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LOWER IONOSPHERIC TURBULENCE VARIATIONS DURING THE RECENT ACTIVITY OF ETNA'S VOLCANO, SICILY, IN DECEMBER 2018

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Abstract

In this paper, we present an investigation on the ionospheric turbulence from TEC observations before and during the recent activity of Etna's Volcano. Mount Etna is located close to the eastern coast of Sicily. The last eruption of Etna volcano took place on 24 December 2018 while two days later (26 December, 02:19 UTC) an earthquake of M=5.0 occurred ~15 km to the ESE of the volcano, causing damage to the nearby city of Catania. The results of our investigation, on the occasion of the Etna's Volcanic activity, indicate that the high-frequency limit f_o of the ionospheric turbulence band content, is increasing with time to the volcano eruption while, at the same time, f_o is decreasing with distance from the volcano. We conclude that the LAIC mechanism through acoustic or gravity waves could explain this phenomenology, as it has happened in cases of earthquake activity. Our observations indicate that the effect of volcanic eruption on the band content of the ionospheric turbulence is insignificant at distances greater than 1000km (at the most), a fact that we must consider in our research on Ionospheric turbulence in relation to earthquake precursors research.

Keywords: *Volcanic activity, Ionospheric turbulence, Fast Fourier Transform Analysis, Brownian Noise*

Περίληψη

Σ' αυτή την εργασία παρουσιάζουμε μια μελέτη της ιονοσφαιρικής τυρβώδους ροής δια της αναλύσεως των παρατηρήσεων του Ολικού Ηλεκτρονιακού Περιεχομένου (TEC) πριν και κατά την διάρκεια της πρόσφατης ηφαιστειακής δραστηριότητας του ηφαιστείου της Αίτνας. Το όρος Αίτνα ευρίσκεται πλησίον της ανατολικής ακτής της Σικελίας. Η τελευταία έκρηξη του ηφαιστείου της Αίτνας έλαβε χώρα στις 24 Δεκεμβρίου του 2018 ενώ δύο ημέρες αργότερα (26 Δεκεμβρίου, 02:19 UTC) έλαβε χώρα ένας σεισμός μεγέθους M=5.0 σε απόσταση ~15km ΑΝΑ από το ηφαίστειο, προκαλώντας καταστροφές στην γειτονική πόλη της Κατάνιας. Τα αποτελέσματα της έρευνάς μας, για την περίπτωση της ηφαιστειακής δραστηριότητας της Αίτνας δείχνουν ότι το ανώτερο όριο συχνοτήτων f_o των τυρβωδών διακυμάνσεων της δέσμης τυρβώδους ροής της κατώτερης ιονόσφαιρας αυξάνει καθώς προσεγγίζεται ο χρόνος εκρήξεως του ηφαιστείου και την ίδια στιγμή το ανώτατο όριο συχνοτήτων f_o ελαττούται καθώς η απόσταση από το σημείο της ηφαιστειακής έκρηξης αυξάνεται. Συμπεραίνουμε λοιπόν ότι ο μηχανισμός Διασύνδεσης Λιθόσφαιρας-Ατμόσφαιρας-Ιονόσφαιρας (LAIC) δια των ακουστικών κυμάτων ή κυμάτων βαρύτητας θα μπορούσε να ερμηνεύσει αυτή την φαινομενολογία, όπως συμβαίνει και στην περίπτωση της σεισμικής δραστηριότητας. Οι παρατηρήσεις μας δείχνουν ότι η επίδραση της ηφαιστειακής έκρηξης στο περιεχόμενο συχνοτήτων των τυρβωδών διαταράξεων της δέσμης τυρβώδους ροής της κατώτερης ιονόσφαιρας είναι μηδαμινή σε αποστάσεις μεγαλύτερες των 1000 km το πολύ, ένα γεγονός που πρέπει να λαμβάνομε υπόψιν στην έρευνα της τυρβώδους ροής της κατώτερης ιονόσφαιρας σε σχέση με την σεισμική δραστηριότητα.

Λέξεις Κλειδιά: *Ηφαιστειακή δραστηριότητα, Ιονοσφαιρική τυρβώδης ροή, Ταχείς Μετασχηματισμοί Fourier, Brownian Θόρυβος*

1. Introduction and Seismotectonic Background

Mount Etna is located close to the eastern coast of Sicily. With a height of ~3,330 m, is considered as the highest volcano of Europe's mainland while it is classified among the most active ones globally. Its activity has started back in the Early-Middle Pleistocene (Wezel, 1967). It is characterized as a composite volcano (cone-shaped mountain), while its eruptions are mostly of strombolian type (moderate bursts of expanding gases). Etna is created at the region where two major faults, the NNW striking Malta Escarpment and the NE striking Messina-Fiumenfreddo fault, are intersecting at the Apennine-Maghrebian thrust belt (Azzaro, 1999). This setting is responsible for the generation of moderate, as well as of strong, shallow earthquakes. To the north of Mount Etna, intermediate depth seismicity is also observed which is connected to the subduction zone of the Calabrian Arc. This arc is formed due to the collision and subduction of the Mediterranean tectonic plate under Eurasia. The background seismicity of the broader region is presented on the map of Figure 1.

