Radio VHF Precursors of Earthquakes

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ORIGINAL PAPER

Radio VHF precursors of earthquakes

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Abstract On the basis of our analysis of a number of continuous observations made by the monitoring network on Crete, we assume that electrically active clouds are produced in an atmosphere above the sea on the eve of earthquake. These electrically active clouds, which occur at heights of 0.1–10 km, create the conditions for electrical discharges in an atmosphere that may be the source of the very high frequency (VHF) radio-emissions registered on Crete. We further suggest possible mechanisms of thunder electricity generation. We present the model of convection transport in which the first condition in the generation of thunder electricity is an atmosphere with a horizontal gradient of temperature. Base on this model, the occurrence of electrical charges on the surface of the sea and their transportation further upwards to heights of up to 10 km is due to pollution energy allocated within the bottom of the sea as gases and heat injection. The average flux density and power estimations of the VHF precursors were made for the Crete net situation to compare with published VHF data and radio star sources.

Keywords Atmosphere · Earthquake · Electrical discharges · Radio-emission · VHF precursors

1 Introduction

Several groups of researchers have recently reported on the occurrence of abnormal increases in electromagnetic noise intensity before or during earthquakes (see Fujinawa and Takahashi 1991; Hayakawa and Fujinawa 1994; Ruzhin and Depueva 1996). We report here on natural noise phenomena around 50 MHz, which is in the

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range close to the broadcasting frequency of audio and television transmitters, and our results of our investigation on the correlation between earthquakes around Crete and such natural noises at the very high frequency (VHF) band. These precursory HF/VHF signals have been observed and reported three times prior to our investigation:

1. Warwick et al. (1982) discussed the possibility that an 18-MHz radiation emissions observed in the decametric band about 6 days before the great Chilean earthquake (EQ) in 1960 was due to a stress-induced micro-fracture along the Chilean fault. These 18-MHz emissions of Warwick et al. (1982) represent the first reported earthquake radio observations in the decametric band. The emissions continued for a total duration of about 20 min, showing smooth intensity variations that lasted for several minutes.
2. Precursory VHF phenomena based on radar measurements and the monitoring of 74-MHz radio emissions from an astronomy radio source Swan A were reported for the 1988 Spitak (Armenian) earthquake by Voinov et al. (1992). The effective receiving area of the radio astronomical installation was 40 m^2 and the viewing direction was local zenith.
3. Both before and after the 1995 Kobe earthquake Maeda and Tokimasa (1996) observed unusual pulsed radio emissions at 22.2 MHz with a radio interferometer installed at the Nishi-harima Astronomical Observatory (NHAO) located about 77 km from the epicenter. Two horizontally polarized three-element Yagis were used for these observations. Each Yagi, having a gain of about 8 dB, was aimed toward the south at an elevation angle of about 40°.

A telemetric network was installed on Crete (South Aegean, Greece) in order to investigate the coexistence of electromagnetic and telluric variations observed prior to shallow and intermediate depth earthquakes. This network comprises four field stations on Crete which record the Earth's electromagnetic field variations. The variation in the number of VHF and VLF electromagnetic noises has been continuously observed since 1992 (Nomicos et al. 1995). $\lambda/2$ dipoles were used to observe variations in 41- and 53-MHz radiation emissions (VHF range), and continuous monitoring enabled the appearance of anomalous electromagnetic radiations prior to earthquakes to be monitored and collected during the period from October 1992 to December 1995. We report here new aspects of the basic conclusions (Ruzhin et al. 2000) drawn from regular observations of the VHF earthquake precursor emissions collected by the Crete network.

2 Earthquake VHF radio emissions monitored by the Crete network

Preliminary analysis of the Crete data revealed the presence of a VHF signal beyond (3–10 kHz) the VLF range 1–3 days prior to earthquake events (Nomicos et al. 1995). The long duration of these signals—from several hours up to 1 day—are shown in Fig. 1. As the island of Crete (Fig. 2) is a good distance removed from the industrial interference of Greece and Turkey, it is an ideal place for the reception of seismic-effective electromagnetic VHF radio emission. To make sure that the observation frequencies were silent, they were checked using a radio receiver for several months. A strong criterion for a pre-seismic electromagnetic signal (Nomicos

