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Lower Ionospheric turbulence variations during the intense seismic activity of the last half of 2019 in the broader Balkan region.

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In this paper, we investigate the ionospheric turbulence from TEC observations, before and during the intense seismic activity of September 2019 in Albania and in Marmara sea as well as of November 2019 in Albania, and in Bosnia &Herzegovina. The Total Electron Content (TEC) data of 6 Global Positioning System (GPS) stations of the EUREF network, which are being provided by IONOLAB (Turkey), were analysed using Discrete Fourier Analysis in order to investigate the TEC variations. The results of this investigation indicate that the High- Frequency limit f_o, of the ionospheric turbulence content, increases by aproaching the site and the time of the earthquake occurrence, pointing to the earthquake location (epicenter). We conclude that the LAIC mechanism, through acoustic or gravity wave, could explain this phenomenology. In addition the proximity of the tectonic active areas to the GPS stations offers the opportunity to discriminate the origin of the disturbances.
Key words Seismicity, Lower Ionosphere, Ionospheric turbulence, Brownian walk

1. Introduction

It is generaly accepted that the original cause of the earth surface perturbation is the increasing stress and the rapture of the rocks at the earthquake preparation area where radon release take place. The coupling of radon with atmosphere at the earth surface results to the increase of the Ionization, Temperature (Tramutoli et al. 2018) and of the Electromagnetic field and to disturbances in the air electrical contuctivity. This perturbation are transmitted to the Ionosphere by some LAIC mechanism. The proposed possible hypotheses on the mechanism of coupling between lithospheric activity and ionosphere are transmission through the (a) chemical channels (Pulinets et al. 2018) (b) atmospheric oscillation (or acoustic) channels (Hayakawa et al. 2018) and (3) electromagnetic channels (Pulinets et al. 2018, Hayakawa et al. 2018). Finally a hypothesis of electrostatic channel has been proposed by Freund (2009) on the basis of positive hole charge carriers release in crustal rocks, alongside electrons.When the positive holes arrive at the Earth's surface, they can cause massive ionization of the air molecules and positive surface potential. Subsequently these perturbations are transmitted to Ionosphere. From all these hypotheses for the LAIC mechanism, we believe that the one of the atmospheric oscillation (or acoustic) channel (Hayakawa et al. 2018) is most suitable for the explanation of our observations so far (Contadakis et al. 2008, Contadakis et al. 2012, Contadakis et al. 2015), since the observed frequency band of the suggested gravity waves of our work complies with the observed frequency band of the Internal Atmospheric Gravity waves (Acoustic standing waves) by Horie et al. (2007) and Molchanov et al. (2004, 2005). Thus according to the LAIC mechanism through acoustic channel, acoustic or gravity waves affect the turbulence of the lower ionosphere. Subsequently the produced disturbance starts to propagate in the ionosphere's waveguide as gravity wave. The inherent frequencies of the acoustic or gravity wave range between 0.003Hz (period 5min) and 0.0002Hz (period 83min), which, according to Molchanov et al. (2004, 2005), correspond to the frequencies of the turbulent produced by tectonic activity during the earthquake preparation period. During this propagration the higher frequencies are progressively damped. Thus observing the frequency content of the ionospheric turbidity we will observe a decrease of the higher limit of the turbitity frequency band. So far, our investigations on the occasion of strong earthquakes are approving this view. Nevertheless, since the approval of the theoretical view depents mainly on the compliance of the observational results to the theoretical clues, further obsrvational results are always welcome.

In this paper, we investigate the ionospheric turbulence from TEC observations, before and during the intense seismic activity of September 2019 in Albania and in Marmara sea as well as of November 2019 in Albania, and in Bosnia $Herzegovina.

2. The Seismic Activity

During September-November 2019, a series of moderate and strong earthquakes occurred in the Balkan region (figure 1). The first one occurred on September 21 at 14:04 UTC with magnitude M=5.6 and epicenter close to the west coasts of Albania (a few kilometers north of the city of Durres). This earthquake was followed, five days later (September 26, 10:59 UTC) by a moderate (M=5.7) earthquake in the Sea of Marmara (Turkey). Almost one month later, on November 26 (02:54 UTC), a strong (M=6.4) mainshock shook the same region of Albania, causing severe damage to the city of Durres and the surrounding areas, 51 casualties and about 3,000 injuries. A few hours later (09:19 UTC) and during the same day (November 26, 2019) another moderate earthquake (M=5.4) occurred in Bosnia-Herzegovina. The focal parameters of the above earthquakes are given in table 1.

