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Analysis of observations backing up the existence of VLF and ionospheric TEC anomalies before the Mw6.1 earthquake in Greece, January 26, 2014

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ABSTRACT

The present work integrates ground-based ionosphere measurements using very-low-frequency radio transmissions with satellite measurements of the total electron content to draw common conclusions about the possible impact that the Mw6.1 earthquake that took place in Greece on January 26, 2014, had on the ionosphere.

Very-low-frequency radio signals reveal the existence of an ~4-day anomaly in the wavelet spectra of the signals received inside the earthquake preparation zone and a significant increase in the normalized variance of the signals prior to the earthquake (approximately 1 day before).

Through total electron content analysis, it was possible to identify a clear anomaly from 15:00 until 20:00 UT on the day before the earthquake that appears again on the day of the earthquake between 07:00 UT and 08:00 UT. The anomalous values reach *TEC∗Sigma* ~4.36 and 3.11, respectively. Their spatial and temporal distributions give grounds to assume a possible link with the earthquake preparation. The geomagnetic, solar and weather conditions during the considered period are presented and taken into account.

This work is an initial and original step towards a multi-parameter approach to the problem of the possible earthquake-related effects on the ionosphere joining observations made from both ground stations and satellites. A well-founded knowledge of these phenomena is clearly necessary before dealing with their application to earthquake prediction purposes.

1. Introduction

The study of lithosphere–atmosphere–ionosphere coupling (LAI) is mainly focused on the analysis and comprehension of atmospheric and ionospheric anomalies caused by extreme lithospheric events (Molchanov et al., 2004; Pulinets and Ouzounov, 2011). Earthquakes are considered to be sources of atmosphere–ionosphere anomalies mainly because of the surface ionization resulting from the radioactive decay of radon emanations (Silva et al., 2013) and the generation of geo-electric charges (Freund, 2013). Such phenomena propagate through the atmosphere causing thermal anomalies (Kakinami et al., 2013) and atmospheric electric field perturbations (Silva et al., 2011). Ultimately, they affect the ionosphere causing very-low-frequency and low-frequency (VLF/LF) radio transmission disturbances (Righetti et al., 2012), extremely low-frequency and very-low-frequency (ELF/VLF) magnetic-field radiation (Nemec et al., 2008) and total electron content (TEC) anomalies (Yao et al., 2012), among other phenomena. A consistent model that was recently developed (Harrison et al., 2014) considers the global atmospheric electric circuit to be the coupling agent between the surface ionization and the ionosphere perturbation, validating LAI observations. Actually, the first observation of a possible effect of earthquakes on the ionosphere was obtained on the occasion of the Alaska, March 1964, earthquake. The comparison of seismograms of this 9.2 magnitude

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event with ionograms recorded in observatories close to the epicentre revealed the presence of anomalous vertical displacements of the ionosphere before and after the earthquake (Moore, 1964; Davies and Baker, 1965). From this point on, the research into possible earthquake-ionosphere relationships bloomed and was initially aimed at the behaviour of different layer characteristics, such as height, density, and composition. (see Kazimirovsky et al., 2003; Pulinets and Boyarchuk, 2004, for further references).

On the one hand, radio transmissions have been widely used in atmospheric electricity studies to detect thunderstorms and sprites. Such studies considered radio signals from networks developed for navigation, such as OMEGA and LORAN, until their elimination in 1997 and 2010, respectively. Similarly, these radio transmissions were used to search for ionospheric precursors possibly related with significant magnitude earthquakes since the pioneering work of Gokhberg et al. (1989). More recently, signals of 15–50 kHz from powerful VLF/LF transmitters for navigational and time services have been deployed in Europe, Asia, USA and Australia and are being used to study possible ionosphere perturbations related to earthquakes. Much work has been done on this subject in Europe both for LF (Biagi et al., 2006) and VLF signals (Biagi et al., 2008; Rozhnoi et al., 2009), but Japan and the Far Eastern regions, i.e., areas with very high seismic activity, are where the subject has received the most attention. Important results have been achieved in recent years. Saha et al. (2014) proved that the fluctuation ratio of the impulsivity of LF signals shows a significant correlation with the closeness parameter defined as the ratio between the earthquake preparation radius, R, (Dobrovolsky et al., 1979) and the distance of the earthquake epicentre to the radio transmitter, D. This result is consistent with the work of Silva et al. (2013) who found a correlation between radon anomalies and the parameter S defined by the ratio $S = R/D - 1$.

