The analysis of earthquake precursors in variations of TEC in the ionosphere and the subsequent impact on the environment

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Abstract. Ionospheric storms are general perturbations of the upper atmosphere which affect space- and ground-based technological systems. These storms are triggered by an increased flux of energetic electrons that are released by the Sun. Extreme solar activity may originate from Coronal Mass Ejections (CME) and solar flares that may result in ionospheric storms. The ionospheric anomalies usually happen in D-layer, E-layer and F-layer. They may be observed from 1 to 10 days prior to the earthquake and stay until 1 to 2 days after the earthquake. Comparatively the ionospheric precursors, the geomagnetic indices Dst, Kp and AE-indexes have been selected for pre-earthquake disturbed states. In the present study we are taking into account the existence of correlational changes in the ionosphere before strong earthquakes triggered by geomagnetic storms and we consider the subsequent impact on the environment. The statistical analysis presents the ionospheric precursors during geomagnetic storm conditions which occurred during March 2018 and correlated with them strong earthquakes.

1. Introduction
As we know one of the most dangerous natural disasters is an earthquake. More than 40 strong earthquakes happen over the world every year. They cause many losses and destroy cities. As well, there are considerable environmental impacts. Volcanic eruptions or tsunamis can be also produced by an earthquake. Tsunamis in particular commonly occur after coastal and shallow earthquakes. The damage an earthquake causes depends on the magnitude and duration. Previous studies regarding earthquake prediction over the past ten years have highlighted the existence of many earthquake precursors in the lithosphere, atmosphere and ionosphere. Therefore, there are perturbations generated from a few days to a few hours before earthquakes occur in the geomagnetic field [1]. Nowadays, the main task of scientists is to describe the nature and behavior of complex earthquake precursors. We are considering the precursors as phenomena, which would allow for the solution of three forecasting problems: finding the place, magnitude and time of a seismic event. The focus of this research is the estimation and definition of the parameters expected in strong earthquakes in short-term prediction. In the present study we analyze the seismo-ionospheric precursors that appear in the proximity of the forthcoming earthquake epicenter. The reaction of the ionosphere to changes in solar and geomagnetic activity is manifested mainly in the geomagnetic storms and the substorms ionospheric disturbances [2].
The existence of correlational changes in the ionosphere before strong earthquakes triggered by geomagnetic storms was taken into account. The ionospheric anomalies usually happen in D-layer, E-layer and F-layer [3]. They may be observed from 1 to 10 days prior to the earthquake and stay until 1 to 2 days after the earthquake. Comparatively the ionospheric precursors, the geomagnetic indices Dst, Kp and AE have been selected for pre-earthquake disturbed states from other anomalies correlated to the geomagnetic activities, as well as the total electron content (TEC) and F2-peak density (Nmf2). The precursor appeared as an increase in TEC and Nmf2 from six days to ten hours before the earthquake. As well, the Total Electron Content (TEC) is used to obtain the TEC changes in the geomagnetic storms of the latest solar activity cycle. Obtained data showed that there are perturbations in the TEC variations before strong earthquakes; these could be viewed as precursors to strong earthquakes. In general, the short-term behaviour of TEC shows clear positive and negative phases, a negative phase is observed during winter. There is a strong correlation between geomagnetic storms and ionospheric perturbations. The objective of this paper is to present a statistical analysis of the correlation between changes in the ionosphere and strong earthquakes. For this purpose we studied the ionospheric effects of the preparation processes during earthquakes M ≥ 6. We took into account geomagnetic storms that occurred during March 2018 and connected to them to four strong earthquakes that occurred in Papua New Guinea and Indonesia. There was anomalous behavior in the ionosphere before the earthquakes occurred. Precursory activity had been observed for the two strong earthquakes in Papa New Guinea and these provide evidence about the existence of ionospheric perturbations before strong earthquakes. In the case of the three earthquakes (M>6, with depths of less than 50 km) they clearly displayed precursor features in the ionosphere that depended on local time and latitude. With regards to the earthquake that occurred deeper it didn’t show obvious variations.

