Relation of atmospheric and ionospheric anomalies prior to three large earthquakes in Greece

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Abstract

This investigation aims to identify possible pre-earthquake ionospheric and atmospheric anomalies and observe their possible relationship, by employing various methodologies. Three large earthquakes in Greece are selected (6.9Mw, 6.6Mw and 6.3Mw, during 24 May 2014, 20 July and 12 June 2017 respectively). For this purpose, Total Electron Content (TEC) obtained from Global Navigation Satellite System (GNSS) networks and Atmospheric Chemical Potential (ACP) variations retrieved from atmospheric model are examined with the aid of spectral analysis on TEC measurements and of ACP time series. It is shown that ionospheric anomalies which take place from one to few days prior to the three seismic events are most probably related to the forthcoming events and they are synchronous (in the same day) or they are following ACP anomalies (up to 5 days later). This sequence of different type pre-earthquake anomalies reveals the existence of successive pre-earthquake processes of a system which is moving towards a critical point which is the main shock.

1 Introduction

The detection of earthquake precursory phenomena and the understanding of their generation mechanism though it has been initiated from the ancient times and continues at present, it is still an item under debate. This human endeavor through centuries, to comprehend and predict earthquake precursors is well-described by [1, 2]. Such phenomena have been observed underground, in the atmosphere, in the ionosphere and in the magnetosphere, which is indicative of the fact that the earthquake preparation process is characterized by different pre-earthquake variations and modifications of a unified physical system. In recent decades, various models have been developed to explain these modifications focusing either to atmospheric or magneto-ionospheric pre-seismic anomalies [3–11]. These models are well-compared by [12, 13], that also present their Lithosphere, Atmosphere, Ionosphere-Magnetosphere coupling model (LAIMC). According to LAIMC, several days (mainly up to 12) prior to earthquakes radon emissions from the surface are intensified, producing increased air ionization and water

condensation nuclei. As a result, latent heat is released which modifies atmospheric and thermal properties such as temperature, humidity and outgoing longwave infrared radiation. The air conductivity is also affected, leading to the development of an anomalous vertical electric field over active tectonic faults. Through the global electric circuit, this electric field may modify electron and ion plasma densities in the ionosphere. These ionospheric anomalies are then mapped to the magnetosphere through geomagnetic field lines. Experimental proof of this theory can be found in [14-17], while earthquake cases where radon is identified as a precursor have been reported in hundreds of articles [18-19]. It is shown, relatively recently, that the different types of earthquake precursory phenomena do not occur independently, but they are related, with the atmospheric anomalies preceding the magneto-ionospheric anomalies [13]. To this end, the purpose of this study is to identify pre-earthquake atmospheric and ionospheric anomalies that are related to the coming seismic events and to examine the possible interrelation of the detected anomalies.

2 Data and Methods

The information concerning the earthquake characteristics is retrieved from the earthquake catalog of the United States Geological Survey's (USGS) Earthquake Hazards Program and is shown in Table 1. TEC values for the periods under investigation were obtained from the International GNSS IGS network, as well as from permanent stations in Greece managed by the GNSS_QC team of the Aristotle University of Thessaloniki [20]. Figure 1 presents the map of the area where the three earthquakes occured. The ionospheric analysis is based on spectral analysis on slant TEC observations (on the satellite signal path) retrieved from GNSS stations located inside the earthquake preparation zone and very close to the three examined events. The slant TEC is calculated by using an algorithm created by [21] which utilizes equations given by [22]. To avoid hardware biases from satellite and receiver hardware, Spectral analysis was applied on differential slant TEC data (dSTEC), defined as the difference of slant TEC observations between two consecutive satellite epochs. The method can be applied during geomagnetically disturbed periods, since by

choosing the period of TEC oscillations to be lower than 40 min. the geomagnetically induced TEC oscillations with periods of ~1 hour are excluded.

Table 1. List of seismic events and their characteristics

Events No	Date	Hour (UT)	Magni- tude (R)	Depth (km)	Epicenter region
1	24-May-14	9:25	6.9	6.43	Samothraki,
2	12-Jun-17	12:28	6.3	12	Lesvos,
3	20-Jul-17	22:31	6.6	7	Kos

The atmospheric analysis includes the ACP temporal variations for about one month before the event over a certain location close to the epicenter. ACP is indicative of the radon variations prior to the earthquake and was firstly introduced by [13]. Radon emitted from the ground prior to the earthquake causes formation of additional ions in the air through nucleation. Latent heat is therefore released due to water condensation not only through water droplets, but also through ions. Thus, the total latent heat is corrected by adding a new component, namely the ACP parameter (ΔU) in the following equation of relative humidity H(t):

$$H(t) = \frac{\exp(-U(t)/kT)}{\exp(-Uo/kT)} = \exp\left(\frac{Uo - U(t)}{kT}\right) = \\ = \exp\left(-\frac{0.032\Delta U cos^2 t}{(kT)^2}\right). \quad (1)$$

where $U(t) = Uo + \Delta U cos2t$, with ΔU being the volume averaged correction of chemical potential, due to the external forcing of the environment, and Uo is the chemical potential for pure water. According to [23] ΔU is a function of air temperature at Earth's surface (Tg) and relative humidity of air (H):

$$\Delta U \text{ (in eV)} = 5.8 \times 10^{-10} \left(20T_g + 5463\right)^2 \ln\left(\frac{100}{H}\right). \quad (2)$$

It is known that the latent heat for water molecules during phase transitions is equal to its chemical potential. ΔU is reflecting the creation of cluster ions. In this study ACP is retrieved from NASA's atmospheric assimilation model.