On the other hand, the directions of the studies related to possible earthquake-induced ionospheric perturbations changed dramatically in the early years of this century, when the Total Electron Content, TEC, data obtained from Global Navigation Satellite System (GNSS) signal delays were considered. These data allow for the detection of changes in the electronic density of the ionosphere worldwide in a very accurate and quick way and can be applied to both earthquakes and tsunamis (Artru et al., 2005; Liu et al., 2012).

The present work integrates ground-based measurements (VLF) and satellite derived data (TEC) to draw common conclusions about the possible impact that the Mw6.1 earthquake in Greece (January 26, 2014) had on the ionosphere. This is a first step towards a multi-parameter approach to earthquake precursors as discussed in the literature (Ouzounov et al., 2011).

2. Seismic characterization

In the Mediterranean region, the seismic activity is due to the northward convergence, with velocities ranging between 4 and 10 mm/yr, of the African plate with respect to the Eurasian plate along a complex plate boundary. This region is marked by a pre-instrumental seismicity (pre-20th century) and several strong earthquakes recorded during the last centuries. Earthquakes have historically caused extensive damage across central and southern Greece (e.g., the 1903 M8.2 Kythera earthquake), along the North Anatolian Fault Zone (e.g., the 1939 M7.8 Erzincan and 1999 M7.6 Izmit earthquakes), Cyprus, Sicily (e.g., the 1693 M8.0 Sicily earthquake; the M7.2 December 28, 1908 Messina earthquake), Crete, the Nile Delta, Northern Libya, the Atlas Mountains of North Africa (e.g., the 1980 M7.3 El Asnam earthquake) and the Iberian Peninsula (the Lisbon earthquake of November 1, 1755, M8.5).

2.1. Greece seismicity

Focusing on Greece, Fig. 1 shows the earthquakes for the period 1980–2014 (USGS data base) with magnitudes greater than 4.0. From this figure we can deduce that the seismicity of this area is very high, especially along the Hellenic subduction zone of southern Greece where the plate velocity reaches 35–40 mm/yr and generates the highest rates of seismicity of the Mediterranean region. This seismicity is a manifestation of crustal normal faulting and extensional tectonics associated with back-arc spreading. Greece is the most seismic country in Europe, and Cephalonia, Western Greece, is particularly liable to experience earthquakes because it is located just to the east of a major tectonic fault line where the European and Aegean plates meet at a slip boundary.

2.2. The 26th January earthquake

On 26th January 2014 at 13:55 UTC (15:55 local time), an earthquake (Mw6.1) occurred at Argostólion, Cephalonia, (38.23°N, 20.48°E). It had a focal mechanism dominated by a strike-slip (Fig. 1) compatible with the fault that possibly generated the event, the Cephalonia Transform Fault that is a dextral strike-slip fault with a thrust component. A black star on Fig. 2 represents the earthquake epicentre. Eight days later, on 3rd February, a second M6.0 earthquake hit this region at 03:08 UTC (05:08 local time). This earthquake sequence led to important damages in the area and numerous aftershocks were recorded following the main shock. In the first 9 days, 434 M3+ earthquakes, 51 M4+ earthquakes, and 3 M5+ earthquakes struck the zone. The two M6 earthquakes took place on the same island as the 3 destructive events that occurred between August 9th and 12th of 1953 (Fig. 2). Those earthquakes had magnitudes of 6.4, 6.8 and 7.2 and resulted in hundreds of casualties and significant damage all over the island and also in Zante and Ithaca. In the following months, 80% of the population left the island.

2.3. Temporal evolution of the local seismicity

The upper panel of Fig. 3 shows the temporal distribution of the local seismic activity over approximately 10 years (Mw > 2.0, EMSC database). Clustering cases are clearly observed when magnitudes are plotted for the period from 2004-10-10 to 2014-06-30. In this figure, there are 4 seismic clusters (marked with vertical lines) that can be very well identified by intense seismic activity triggered by an earthquake larger than Mw5.5. These events are represented with large circles; the main shock (MS) of 26th January 2014 (Mw6.1) is marked with a star. The time succession shows that most of the largest events could be related to their aftershock area. In fact, we observe a typical aftershock distribution, with an activity that decreases in time after each main shock. A lack of seismic activity with Mw > 4.0 nearly 100 days before the MS can be seen in the lower panel of Fig. 3. The zoom around the MS time period clearly shows a moderate foreshock, F (marked by a diamond) of Mw4.8, on 11th January 2014, ~15 days before MS, and a large aftershock, A (marked by a large circle) of Mw6.0, on 6th February 2014. The seismic swarm triggered by the MS is the most significant feature of the represented seismic catalogue for this region.

3. Physical conditions

There are different physical phenomena that are able to affect the ionospheric conditions producing small perturbations that can be misinterpreted as earthquake-related disturbances. We pay attention to the three that are considered the most important.