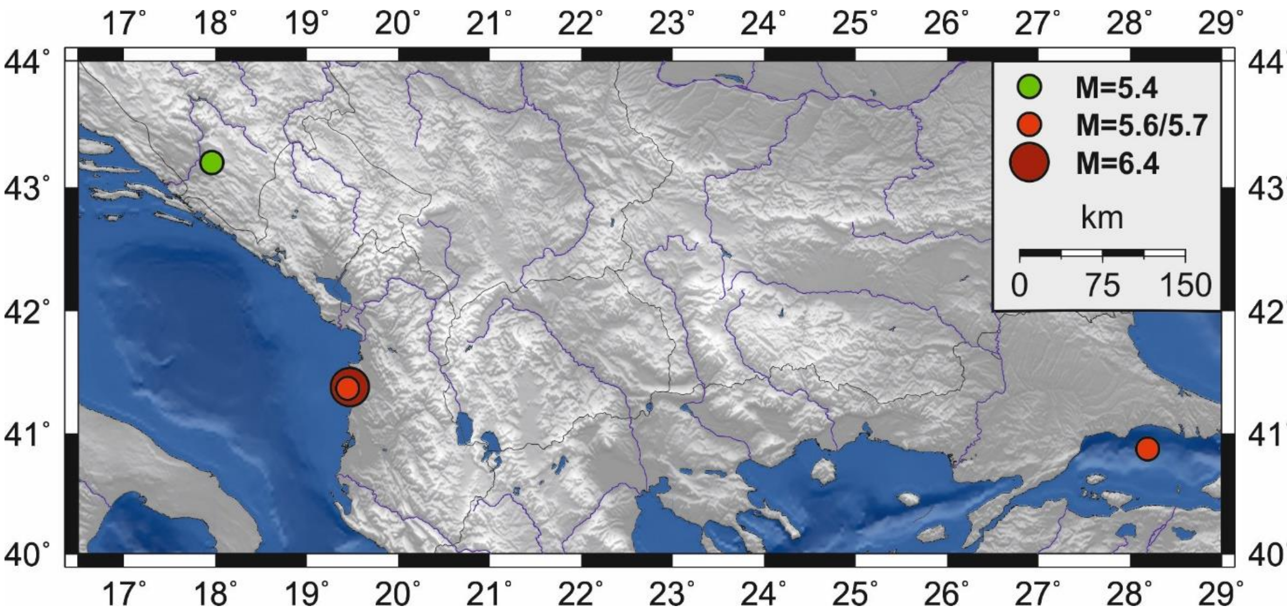

Figure 1. *Epicenters of the four moderate to strong earthquakes that occurred in the broader Balkan region during September-November 2019.*

Table 1. *The focal parameters of the four moderate to strong earthquakes that occurred in the broader Balkan region during September-November 2019 (source: https://www.emsc-csem.org).*

Date	Origin Time	Latitude (°N)	Longitude (°E)	Depth (km)	M_w	Region
21 Sep 2019	14:04	41.372	19.445	20	5.6	Albania
24 Sep 2019	07.49	34.49	26.17	15	5.0	Iraklion
26 Sep 2019	10:59	40.872	28.193	7	5.7	Marmara
26 Nov 2019	02:54	41.381	19.470	10	6.4	Albania
26 Nov 2019	09:19	43.196	17.961	10	5.4	Bosnia-Herzegovina

3. TEC Variation Over Mid Latitude in Europe

In this paper, we investigate the ionospheric turbulence from TEC observations, before and during the intense seismic activity of September 2019 in Albania and in Marmara sea as well as of November 2019 also in Albania, and in Bosnia-Herzegovina. To this purpose we use the TEC estimates provided by IONOLAB (http://www.ionolab.org) (Arikan et al. 2009) for 6 mid latitude GPS stations of EUREF, which cover epicentre distances from the active areas ranging from 26 to 2693 km, for the time periods between 15/09/2019 to 15/12/2019. The selected GPS stations are at about the same latitude and are expected to be affected equally from the Equatorial Anomaly as well as from the Auroral storms. Table 2 displays information on the 6 EUREF stations while Figure 2 displays their locations in relation with the epicentres of the earthquakes of table 1.

Table 2. *Coordinates and distance of GPS stations from the epicental regions*

GPS STATION	Longitude (°E)	Latitude (°N)	Distance from Istanbul (km)	Distance from Tirana (km)
ISTANBUL	28.977377	41.014530	0	766.6
ORID	20.801771	41.123657	686	85
MATERA	16.604445	40.666946	1039	279.8
ZELENCHUSKAYA	41.577686	43.916985	1080	1799.6
TOULOUSE	1.732094	43.607230	2304	1500.4
YEBES	-3.111166	40.533615	2693	1922.9