Figure 1. Map showing epicenters (orange marks) of the three large earthquakes in Greece.

3 Results

In all three earthquake cases, the ionospheric analysis reveals the occurrence of intensified TEC wave fluctuations one day prior to the event, over regions near the epicenter, which have period of about 20min (Figures 2c, 3c and 4c). In addition to these, enhanced TEC fluctuations are observed four days before the 6.9Mw and 6.3Mw events and six days before the 6.6Mw event with the same period (Figures 2b, 3b and 4b respectively). Since geomagnetically induced TEC perturbations are excluded and no severe weather conditions, such as cyclones, were prevailing prior to these seismic events, we may attribute the observed TEC fluctuations to the forthcoming earthquakes.
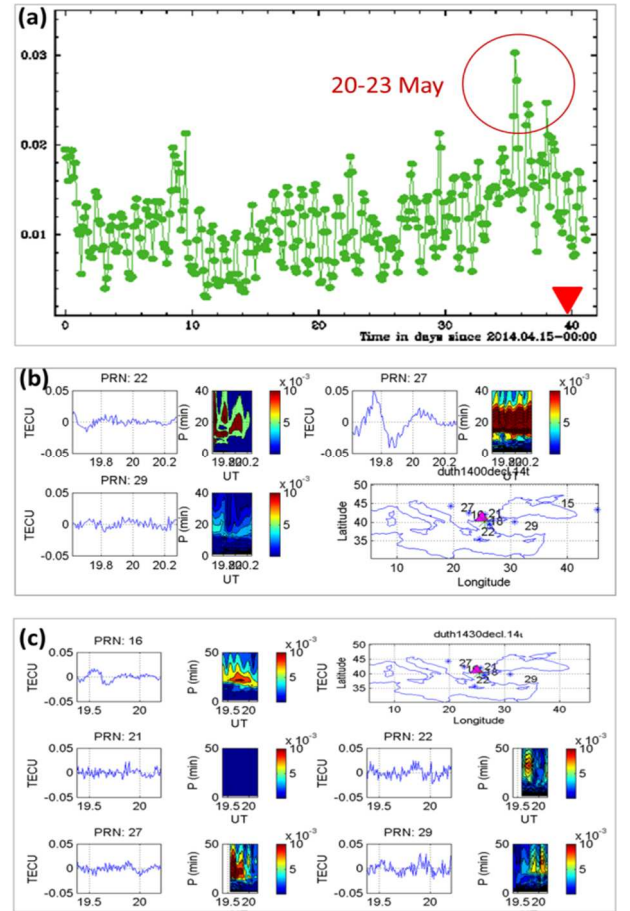
Figure 2. Upper panel (a): Temporal ACP variations 40 days before the earthquake on 24 May 2014. Red triangles indicate the earthquake time. Red cirlces denote ACP increase. Middle panel (b): Temporal fluctuations of dSTEC obtained from GNSS station close to the event and PRN satellites passing over the earthquake preparation area on 20 May around 19-20UT. Lowel panel (c): Similar to (b) but for 23 May around 19-20 UT. Power spectrograms of normalized amplitude are also shown. Maps show earthquake epicenter (green asterisk), GNSS station (pink triangle), number and position of satellite (blue asterisks).

