Lower Ionospheric turbulence variations during the tectonic activity of the last quarter of 2019 in the Hellenic Arc (Greece)

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In this paper we investigate the ionospheric turbulence from TEC observations before and during the tectonic activity of the last quarter of 2019 in the Hellenic Arc, Greece (main shock at λ =23.16°E, φ =35.66°N, M_w= 6.0). 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_0, 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.

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. These perturbations 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, along side electrons. 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; Contadakis et al. 2019). 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. During this propagation 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. Our investigations so far, 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 tectonic activity of the last quarter of 2019 in the Hellenic Arc, Greece (main shock at λ = 23.16°E, φ = 35.66°N, M_w= 6.0). 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 (Contadakis et al. 2008; Contadakis et al. 2012; Contadakis et al. 2015; Contadakis et al. 2019).

2. Seismotectonic Information

On November 27, 2019 (07:23 UTC) a strong earthquake of magnitude M=6.0 occurred in South Aegean (W-NW of Crete Island, Figure 1). It was an intermediate depth (h=67km) earthquake connected with the collision and subduction of the Mediterranean oceanic lithospheric plate under the continental Eurasian plate that takes place along the well-known Hellenic Arc (Figure 1), resulting in high shallow, as well as intermediate depth, seismicity in the broader Aegean region. In 2019 six strong earthquakes (M >5.0) occured in the Kythira-Rodos segment of the Hellenic Arc, while three of them occured in the last quarter of the year. The focal parameters of the these last three earthquakes are given in Table 1.

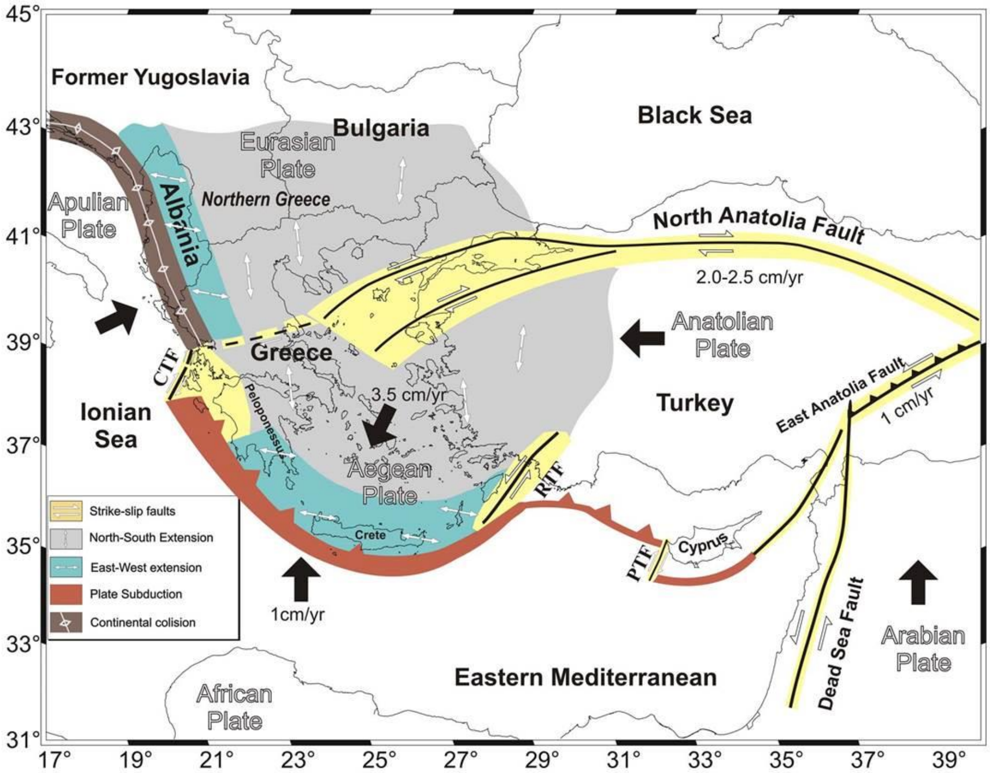

Figure 1. *Moves of tectonic plates defining the active tectonics of Aegean and surroundings (Papazachos et al., 1998).*

Table 1. *The focal parameters of the three strong (M>5.0) earthquakes which occured during the last quarter of 2019 along the Hellenic Arc (source: https://www.emsc-csem.org).*