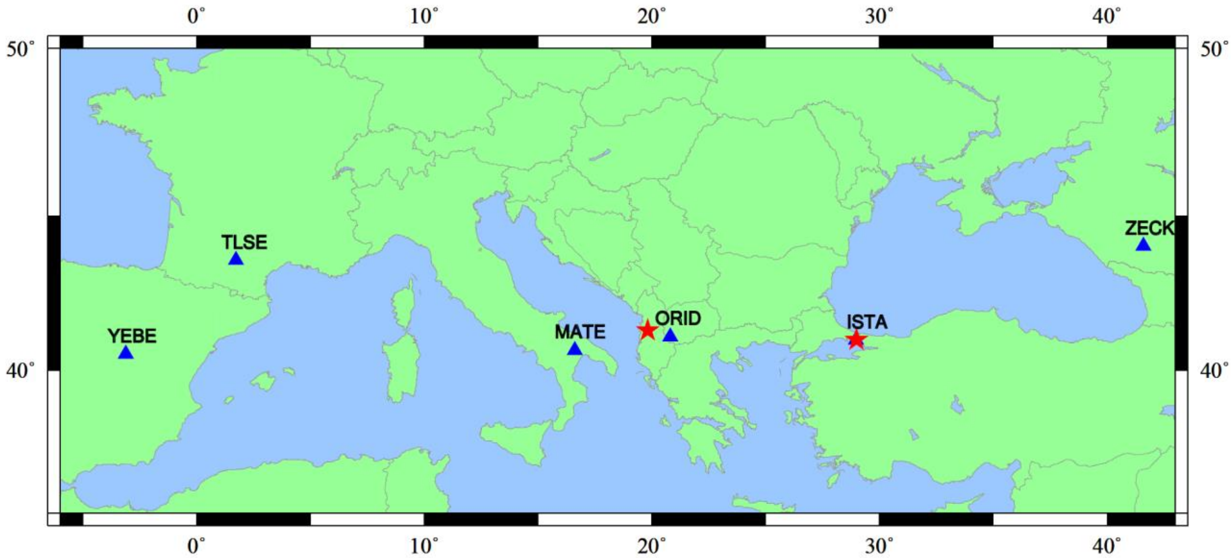

Figure 2. *The six GPS stations (triangles) and the epicentres of the four mainshocks (stars) of table 1.*

