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A possible explanation for electric perturbations recorded by the Italian CIEN stations before the 2012 Emilia earthquakes

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ABSTRACT A network of Extremely Low Frequency (ELF) electromagnetic detectors consisting of identical instruments that continuously record the electrical component of the electromagnetic field, ranging from a few Hz to tens of kHz has been operating in central Italy for several years. These signals are analysed in real time, their power spectrum contents and time/frequency data are saved for further analysis. The spectral contents have evidenced very distinct power spectrum signatures that increase in intensity when strong seismic activity occurs near the stations. During the Emilia seismic sequence in 2012, the network consisted of nine stations, seven in central Italy and two in northern Italy, at Zocca (Modena province) and at Torre Pellice (Turin province). Data recorded by the Zocca station, near Modena, at about 60 km from the Emilia epicentres were analysed. Data analysis shows the existence of several ELF oscillations of the horizontal electric field started on April 2012 and lasted up to the end of June 2012. Recorded ELF oscillations were similar to those recorded before and after the L'Aquila earthquake in 2009. However, since May 2012 was interested by significant rainfall close to the station, it is possible that the selected signals were linked to it. A theoretical model which could explain recorded ELF oscillations in concomitance with seismic and rain events is proposed.

Key words: atmospheric electric field measurements, electromagnetic emissions, Emilia earthquakes, meteorology.

1. Introduction

In May and June 2012, a seismic sequence shook intensely the southern Po area. Seven earthquakes characterized by magnitudes in the range of 5.0-5.9 occurred (Govoni *et al.*, 2014). The May 20, 2012 event, M_L=5.9 main shock [lat. 44°53'23" N, lon. 11°13'47" E, h: 6.3 km ISIDe Working Group, (2012)] , occurred at 2:03UT on about E-W trending, S-dipping blind thrust faults. Further six significant earthquakes occurred in the same area: at 2:07 UT on May 20, M_L=5.1; at 13:18 UT on May 20, M_L=5.1; at 7:00 UT on May 29, M_L = 5.8; at 10:55 UT on May 29, M_L=5.3; at 11:00 UT on May 29, M_L=5.2; at 19:20 UT on June 3, M_L=5.1. Focal depths were in the range 3-9 km. The pattern time and epicentres of the seismic activity, which resulted in 28 deaths and hundreds of injuries, 15,000 homeless, severe damage to historical centres and

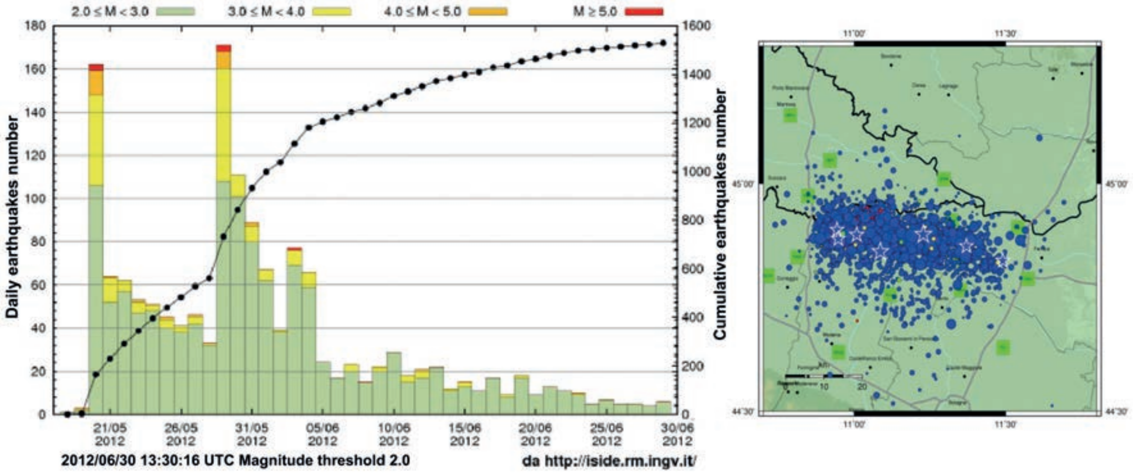

Fig. 1 - The Emilia sequence (from http://terremoti.ingv.it/it/ultimi-eventi/842-terremoti-in-pianura-padana-emiliana.html) indicates the number of events per day, their magnitude, the cumulative number of events over time, and the epicentres on the right.

industrial areas, and an estimated economic toll of about 2 billion euros (EMERGEO Working Group, 2013) is shown in Fig. 1. The sequence occurred in the E-W oriented part of the Ferrara Arc, also known as the buried replica of the northern Apennine belt. The buried anticline is covered by Quaternary sediments of the Po area while the minimum depth of the anticline is 75 m close to the town of Mirandola. The buried structures are part of a seismically active belt, where stresses connected in a complex way to the Neogene or earlier deformation history are still active (Boccaletti *et al.*, 2011). Plio-Quaternary stress field evaluations have evidenced that the tectonic regime is characterized by a N-NE compressive axis, while Cenni *et al.* (2012) measured deformation rates in the range of 4-7 mm/year.

A continuous monitoring of horizontal components of the electric field by the Central Italy Electromagnetic Network (CIEN) started in August 2010 at Zocca (Modena), about 60 km south of the earthquake epicentre. It was the closest CIEN station to the epicentre. Characteristic ELF signals were monitored in relation to seismic activity in Fermo, Marche region, Italy, from 2006 (Fidani, 2009). They were detected also during low seismic activity close to Perugia in 2008 (Fidani, 2010a). Finally, strong signals were recorded at the time of the L'Aquila earthquakes in 2009 (Fidani, 2011a). Further signals were detected during the M=5.0 Ancona earthquake (Siciliani *et al.*, 2013) and by the recently installed Avigliano Umbro, Città di Castello and Gubbio stations in the Umbria region, during the Pietralunga and Massa Martana seismic swarms (Siciliani *et al.*, 2014). CIEN is presently composed by 14 stations including the Pozzuolo del Friuli and Camerino stations added on April and May 2014 in Udine and Macerata provinces, respectively (Fig. 2). In summer 2012 the four stations of Torre Pellice (Turin), Fagnano (L'Aquila), Siena and Capitignano (L'Aquila) were out of order. During May 2012 nine stations were recording. All of them were equipped with two wide band amplifiers in ELF in the range of 4 to 1000 Hz and in VLF in the range of 1 to 25 kHz; while four stations Chieti, Fermo, Città di Castello (Perugia) and Torre Pellice (Turin) monitor LF in the range 1 to 50-100 kHz. VLF and LF range allowed to monitor several sub-ionospheric signals by various VLF and

Fig. 2 - The Emilia earthquake epicentre is indicated by a red star, sites of the 14 CIEN stations are indicated by coloured circles.

