Preseismic Modification of the Ionosphere for Greece 2006 Earthquake: GPS TEC Measurements and Modeling Results

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In this paper we present the specific features of TEC (total electron content of the ionosphere) behavior as possible precursors of Southern Greece earthquake of January 8, 2006 (M6.8). The ionosphere modification as the cloud like increase of electron concentration situated in the immediate vicinity from the forthcoming earthquake epicenter has been revealed 1 day prior to the main shock. The amplitude of modification reached the value of 50% relative to the non-disturbed condition and was in existence from 10 UT till 22 UT. The area of significant TEC enhancement had the sizes of about 4000 km in longitude and 1500 km in latitude.

The model calculations of the ionosphere response to the action of zonal electric field produced by seismogenic sources located at the middle latitudes were done. The results of calculation were compared with observational data obtained.

Introduction

The problem of the earthquake forecast still remains one of the major unsolved tasks of modern geophysics. In view of the last disastrous earthquakes the urgency of development and perfection of the forecast methods does not decrease. The numerous researches of the last years convincingly proved the existence of connection between processes in the Earth lithosphere and disturbances in the atmosphere and ionosphere. It is shown that during the earthquake preparatory phase the numerous abnormal changes of fields and parameters of the nearground space are revealed [1-4].

The vertical TEC is very sensitive to changes of foF2 electron density. As the electron concentration in the maximum of F2 ionosphere layer is one of the most sensitive parameter connected to seismic activity, we can use the TEC data to estimate spatial sizes and temporal dynamics of pre-earthquake ionospheric effects in any seismo-active region.

In this paper, the analysis of the GPS TEC variations during the Kythira (Southern Greece) earthquake is presented. It is rather strong earthquake – the majority of strong earthquakes of European region has magnitude of 5.0-6.5. Discussed in this paper earthquake was registered at 11.35 UT on January 8, 2006, its magnitude was 6.8. The geographical coordinates of epicenter were 36.30°N, 26.36°E, the depth of seismic focus was about 66 km.

Figure 1 presents the variations of geomagnetic activity indices (Kp, Ap, Dst) for the period of January 1-10, 2006. One can see that geomagnetic activity during the considered period was weak and weakly varied. The sum of Kp did not exceed the value of 20.

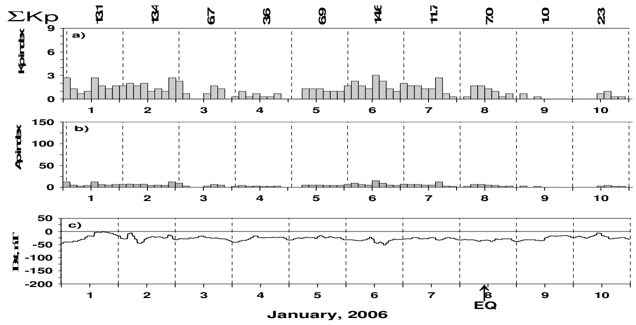

Fig.1. Variations of geomagnetic activity indices for January 1-10, 2006: a) Kp index, b) Ap index, c) Dst index

So, the quiet geomagnetic situation was favorable circumstance to investigate the midlatitude ionosphere behavior before Greece earthquake.

Data Analysis

Diurnal variations of TEC

The condition of the ionospheric plasma in the vicinity of earthquake epicenter and far from it was determined on the basis of the simultaneous observations of the navigating satellites from four IGS stations located in European region: TUBI (40.47°E, 29.27°E), ORID (41.07°N, 20.47°E), MATE (40.39°N, 16.42°E) and NOT1 (36.52°N, 14.59°E).

The current observations are indicated with a thin line and represent the vertical TEC in TEC units (1 TECU=10^{16} el/m^2) for these stations (Fig. 2). The thick line is the median value obtained by TEC calculated for the pre-earthquake period. The visual viewing of daily variations shows that 1 day prior to the main event the significant deviations of the current TEC variations from the median meanings were observed at all stations. Diurnal TEC variations for other days of the given period have very similar shape as the median one.