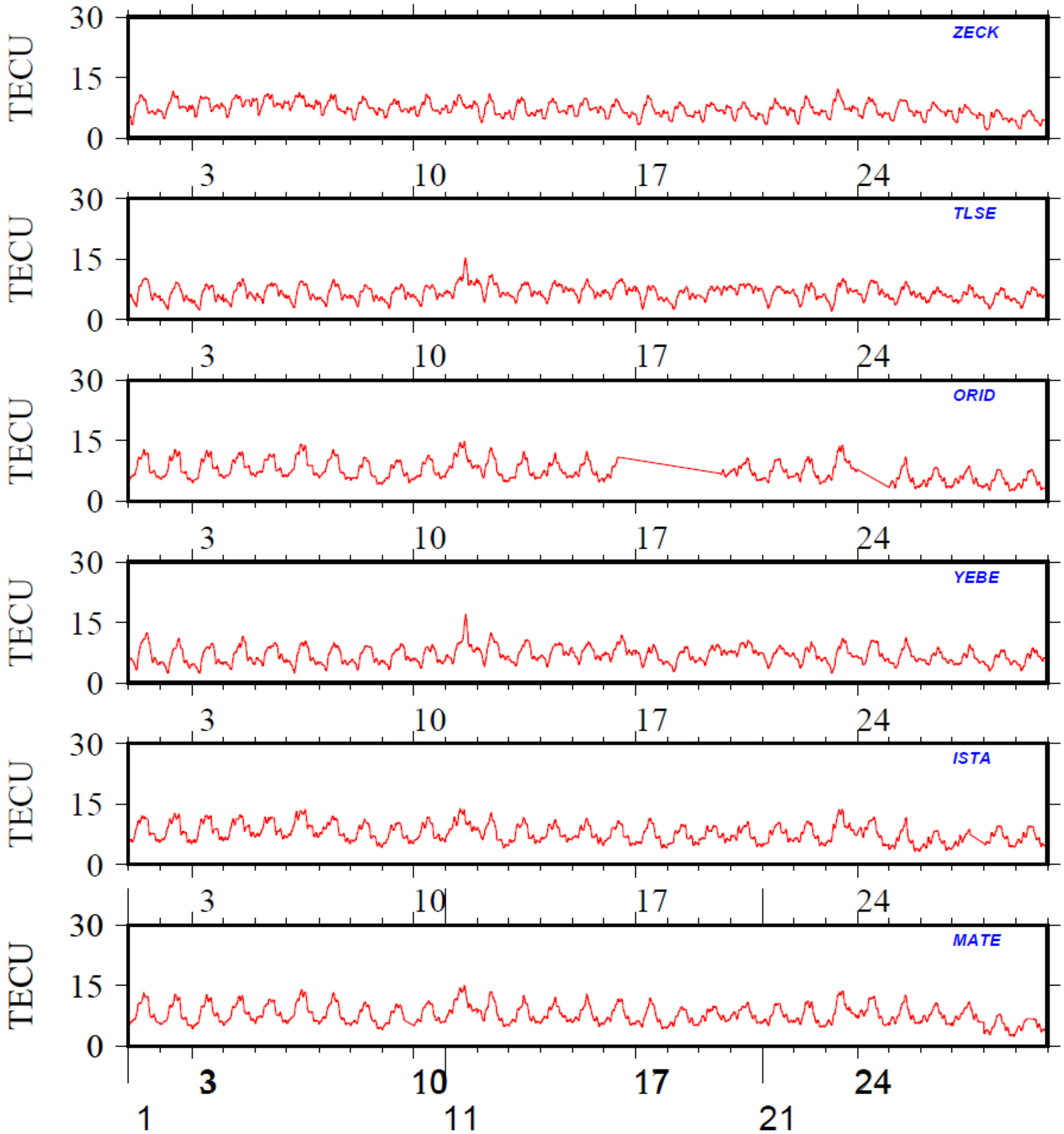

Figure 3. *The TEC variation over the 6 EUREF stations during November 2019.*

The IONOLAB TEC estimation system uses a single station receiver bias estimation algorithm, IONOLAB-BIAS, to obtain daily and monthly averages of receiver bias and is successfully applied to both quiet and disturbed days of the ionosphere for the station position at any latitude. In addition, TEC estimations with high resolution are also possible (Arikan et al. 2009). IONOLAB system provides comparison graphs between its TEC estimations and the estimations of the other TEC providers of IGS, in its site. In this work only TEC estimations in perfect accordance among all providers were used. The TEC values are given in the form of a Time Series with a sampling gap (resolution) of 2.5 minutes. As an example Figure 3 displays the TEC variation over the 6 EUREF stations during November of 2019.

4. Fast Fourier Transform Analysis

The Power Spectrum of TEC variations will provide information on the frequency content of them. Apart of the well known and well expressed tidal variations, for which the reliability of their identification can be easily inferred by statistical tests, small amplitude space-temporal transient variations cannot have any reliable identification by means of a statistical test.

Nevertheless looking at the logarithmic power spectrum we can recognize from the slope of the diagram whether the contributed variations to the spectrum are random or periodical. If they are random the slope will be 0, which correspond to the white noise, or -2 which correspond to the Brownian walk noise, otherwise the slope will be different, the so called Fractal Brownian walk (Turcotte, 1997). This means that we can trace the presence of periodical disturbances in the logarithmic power spectrum of TEC variations. As an example, Figure 4 displays the logarithmic power spectrum of TEC variations over the GPS station of Istanbul at the days of 04 to 06/09/2019. It is seen that the slope of the diagram up to the log(f)=-3.0, is -2. This means that for higher frequencies the TEC variation is random noise. On the contrary the variation of TEC for lower frequencies contains not random variations i.e. turbulent. So we conclude that the upper frequency limit f_o of the turbulent band is: Instrumental frequency f_i=0.0498 circle/s = 331.91μHz. or, equivalently, the lower period limit Po of the contained turbulent is 50.2138 minutes.

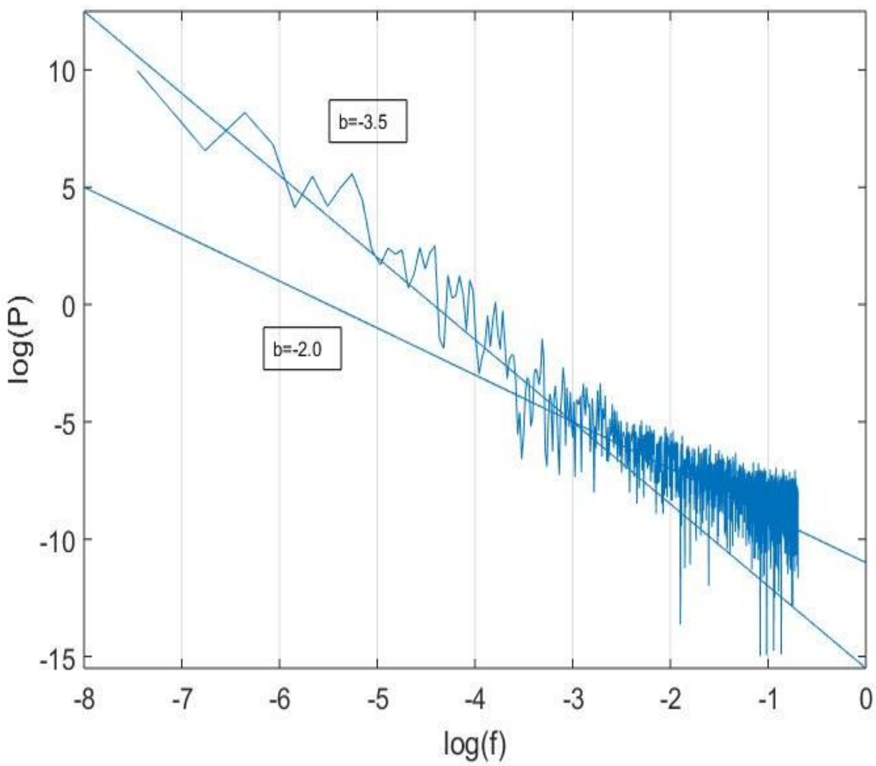

Figure 4. *The logarithmic power spectrum of TEC variations over the ISTA GPS station around the days 04-06/09/2019.*