The last eruption of Etna volcano took place on 24 December 2018 and it was accompanied by numerous earthquakes, while two days later (26 December, 02:19 UTC) an earthquake of M=5.0 occurred ~25 km to the SE of the volcano, causing damage to the nearby city of Catania. The seismic activity of the region, during the period 15-31 December 2018, is presented on the map of Figure 2. As Johnston (1997), in his "*Review on Electric and Magnetic Fields Accompanying Seismic and Volcanic Activity*", points out, the subset of ionospheric disturbances, generated by trapped atmospheric pressure waves (also termed gravity waves and/or acoustic waves, traveling ionospheric disturbances or TID's) that are excited by earthquakes and volcanic eruptions, are common and propagate to long distances. These are known and expected consequences of earthquakes, volcanic explosions (and other atmospheric disturbances), that must be identified and their effects have to be removed from VLF/ULF electromagnetic field records before associating new observations of ionospheric disturbances with earthquake activity.

In this paper we investigate the ionospheric turbulence from TEC observations before and during this recent activity of Etna's Volcano. This is an effort to further investigate Ionospheric Turbulence frequency content in relation to seismo-volcanic activity as well as its possible connection to pre-seismic and pre-volcanic activity (i.e. Contadakis et al., 2008, 2012, 2015).

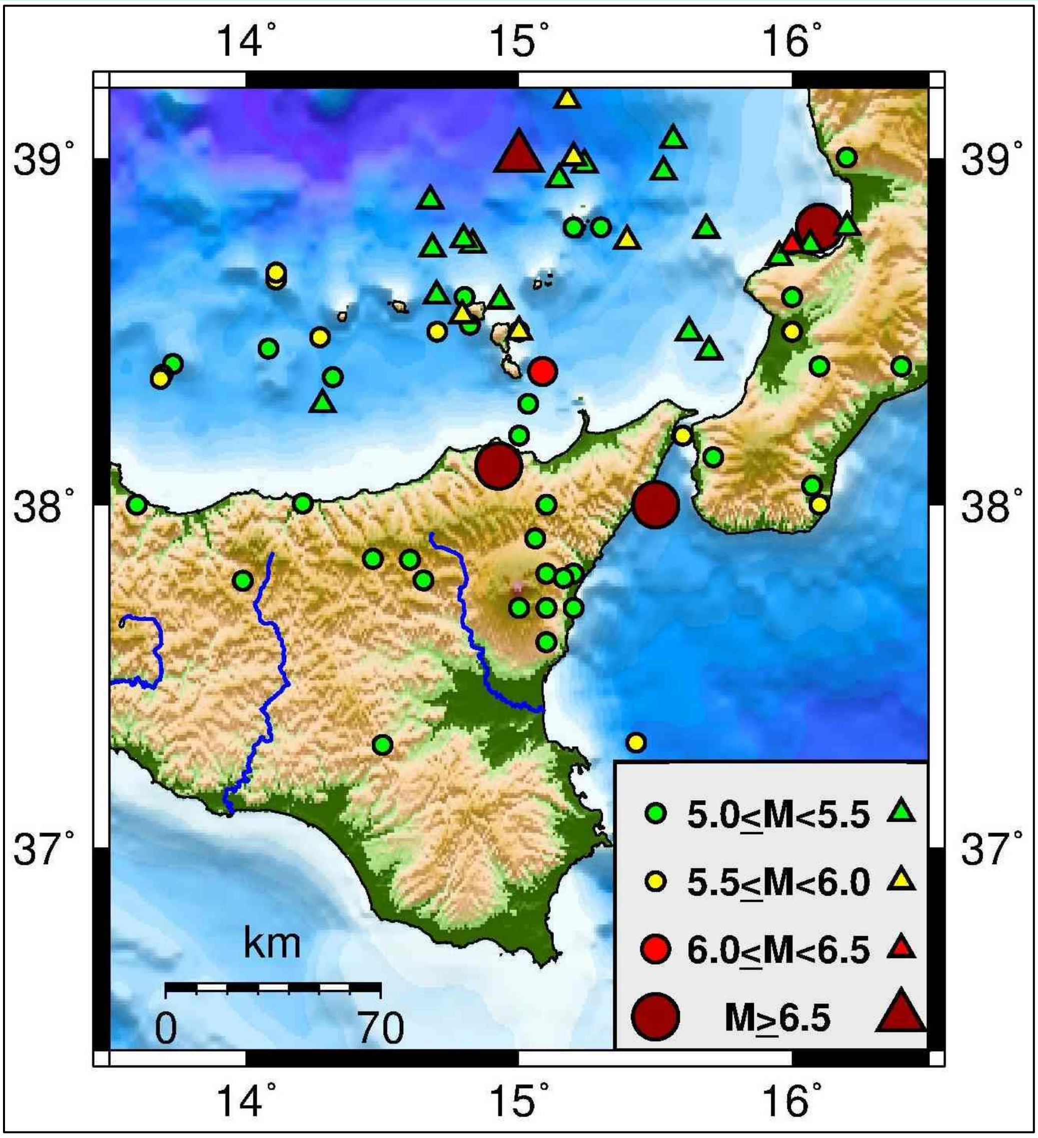

Fig. 1: Epicentres of all known earthquakes with M≥5.0 that occurred in the broader region of Mount Etna during the period 1900-2016. Circles correspond to epicentres of shallow (depth < 60 km) earthquakes while triangles denote epicentres of intermediate depth ones (60 < depth < 300 km) (source: http://www.isc.ac.uk).

