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Disturbances in LF radio-signals as seismic precursors

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Abstract

Low Frequency (LF) radio signals lie in the band 30-300 kHz. Monitoring equipment able to measure the electric strength of such signals, at field sites with very low noise levels, were designed and assembled in Italy. From 1993 onwards, the electric field strength of the MCO (216 kHz, France) broadcasting station has been measured at two sites in Central Italy. At the end of 1996, radio signals from the CLT (189 kHz, Italy) and the CZE (270 kHz, Czech Republic) broadcasting stations were included in the measurements. During this monitoring period, evident attenuation of the electric field strength in some of the radio signals was observed at some of the receivers. The duration of the attenuation observed was several days and so it could have been related to particular meteorological conditions. On the other hand, this phenomenon could also represent precursors of moderate ($3.0 \le M \le 3.5$) earthquakes that occurred near the receivers (within 50 km) along the transmitter-receiver path. In this case it is possible that some local troposphere defocusing of the radio signals, produced by the pre-seismic processes, might have occurred. These observations were related only to moderate earthquakes and in these cases it may be that suitable meteorological conditions are needed to observe the effect. During February-March 1998 at one measuring site, we observed a significant increase in the CZE electric field strength. Unfortunately, the data of the other receiver could not be used in this case because of frequent interruptions in the recordings. The increase might have been a precursor of a strong earthquake ($M = 5.3$) that occurred on March 26, 1998 in the Umbria-Marche zone at a location over 100 km from the receiver, but which lay along the transmitter-receiver path. In this case, it is possible that an ionospheric disturbance, produced by the pre-seismic processes, might have occurred. If this pre-seismic behaviour of the LF signals could be confirmed then this type of precursor would seem capable of giving information on the direction, and perhaps even the rough location, of a forthcoming earthquake.

Key words *radio-signals – seismicity – precursors*

1. Introduction

For many years, research into the interaction between seismic activity and disturbances in radiobroadcasts has been carried out. One of the first results was obtained using 18 MHz receivers on the occasion of the great ($M = 8.5$) Chilean earthquake of May 22, 1960 (Warwick *et al.*, 1982). The receivers were part of a network used for studying cosmic noise. Warwick *et al.* (1982) proposed that the observed pre-seismic anomaly was the result of emissions at 18 MHz caused by micro-fracture of quartz-bearing rock due to pre-seismic stress increase in the Chilean fault zone. Later, pre-seismic disturbances in the Omega and Loran radio waves, that lie in the VLF (3-30 kHz) frequency band, have been presented (Gokhberg *et al.*, 1989; Hayakawa

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and Sato, 1994; Morgounov *et al.*, 1994; Hayakawa *et al.*, 1996; Molchanov and Hayakawa, 1998). These radio signals are used for worldwide navigation support and propagate in an earth-ionosphere wave-guide mode along great circle propagation paths. The analysis is based on the amplitude and the phase variations of the radio signals propagating from different transmitting stations. The anomalous variations detected several days before strong earthquakes have been explained by the abnormal ionisation in the lower ionosphere produced by emissions of radon, ions or electromagnetic waves from the focal zone of the forthcoming earthquake (Hayakawa and Sato, 1994). Since 1991 research of possible seismic disturbances in LF (30-300 kHz) radio waves has been carried out in Italy (Bella *et al.*, 1998; Biagi, 1999). In this paper we present the anomalous case records revealed so far and discuss the possibility that they represent earthquake precursors.

2. Method

In 1991 we designed and built a receiver able to measure the electric field strength of one LF frequency at field sites where the noise level is very low. We selected the LF broadcasting station MCO located in France. The monitoring equipment is composed of a short vertical antenna and a data recording system containing both analogue and digital units. The analogue unit consists of an amplifier module, a frequency filter with an uncertainty of 1% and an analogue-to-digital converter. The digital has a divider, a decade scaler and an exponent counter. The A/D converter and the digital unit are detailed in Bella *et al.* (1989). A 12-V battery connected to solar cells supplies the power. The electric field strength is sampled every 10 min and the digital output is stored in a solid-state memory. At the beginning of 1993 we began operating receivers at two sites in Central Italy called AS and PE, which are located 60 km apart. In 1996 the experiment was extended to record two additional broadcasting stations, CZE (Czech Republic) and CLT (Sicily South Italy).