LF transmitters (Fidani, 2011b). Further differently located sub-ionospheric channel monitoring stations allow channel overlapping techniques. The overlapping of the same channels allows to verify each single channel perturbation and is the result of a comparison of at least two signals (Fidani, 2011b). However, no significant perturbations in VLF and LF bands data related to the 2012 seismic activity (Fidani *et al*., 2012) were evident. Thus, signal analysis focused on ELF activity in connection with the Emilia earthquakes.

2. Equipments and methods

Continuous long-term EM monitoring is necessary for obtaining reliable results on possible correlations with seismic activity (Uyeda *et al*., 2009). An EM network which includes 14 CIEN stations is presently recording. Their characteristics are listed in Table 1.

Historical observations of electric phenomena and earthquake lights (EQL) reported since the 18th century (Bina, 1751; Volta, 1784; Vannucci, 1787), initially stimulated electric investigations of earthquakes (Beccaria, 1754; Vannucci, 1787). Furthermore, recent researches reported several cases of a possible link between earthquakes and magnetic perturbations (Rikitake *et al*., 1980; Akinaga *et al*., 2001). Some of them resulted in an artefact (Thomas *et al*., 2009). More complex observation systems using satellite techniques are needed to detect external sources (Balasis and Mandea, 2007) and to exclude the possibility of geomagnetic

Table 1 - Characteristics of the 14 CIEN stations; MT: meteorological station, RD: Radon meter, TT: thermometer, SS: seismometer, MG: magnetometer: TC: telluric currents, LP: luminous phenomena, SO: infra-sounds; GE: geophone; RR: radio receiver.

Station	Lat. N	Lon. E	Alt. (m)	Band	Service	Instrument
Fermo	43°04′08″	13°56′58″	210	U-E-V-LF	Web UPS	MT, RD, TT
Perugia	43°07′13″	12°23′12″	460	U-E-VLF	Web UPS	MT, SS
Zocca	44°21′21″	10°59′29″	750	E-VLF	Web UPS	RR
Capitignano	42°31′59″	13°17′27″	920	E-VLF	UPS	-
Chieti	42°22′05″	14°08′52″	60	E-V-LF	Web UPS	MG, TC
Siena	43°18′52″	11°19′20″	320	E-VLF	Web UPS	-
Fagnano A.	42°15′57″	13°35′01″	710	E-VLF	Web UPS	RD
Rieti	42°24′37″	12°46′10″	430	E-V-LF	Web UPS	LP, SS
Torre Pellice	44°49′24″	7°12′03″	660	E-V-LF	UPS	MT, MG, SO
C.di Castello	43°28′41″	12°15′13″	310	U-E-V-LF	Web UPS	MG
Avigliano U.	42°38′41″	12°26′06″	370	U-E-VLF	Web UPS	MG
Gubbio	43°22′17″	12°31′26″	450	U-E-VLF	Web UPS	GE
Pozzuolo F.	45°59′04″	13°11′50″	70	U-E-VLF	Web UPS	MG, SS
Camerino	43°08′22″	13°04′04″	580 m	U-E-VLF	Web UPS	MT

Table 2 - Periods in which the Zocca station recorded data utilized in this study.

Year	Period	Days	Active Bands	sensibility
2010	August 7-9 and 20-23	7	ELF	-100 dB
2010	September 9-13	5	ELF	-100 dB
2010	October 9-18 and 30-31	12	ELF	-100 dB
2010	November 6-December 11	36	ELF	-100 dB
2010/2011	December 31-February 9	41	ELF	-100 dB
2011	April 10-August 20	133	ELF, VLF	-120 dB
2011/2012	December 30-June 6	158	ELF	-120 dB
2012	June 6-September 18	105	ELF, VLF	-120 dB
2012/2013	September 18-July 5 (not used)	290	ELF 4-50 Hz	-120 dB

perturbations not linked to crustal phenomena. Thus, CIEN focused the monitoring activity of the EM fields via their electric components. CIEN instruments are made up of two principal parts (Fidani, 2009, 2010a, 2011a, 2011b): an outdoor sensor and an indoor recording system. The sensor is composed by 10 m long wires equipped with amplifiers. The wire length is very much smaller than the minimum wave length of monitored signals (3 km in LF at 100 kHz) and may induce signals both along their length and for capacitive effect (Fidani, 2011b). Wires are used as electrodes linked to an amplifier. These wires must be positioned outdoors since they are responsible for picking up EM signals in the atmosphere. The recording system is made up of a standard PC audio card with Spectrum Laboratory software in order to carry out a real time analysis and to store data. It is also used to determine recording parameters and to analyse signals using Fast Fourier Transform (http://www.qsl.net/dl4yhf/spectra1.html).