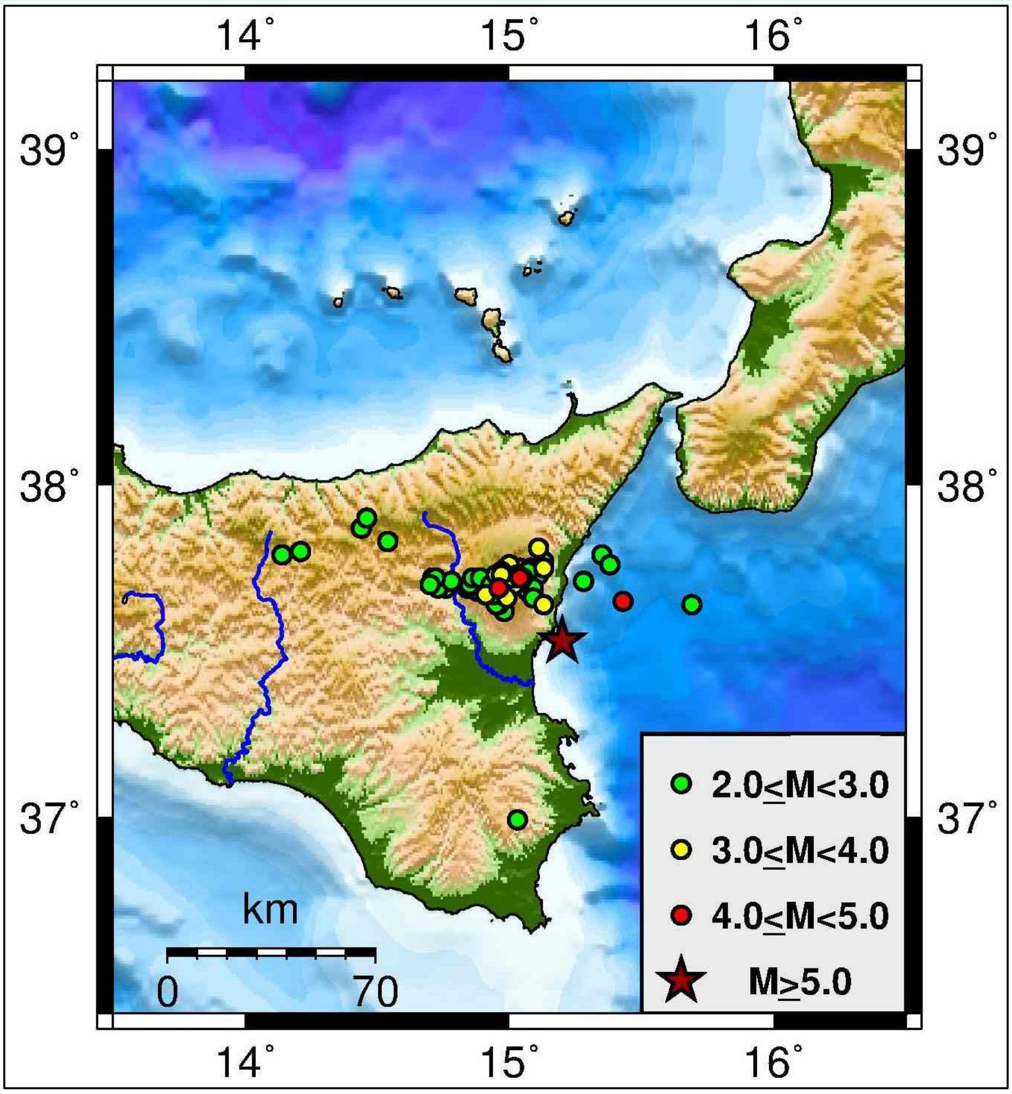

Fig. 2: Seismic activity around the Mount Etna during the period 15-31 December 2018 (source: https://www.emsc-csem.org).

2. Observational Data

To this purpose, we use the TEC estimates provided by IONOLAB (http://www.ionolab.org) (Arikan et al., 2009) for five mid latitude GPS stations of EUREF network, which cover epicentral distances of 359.08-2,327.29 km and for the period 07/11/2018-05/01/2019. The selected GPS stations are at about the same latitude and, therefore, it is expected to be affected equally from the Equatorial Anomaly as well as from Auroral storms. Table 1 displays the coordinates of the selected GPS stations and their distances from Etna. Figure **3** displays the sites of the five GPS stations and of the Etna Volcano.