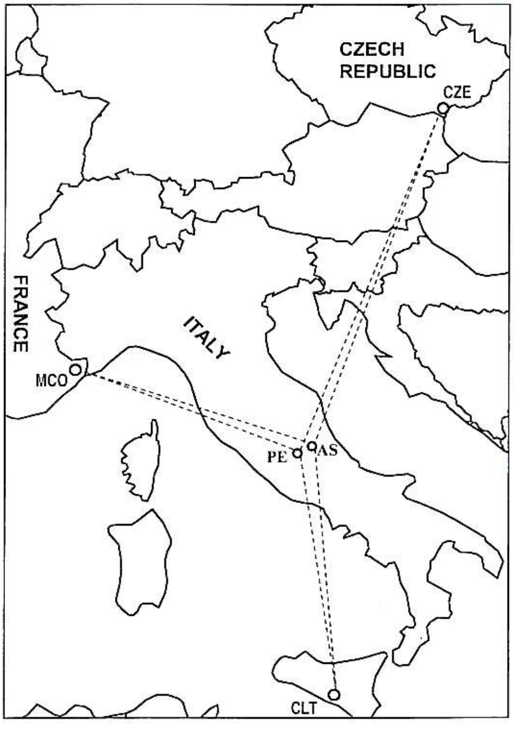


Fig. 1. Map showing the radio broadcasting stations (CLT, MCO, CZE) and the measurement sites (AS, PE).

Table I. Parameters of the broadcasting stations.

Label	Radiated power (kW)	Frequency (kHz)	Mean distance from receivers (km)
CLT	60	189	540
MCO	1400	216	520
CZE	1500	270	820

These stations are received clearly in Central Italy and monitoring equipment was built similar to that detailed above, but able to measure the electric field strength of the three transmitters simultaneously. At the end of 1996 the new receivers were commissioned. The radiated power and frequency of the broadcasting stations, together with the mean distance from the receivers, are indicated in table I. Figure 1 shows the location of the transmitters and receivers.

3. Results

An example of the radio signals measured at the AS site is shown in fig. 2. The LF signals received are characterised by the ground wave and the sky-wave propagation modes. The day-time electric field strength is lower than at night because the sky-wave is greatly attenuated by the lower ionosphere and, in effect, the ground-wave alone provides the signal which is faint. At night-time the low attenuation of the lower ionosphere permits an increase of 10-15 dB in the sky-wave signal such that the received signal is practically all due to sky-wave propagation. At the centre of each night-time enlargement shown in the plots of fig. 2 there is a sudden decrease which is due to a daily reduction of the transmitting power of the broadcasting stations. Figure 3a shows the two anomalous decreases in the electric field strength of the MCO signal revealed at AS site with the old equipment (for only the MCO transmitter). The duration of the attenuation is 11 days (upper