Temporal variations of TEC

As the diurnal TEC variation is calculated by means of averaging of measurements from many satellites, we have considered more detailed picture of TEC behavior at the individual satellite passes. As GPS satellites are in the 12-sideral-hour orbits constellation, a satellite arrives at the same point 4 min earlier each day.

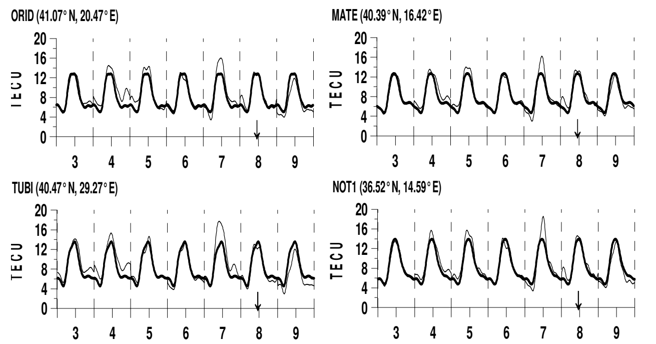

Fig.2. Diurnal variations of TEC for GPS stations during January 3-9, 2006. Thin line – current TEC variation, thick line – median value. The strong TEC enhancement is clearly seen at all stations 1 day prior to EQ

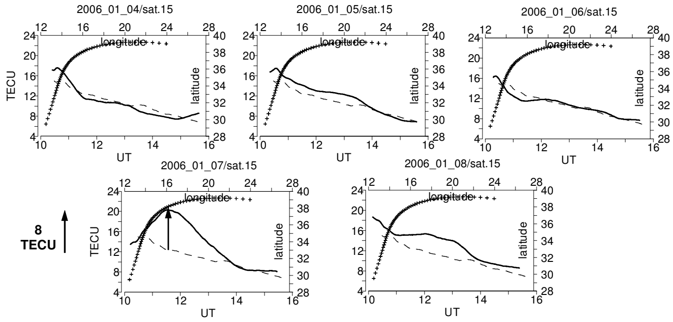

Fig.3. Temporal TEC variations along satellite N15 passes observed at NOT1 station during January 4-8, 2006. Solid line – the current TEC values, dotted line – January 03 (quiet day).

Temporal TEC variations along individual satellites passes are presented for NOT1 station in Fig.3. Solid line – the current values of TEC and dotted line – 03.01 (quiet day - ΣKp=6.7). These graphics also show satellite subionospheric points tracks at the altitude of 400 km, in geographic coordinates (cross line).

One can see that TEC variations during January 4-6 do not noticeably differ from the control day line. Anomalous TEC enhancement was observed on January 7 during 11-14 UT. The maximal increase of TEC reached the value of 8 TECU (~60-65%). The TEC increase on January 8 during the same temporal interval is probably related to the ionosphere response on the earthquake that took place at 11.35 UT.

Spatial variations of TEC

To clearly identify the spatial scale and temporal dynamics of seismo-ionospheric variations the differential mapping method was used. The current day TEC was compared with the quiet time map taking the quiet time variation (as a median for the considered period) as a background. The differential percents TEC maps for January 7 are shown in Fig. 6. Since 10 UT one can see formation of the positive modification area situated in the nearest of the forthcoming earthquake epicenter. The amplitude of the ionosphere modification reached the value of 38-43% relative to the non-disturbed conditions. Anomalous TEC enhancement was registered during all next hours and reached the maximal value of 55% at 18-20 UT.