Table 1: The sites of the GPS stations and their distances from Etna.

GPS Station	Longitude (degrees)	Latitude (degrees)	Distance (km)
MATE	16.604158E	40.730175N	359.08
ORID	20.801647E	41.123894N	623.81
ISTA	28.979339E	41.015269N	1253.98
ZECK	41.584978E	43.856928N	2324.77
YEBE	3.111183W	40.533622N	1594.80

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 station position at any latitude. In addition, TEC estimations with high resolution are also feasible (Arikan et al., 2009). The 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, which are 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. Figure **4** displays the Variation of TEC over the selected GPS stations during December of 2018.

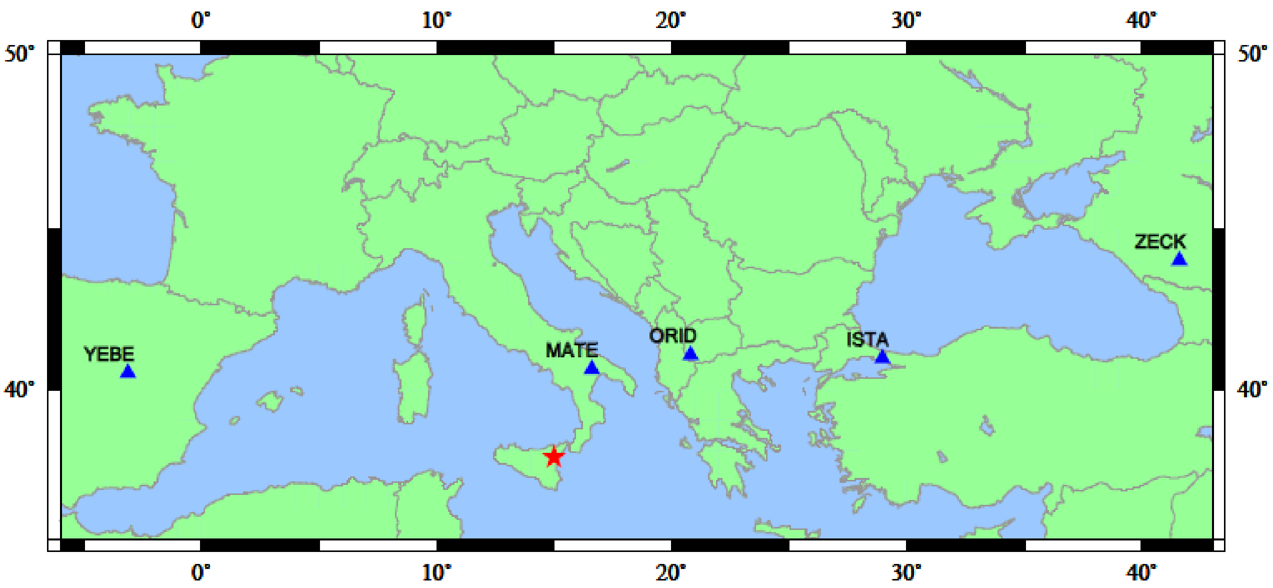

Fig. 3: The sites of the EUREF stations (triangles) and the Etna Volcano (star).