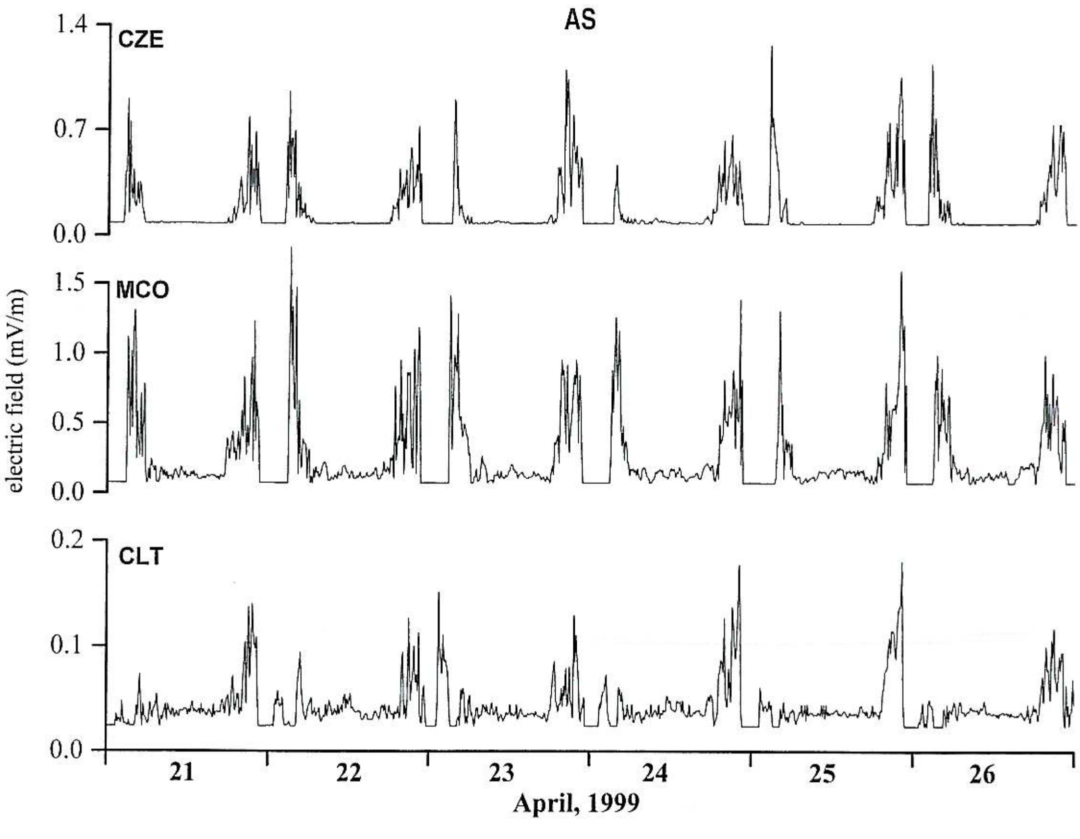


Fig. 2. CLT, MCO and CZE electric field strength measured at the AS site over a 6-day period.

curve) and 5 days (lower curve) and the range is up to 15 dB. No anomaly at the PE site was revealed at that time. About 15 days after the end of the 1993 radio-anomaly, an earthquake with $M = 3.5$ occurred 25 km from the receiver, along the MCO-AS path. Furthermore, 4 days after the end of the 1994 radio-anomaly, a seismic sequence happened along the MCO-AS path at about 40 km from AS, with magnitude 3.0-3.5. The location of these seismic events is shown in fig. 3b and the time they occurred is indicated in fig. 3a. With the new equipment (for the MCO, CLT and CZE transmitters) twice as much attenuation was observed in the radio-signals of up to 10-15 dB lasting several days, as shown in fig. 4a and in fig. 5a. The attenuation appeared in the CLT signal and the first one (fig. 4a) was detected only at the PE site and the second one at the AS site. Some days following the end of these radio-anomalies, earthquakes with magnitude 3.5 and 3.3 occurred at distances less than 50 km from the receivers, just along the transmitter-receiver path. The location of these earthquakes is shown in figs. 4b and 5b and the time they occurred is shown in figs. 4a and 5a.

In our analysis, all the data recorded since January 1997 was examined, *i.e.* from the beginning of the measurements with the new equipment, up to March 2000. At first, we applied a 7-day high pass filter to the raw data in order to remove high frequency components and then we determined the smoothed trend of the filtered data by fitting a 9th order polynomial. Next we examined the data sets representing the difference between each filtered trend and its polynomial fit before finally calculating the standard deviation σ over each of these sets. The trend of the CLT, MCO and CZE radio-signals we obtained at AS site is reported in fig. 6a. The horizontal dashed lines in each trend represent the $\pm 3\sigma$ level. Considering values over 3σ to be anomalous, from fig. 6a it is possible to note