As we know that numerous geophysical parameters are associated with strong earthquakes. Monitoring these parameters is one of the research tasks with a purpose to reduce the effects of expected hazards. Changes before a strong earthquake may have different physical effects on the lithosphere, atmosphere and ionosphere. These variations before the strong earthquakes are considered as earthquake precursors. The perturbations could be manifested in the form of negative or positive deviations from an undisturbed level. The ionosphere perturbation takes place in all heights of the ionosphere up to the magnetosphere [4] and leads to height range changes.

Many scientists believe that there is a strong relationship between geomagnetic storms and ionospheric perturbations. Known as the «background» level of geomagnetic activity (Kp < 4) it influences the TEC behavior [5]. There is geomagnetic forcing during storms. The ionospheric storms go through an initial «positive» phase, at middle latitudes, when the electron density and the electron content are greater than the normal (median) values, followed by the main «negative» phase when the previously mentioned quantities are reduced below their normal pre-event values [4]. Nevertheless, there are differences from storm to storm, and certain storm characteristics can significantly vary depending on latitude, season, local time, etc. [6]. Each storm has its own individual characteristics.

The current investigation is dedicated to the study of disturbances in the total electron content (TEC) of the ionosphere during the preparation process of strong seismic events [4].

2. Data and methods

In order to detect anomalies, it is necessary to identify the normal and natural phase of the phenomenon. Using recorded geomagnetic and ionospheric data we have analyzed earthquake precursors to observe the normal deviations. The appropriate time showing the normal behavior could be considered to be about 30 days before the event. This time is long enough to analyze regular and irregular perturbations. For the purpose of this study we took into account geomagnetic storms that occurred during March 2018. Four earthquakes occurred during this time; the first event took place on March 24, 2018 with a magnitude of 6.3 in Papua New Guinea, the second event took place on March 25, 2018 with magnitude of 6.4 in Indonesia and the third event took place on March 26, 2018 with magnitude of 6.6 in Papua New Guinea, the fourth event took place on March 29, 2018 with magnitude of 6.9 in Papua New Guinea.
Firstly, we carry out a physical study of perturbations to identify and characterize the most recurrent features with the purpose to describe the physical processes in the ionosphere and the thermosphere during storms and the ionospheric response to geomagnetic storms and the strong earthquakes associated with them. Next, we develop a method for the reconstruction of vertical electron density profiles ionospheric abnormality occurrence, based on a statistical analysis of the dataset.

The statistical analysis presents the ionospheric precursors during geomagnetic storm conditions which occurred during March 2018. Total Electron Content (TEC) derived from Global Positioning System (GPS) data was analysed for the storms and associated with it strong earthquakes that occurred during 2018. A comprehensive analysis of the critical frequency of the F2 layer (foF2) and TEC was done. To identify the geomagnetically disturbed conditions the Disturbance storm time (Dst) index with the storm criteria of Dst ≤ −50 nT was used. The geomagnetic effects in the ionosphere were categorized into two responses; a positive phase and a negative phase of the ionospheric storm. We suppose that the positive phase is less pronounced and the negative phase should start immediately after the storm onset.

The final section of this work deals with the impact of geomagnetic storms on the ionosphere and indicates that negative ionospheric effects follow the solar cycle. The geomagnetic activity characterization is based on evaluation of the geomagnetic disturbances with two major types of indices in use – the K and Dst. We also will collect the critical frequency (foF2) measurements, peak density (NmF2), Total Electron Content (TEC) and slab thickness. We are also studying this EQ using ground-based data NmF2 and TEC in addition to satellite data. Finally, the relationship between the ionospheric response under turbulent and storm conditions was analysed. We present the responses of the ionosphere during geomagnetic storms and discuss the statistics of the ionospheric storm effects.