5. Results and Discussion

Figures 5 and 6 display the variation with distance of TEC turbulence frequency band upper limit f_o over the selected EUREF GPS stations for the day of the mainshocks, of Marmara (26 September 2019) and of Albania (26 November 2019). It is shown that at the day of the earthquake a strong dependence of the upper frequency f_o limit of the Ionospheric turbulent content with the epicentral distance is observed. In particular, the closer of the GPS station to the active area the higher frequency f_o limit is. As it is seen from Figures 5 and 6, the upper frequency limit, f_o, of the turbulence band at remote GPS stations during the days of seismic activity, ranges between 400-200 μHz (equivalently the period P_o ranges 41.5-83 min). These frequencies are in the range of the observed Acoustic Gravity Waves on the occasions of strong earthquakes, which correspond to periods of 30 to 100 min (Molchanov et al., 2004; Molchanov et al., 2005) or 20 to 80 min (Horie et al., 2007).

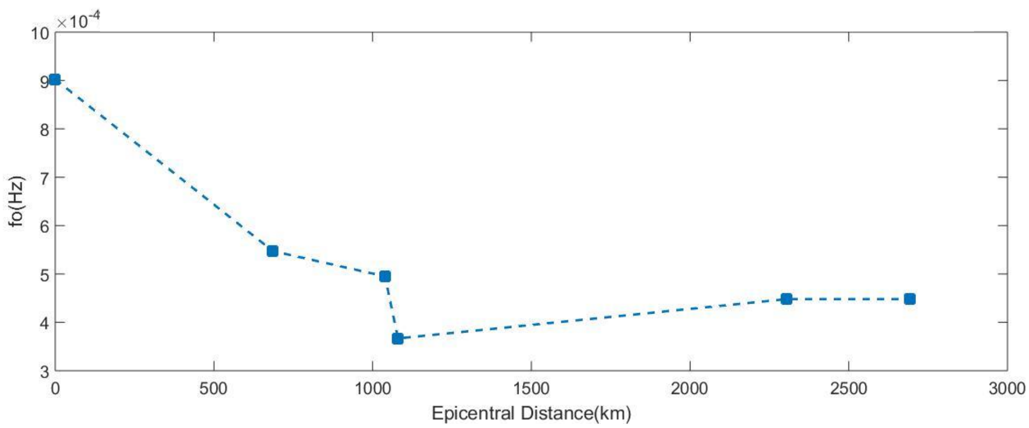

Figure 5. *Variation of TEC turbulence frequency upper limit f_o over the GPS stations with the epicentral distance, at 26/09/2019 i.e. the day of the main earthquake of Marmara*.

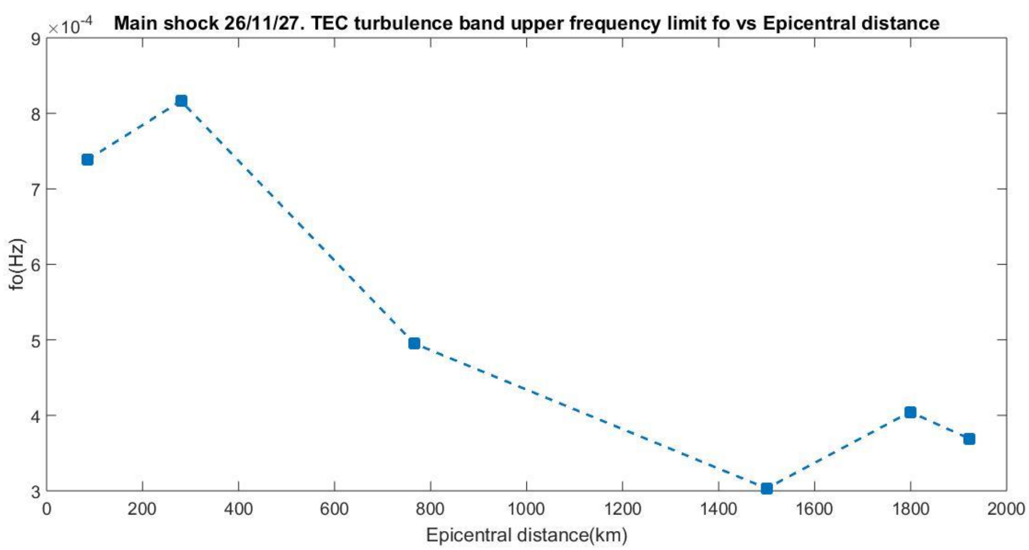

Figure 6. *Variation of TEC turbulence frequency upper limit f_o over the GPS stations with the epicentral distance, at 26/11/2019 i.e. the day of the main earthquake of Albania*.

Figures 7 and 8 show the variation of the upper frequency f_o and of the lower period P_o, limits of ionospheric turbulence band content over the nearest to the seimic activities GPS stations, ORID for Albania and ISTA for Marmara, as well as over the remote GPS station of Zelenchuskaya for comparison. Figures 10 and 11 show the respective variation over the same stations at the same days for the lower Period limit P_o of the turbulence bands. In the same figures the occurrence times of the strong examined earthquakes (M>5.0) are shown with arrows. It is seen that at the days of strong earthquakes the ionospheric turbulence upper frequency limit, f_o, increases (or the respective lower period limit, P_o, decreases). These results indicate time and space convergence of increasing turbulence frequency band upper limit f_o to the earthquakes occurrence.