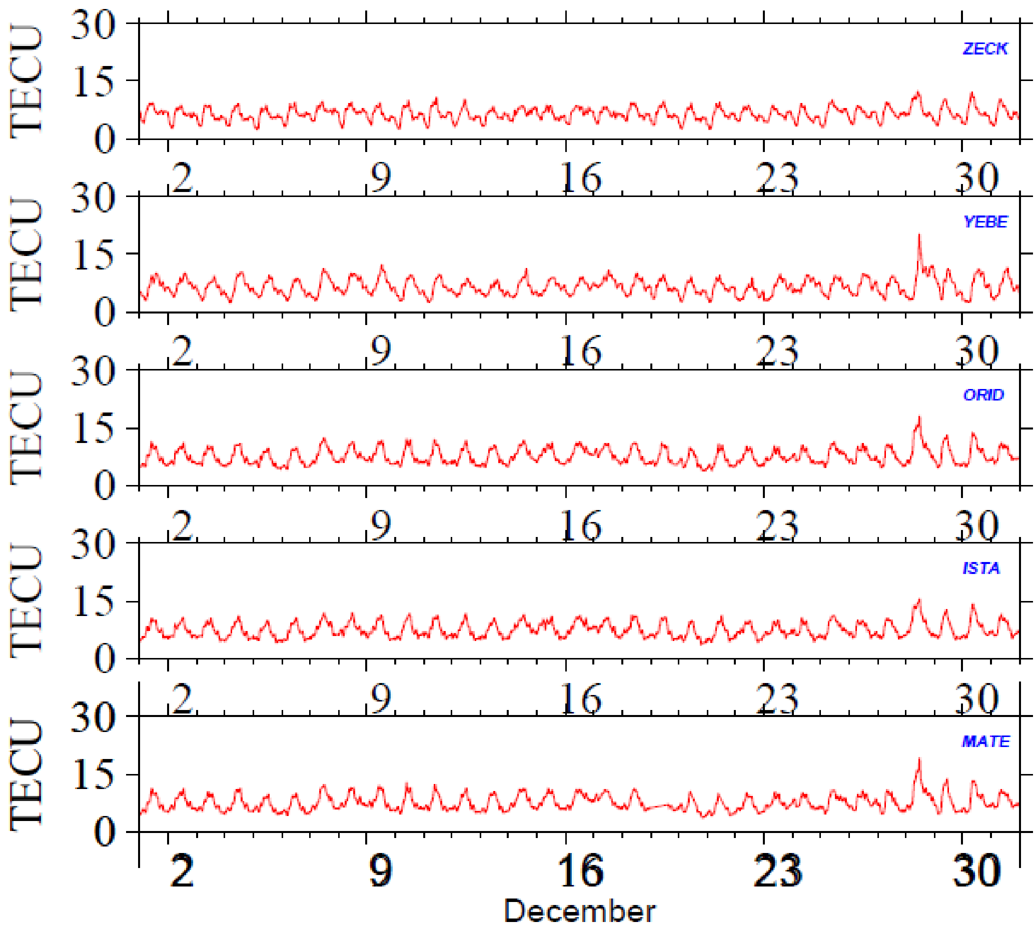

Fig. 4: Variation of TEC over the selected GPS stations during December of 2018.

3. Data Analysis

The observational data, which constitute a time series, are analysed using Fast Fourier Transform analysis. Since the data resolution is 2.5 min, the nyquist frequency and consequently the power spectrum resolution is 0.00667 Hz. In this work, we are interested in the upper limit of the ionospheric turbulence frequency band which corresponds to the faster propagation dambing constituent of the band. From the slope of the logarithmic power spectrum diagram (as a whole or for each segment of it), we can recognize whether the contributing to the spectrum variations 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, otherwise the slope will be different, the so-called Fractal Brownian walk (Turcotte, 1997). In order to find the turn point of the slopes in the logarithmic power spectrum we act as follows: From a variety of the lines with slope -2.0 we chose the best fitted line in the high frequency segment of the spectrum by successive trials.We repeated the same procedure with a variety of lines with slope -3.5. These lines intersect at the point of our interest. As an example, Figure **5** displays the logarithmic power spectrum of TEC variations over the GPS station of Matera at the days of the volcano eruption i.e. 25-27/12/2018. It is seen that the slope of the diagram up to the *log(f)*=-2.2, is -2. This means that for higher frequencies the TEC variation is random noise. On the contrary, the TEC for lower frequencies exhibits random variations i.e. turbulent. It should be noted that the frequency unit in this particular diagram is the instrumental one, which uses as time unit the sampling gap of the data set (not Hz units). The frequency, in instumental units, is exp(-2.2)=0.1108 which corresponds to 0.1108/(2.5*60)= 0.00073867 Hz=738.67 μHz. Therefore, we conclude that the upper frequency limit f_o of the turbulent band is 738.6 μHz. Equivalently, the lower period limit P_o of the contained turbulent is 22.563 minutes. This means that we can trace the presence of periodicity in the logarithmic power spectrum of TEC variations. This method was successfully applied in our previous work (Contadakis et al., 2015) in order to find the frequency content of TEC turbidity. It is realized that the upper frequency limit f_o of the spectrum of TEC variations increases as we approach the source of the ionospheric turbidity modulation, in our case the Etna's Volcano eruption.

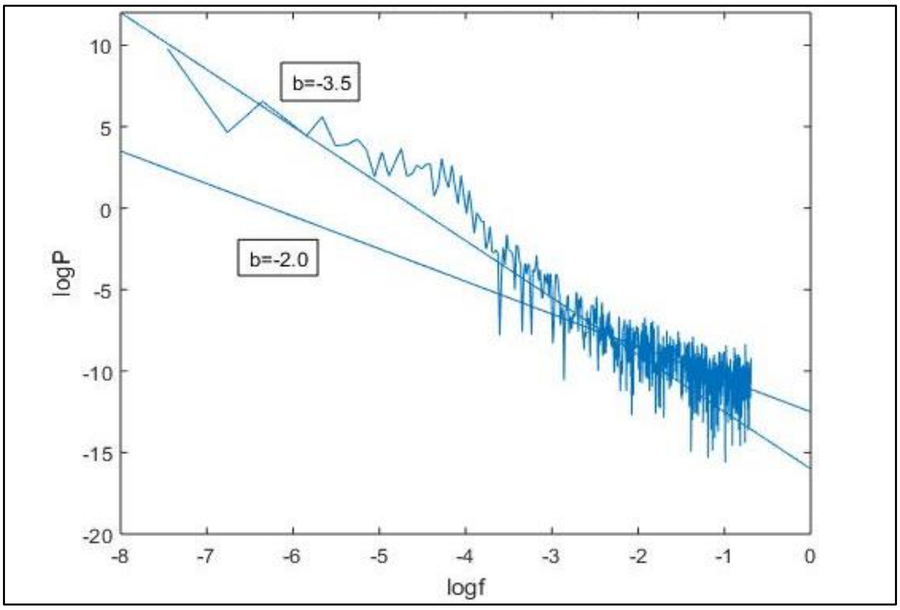

Fig. 5: The Logarithmic power spectrum of Ionospheric TEC variations over the GPS station of Matera during the Volcano eruption period.