The Zocca station has collected data since August 2010 (see Table 2.) However, during 2010 the ELF data were recorded discontinuously, because of many power shortages. Continuous data storage was possible in the following periods: August 7-9, August 20-23, September 9-13, October 9-18 and 30-31, November 6 to December 11 and December 31, 2010, to February 9, 2011. During these periods, data were saved in both spectrogram images and time signals

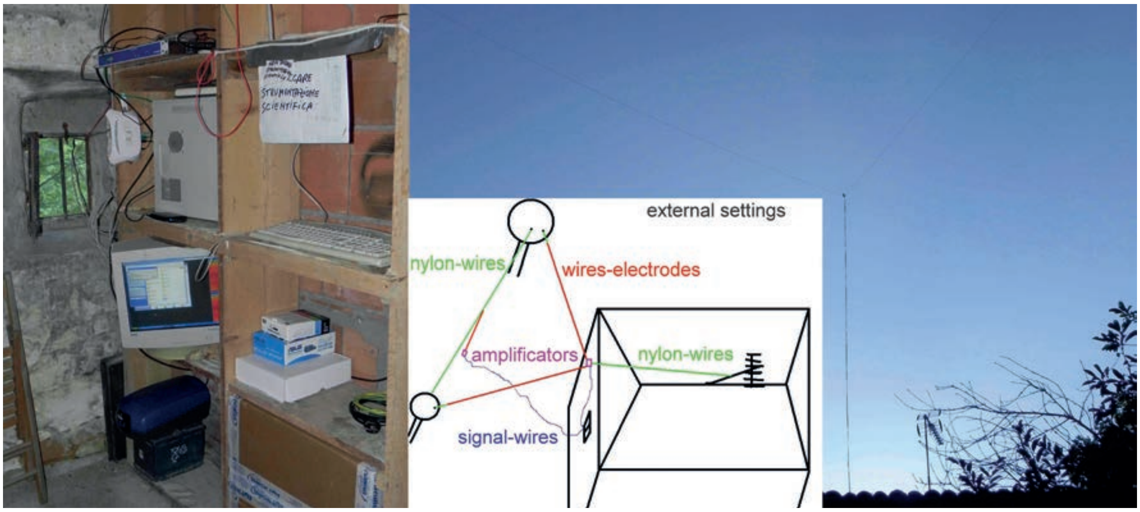

Fig. 3 - The Zocca station: the internal is equipped with a standard PC, a UPS and a web connection; outside, there are two horizontal and perpendicular electrodes 8 - m tall (visible in the photo) and one vertical electrode; the external setting scheme is shown.

in wave format files (.wav) from both horizontal electrodes. Utilized data are summarised in Table 2. In April 2011 the Zocca computer was replaced, and UPS was added to avoid interruptions of recording during power outages. Furthermore, recording was improved in sensibility by compressing data. From August 20 to December 30, 2011, it was not possible to collect data due to the fact that old data had not been deleted from the hard disk. VLF data recordings were also activated in April 2011 by saving spectrogram images only in JPEG files. However, these recordings were not active between January and June 2012 because the save command was out of order. VLF data recording was reactivated on June 6, 2012. While on September 18, 2012, the ELF recording resulted being damaged because of an oscillating noise above 50 Hz. Thus, only the range between 4 to 50 Hz was correctly recorded up to the beginning of July 2013. This last interval of data was not utilized. Anyway, most significant seismic activity near Zocca characterized by earthquakes with M>4.0 occurred during the period when the station was active. The hardware of the station was replaced in July 2013, and a web connection was installed to allow a remote control. All instruments were positioned in a cellar (see Fig. 3 left), while the two horizontal electrodes were suspended about 8 m above the station through wires placed across 3 trees; finally, a third vertical wire was activated in November 2014 (see the scheme in Fig. 3). Fig. 4 shows two dynamical spectres of the typical signals from both horizontal electrodes at the Zocca station. The white lines in the blue band at the top of spectrograms in Fig. 4 are the time amplitude evolutions of the entire signals over two 80-minute period of recording. Each vertical white dotted line indicates a 5-minute interval. Logarithmic scales of spectrograms were chosen to better evidence anomalous signals in ELF band, while power intensities are indicated by different colours and measured in dB. These spectrograms show the same kind of signals recorded at all the other CIEN stations (Fidani *et al.*, 2012). A relatively higher intensity of 50 Hz power supply was evidenced at the Zocca station compared to other CIEN stations. This was probably due to a not very well grounding. Furthermore, since the Zocca station is densely surrounded by toll and mature trees

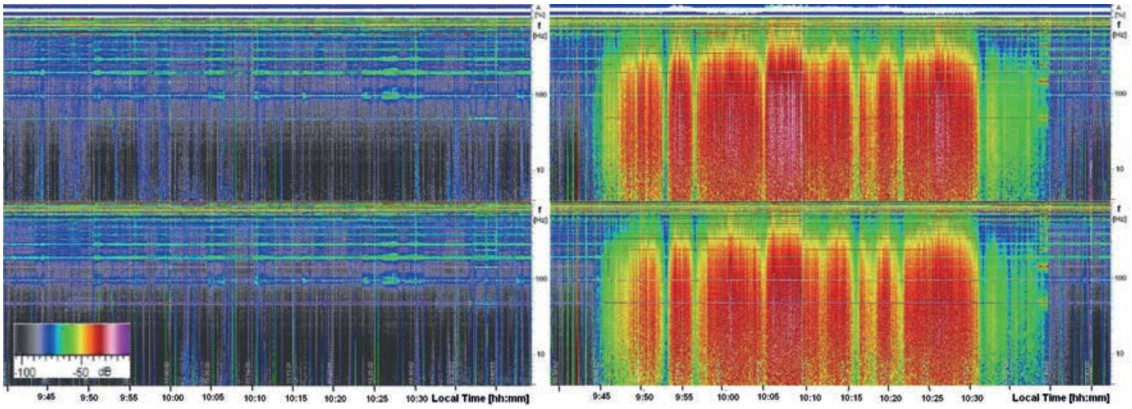

Fig. 4 - Two spectrograms recorded at the Zocca station on April 17 (left) and 20 (right), 2012.