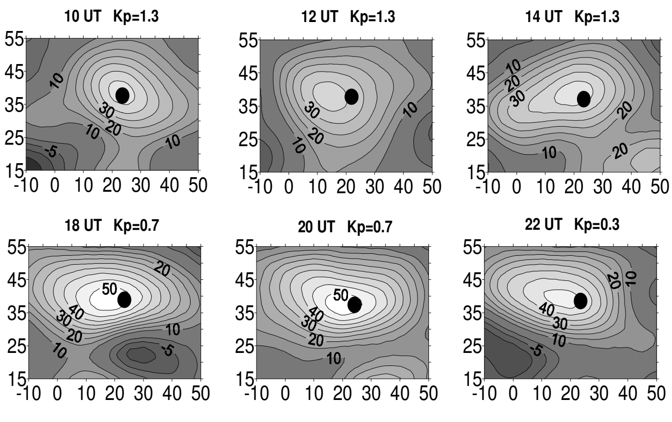

Fig.4.Differential percentage TEC maps over European region calculated for fixed moments of universal time for January 7, 2006

So, the seismo-ionospheric anomaly was found out as the dome-shaped increase of total electron content of the ionosphere, it had a well-defined local character and it was situated in the immediate vicinity of the earthquake epicenter area. The zone of the anomaly maximum manifestation (TEC enhancement more than 35%) had spatial scale of about 4000 km in longitude and 1500 km in latitude.

Numerical Modeling

The vertical plasma drift caused by the eastward electric field is considered as the most probable cause of the observed TEC enhancements [5]. The electric potential distribution at the near-epicenter region boundary required for such electric field maintenance is proposed. The results of the corresponding numerical model calculations of the electric field and its effects in the ionospheric F2-layer are presented. We have studied the influence of the additional mid-latitude electric field sources on the TEC variations by means of numerical simulations with the first principle time-dependent Upper Atmosphere Model (UAM) [6]. All UAM equations (continuity, momentum and heat balance) for neutral and ionized gases have been numerically solved jointly with the modified electric potential equation.

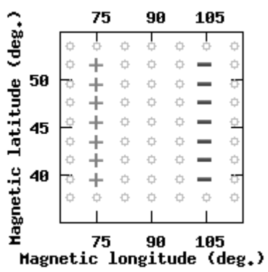

Fig.5. The model numerical grid with additional potentials: pluses, minuses, gray circles – not modified

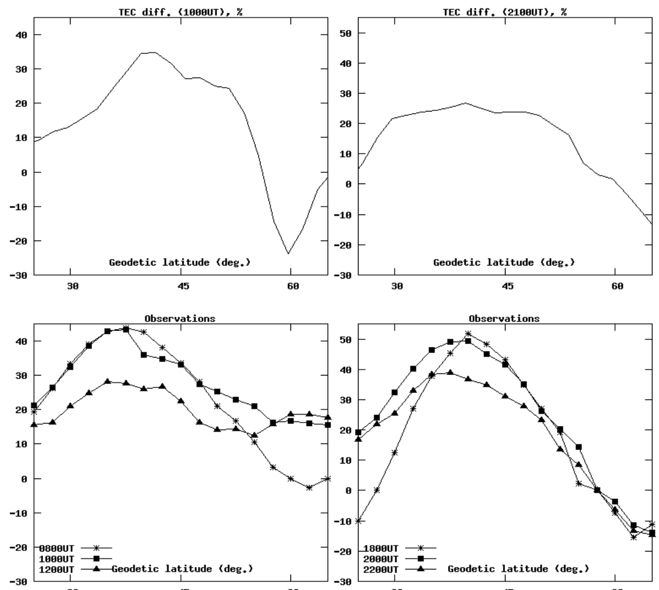

Fig.6. Latitudinal TEC disturbances (%) induced by the seismogenic sources: modeled (top panels) and observed (bottom panels) data