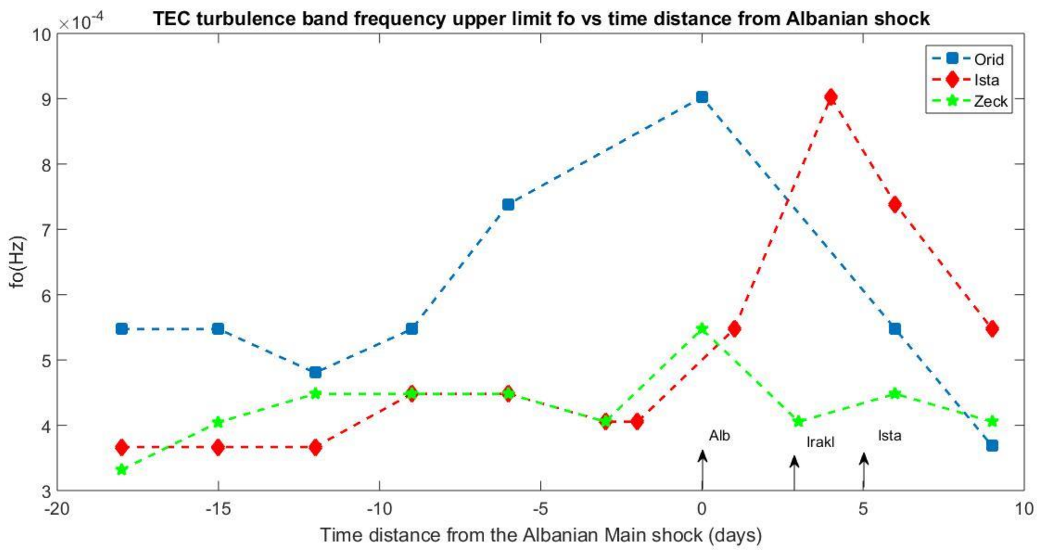

Figure 7. *Variation of TEC turbulence frequency upper limit f_o over the GPS stations of ORID, ISTA and ZECK*

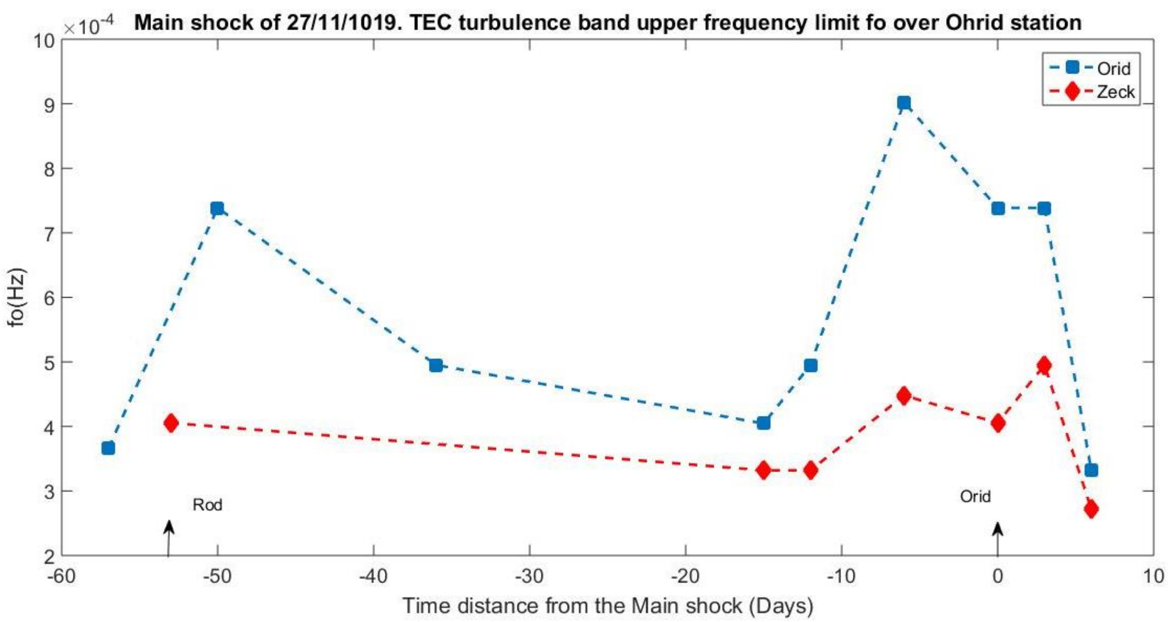

Figure 8. *Variation of TEC turbulence frequency upper limit f_o over the GPS stations of ORID and ZECK*