4. Results and Discussion

Figures **6** and **7** display the variation with time and distance of the TEC turbulent frequency upper limit f_o (lower Period limit P_o), over the nearest to Etna EUREF GPS station of MATE. It is observed a strong dependence of the upper frequency f_o (lower period P_o) limit of the Ionospheric turbulent content on the time to the eruption and on the distance to the nearest to the volcano GPS station of MATE. In particular, the closer to the Volcano eruption day the higher the frequency f_o limit is (lower period P_o). For comparison reasons, the upper frequency limit f_o of the turbulent band over YEBE, a sufficiently remote to Etna EUREF GPS station, is added in Figure **6**.

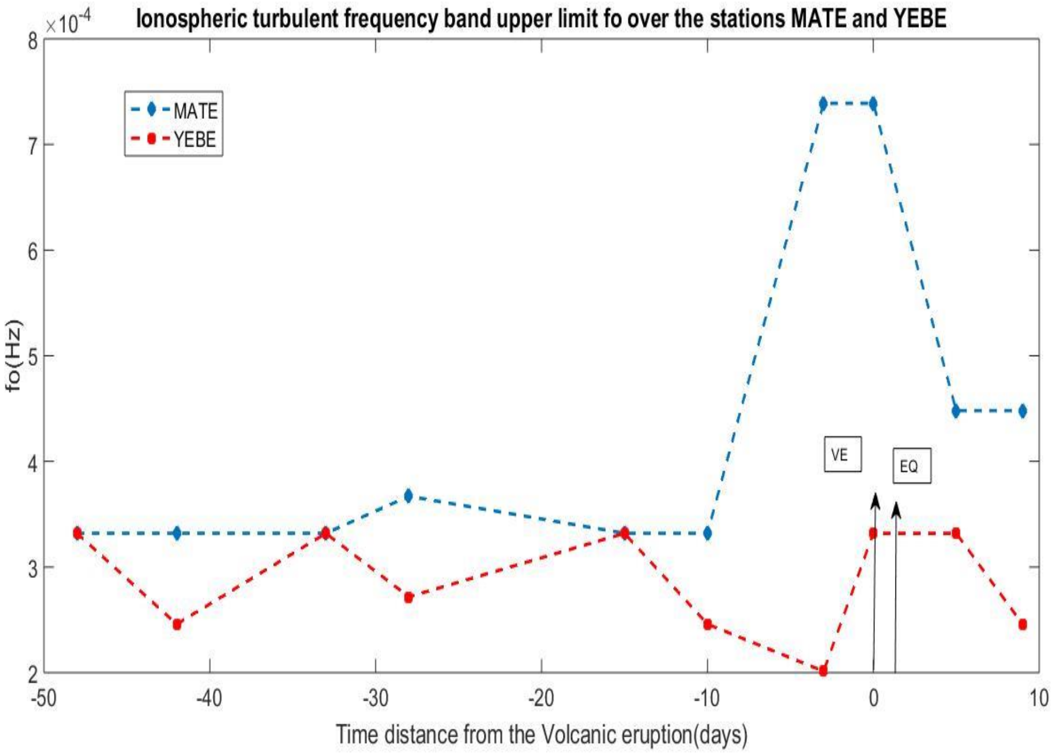

Fig. 6: Ionospheric Turbulent Frequency Upper limit f_o vs time for the nearest to Etna EUREF GPS station of MATE and a distant one (YEBE). The arrows indicate occurrence times of the eruption and the M=5.0 earthquake**.**