Date	Origin Time	Site	Latitude (°N)	Longitude (°E)	Depth (km)	M
03 Oct 2019	04:45	37.5 km ESE of Rodos	36.288	28.59	14	5.1
27 Nov 2019	07:23	66.1 km SSE of Kythira	35.66	23.16	67	6.0
10 Dec 2019	21:58	65.8km WSW of Karpathos	35.41	26.49	29	5.3

3. TEC Variation Over Mid Latitude in Europe

In this paper, we investigate the ionospheric turbulence from TEC observations, during the seismic activity of the last quarter of 2019 in the Hellenic Arc, Greece. 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 527 to 2788 km, for the time periods between 30/09/2019 to 20/12/2019. The selected GPS stations have 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 Kythira, Karpathos and Rodos.

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

GPS STATIONS	**Longitude (°E)**	**Latitude (°N)**	**Distance from Kythira (km)**	**Distance from Rodos (km)**
ISTANBUL	28.977377	41.014530	755.7	527.5
ORID	20.801771	41.123657	623.7	863.5
MATERA	16.604445	40.666946	791.4	1150.4
ZELENCHUSKAYA	41.577686	43.916985	1791.8	1390.5
TOULOUSE	1.732094	43.607230	2023.7	2414.6
YEBES	-3.111166	40.533615	2356.4	2787.9

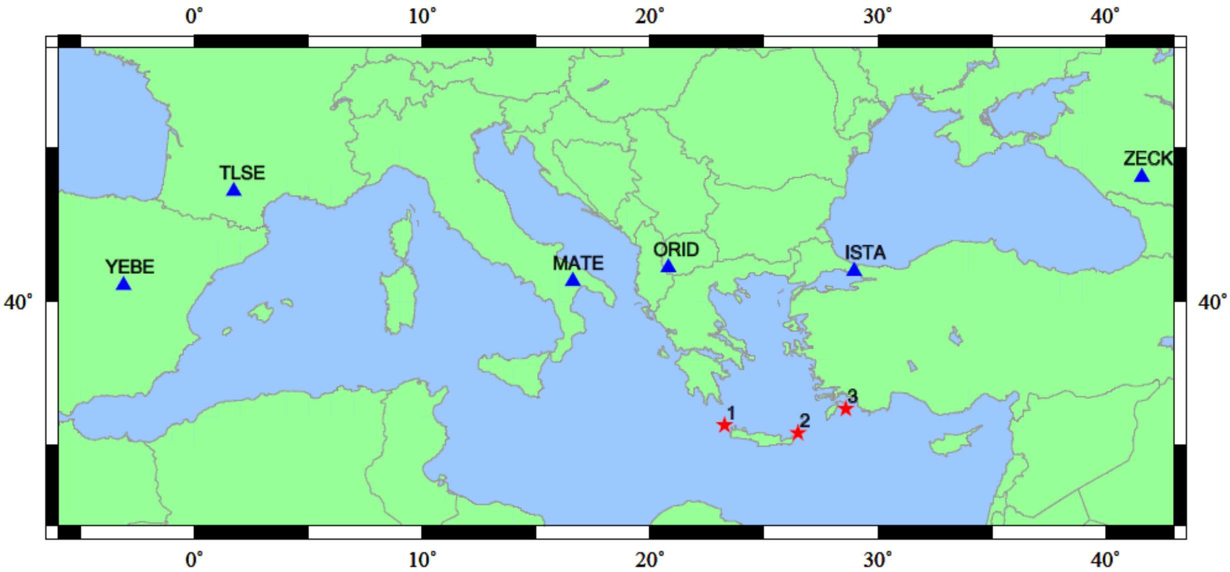

Figure 2. *The six GPS stations (triangles) and the epicentres of the three mainshocks (stars) of table 1.*

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 of its TEC estimations with 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 for November of 2019.