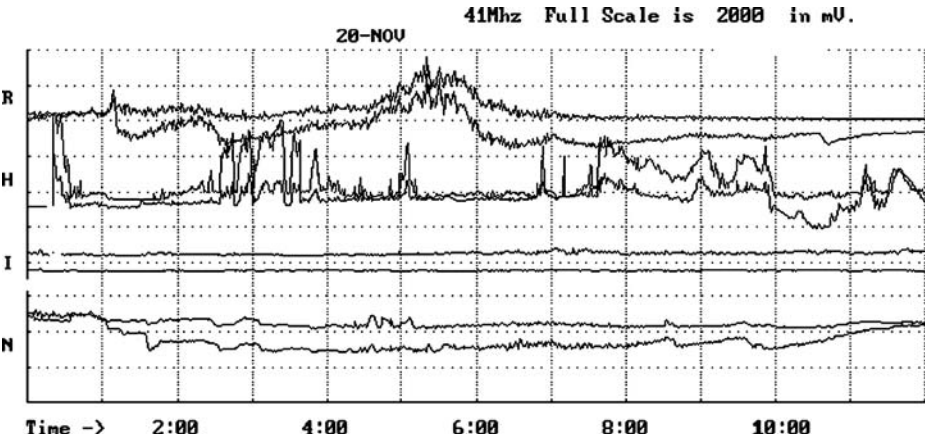


Fig. 1 The pre-seismic VHF signals for the November 21, 1992 earthquake ($M = 6.0$). The output voltage of the receivers presented is given on the *vertical axis*. Full scale is 2 V. *N*, *I*, *H* and *D* represent Nipos, Ierapetra, Heraklio and Drapania, respectively, the Crete monitoring stations

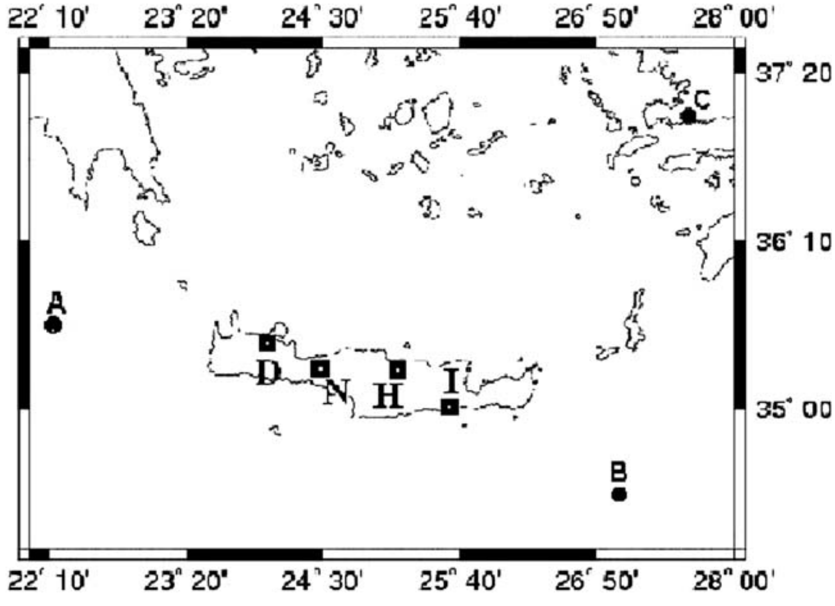


Fig. 2 Map of selected earthquake location and Crete net stations (see distance in Fig. 3). *A*—Earthquake of November 21, 1992 ($M = 6.0$), *B*—earthquake of July 29, 1995 ($M = 5.0$), *C*—earthquake of March 7, 1995 ($M = 5.0$)

et al. 1995) should be its simultaneous presence in both frequencies of each observation band, otherwise the signal could be artificial interference. The following list is a formulation, based on Ruzhin et al. (1999, 2000), of the peculiarities that distinguished the Crete VHF pre-seismic radio emissions from those reported previously:

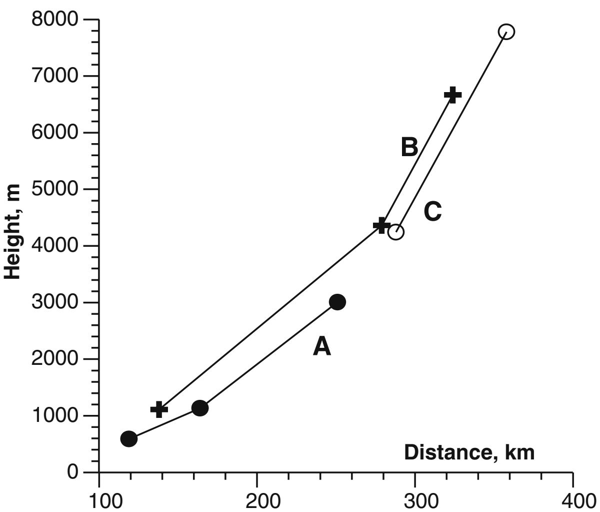
- The VHF signals were monitored on two frequencies of the VHF range (41 and 53 MHz) by two radio receivers and at several stations simultaneously.