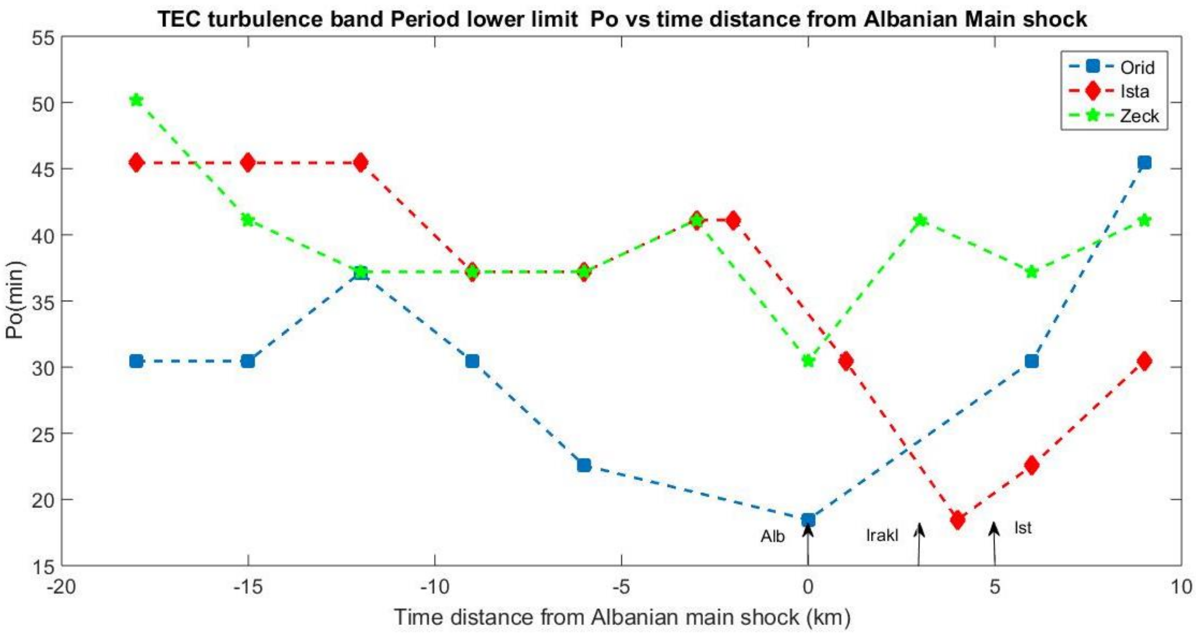

Figure 9. *Variation of TEC turbulence lower period limit P_o over the GPS stations of ORID, ISTA and ZECK*

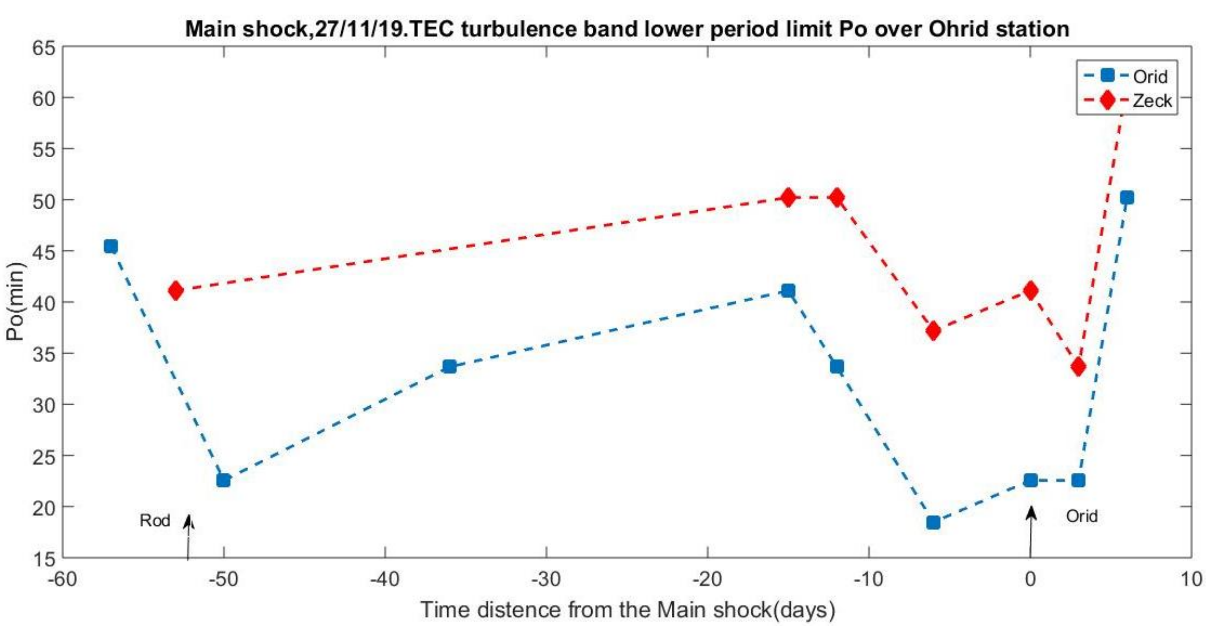

Figure 10. *Variation of TEC turbulence lower period limit P_o over the GPS stations of ORID and ZECK*