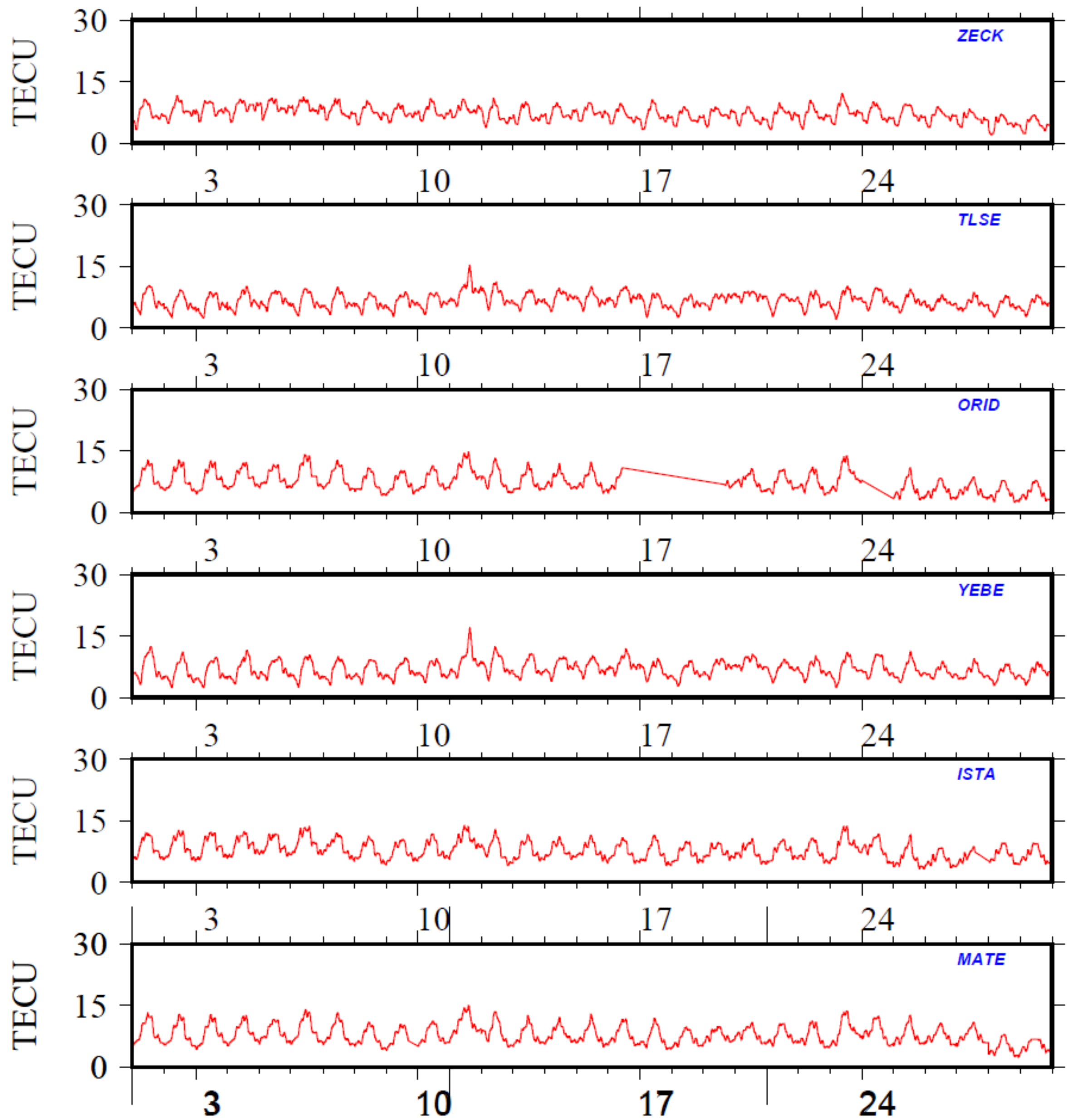

Figure 3. *The TEC variation over the 6 EUREF stations during November 2019.*

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.