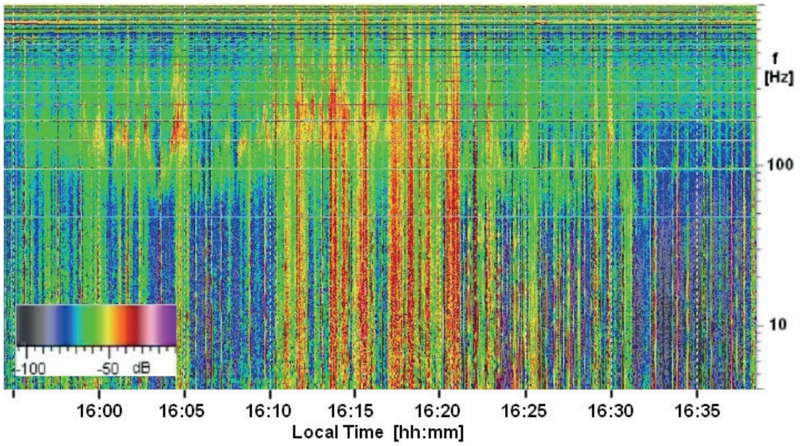

Fig. 5 - The ELF electric perturbations recorded at the Zocca station on May 7, 2010; the oscillations lasted 25 minutes and reached -40dB between 150 Hz and 250 Hz; during the oscillation a series of electrical discharges of meteorological origin (vertical lines) took place near the station, without any rain in the station area.

higher than the electrodes, atmospheric electric signals could have been attenuated producing a lower intensity of the power scale with respect to other CIEN stations. Nevertheless, natural electric activity such as thunderstorms (see Fig. 4 right), day-night and seasonal modulations of spherics were reliably monitored. Schumann resonances were also slightly visible in the ELF spectrograms as shown in grey horizontal bands under 50 Hz of Fig. 4 left. These features confirm a very good sensitivity of the apparatus even with the high 50-Hz disturbances.

Appearing with differently coloured power spectra, oscillations of the electric field such as those reported in connection with the 2009 L'Aquila earthquake (Fidani, 2011b) were also detected at the Zocca station (see Figs. 5, 6 and 7). In particular, the pattern shown in Fig. 5 was recorded on May 7, 2012, starting from 15:55 LT in the S-E electrode having a 35 minute oscillation of the electric field ranging between 50 and 250 Hz. The pattern shown in Fig. 6 was recorded on May 10, starting from 3:55 LT in the N-E electrode having a 62-minute oscillation of the electric field ranging between 30 to 100 Hz. Finally, the pattern shown in Fig. 7 was recorded on May 26, starting from 7:25 LT in the N-E electrode having a 25-minute lasting oscillation of the electric field ranging between 60 and 400 Hz. To verify if observed

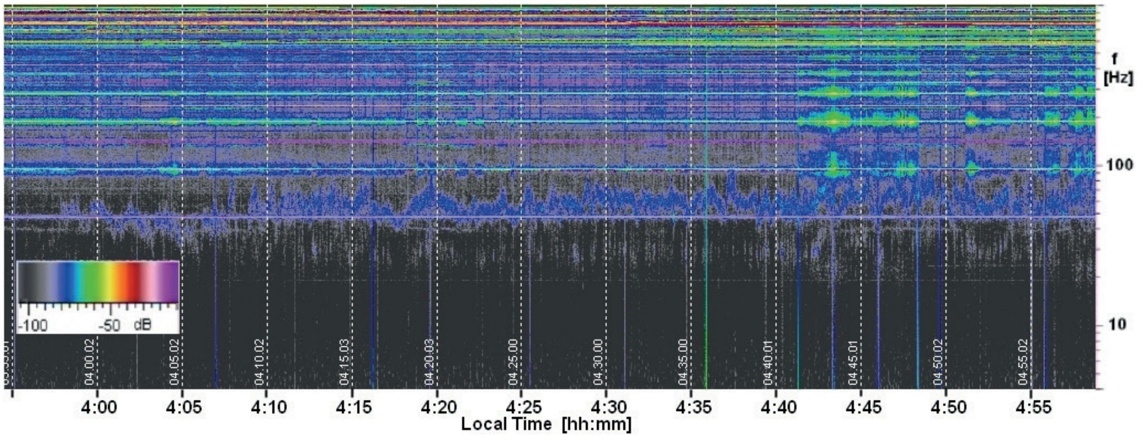

Fig. 6 - The ELF electric perturbations recorded at the Zocca station on May 10, 2010; the oscillations lasted 62 minutes and were localised between 40 Hz and 100 Hz with a relative magnitude of about -75 dB; the very long electric perturbation restarted for about one more hour after 5:00 LT and had the same characteristics.

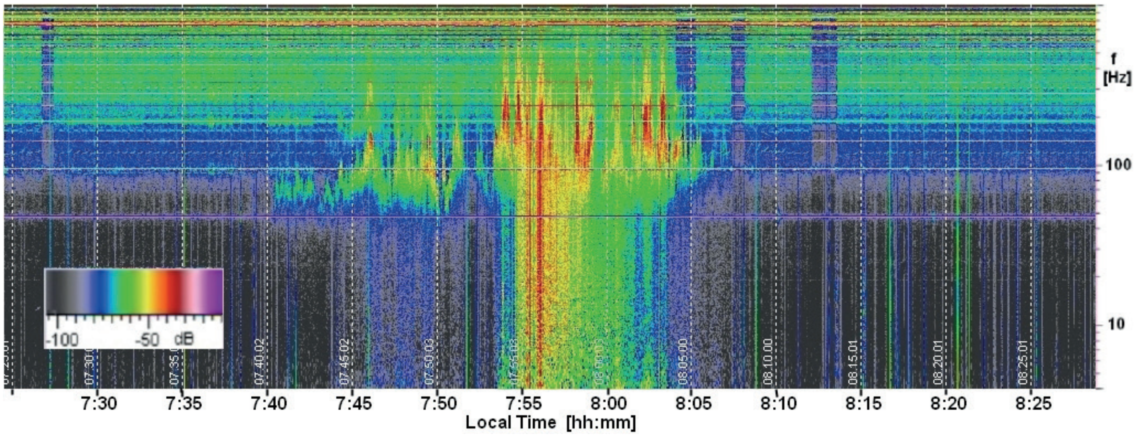

Fig. 7 - The ELF perturbations recorded at the Zocca station on May 26, 2012, during a rainfall event.