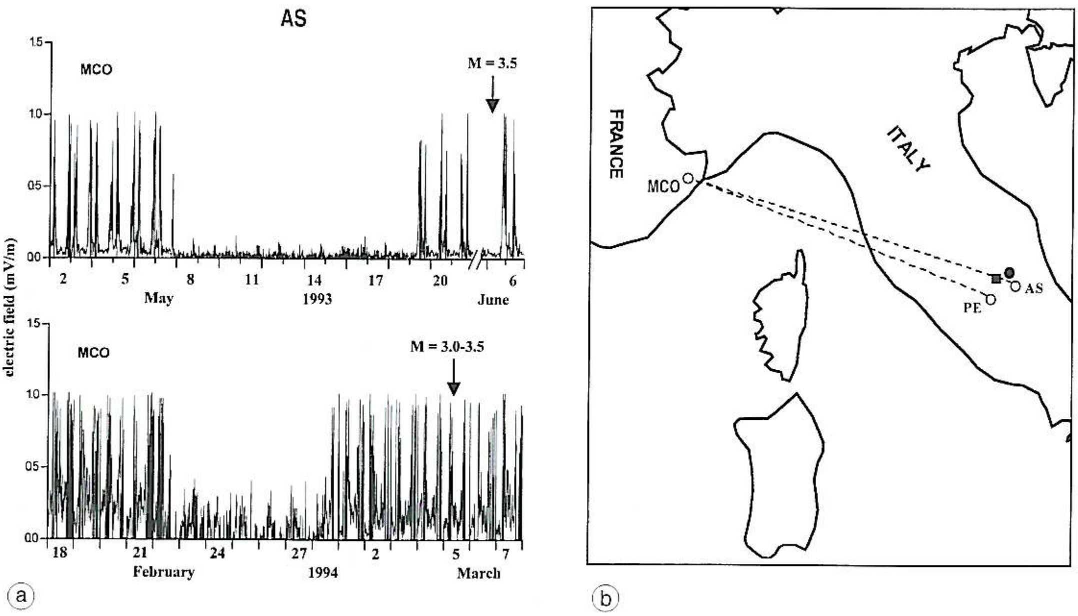


Fig. 3a,b. a) Anomalous decreases in the MCO electric field strength at AS measurement site occurred in May 1993 and February 1994. The arrows indicate the earthquake ($M = 3.5$) which occurred on June 5, 1993 and the seismic sequence ($M = 3.0$-3.5) on March 4 and 5, 1994. b) Map showing the location of the 1993 earthquake (black circle) and of the 1994 seismic sequence (black square).

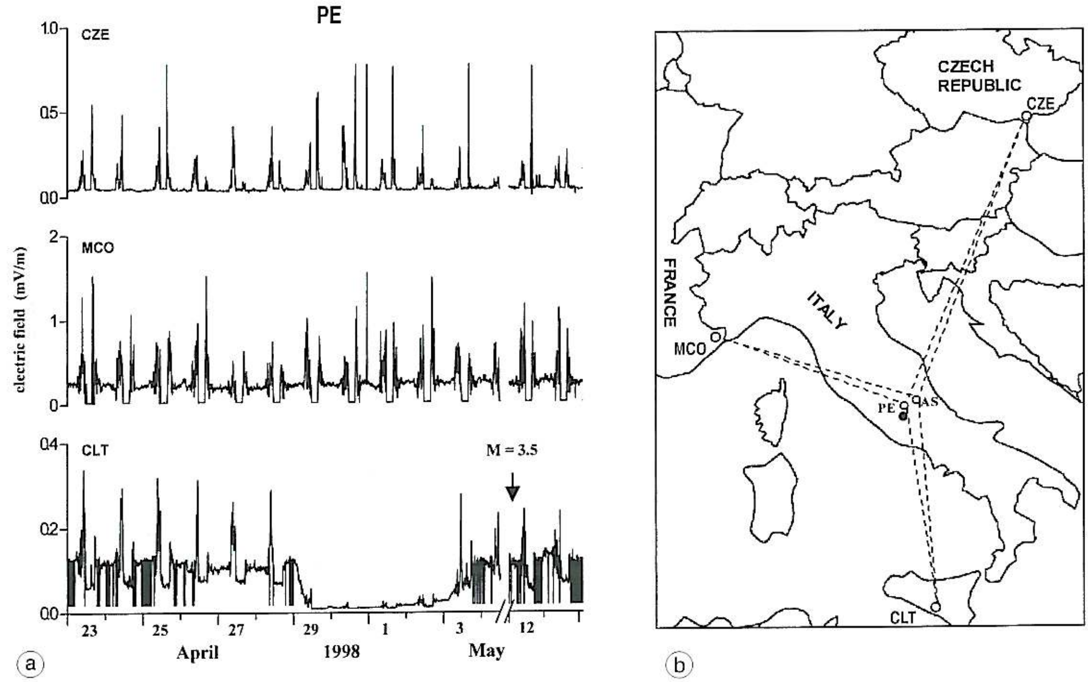
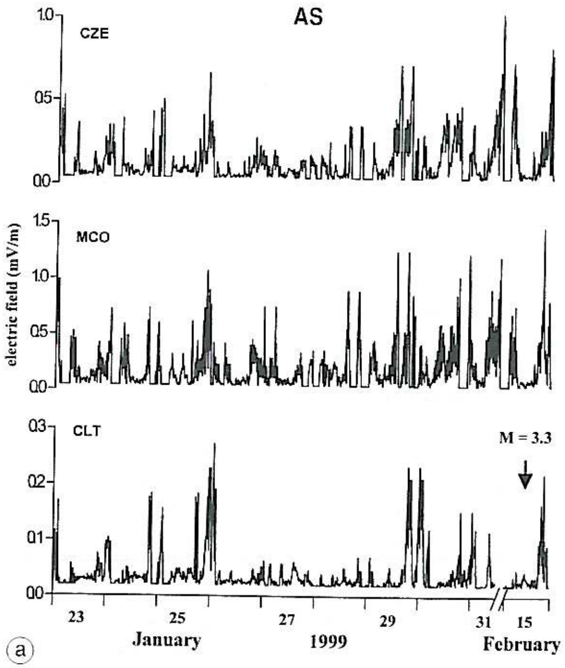