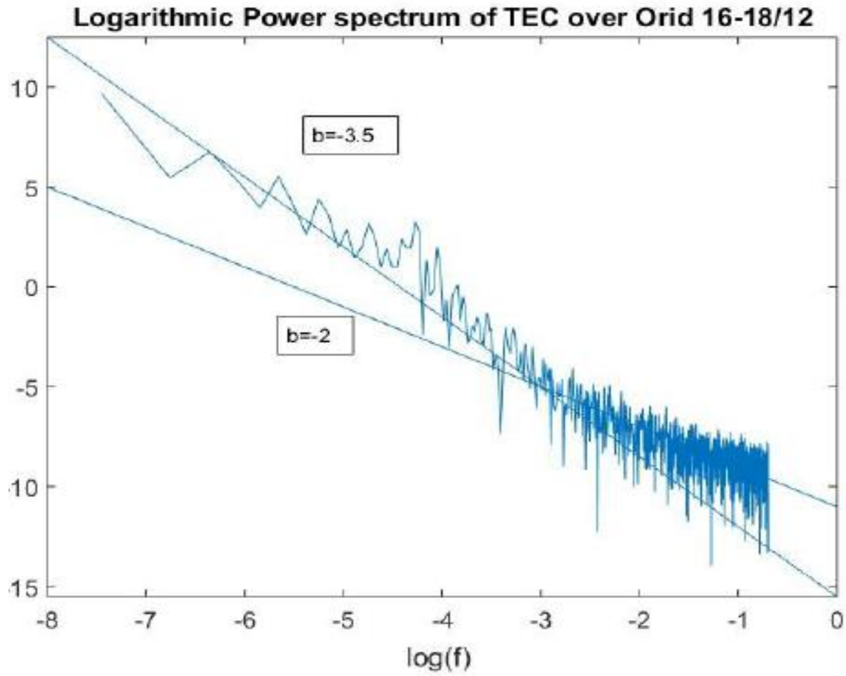

Figure 4. *The logarithmic power spectrum of TEC variations over the ORID GPS station around the days of 16-18/12/2019.*

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 corresponds to the white noise, or -2 which corresponds to the Brownian walk noise, otherwise the slope will be different, that of 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 ORID at the days of 16 to 18/12/2019. 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 contain not random variations i.e. turbulent. So we conclude that the upper frequency limit f_o of the turbulent band is: Instrumental frequency f_{oi}=0.0498circle/s=>

f_o=331.91μHz or , equivalently, the lower period limit P_o of the contained turbulent is 50.2138 minutes.

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 Main shocks, of Kythira (November 27) and of Karpathos (December 10). Figures 7 and 8 dispay the respective variations of lower Period limits P_o. It is shown that, at the day of the earthquakes a strong dependence of the upper frequency f_o limit (lower Period P_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 (or equivelently the lower Period limit P_o) 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 500-800 μHz (equivalently the period P_o ranges 21-55 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).

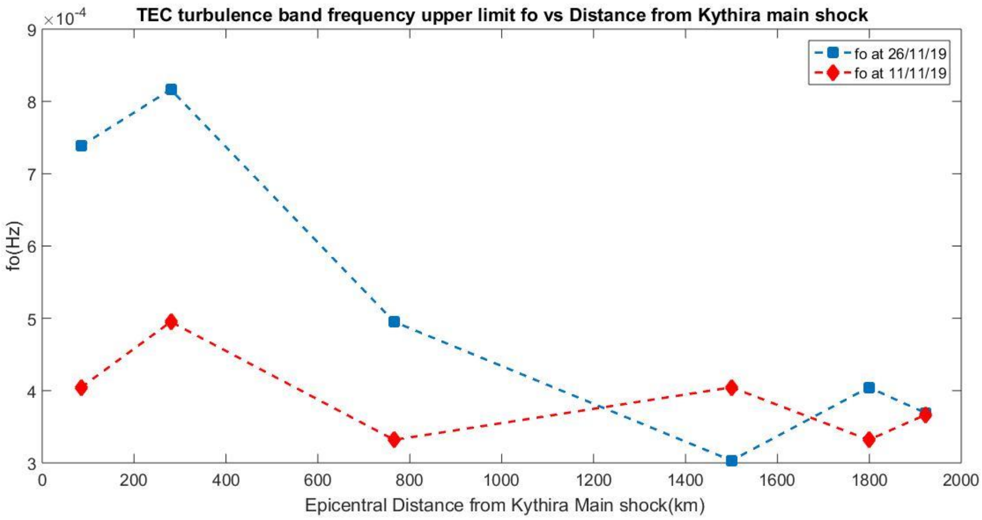

Figure 5. *Variation of TEC turbulence frequency upper limit f_o over the GPS stations with the epicentral distance, at 27/11/2019 i.e. the day of the Kythera earthquake.*