oscillations of the electric field could have been influenced by the meteorological precipitation, data from the Monteombraro and Vignola meteorological stations, respectively 3 and 14 km north of the Zocca station, were retrieved from August 1, 2010 to September 20, 2012. The data regarded daily cumulative precipitation as well as mean daily temperature reported at the Monteombraro station (lat. 44.376323° N; lon. 11.008752° E; h 700 m), and mean daily pressure measured at the Vignola station (lat. 44.504051° N; lon. 11.004141° E; h 100 m). Precipitation events were also recorded in ELF data at the Zocca CIEN station, as shown in Fig. 4. These latter data were used to label ELF oscillations occurring during rainfalls. Data from meteorological stations were used to verify the entity of rainfalls as well as to synchronise recording periods. Closest meteorological station to Zocca is the Monteombraro station which is considered representative of local climatological conditions in Zocca.

The Zocca area is located on an arenaceous rock formation (Bettelli and Bonazzi, 1977; Panini *et al.*, 2002). Local arenaceous rocks are known to have relatively high permeability and local rain can be drained by permeable rocks often affected by local small sinkholes. The sub-surface structure of the Emilia sector of the Po area consists of south to SW dipping sub-parallel

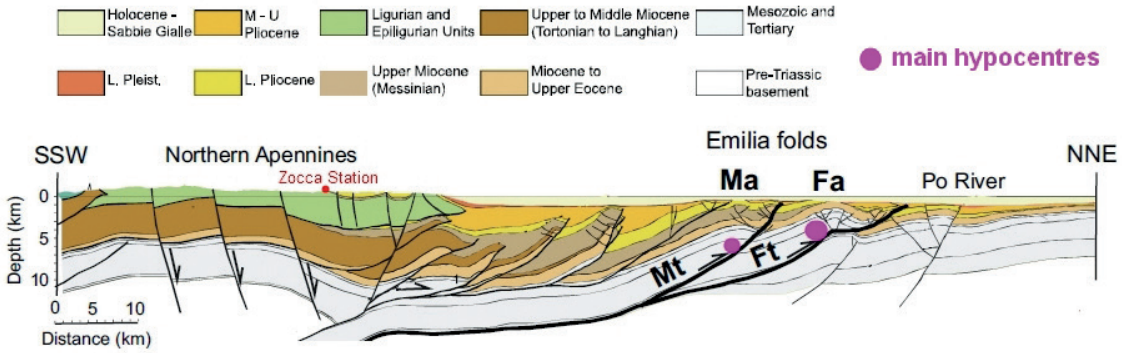

Fig. 8 - Geological, SSW-NNE oriented cross-section of the Po Plain modified from Martelli and Rogledi (1998) and Picotti and Pazzaglia (2008). Mt and Ft are the Mirandola thrust and the Ferrara thrust, respectively. Ma and Fa are the Mirandola anticline and the Ferrara anticline. Thicker lines marks Mt and Ft. The Zocca station site is indicated in red; the mainshock M_L=5.9 as well as the shock with M_L=5.8 are indicated in violet.

thrusts striking about N100°E (Fig. 8). These include the Ferrara and Mirandola thrusts (Ft and Mt) and the associated Ferrara and Mirandola anticlines (Fa and Ma). Specifically, Ft and Mt coalesce at about 10-15 km depth, at the interface between Mesozoic to Tertiary terrains and the underlying pre-Triassic crystalline basement (Picotti and Pazzaglia, 2008). The Zocca station is located about 60 km south of epicentral area and is indicated by a red circle in Fig. 8. The hypocentres of May 20 and 29 events are indicated by violet circles in the same figure.

3. Results

ELF data were analysed from August 2010 to September 2012 (19,782 hours of recordings and about 175 Gb of data). Spectrograms were prepared to better identify ELF anomalies compared to electromagnetic noise. Horizontal oscillations of the electric field as those identified in past publications (Fidani, 2010a, 2011b, 2012) were considered anomalous signals. These signals were generally characterized by different patterns along the two horizontal electrodes. Between January and February 2012 oscillations of the electric field were also reported many times on both electrodes of the Zocca station. This phenomenon was observed at frequencies lower than 100 Hz and had long durations lasting more than 30 minutes. Their intensities were also low, around -100 dB, but at such low frequency they were generally more intense than Schumann resonances. From March 2012, oscillations having the same intensities on both electrodes slightly disappeared. All oscillations were completely irregular in frequency, even if they always had ELF band ranges between 30 and 400 Hz. A scale of colours corresponding to 5 dB variations in power spectral amplitudes was sufficient to distinguish eventually anomalous oscillations. Being so, all anomalies > 5 dB above noise were collected.

Several oscillations of the horizontal electric field during April, May and June 2012 were observed. Other oscillations were recorded during spring 2011 (Fig. 9). Their relative intensities were generally lower than those recorded at other CIEN stations during the same period because of a low signal/noise ratio which inhibits further signal amplifications. Most of the oscillations of the electric field appeared in a range between 30 and 400 Hz during rainy days.