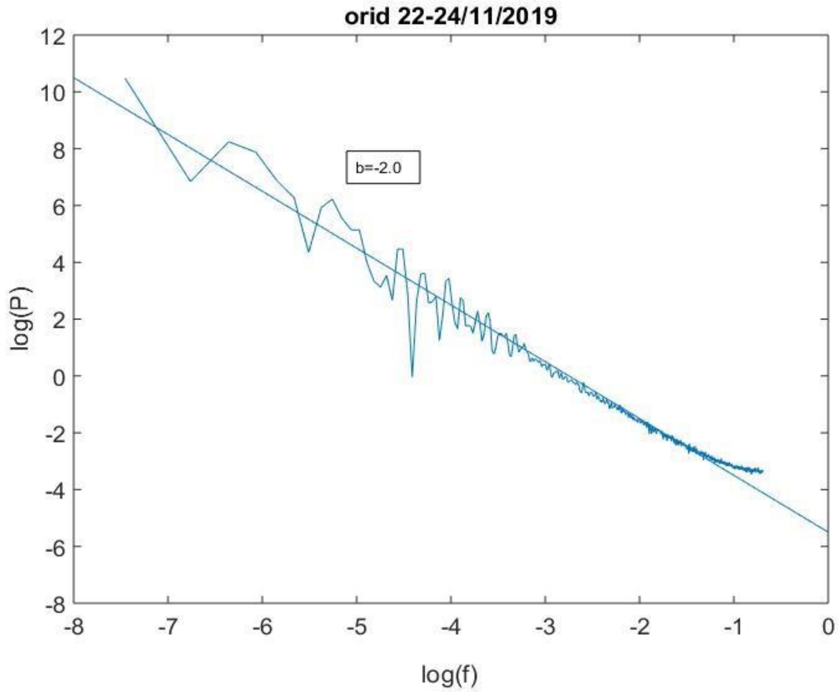

Figure 11. *Logarithmic power spectrum of TEC variation over Orid GPS station 2.5 days before the main shock of* the Albania seismic activity at 26/11/2020

Hobara et al.(2005) in a study on the ionospheric turbulence in low latitudes concluded that the attribution of the turbulence to earthquake process and not to other sources, i.e. solar activity, storms etc is not conclusive. Nevertheless in our case, the steady monotonic, time and space, convergence of the frequency band upper limit f_o increment, to the occurrence of the examined strong earthquakes is a strong indication that the observed turbulence is generated by the respective earthquakes preparation processes.

The qualitative explanation of this phenomenology can be offered on the basis of the LAIC: Tectonic activity during the earthquake preparation period produces anomalies at the ground level which propagate upwards in the troposphere as acoustic or standing gravity waves (Hayakawa et al. 2011, Hayakawa 2011). These acoustic or gravity waves affect the turbulence of the lower ionosphere, where sporadic Es-layers may appear too (Liperovsky et al., 2005), and the turbulence of the F layer. Subsequently, the produced disturbance starts to propagate in the ionosphere's waveguide as gravity wave and the inherent frequencies of the acoustic or gravity waves can be traced on TEC variations [i.e. the frequencies between 0.003Hz (period 5min) and 0.0002Hz (period 100min)], which, according to Molchanov et al. (2004, 2005) and Horie et al. (2007), correspond to the frequencies of the turbulent induced by the LAIC coupling process to the ionosphere. As we

move far from the disturbed point, in time or in space, the higher frequencies (shorter wavelength) variations are progressively attenuated.
Finally, Figure 11 displays the Logarithmic power spectrum of TEC variation over Orid GPS station 2.5 days before the main shock of the Albania seismic activity at 26/11/2020. It is very interesting that the turbidity is completely chaotic (b=-2) across all the spectrum. This mean that, due to the proximity of the tectonic active areas to the GPS stations, the modulation of the Ionosphere turbulence band just took place and the differential propagation damping has not yet been activated in order to lead to the appearance of the different wave constituent.

6. Conclusions

The results of our investigation, on the case of the recent eseismic activity in the Balkan region (and in different seismotectonic environments), indicate that the High-Frequency limit f_o, of the ionospheric turbulence content, increases as we are getting close to the site and the time of the earthquake occurrence, pointing to the earthquake location. We conclude that the LAIC mechanism through acoustic or gravity wave could explain this phenomenology. That is, tectonic activity during the earthquake preparation period produces anomalies at the ground level, which propagate upwards in the troposphere as acoustic or standing gravity waves. These acoustic or gravity waves affect the turbulence of the lower ionosphere, where sporadic *Es*-layers may appear too, as well as the turbulence of the *F* layer. Subsequently the produced disturbance starts to propagate in the ionosphere's wave guide. Thus, observing the frequency content of the ionospheric turbulence we will observe a decrease of the higher limit of the turbulence frequency band, as a result of the differential frequency attenuation of the propagating wave.

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