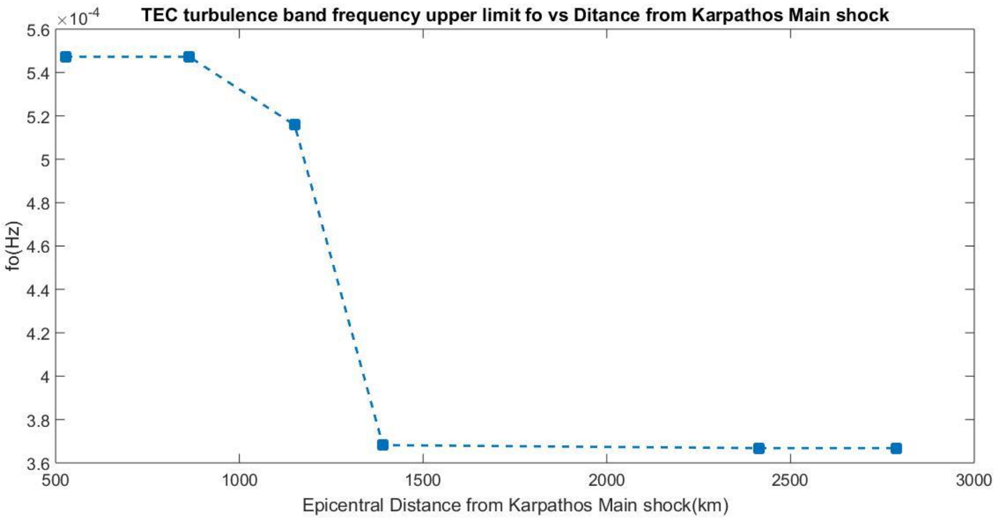

Figure 6. *Variation of TEC turbulence frequency upper limit f_o over the GPS stations with the epicentral distance, at 10/12/2019 i.e. the day of Karpathos earthquake.*

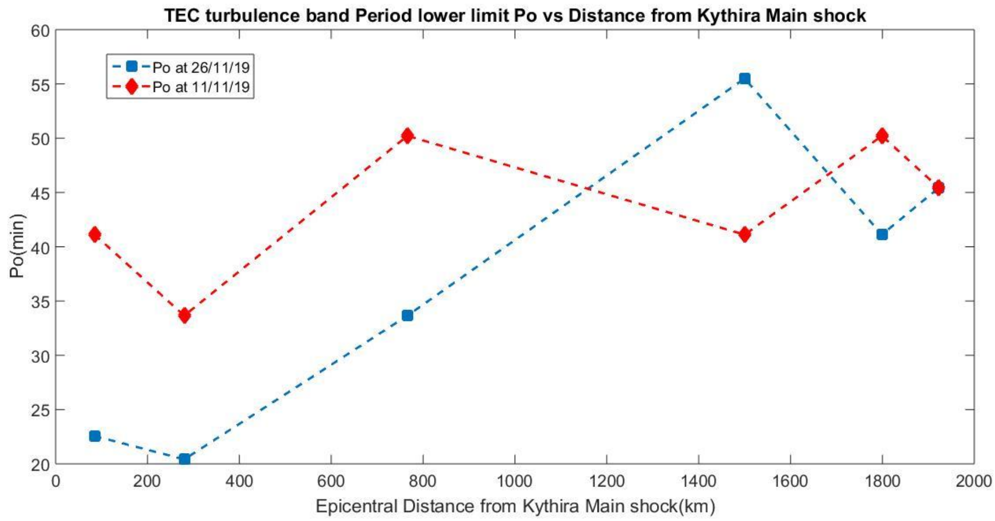

Figure 7. *Variation of TEC turbulence Period lower limit P_o over the GPS stations with the epicentral distance, at 27/09/2019 i.e. the day of the Kythera earthquake.*