Geomagnetic data has been collected from Geomagnetic Data Service such as Dst-index, AE-index, Kp-index in real time [7]. The storm-time (ST) begins with the storm onset. The storm onset is relatively easy to determine for storms with sudden storm commencement (SSC), however, there are many storms with gradual commencement or storms that occur during the recovery phase of another storm. Here, for the SSC storms, the onset is set at the moment of the Dst peak and, for the non-SSC storms, at the moment just before a persistent decrease in Dst. In all cases the Dst minimum should be reached within 36 hours. If a period of increased geomagnetic activity shows multiple Dst minima, we assign these as two separate storm events provided that the two minima are separated by at least 24 hours [8]. The selected storms could be classified according to their intensity using the standard nomenclature: Class II («moderate», Dst minimum between −100 and −50 nT) and Class I («intense», Dst minimum −100 nT). Also, we describe the «extreme» storm class, Class X (Dst minimum −200 nT), which is in fact a sub-class of Class I. The ionospheric response to geomagnetic storms depends heavily on the season [8].

3. The analysis of the correlation between ionospheric perturbations and strong earthquakes

We are taking into consideration four earthquakes that occurred during March, 2018. The first earthquake happened on March 24 at 11:23 UTC with M6.3, 148 km east of Kimbe, Papua New Guinea. The depth was 33 km. The second earthquake occurred on March 25 at 20:14 UTC with M6.4 241 km North-West of Saumlaki, Indonesia. The depth was 169 km. The third earthquake took place on March 26 at 09:51 UTC with M6.6, 139 km East of Kimbe, Papua New Guinea. The depth was 40 km. The fourth earthquake took place on March 29 at 21:25 UTC with a magnitude of 6.9, 150 km East of Kimbe, Papua New Guinea. The depth was 35 km.

The geomagnetic activity during the period between March 19 and March 22 was quiet, except for the period between March 22 and March 26. Some anomalies were observed on 23-24 March (20:00-02:00 UTC), on 25-26 March (22:00-01:00 UTC) and on 26 March (20:00-23:00 UTC).

The recorded geomagnetic disturbances can be qualified as a substorm (the Dst index did not exceed −50) started on March 22 and all ionospheric stations from the region demonstrated the negative disturbance of the critical frequency. The changes in ionosphere were observed 2 days before
the first earthquake. During the storm onset phase, the Dst-index decreased to minimum (negative) value. The Dst-index fell below –50nT (Class II–«moderate»). The corresponding data is shown in the figure 3. The changes in the magnetic field started on March 22 at 21:00 UTC and on March 23 at 09:00 UTC, they were observed during these four earthquakes. The Kp-index had an active phase of more than 10 hours before the first earthquake. In response to this, the Kp-index was between 4 and 5 (see figure 3). The Kp-index was moderate on March 24, with a value between 3 and 4 (see figure 1). Therefore, it had the active phase with value between 4 and 5 on March 25 and March 26, it became «moderate» on March 27. Before the earthquakes the geomagnetic field was active with a value of Dst [-32; -50] nT during March 18 and March 19, correspondingly.

Figure 1. Geomagnetic K-indices, estimated in real time during March 2018.

In this investigation we are analyzing the ionospheric effects of a strong earthquake, before the earthquake AE-index increases, which is an indicator of magnetospheric substorm. Dst-index was in decline since March 18 and it reached the peak at -50 nT in the evening at 22:00 UTC. Two days before the first earthquake occurred there were some changes in the AE-index; they started about 19:00 UTC in the evening on March, 22, and ended of about 09:00 UTC on March, 26. These changes were observed during three strong earthquakes. The perturbations in the AE-index reached the maximum value on March 23 at 21:00 UTC [800] nT, on March 25 from 03:00 to 07:00 [800] nT and it had some perturbations until March 27 in a range [-300; -150]nT.
Figure 3. Distribution of Dst-index. WDC for Geomagnetism, Kyoto Hourly Equatorial Dst-Values (REAL-TIME).

Thus, exemplary results of K-index and AE-index operational production during recent minor geomagnetic events increased the geomagnetic activity. These events were analyzed as phenomena with magnetic storms. It could be assumed that the magnitude of these effects largely depended on the state of a continually varying ionosphere. These storms were quite exceptional in exhibiting a record increase in TEC (see figure 2), but not a particularly large event in terms perturbations of foF2.