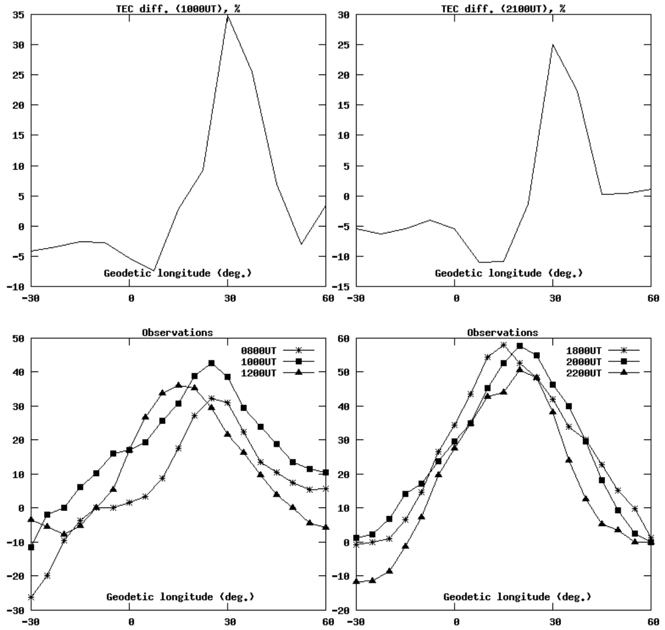

Fig.7. Longitudinal TEC disturbances (%) induced by the seismogenic sources: modeled (top panels) and observed (bottom panels) data

The upper atmosphere states, presumably foregone strong earthquakes, were modeled by means of switching-on of additional sources of the electric field in the UAM electric potential equation which was solved numerically jointly with all other UAM equations (continuity, momentum and heat balance) for neutral and ionized gases. These sources were switched on and maintained as permanent during 24 h in the form of additional positive and negative potentials with values of 10 kV on the western and eastern boundaries of near-epicentral areas (Fig.5).

Results of the model calculations are presented in the form of the latitudinal (Fig.6) and longitudinal (Fig. 7) percentage TEC variations relative to the non-disturbed level for simulated data at 10 UT (daytime – left top panels) and 21 UT (nighttime – right top panels). The modeling results were compared with the observed GPS TEC data (bottom panels of the Fig.6 and Fig.7) for the case of winter earthquake in Greece.

We can see stable positive disturbances (hump-shaped enhancement) in the measured TEC (%) data relative to the non-disturbed level variations at the earthquake epicenter area. We have considered several kinds of additional sources of the electric field potential and only dipole kind was able to reproduce this behavior of TEC.

Analysis of the latitudinal variations has shown that ionospheric effects from different sources are rather similar to each other within their classes (dipole or monopole). The simulated data for the dipole sources reproduce the main features of the observed data behavior. As a whole the form of modeled latitudinal variations rather well follows after the behavior of the observed TEC variations for middle latitudes (the area of earthquake epicenter position). For the given case it was important to analyze the mid-latitudinal modification of the ionosphere.

Analysis of the longitudinal variations has shown rather good agreement of the model results with the observed data for the dipole kind of source. We can clearly see the resemblance of this curve shape with the GPS TEC variations though the amplitude and spatial scale of modeled disturbance in longitudes are smaller.

Considering the above for the modeled set of configurations and magnitudes of the additional electric potential sources the dipole kind of sources is able to produce main features of the observed data. The additional study is needed to improve magnitude agreement for dipole sources.

Locality of the observed effect

To verify the locality of the observed anomaly we used the index of global electron content (GEC) proposed by Prof. E.L. Afraimovich [7]. We calculate the mean TEC values by summation of TEC values in N cells of the network (regional scale):

$$\langle I(t) \rangle = \sum I_{ij} / N$$

We calculated series of mean TEC variations $\langle I(t) \rangle$ over regions with different square. The schematic representation of the considered areas centered to the epicenter position is presented at the Fig.8. We consider 4 squares of: a) 10°×10°, b) 20°×20°, c) 30°×30°, d) 40°×40° and 2 longitudinal areas related to middle latitudes: e) 40°×90°, f) 45°×150°.

The results of calculations are shown at Fig.9. One can see that with increase of the region square the tendency of the anomaly smearing appears. For cases d), e), f) it is practically impossible to recognize any visible deviations for January 7 while for cases a), b), c) the effect of TEC enhancement is pronounced very distinctly. It is necessary to note that during geomagnetic storms the ionospheric disturbances (in particular, in TEC variations) have global character and such increase of the areas over Europe contribute slightly to the calculations of mean TEC – the storm effect has practically the same amplitude independently of such scale dimensions. Moreover we considered the variations of mean TEC over areas with square of 20°×20° situated in different midlatitudinal regions of northern and southern hemispheres of the Earth and we did not find any strong deviations differ from normal day-to-day variability. These facts confirm that this effect was local and was observed closely to the epicentral region.