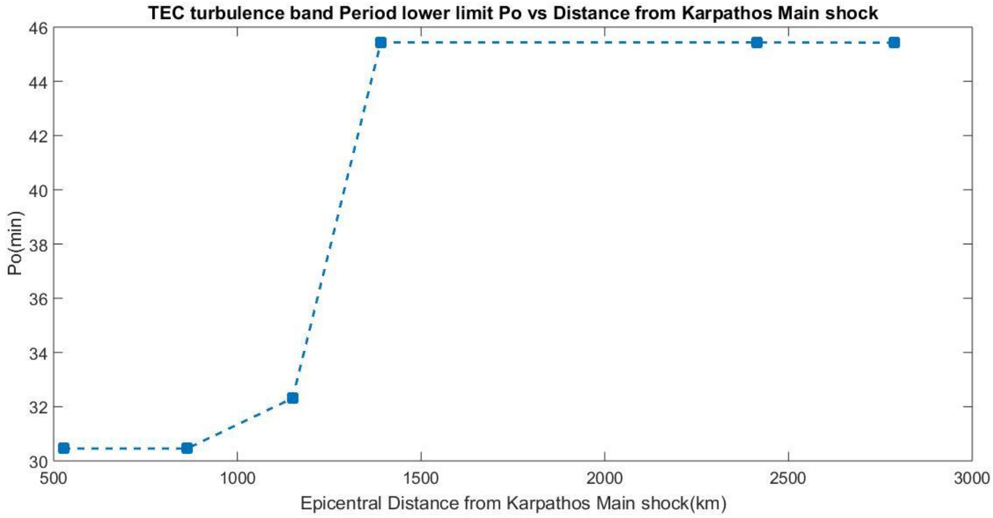

Figure 8. *Variation of TEC turbulence Period lower limit P_o over the GPS stations with the epicentral distance, at 10/12/2019 i.e. the day of the Karpathos earthquake.*

Figures 9 and 10 show the variation of the upper frequency f_o limit of ionospheric turbulence band content over the GPS stations, ORID and MATE and the same variation over the GPS stations ISTA and ZECK. Figures 11 and 12 show the respective variation over the same stations at the same days for the lower period limit P_o of the turbulence band. In the same figures the occurrence times of strong 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 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.

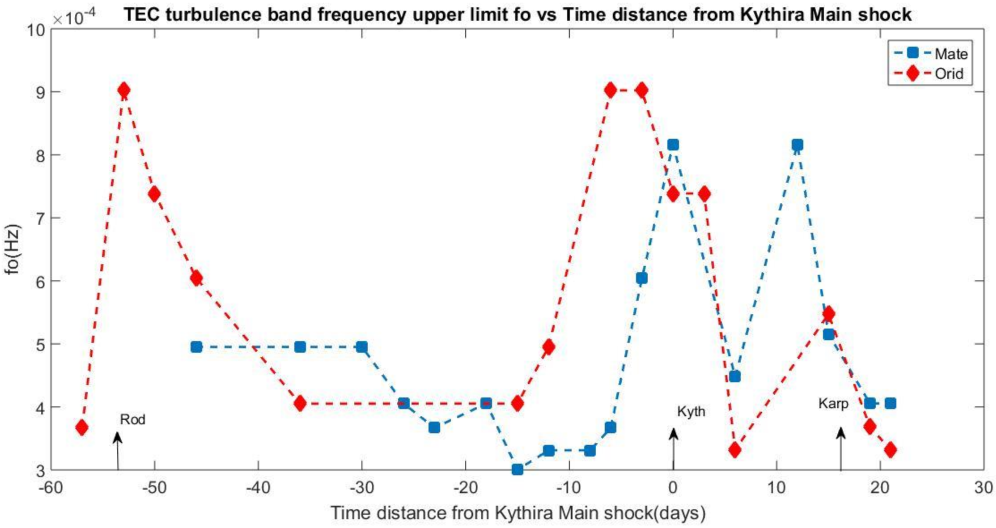

Figure 9. *Variation of TEC turbulence band frequency upper limit f_o over the GPS Stations ORID and MATE*

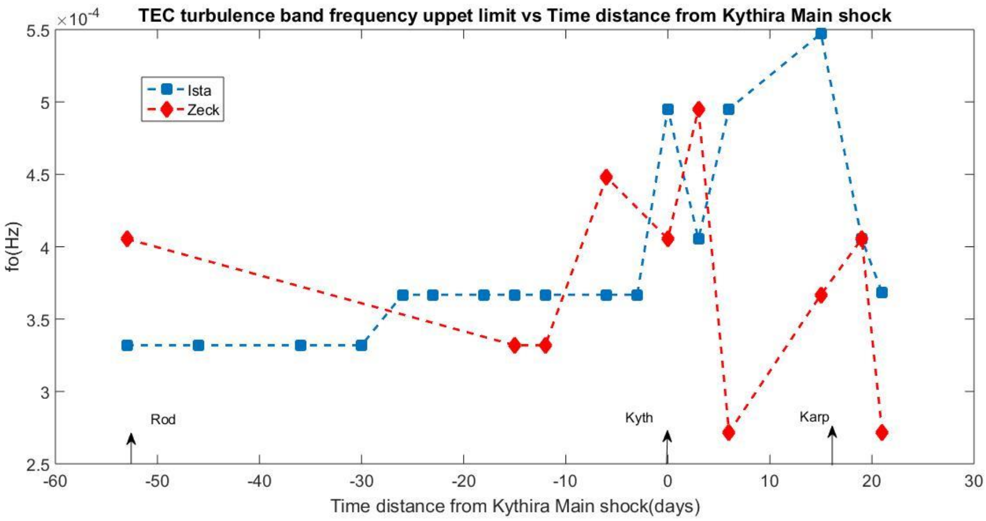

Figure 10. *Variation of TEC turbulence band frequency upper limit f_o over the GPS Stations ISTA and ZECK*