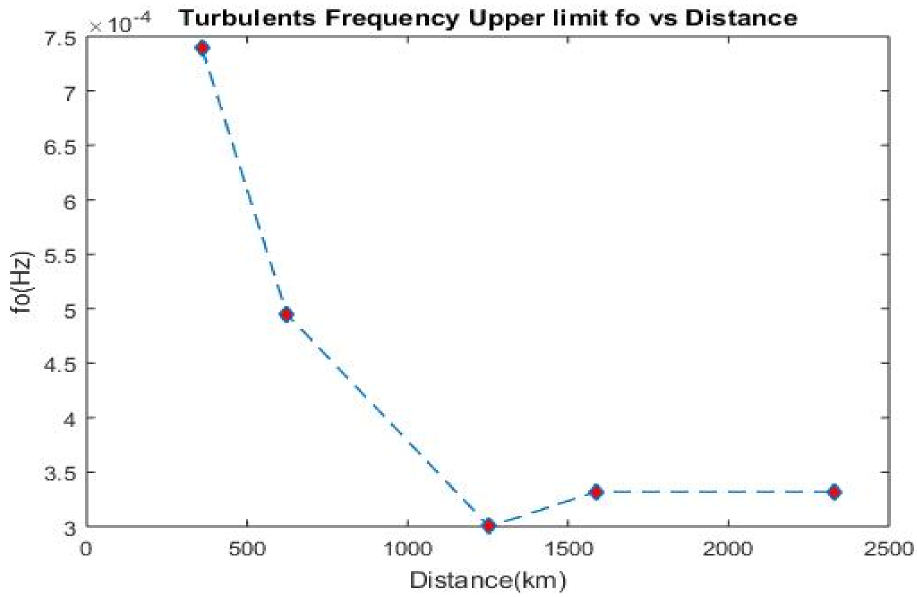

Fig. 7: Ionospheric Turbulent Frequency Upper limit f_o vs distance over the network stations around the eruption days.

Figures **8** and **9** show the variation of the upper frequency f_o and of the lower period P_o, limits of Ionospheric turbulence content over the selected GPS stations at the days of Etna Volcano eruption (25-27/12/2018) and at a period of calm days (07-09/11/2018). It is seen that at the days of Volcano eruption the Ionospheric turbulence upper frequency limit, f_o, decreases (the lower period limit, P_o, increases) with distance. On the contrary, this is not happening during the calm days.

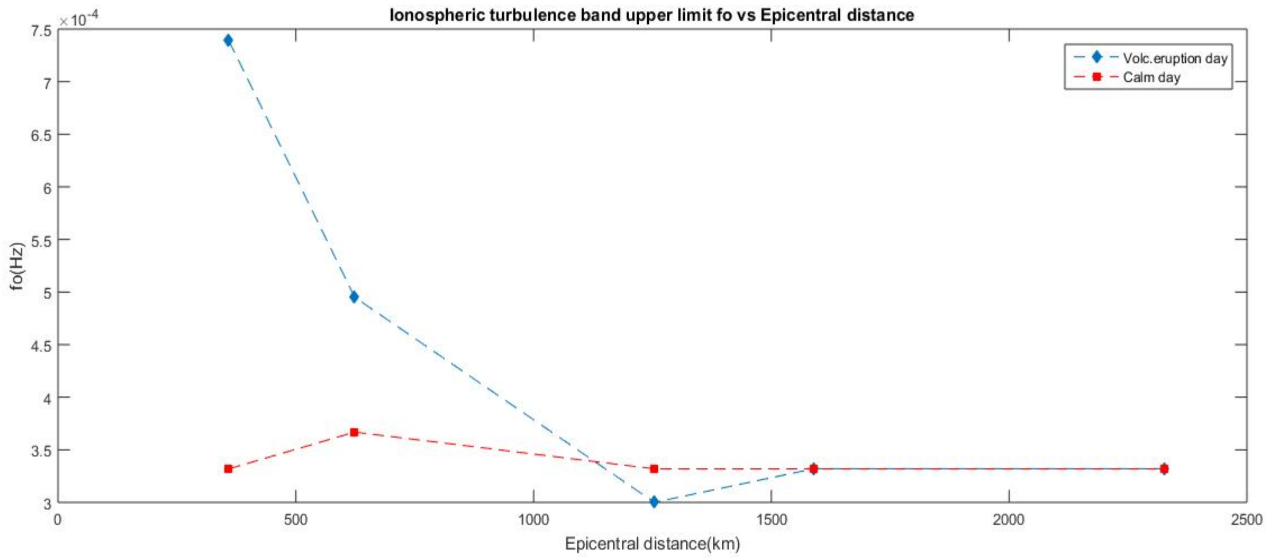

Fig. 8: Turbulent Frequency band upper limit f_o variation with the distance from the Volcano Etna at the days of the eruption (25-27/12/2018) and at one calm period (07-09/11/2018).

These results indicate time and space convergence of increasing turbulence frequency limit f_o to the Etna volcano eruption. Hobara et al. (2005) in a study on the ionospheric turbulence in low latitudes concluded that the correlation of the turbulence with earthquake generation and not with other phenomena, i.e. solar activity, storms etc., is not conclusive. Nevertheless, in our case, the clear increase of the frequency limit f_o with time to the eruption (and its decrease after it) as well as its respective decrease with distance from the volcano (inverse behaviour of the period limit P_o), is a strong and decisive indication that the observed turbulence is generated by the respective eruption process. An important result of our observation is that no effect on Ionospheric turbulence band is observed at distances greater than 1,000 km, at the most, from the Volcano.