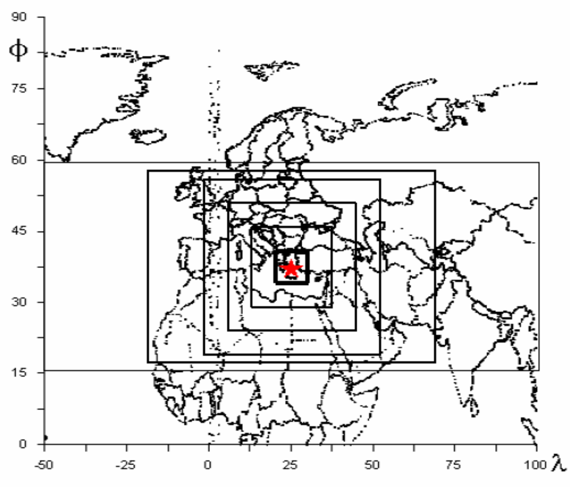

Fig.8. Geographical position of the considered areas involved in calculations of mean TEC

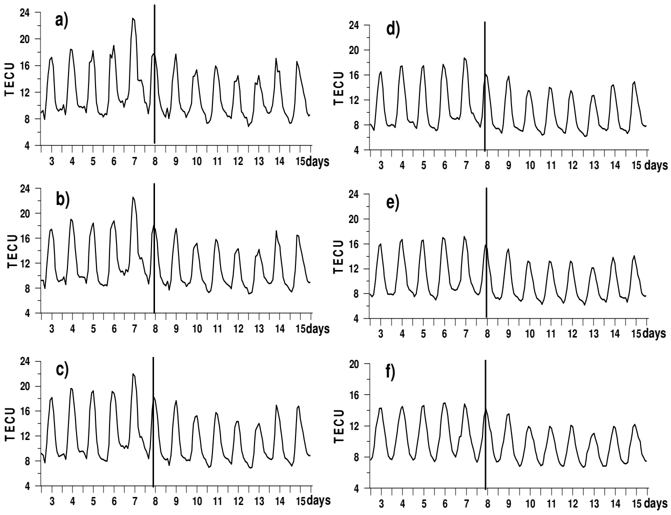

Fig.9. Variations of mean TEC over the epicentral regions

Conclusion

So in this paper the specific features of TEC behavior as possible precursors of Southern Greece earthquake were shown. The ionosphere modification as the cloud like increase of electron concentration situated in the immediate vicinity from the forthcoming earthquake epicenter has been revealed 1 day prior to the main shock. The amplitude of modification reached the value of 50% relative to the non-disturbed condition and was in existence from 10 UT till 22 UT. The area of significant TEC enhancement had the sizes of about 4000 km in longitude and 1500 km in latitude. It was shown that the effect observed had a well-defined local character.

As our model calculations show, the very probable reason of the NmF2 and TEC disturbances observed before earthquakes is the vertical drift of the F2-region ionospheric plasma under the influence of the zonal electric field of seismogenic origin. In case of TEC enhancements in the middle latitudes this field is directed to the east and induces the electromagnetic drift of the plasma across the geomagnetic field with velocity directed upwards and pole wards in the middle latitudes.

The upward plasma drift in the middle latitudes provokes the increase of electron concentration in the F2 region of the ionosphere due to decrease of the dominating ions O^+ loss rate in the ion-molecular reactions.

The pattern of the spatial distribution of the seismogenic origin electric field potential (dipole-like) has been proposed. We show that this kind of electric field can produce the TEC and NmF2 disturbances observed before strong earthquakes. The amplitude of enhancements and its spatial sizes are in a good agreement with the corresponding characteristics of precursors in the TEC observations.

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