 % TECU negative anomaly for the earthquakes of $7.5 \leq Mw < 8.0$; 40.0 % TECU positive anomaly and 38.9 % TECU negative anomaly for the earthquakes of $8.0 \leq Mw < 8.5$; 41.7 % TECU negative anomaly for the earthquakes of $8.5 \leq Mw < 9.0$; 54.2 % TECU positive anomaly for the earthquakes of $9.0 \leq Mw < 9.5$ (Fig. 9).

4. Conclusions

In this study, the effects of strong earthquakes occurring at different magnitudes on ionospheric TEC variations were examined. The relationships of GPS-TEC day-to-day changes to the magnitude of the earthquakes have been investigated. Although many researchers reported the existence of pre-earthquake ionospheric anomalies and discussed the possible origins, the coupling mechanisms among the lithosphere, atmosphere and ionosphere are still not fully understood. This study focuses only on the relationship between ionospheric TEC changes and different earthquake magnitudes before the main shock of

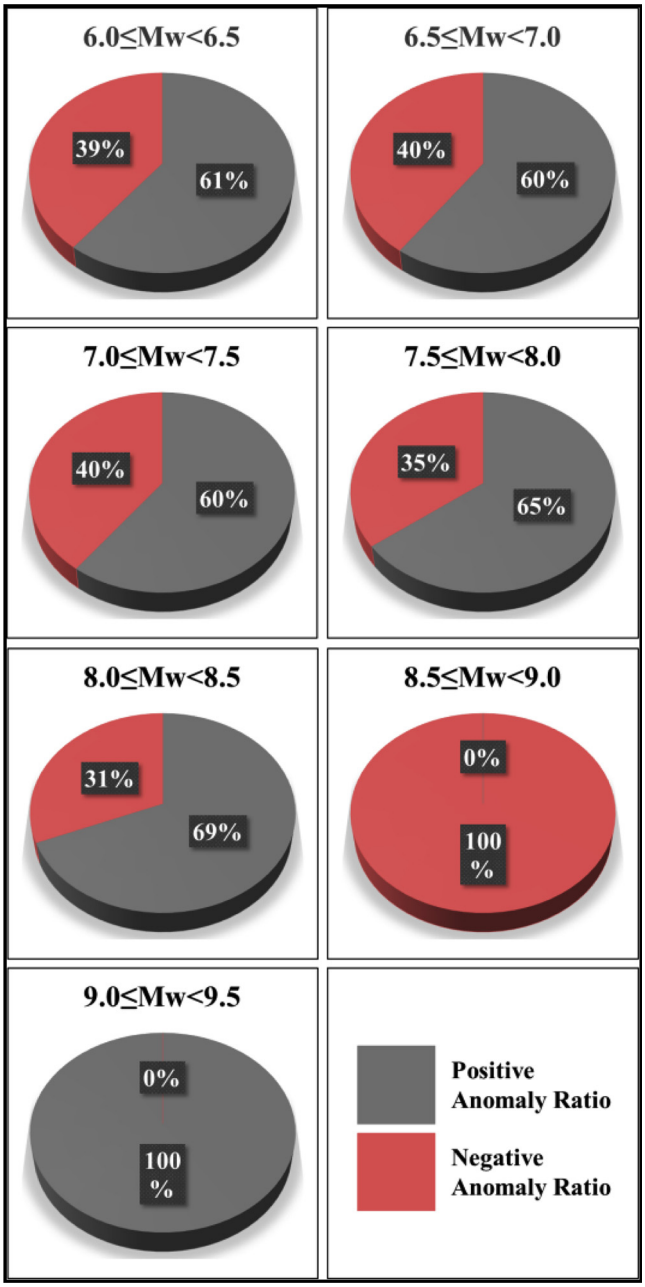

Fig. 8. Ratio of positive and negative anomaly numbers appeared in the quiet days before the earthquakes of $6.0 \leq Mw < 9.5$.

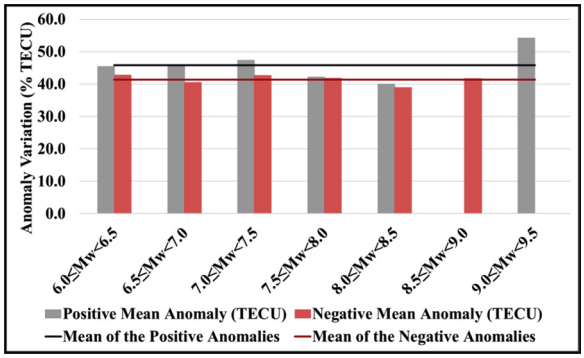

Fig. 9. Positive and negative mean anomaly variations.

seismic events.

In the scope of this study, an evaluation on the detection of precursors by using ionospheric TEC anomalies was achieved for different magnitude groups including 2942 earthquakes with magnitudes larger than and equal to 6.0 between 2000 and 2019. In this context, space weather condition indices (geomagnetic storm indices: Dst, Kp, Bz, P_d; solar activity: F10.7, $EUV_{01\text{-}50}$ and $EUV_{26\text{-}34}$, Pf at six different energy levels) more than 3 different indices (Dst, Kp, F10.7) commonly used in the literature were preferred in order to make more reliable detection of the quiet days with space weather conditions affecting ionospheric TEC anomalies.

Global earthquakes of $6.0 \leq Mw < 9.5$ were considered for the statistical analysis and earthquakes were divided different magnitude groups with a 0.5 magnitude increment. Ionospheric TEC changes were taken from GIM-TEC maps and, positive and negative anomalies occurred in quiet space weather conditions in the day were identified by using for 15-days moving median statistical analysis method. It was accepted that as a possible earthquake precursor can be stated on that day if the ratio of the total number of anomalies observed to the total number of data in a day is larger than 4/12. In this way, precursory anomalies for each magnitude group were observed in approximately 5–13, ~5-10, ~5-15, ~3-13, ~7-15, ~1 and ~5-8 days ago for the earthquakes of $6.0 \leq Mw < 6.5$, $6.5 \leq Mw < 7.0$, $7.0 \leq Mw < 7.5$, $7.5 \leq Mw < 8.0$, $8.0 \leq Mw < 8.5$, $8.5 \leq Mw < 9.0$, and $9.0 \leq Mw < 9.5$, respectively. Thus, we observed that ionospheric TEC anomalies were detected with earthquake precursor in earlier day from the earthquake as the earthquake magnitudes increases. However, changes of the mean TEC anomaly value were calculated as 44.2 % TECU for different magnitude groups and it was identified that the numbers of positive anomaly in each group are more than the numbers of negative anomaly. Consequently, the results of this study can finally contribute to the earthquake prediction in the short term providing an empirical and a proven statistical technique to the literature.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jog.2020.101721.

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