From the relative TEC disturbances maps description and analysis provided above, one of them can be marked out as common pre-earthquake TEC variations features in all considered cases: TEC anomalies were observed two days before the first event. The integration of earthquakes parameters retrieved from different precursors indicated that the seismo-generated zonal geomagnetic field does not act alone. Thus, it is important to create a comprehensive database to describe the nature and behaviour of complex earthquake precursors.

4. Conclusion
The motivation for this research was to gain a better understanding of the changes in the ionosphere prior to forthcoming earthquakes and prevent the following impact on the environment. For better estimation of earthquake parameters, we assume that the earthquake parameters using any single precursor is associated with some uncertainties. Therefore, this study is concerned with the incorporation of different parameters of strong earthquakes. This article analysed the strong earthquakes during March, 2018, here we found anomalous behavior of the ionosphere before the earthquakes. Precursory activity had been observed for the two strong earthquakes in Papua New Guinea and these provide evidence about the existence of ionospheric perturbations before strong earthquakes.

By analyzing the strong earthquakes during March, 2018, we found abnormal behavior of the ionosphere before the earthquakes. Precursory activity had been observed for the two strong earthquakes in Papua New Guinea. Regular features were observed in the ionosphere from March 22, 2018 to March 29, 2018. The ionospheric precursors within the interval 2 days before the seismic event were registered for the earthquakes with a magnitude more than 6. We can assume the magnitude of 5 as a threshold of ionosphere sensitivity for earthquake preparation process. In the case of the three earthquakes (M>6, with depths of less than 50 km) they clearly displayed precursor features in the ionosphere that depended on local time and latitude. With regards to the earthquake that occurred deeper it didn’t show obvious variations.

Thus, we can suppose that there is a correlation between changes in the ionosphere and the preparation process of the strong earthquake triggered by the geomagnetic storms. Understanding the nature of earthquake precursors could contribute to earthquake hazard reduction. We believe that the present study will help to describe the nature and behaviour of complex earthquake precursors. It is important to promptly and reliably determine the location, intensity and time of the expected earthquake, for the purpose of real-time prediction of seismic hazards. Therefore, to control or reduce the occurring earthquake, it is necessary to develop effective methods of geomonitoring of complex
precursors such as recording, processing and the analysis of observational data expected in strong earthquakes for the preparation process for the selected focal area, the creation of models describing the mechanisms of earthquake precursors. It could help to develop the technology for rapid evaluation of seismic hazards, thus minimizing the negative impact on the environment.

References
[1] Namagaladze A, Klimenko M, Klimenko V and Zakharenlova I 2009 Physical mechanism and mathematical modeling of earthquake ionospheric precursors registered in total electron content Geomagn. Aeron. 49 252–62
[2] Klimenko M, Klimenko V, Zakharenlova I, Pulinets S, Zhao B and Tsidilina M 2011 Formation mechanism of great positive TEC disturbances prior to Wenchuan earthquake on may 12, 2008 Adv. Space Res. 48 (3) 488–99
[3] Buresova D, Lastovicka J, Hejda P and Bochnicek J 2017 Ionospheric disturbances under low solar activity conditions Advances in Space Research 54(2) 185–96
[4] Stankov S, Jakowski N, Tsybulya K and Wilken V 2006 Monitoring the generation and propagation of ionospheric disturbances and effects on GNSS positioning. Radio Sci. 41
[5] Jodogne J and Stankov S 2002 Ionosphere–plasmasphere response to geomagnetic storms studied with the RMI-Dourbes comprehensive database Ann. Geophys. 45(5) 629–47
[6] Araulo-Pradere E, Fuller-Rowell T, Spencer P 2006 Consistent features of TEC changes during ionospheric storms J. Atm. Sol.-Terr. Phys. 68(16) 1834–42
[7] Katamzi Z, Smith N, Mitchell C, Spalla P and Materassi M 2012 Statistical analysis of travelling ionospheric disturbances using TEC observations from geostationary satellites Journal of Atmospheric and Solar-Terrestrial Physics 74 64–80
[8] Katamzi Z and Habarulema J 2014 Traveling ionospheric disturbances observed at South African midlatitudes during the 29–31 October 2003 geomagnetically disturbed period Advances in Space Research 53(1) 48–62