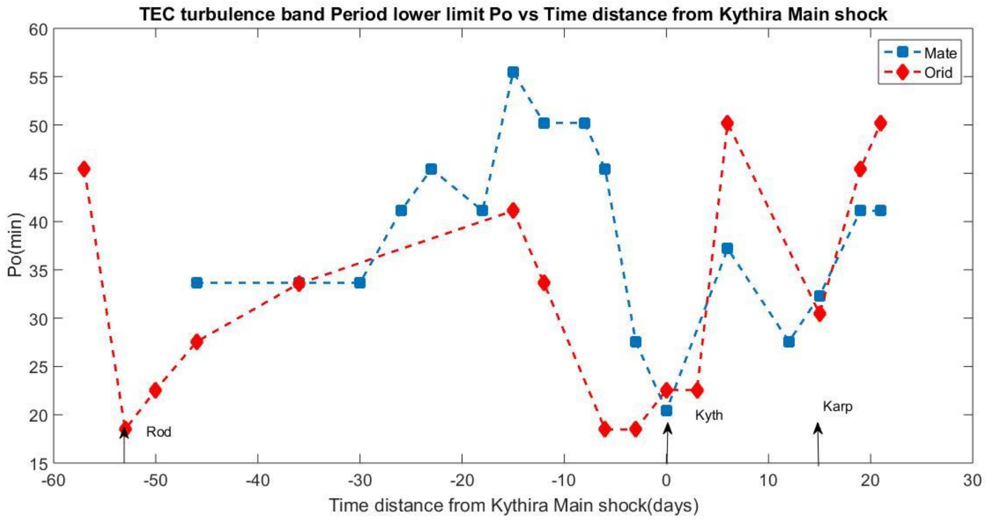

Figure 11. *Variation of TEC turbulence band Period lower limit P_o over the GPS Stations ORID and MATE*

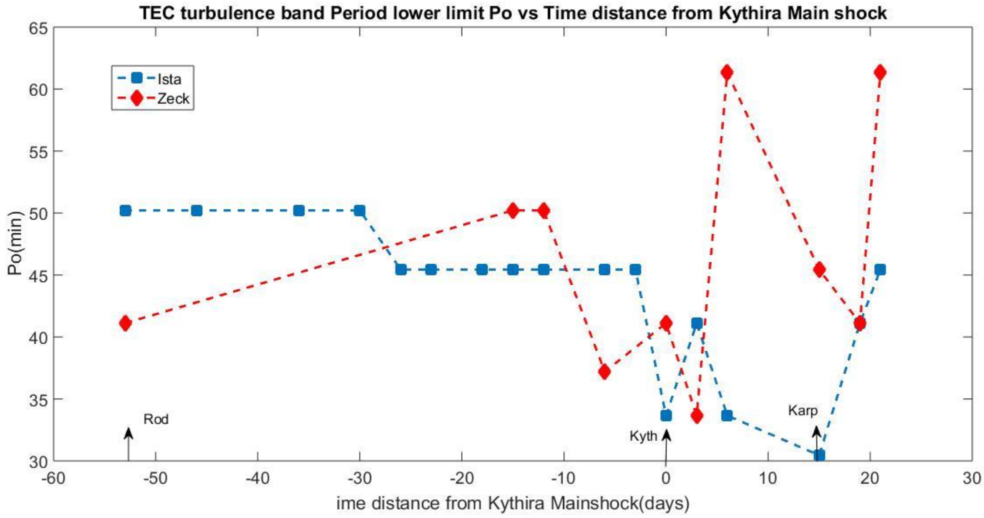

Figure 12. *Variation of TEC turbulence band Period lower limit P_o over the GPS Stations ISTA and ZECK*

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 South Aegean 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, Hayakawa et al. 2018). 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.

6. Conclusions

The results of our investigation, on the case of the recent Hellenic Arc tectonic activity, 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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