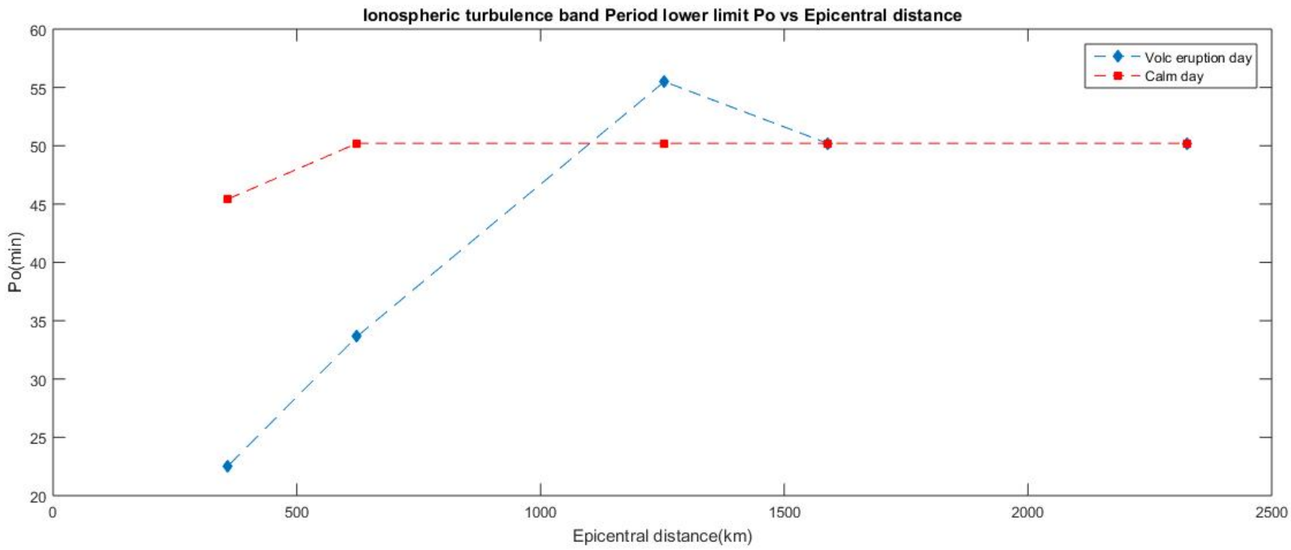

Fig. 9: Turbulent band lower limit P_o variations with the distance from the Volcano Etna at the days of the eruption (25-27/12/2018) and at one calm period (07-09/11/2018).

As Johnston (1997) pointed out, the subset of ionospheric disturbances generated by trapped atmospheric pressure waves (also termed gravity waves and/or acoustic waves, traveling ionospheric disturbances or TID's) that are triggered by earthquakes and volcanic eruptions are common and propagate to long distances. These are known and expected consequences of earthquakes, volcanic explosions and atmospheric disturbances, that must be identified and their effects must be removed from VLF/ULF electromagnetic field records before associating new observations of ionospheric disturbances with earthquake activity.

Thus, a qualitative explanation of our results can be offered based on the LAIC mechanism, through the Acoustic gravity wave. Tectonic activity during the earthquake preparation period or volcanoes activity, produce anomalies at the ground level which propagate upwards in the troposphere as Acoustic or Standing gravity waves (Hayakawa, 2011; Hayakawa et al., 2011, 2018; Pulinets et al., 2018). These Acoustic or Gravity waves affect the turbidity of the lower ionosphere, where sporadic Es-layers may appear too, as well as the turbidity of the F layer. Subsequently, the produced disturbance starts to propagate in the ionosphere's waveguide as gravity wave. At the same time, the inherent frequencies of the acoustic or gravity waves can be traced on TEC variations (i.e. the frequencies between 0.003 Hz, period 5 min, and 0.0002 Hz, period 100 min), which, according to Molchanov et al. (2004, 2005) and Horie et al. (2007), correspond to the frequencies of the turbulence 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.

5. Conclusions

The results of our investigation, on the occasion of the Etna's volcanic activity of December 2018, indicate that the high- frequency limit f_o , of the ionospheric turbulence band content, is increasing with time to the volcano eruption. At the same time, f_o decreases with distance from the volcano. We conclude that the LAIC mechanism by acoustic or gravitational waves could explain this observation in an analogous way that deduced the connection of f_o with the seismic activity. That is, tectonic activity during the volcanic and/or earthquake preparation period produces anomalies at the ground level, which propagate upwards in the troposphere as Acoustic or Standing Gravity waves (Hayakawa, 2011; Hayakawa et al., 2018). These Acoustic or Gravity waves affect the turbidity of the lower ionosphere. Subsequently, the produced disturbance starts to propagate in the ionosphere's waveguide as gravity wave. During this propagation, the higher frequency constituents of the turbulent band are damping faster. As a result, the upper limit frequency of the turbulent band moves to lower values as we move away, in space or in time, from the site or the time of the eruption. Our observations indicate that the effect of volcanic eruption on ionospheric turbulence band content is insignificant at distances greater than 1000 km (at the most), a fact that we must also have in mind in our research on Ionospheric turbulence in relation to earthquake precursors research. It should be noted that the present distribution of the GPS stations does not allow the detection of a possible shorter distance for the volcano's unaffected ionospheric turbulence band content.

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