The atmospheric analysis, through the ACP time series analysis prior to all the selected earthquake cases, demonstrated the occurrence of a certain pattern of ACP variation in all three seismic events. As it is obvious from Figures 2a, 3a, and 4a, ACP increases a few days prior to all the events and then it reduces up to the earthquake time. Despite the fact that ACP is significantly influenced by meteorological conditions, topography and radon concentration over a region, the ACP temporal variability patterns are specific and without any doubt linked to the impending earthquakes. In the selected cases, ACP values increase 4-6 days before the earthquakes, while in the largest earthquake of 6.9 magnitude, increased ACP values are noted from one to four days before the earthquake (Figure 4a).
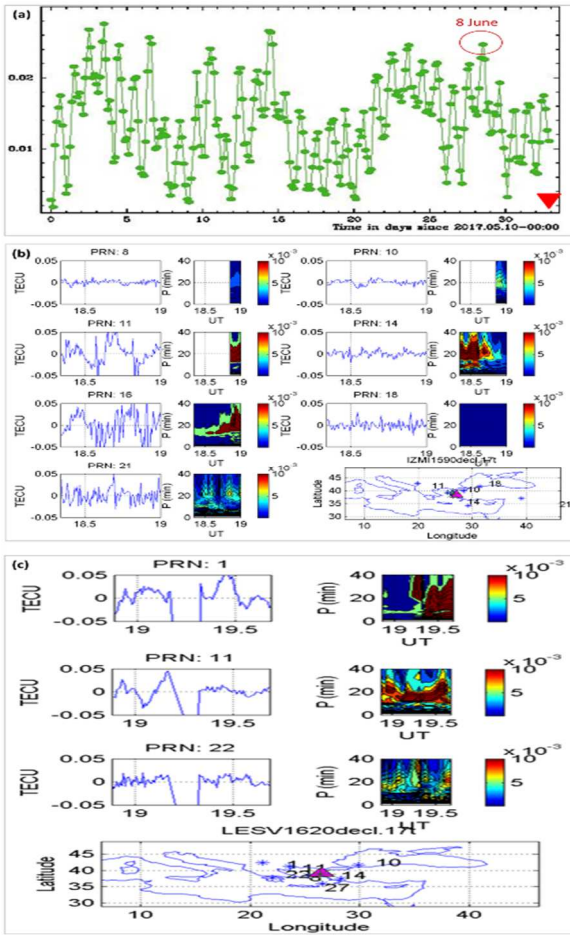
Figure 3. Upper panel (a): Temporal ACP variations 33 days before the earthquake on 12 June 2017. Red triangles indicate the earthquake time. Red cirlces denote ACP increase prior to the event. Middle panel (b):Temporal fluctuations of dSTEC obtained from GNSS station close to the event and PRN satellites passing over the preparation area on 8 June around 18-19 UT. Lowel panel (c): Similar to (b) but for 11 June around 19-20 UT.

The observed ACP increase 4-6 days prior to all the events are accompanied by enhanced TEC fluctuations, which appear with some delay during the same day, over the earthquake preparation region. Further to this, in the

case of the largest 6.9 Mw earthquake, both ACP and TEC anomalies are found one day before the earthquake as well (Figure 2). The successive occurrence of atmospheric and ionospheric anomalies was shown for the first time in the case of L' Aquilla earthquake on April 2009 [13]. This sequence of observed pre-earthquake atmospheric and ionospheric anomalies is also demonstrated by [2] and is complementary to the LAIMC conception, that the consecutive different earthquake precursory anomalies are induced by the evolvement of the earthquake preparation processes, which are elements of a united system. These consecutive processes are directed towards the critical point of the system, which is the main earthquake shock.
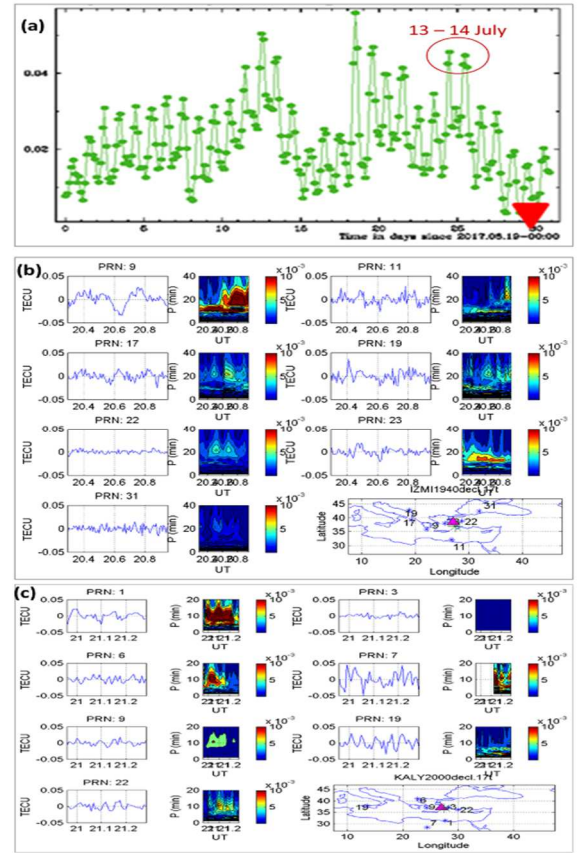
Figure 4. Upper panel (a): Temporal ACP variations 30 days before the earthquake on 20 July 2017. Red triangles indicate the earthquake time. Red cirlces denote ACP increase prior to the event. Middle panel (b):Temporal fluctuations of dSTEC obtained from GNSS station close to the event and PRN satellites passing over the preparation area on 13 July around 20-21 UT. Lowel panel (c): Similar to (b) but for 19 July around 21-22 UT.

4 Conclusions

Atmospheric and ionospheric earthquake precursory phenomena are interrelated and are found to occur successively. Additional experimental evidence is needed

in order to understand specific characteristics of this sequence in time.

5 Acknowledgements

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