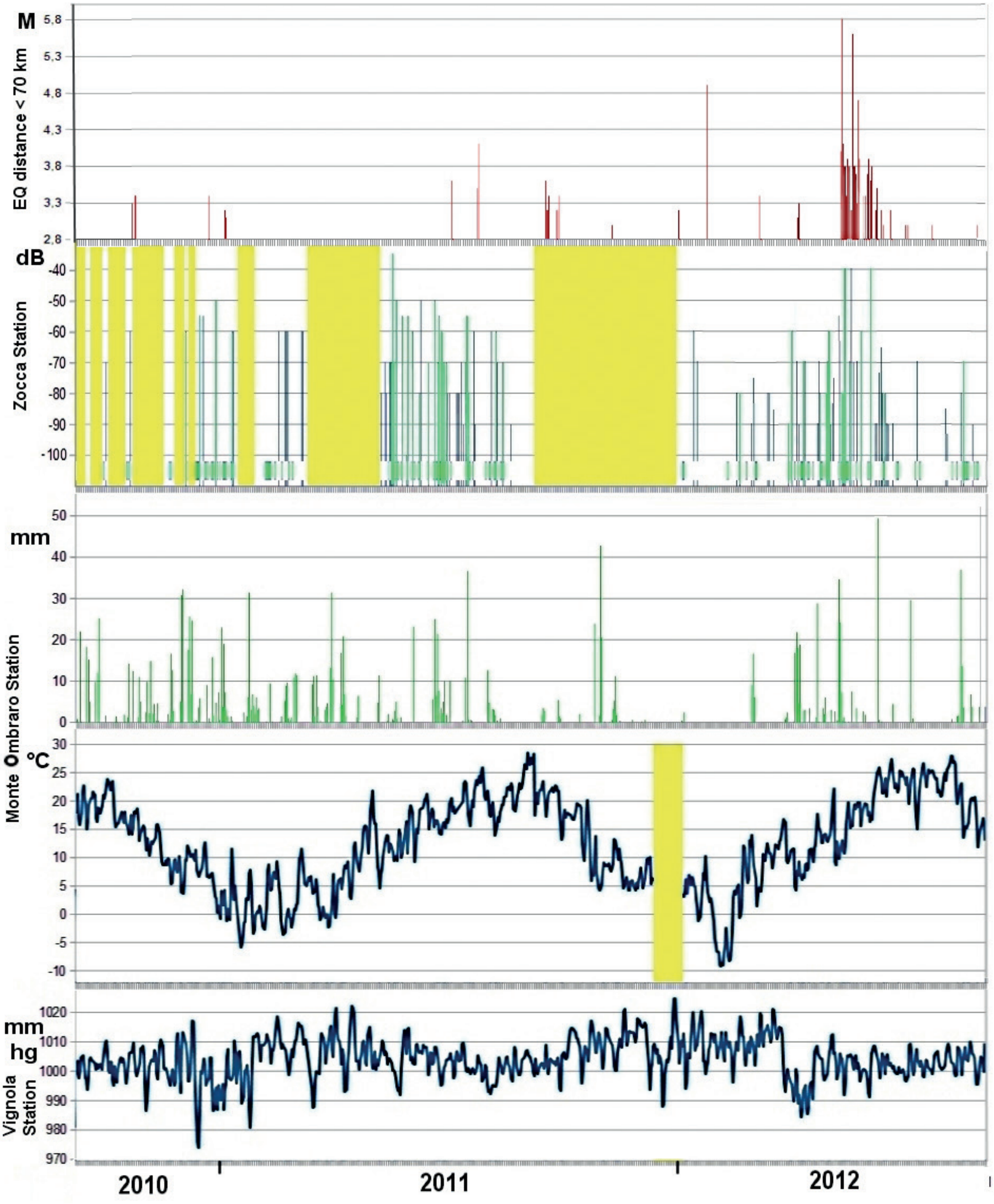

Fig. 9 - Emilia swarms and other M>3.0 seismic events at distances less than 70 km from the Zocca station recorded from August 2010 to September 2012, are shown by red bars on the top panel. Intensities in ELF oscillations of the electric field are shown below; yellow areas indicate lost data; green bars indicate that oscillations of the electric field occurred on a day when rainfall was recorded; and green bands under ELF oscillations indicate rainfall detected by the Zocca station; the blue bars indicate that oscillations of the electric field occurred during days without precipitation; meteorological data from Monteombraro and Vignola stations were also included at bottom.

Rainfall occurred during 16 days in May 2012, mostly between 18-26. The ELF oscillations were directly linked to rain in a few cases; however, ELF oscillations measured during days in which rain occurred were about 60%. These ELF oscillations are indicated by green bars while those occurred without rain by blue bars in Fig. 9. Their association with earthquakes was indicated by red bars. Oscillations of the electric field under 100 Hz, which have been more seldom associated with seismic activity (Fidani, 2011b), occurred on May 10 and 11, 2012, when no rain was recorded. On May 26 strong ELF oscillations were recorded at the Zocca station during rainfall. On May 5-8, 11, 16, 18, 20, 21, 25, 28 and 31 other significant ELF oscillations were recorded at the Zocca station. Further oscillations of the electric field occurred in Zocca were also recorded in different periods, in particular in the period of March-August 2011. All electric field oscillations recorded in Zocca usually lasted between 1 to 15 minutes, while they persisted for up to 3 hours in few cases before the main shock (Figs. 6 and 7). Rainfall data were superimposed to ELF data to verify when meteorological phenomena could have affected electrical perturbations. Patterns shown in Fig. 9 suggest that several ELF oscillations, as for example those recorded on May 7, 18, 20, 21, 26, and 31, could had been linked to meteorological phenomena. Some ELF oscillations appeared directly connected to rainfall events in particular on May 26. Many rainfall events recorded during the Emilia earthquake period also occurred without ELF signals. Additionally, atmospheric pressure recorded at the Vignola station, as well as temperature recorded at Monteombraro station are shown in Fig. 9. ELF oscillations occurred principally during spring seasons in 2011 and 2012, when rainfall was more frequent.

Frequencies and time laps of ELF oscillations changed from previous to successive times compared to earthquake time occurrence. Fig. 6 shows the ELF oscillation recorded at the Zocca station before the Emilia earthquakes on May 10, 2012, prior to 5:00 a.m. LT. The oscillation was recorded only on the N-S electrode and lasted about one hour, having frequencies between 40 and 80 Hz and intensity of less than -75 dB. This oscillation was less intense, in its relative value, compared to oscillations recorded before the 2009 L’Aquila earthquake which reached -45 dB. Intensity of ELF oscillations were evaluated according to Schumann resonance intensities (Fidani, 2011b). Schumann resonance intensities were found relatively low at Zocca. Moreover, the sound card transfer function with respect to the frequency was considered (Fidani, 2011b). When this transfer function was implemented, Schumann resonance and ELF oscillation intensities started to appear of the order of nV/m, like those recorded at Fermo and Perugia stations before the 2009 L’Aquila earthquake (Fidani, 2011b). These oscillations were stronger in intensity during the week of the Emilia earthquakes. They were higher in frequency but had smaller lapsed times during rainy days, as reported in previous observations (Fidani, 2011b). Due to the higher frequency with respect to the signals in Fig. 6 and the better response of the PC sound card at these frequencies, their relative intensities were up to -40 dB, as the one recorded on May 26, 2012, after 7:40 LT (Fig. 7).