Fig. 4a,b. a) Anomalous decreases in the CLT electric field strength at the PE measurement site which occurred in April-May 1998. The arrow indicates the earthquake ($M = 3.5$) which occurred on May 12, 1998 along the CLT-PE path. b) Map showing the location of the earthquake (black circle).

that: 1) no anomaly appears in the MCO data; 2) three anomalies appear on the CLT plots in summer time as a quasi-periodic effect, and 3) an anomaly appears in the CZE plot during February-March 1998. When investigating the CLT anomalies, we discovered that the broadcasting station increased the radiated power during the anomalous periods. However, there appears to be no such explanation for the CZE anomaly and the effect is surely unrelated to the broadcasting station. This anomaly is an increase in the order of 6-8 dB and on March 26, 1998 (*i.e.* about 15 days after it finished) an earthquake with $M = 5.3$ occurred in the Umbria-Marche region – this is along the transmitter-receiver path. The location of this earthquake is shown in fig. 6b and its time of occurrence is indicated in fig. 6a. Unfortunately, the data recorded by the other receiver (PE) were affected by problems with both the power supply and saturation of the recorded signals so all the data could not be used in this study.

4. Discussion

LF radio wave reception is characterised by ground-wave and sky-wave propagation modes. For distances greater than 500 km the contribution of the ground wave to the electric field strength is about ten times smaller than the sky-wave contribution. In this case the ground wave provides a weak but fairly stable signal whereas the sky-wave signal is larger but greatly variable between day and night and between Winter and Summer. Our analysis is concerned with observations of the variations in the radio signal strengths, and so we can focus on just the sky-wave signal component. Let us first consider the anomalous decreases in the radio-signals observed. It must be noted that the four cases we showed in figs. 3a, 4a and 5a are the only ones we revealed up to now. Initially we investigated the meteorological conditions prevailing in Central Italy at the time and we noted that during the anomalous periods some thermal inversions in the low troposphere occurred. These thermal inversions are connected with an advection of warm air from Africa. However we found that these meteorological conditions occur quite frequently in Central and Southern Italy and, in fact, happened several times during our measurements, lasting several days, and yet did not produce any detectable change in the radio-signals. Consequently, a connection between the radio-anomalies and meteorological phenomena alone does not seem satisfactory. Next, we checked the validity of the connection with the seismic activity. We found 4 other seismic events with the same energy release happening along the transmitter-receiver paths at distances of less than 50 km from the receivers. In these cases, no anomalies in the field strength of our radio-signals were detected. Thus a possible relationship between radio-anomalies and seismic activity is somewhat doubtful. However, we also observed that on the occasions of seismic events when no radio-anomalies occurred, the meteorological analysis did not reveal thermal inversion connected with advection of warm air. So, these results seem to suggest that the anomalous radio effects detected are connected with a concurrent events, requiring both a preparatory phase of an earthquake and the advection of warm air in the troposphere. The results presented seem to fit with some form of defocusing process of the radio-signals in the troposphere because the epicentres are located at places where the sky-