Hydrological and geochemical variations in ground water and in gas emissions associated with the seismic sequence were observed in the epicentre area within a radius of 20 km from the main shock. Sand ejections due to liquefaction phenomena were the most commonly reported environmental effects (e.g., Bertolini and Fioroni, 2012). In the epicentre area ground water table uplifted (Marcaccio and Martinelli, 2012) while an increase in marine-derived ions was observed in well water due to squeezing of underlying brackish water belonging to Pliocene sedimentation processes (Italiano *et al.*, 2012a, 2012b). Crustal deformation processes associated with the occurrence of the seismic sequence, induced a squeezing of deep-seated ground waters associated with brines of the Miocene-Pliocene geological structures of the Ferrara buried anticline. Eyewitnesses reported numerous liquefaction effects. Based on the magnitude and timing of liquefaction events and the main seismic events on May 20 and 29, it was concluded that liquefaction was caused by these seismic events (EMERGEO Working Group, 2013). Soon after the May 20, 2012 main shock and during the Emilia seismic sequence of May-June 2012, geochemical field investigations were carried out on the epicentre area; the results suggested that soil liquefactions are surface phenomena (Sciarra *et al.*, 2012) not linked to deep geological environments.

Statistical analysis of the spatial surface skin temperature from the Modern Era Retrospective-Analysis for Research and Applications (Rienecker *et al.*, 2011) of April and from May 1979 to 2012, revealed that apparently local temperature enhancements occurred around the epicentres on the nights of May 12, 2012, before the May 20, M_L=5.9 earthquake, and on May 24, 2012, before the May 29, M_L=5.8 earthquake (Qin *et al.*, 2012). The authors concluded that these observations could had been due to an increase in green-house gas emission rates such as carbon dioxide and methane (Saraf *et al.*, 2008). Methane degassing activity detected after main shocks by geochemical investigations appeared to be higher than normal background levels (Sciarra *et al.*, 2012). However, apparent temperature increasing might have been due also to other geophysical effects, such as a reactivation of p-holes (Freund, 2013), water condensation onto seismically-released ions (Pulinets and Ouzounov, 2011) while atmospheric ions could have themselves directly absorbed infra-red radiation (Rycroft *et al.*, 2012). Accordingly, it has been hypothesized that one or more of these phenomena might have also been implicated in northern Italy before the May 2012 Emilia seismic sequence.

4. Discussion of a model and conclusions

Data recorded from the Zocca CIEN station suggest that electric perturbations become slightly more intense and frequent during meteorological and seismically active periods, as recorded before and after the 2012 Emilia earthquakes. In fact, in these periods the power spectra of oscillations of the electric field became greater than noise and of the same order of magnitude of other natural EM phenomena, such as the Schumann resonances. Candidate pre-seismic oscillations in electric field intensity were quantified and resulted being of the same kind and size of the 2009 L'Aquila earthquakes (Fidani, 2011b). Differently from L'Aquila in 2009, when strong oscillations started several months before and ended several months after the main shock, in the case of the Emilia seismic events strong oscillations started to occur about few days before main shock and lasted some weeks after main shock. These oscillations of the electric field were well discriminated from other natural and anthropogenic signals in spectrograms. Furthermore, two strong ELF perturbations were observed few days before eventual temperature enhancements indicated by Qin *et al.* (2012), on May 10 and 20, 2012. Then, meteorological events, such as thunderstorms, pressure variations and temperature variations also occurred during ELF perturbations. In this case a strong association between rainfall and ELF oscillations was observed.

The satellite observations of infrared emissions suggested that the phenomena of increase in