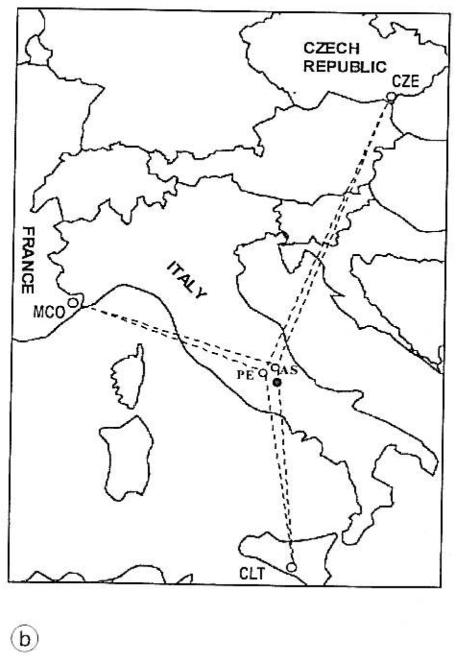


Fig. 5a,b. a) Anomalous decreases in the CLT electric field strength at AS measurement site which occurred in January 1999. The arrow indicates the earthquake ($M = 3.3$) which occurred on February 15, 1999 along the CLT-AS path. b) Map showing the location of the earthquake (black circle).

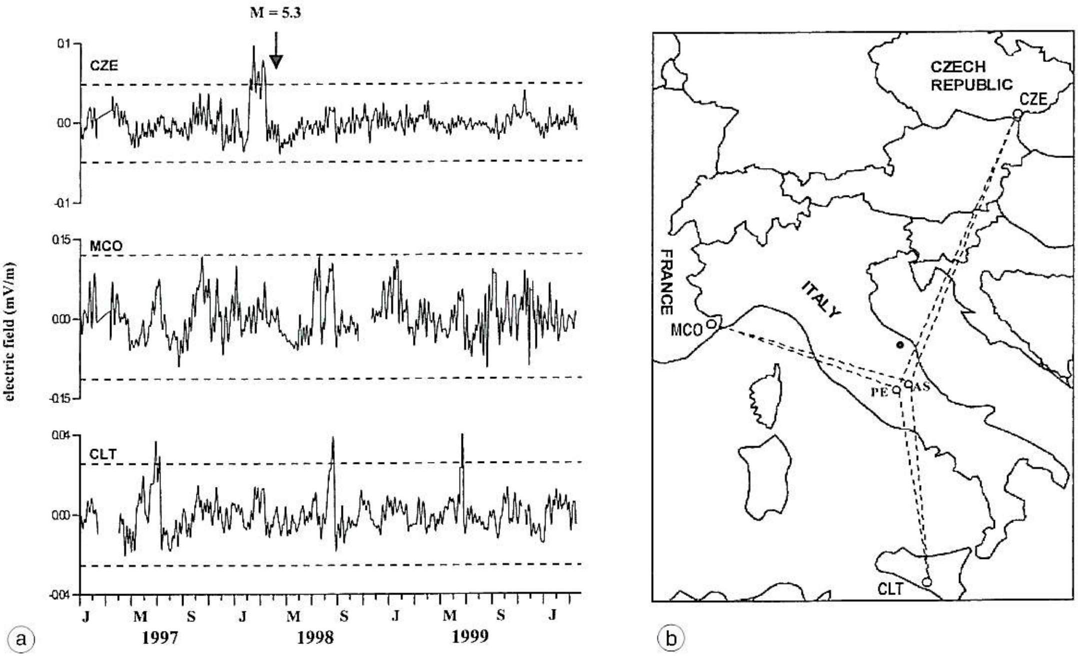


Fig. 6a,b. a) Difference between the filtered and smoothed trends of CLT, MCO and CZE radio-signals at AS site from January 1, 1997 to March 31, 2000; the horizontal dashed lines are the $\pm 3\sigma$ level (σ is the standard deviation). The arrow represents the occurrence of the March 26, 1998 ($M = 5.3$) earthquake in the Umbria-Marche region. b) Map showing the location of the earthquake (black circle).

wave is already in the troposphere. Now, we have to explain the possible origin of the defocusing process. Tropospheric radio broadcasting defocusing can occur due to some irregularities (such as ducts, reflecting layers or scattering zones) in the vertical gradient of the radio refractivity N approximated by