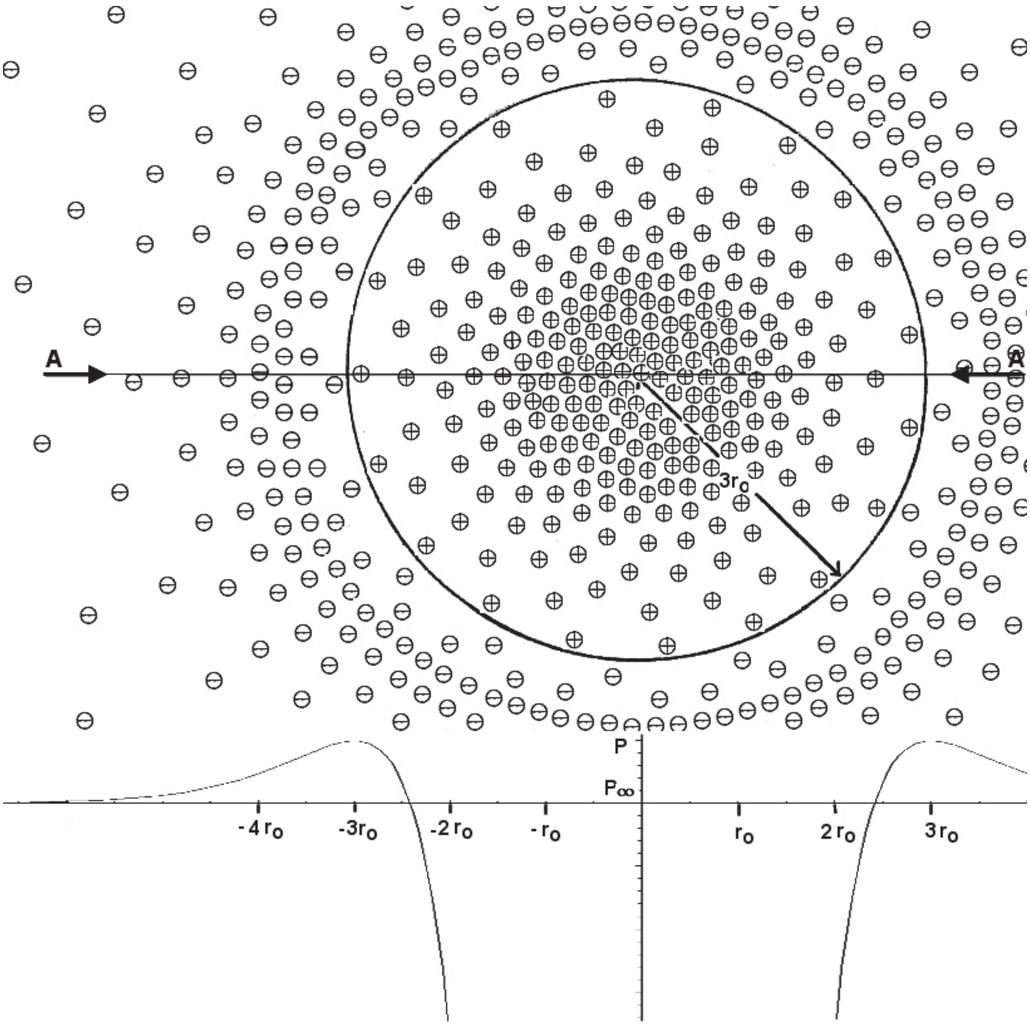

Fig. 10 - Pressure distribution of the section A-A spatial charge distribution; the positive charge is confined to the sphere and the negative charge is located in the external region.

green-house gas emission rates, reactivation of p-holes, water condensation, and increase in air ions could be occurred. CIEN observations evidenced that sources of oscillations of electric field are localized near the stations (Fidani, 2011b). The skin depth in a uniform half space is given by

$$\delta=30.2\ T/\sigma \qquad (1)$$

where the resistivity $1/\sigma$ is about 10 Ωm along the surface and probably lower at greater depth (see also Armadillo *et al.*, 2001). Therefore, δ is about 50 m for a frequency of 100 Hz and it is unrealistic that recorded electric fields were due to an electromagnetic radiation generated at the hypocentre by direct rock fracture generation (Kapiris *et al.*, 2004; Panfilov, 2014). Oscillations of the electric field produced by rock fracture of buried Emilia faults, which are under high conductivity wet sediments, should be completely absorbed (Fidani, 2005).

Electric field oscillations were recorded by CIEN also before many precipitations and without seismic activity. Rainfalls are often preceded by electric ions variations in the atmosphere (Takahashi, 1972). These observations suggest that electric oscillatory phenomena generally occur together with air ions concentration fluctuations and/or meteorological instabilities. It is possible to suppose that, due to the general difference in temperatures between the ground and the atmosphere, when gas escapes from the ground it should produce atmospheric pressure differences. Pressure differences are also characteristics of meteorological perturbations. Pressure differences in atmosphere are responsible for air movements and, if air ions are present in atmosphere, pressure differences are also responsible for air ions movements. Thus, electromagnetic waves could be emitted, in principle, by ion movements. CIEN recording of electric fields revealed relatively stable oscillatory phenomena which lead us to hypothesise that a stable phenomenon of bounded sources occurred. A model for a spherically symmetric and dynamically stable structure has been proposed for the atmosphere by balancing electrostatic forces with air pressure (Tennakone, 2011).

The possibility of forming stable spherically symmetric charge configurations in the atmosphere has been a subject of many past investigations, conducted with the aim of better understanding unusual atmospheric phenomena, such as ball lightning (BL) and EQL (Singer, 1971; Tennakone, 2006). Many EQL were observations of luminous globular structures, stable in luminosity or pulsating, which rose to the atmosphere from the ground, immediately before, during or immediately after an earthquake (Fidani, 2010b). The theoretical model proposed by Tennakone (2011) could explain ELF oscillations registered immediately before, during and after the 2009 L'Aquila and 2012 Emilia seismic events. Specifically, roughly spherical charge distributions could have formed in the atmosphere by expelled charged gases from the ground. The balancing electrostatic forces due to air ions of net zero charge and external pressure can be described by the equation system (Tennakone, 2011):

$$ {dP}/{dr} - \rho E = 0, \tag{2} $$

$$ \nabla E = {\sigma}/{\varepsilon_0} . \tag{3} $$

Considering the solution of the system:

$$ E(r) = E_0 r \cdot e^{{-r}/{r_0}} , \tag{4} $$

some oscillating spherical structures of electrical charges do exist, which could be associated to ions, electrons, charged dust, charged liquid droplets and charged aerosols (Fig. 10). The existence of an oscillating solution indicates that the equilibrium is stable. Pulsation frequency is expressed in terms of one parameter, defining a linear dimension of the object, as:

$$ f = \frac{\sqrt{\left({2P_\infty}/{5\sigma_\infty} \right)}}{2\pi r_0} , \tag{5} $$

where P_∞ and ϱ_∞ are the normal atmospheric pressure and charge density. However, how the charges were eventually associated with atmospheric gas was not taken into account in this work, and frequency of oscillations depended exclusively on the radius of the sphere.

In conclusion, regarding high charge concentrations, corona discharges in the space between the separated charges can render the object luminous, therefore explaining the presence of EQLs. Whereas, for low charge densities, object oscillations can also explain the oscillations of the electric field recorded by CIEN. Moreover, ELF oscillations have been observed both in earthquake periods with and without precipitations. Similarly, BL has been observed before, during and after strong earthquakes as well as during heavy precipitation producing high levels of fulmination. The supposed phenomena of clouds of ions in which electric forces are balanced by atmospheric pressure variations seem to be a possible common origin of EQL and oscillations of the electric field observed during seismic periods as well as BL and oscillations of the electric field observed during rainfalls. BL chiefly occurred in concomitance with strong seismic and meteorological events. Further measurements and experiments are necessary to confirm this hypothesis.

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