$$N = 77.6(p/T) + 3.73 \cdot 10^5 (e/T^2) \qquad (4.1)$$

where p is the atmospheric pressure, T is the absolute temperature and e is the water vapour pressure (CCIR, 1990a). Defocusing was observed many times in studies concerning HF and UHF radio broadcasts under the influence of synoptic processes such as subsidence, advection, or surface heating or radioactive cooling (CCIR, 1990b). Similar observations do not exist for LF radio signals due to the wavelength of some kilometres that implies larger dimensions of the parameters that control the disturbing process. We propose a mechanism here whereby one of the irregularities mentioned above, probably a scattering zone, is able to produce LF radio-wave defocusing as follows. Many well-known effects connected with pre-seismic stress such as electromagnetic emissions, gas emanation and ionisation could produce irregular variations in p, T and e in the troposphere and therefore in the radio refractivity N. Within a normal meteorological framework, such variations do not act on LF radio-signals. But suitable conditions such as warm air advection might permit the diffusion of the irregular variations on a large scale, thus influencing LF radio-wave propagation. In outline, the warm air advection acts as a catalyst for the influence of the irregular variations of the radio refractivity produced by pre-seismic effects on LF radio signals. Our observations were related only to moderate earthquakes and probably, in these cases, suitable meteorological conditions were needed to observe the effect. In our view, such coincident effects would not be needed for larger earthquakes.

Consider now the anomalous increases in the CZE radio-signal observed during February-March 1998. According to the wave hop propagation theory (Knight, 1973), the sky-wave signal received by an antenna can be considered as a ray starting from the transmitter and reflected one or more times (hops) by the lower ionosphere and by the ground. The propagation of the sky-wave is thus controlled (CCIR, 1990c) by several parameters including the elevation angle ψ (relative to the horizontal) of departure and arrival of the ray, the ionospheric reflection coefficient R, the height H of the ionosphere, the transmitting and receiving antenna factors F and the ionospheric focusing factor D. Of these, R is the main parameter of interest. The large day-time attenuation of the sky-wave with respect to the night-time propagation conditions is mainly dependent on the different R values, for example 0.01 during the day and 0.1 during the night. The anomalous increase in the filtered plot of fig. 6a from the middle of February to the end of March 1998 amounts to an increase of 6-8 dB in the recorded signal. This anomaly might be explained by an increase of 2-3 times in the R-value. A large number of solar-terrestrial effects could have caused this increase such as solar flares, geomagnetic phenomena and so on, but because the anomaly was observed only on the CZE signal it means that R must have varied only in the ionospheric zone in the north-eastern part of Italy (fig. 1). Such localised ionospheric variations lasting several weeks are unusual and no abnormal meteorological condition, explosions causing pollution or other factors which occurred during this period that might have explained it. The only perturbing event known to us was the strong Umbria-Marche seismic sequence and so it seems reasonable to relate this to the anomaly. The problem is to determine whether this anomaly was a post-seismic effect of the initial strong earthquakes from September 1997 to the end of December 1997 or whether it was a precursor of the final earthquake at March 26, 1998. There is a finite possibility that it is a post-seismic effect, but given that the anomaly appeared one and a half months after the earthquakes and that it decays just before the March earthquake (fig. 6a), the second possibility, that the anomaly is a precursor of the March earthquake, seems to be more realistic. In our view, modifications of the lower ionosphere produced by the emission of radon, ions, electromagnetic waves, etc. from the focal zone of the forthcoming earthquake may explain our observations of the CZE signal strength anomaly. We are puzzled as to why a premonitory anomaly appeared before the March 1998 earthquake (final strong shock) but not before the September 1997 main shock. We have no explanation for this but we note that the March 1998 earthquake was very unusual because it was characterised by a large focal depth ($\approx$ 50 km). In contrast the September 1997 earthquake was shallow, as is more common for seismic activity in Central Italy.

5. Conclusions

During eight years of measurements, we have observed four anomalous decreases and one anomalous increase in the electric field strength of LF radio signals. After the decreases, moderate ($3.0 \leq M \leq 3.5$) earthquakes occurred near the receivers (within 50 km) along the transmitter-receiver path and, as concomitant phenomenology, advection of warm air happened during the anomalous periods. After the increase, a strong ($M = 5.3$) earthquake occurred at more than 100 km from the receivers, along the transmitter-receiver path. The next step of this research will be a rigorous statistical analysis of the time series in order to confirm that the disturbances we observed are real anomalies. In this paper we have assumed this possibility and advanced the proposal that the previous anomalies are due to modifications in the troposphere (causing decreases) and in the ionosphere (causing increases), which are related to the preparatory phase of earthquakes. Of course, more data are needed because on the basis of a few observations one can only tentatively suggest that these are premonitory anomalies. However, if this pre-seismic behaviour of the LF signals is confirmed then this type of precursor would seem capable of giving information on the direction, and perhaps even the location, of a forthcoming earthquake.

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