- A signal was observed 1–3 days prior to the earthquake, did not depend on the position of the Sun and occurred both during the day and night. The duration of the signal varied from a number of hours to longer than 1 day.
- The precursory VHF signals were observed for a large number of earthquakes during a continuous monitoring period of more than 3 years (see table in Ruzhin et al. 2000).
- The signals were observed to precede earthquakes of moderate energy (all of earthquakes had a magnitude of more than 5.0 but did not exceed 6.0 on the Richter scale).
- The area of imminent earthquakes was under radio horizon and the range of distances between the epicenters of the earthquakes and the VHF receivers was 300–350 km (see Fig. 3).
- The spectrum band of the VHF precursory radiation exceeded 12 MHz.

It is important to note that VHF pre-seismic radio emissions from under seawater or from under the seabed are very unlikely because of the small propagation skin depth of seawater. As the epicenter of the earthquakes was under the seabed (see, for example, A and B events; Fig. 2)—i.e. under the thickness of water—we drew the conclusion that the radiating source of the HF precursor emissions was located above the sea (in the atmosphere). Figure 3 shows examples of the minimum heights of atmosphere locations of VHF-emitting sources estimated for radio emissions propagated over the horizon.

In our model (Ruzhin et al. 2000) the local conditions promoting the generation of thunder electricity are created due to convective transport and the separation of charges, the occurrence and time life of which are defined by processes both in the lithosphere and in an atmosphere. Thus, the occurrence of electrical charges in a surface of the sea and their transportation further up to a height of up to 10 km occurs due to energy allocated within the bottom of the sea as gases and heat. Adjiev et al. (2001) reported data on radio emissions generated during the development of convective thunderclouds. The first group of radiation is characteristic of different types of intra-cloud discharges. This radiation is observed from the moment a thunderstorm

Fig. 3 Distance dependence of expected heights of VHF-radiated points in the atmosphere that correspond to different stations of Crete net and selected earthquakes (see map)



cell originates up to its dissipation. The second type of radiation—according to (Adjiev et al. 2001)—is connected with discharges of cloud-to-cloud and cloud-to-ground types. This information is useful in understanding how the precursor VHF emission is probably generated during the earthquake preparation stage around Crete net.

3 The pre-thunder or non-lightning radio emission of a convective cloud

Pre-thunder electromagnetic radio emission spontaneously arises at the definitive stage of convection cloud development, when its upper boundary reaches a level of a natural crystallization of water drips (Adjiev et al. 2001). In an incipient stage of thunderstorm development, when the size and density of bulk charges in non-homogeneous electrical cloud structure are very small, intracloud discharges (between them) have a small-scale nature. The duration of each packet pulse of radio emission at this stage is in the order of 10–15 μs with three to four pulses per minute. During the development of the convection cloud there is a gradual increase in the density of the bulk charges and a strengthening of the activity of the thunderstorm. In particular, the intensity and duration of radio emission is augmented during the transition of convective clouds to a thunderstorm condition. The duration of pre-thunder conditions can reach 16 min, with average duration of 8 min. In 75% of the cases the duration of the pre-thunder state of a cloud is between 3 and 10 min; if the cloud has not passed into a thunderstorm condition by 14–16 min, it generally disintegrates. The duration of the separate cycles of thunderstorm activity ranges from several minutes to 1 h, with an average of 25 min. The radio emission of a cloud generated between lightnings can be classified (Adjiev et al. 2001) into two groups depending on the duration of signals:

- Radiation with a pulse duration of 20–150 μs;
- Radiation with a pulse duration of above 150 μs.

The maximum number of inter-lightning pulses occurs duringan initial step in the development of the mature stage of a thunderstorm cell. The data plotted in Fig. 4 demonstrate that the pulse duration of the radio emission increases with an approaching discharge. The points on the plot mark the mean time of the appearance of pulses of radio emission of a given duration relative to the time of inter-lightning discharges. The chart is based on the analysis of more than 2000 pulses of radio emission. Typical for all of the intervals between discharges is the pause of about some milliseconds before the discharge, when the pulses of radio emission from a cloud can barely be registered. Depending on the developmental stage of the thunderstorm from a convection cloud, the number of inter-lightning pulses of radiation varies from 4 up to 100 pulses and their duration falls within an interval of 10–130 μs. Similar observations have been reported by Lhermite and Krehbiel (1979), who found a discharge rate of 60 per minute in a relatively small cell of a storm (a large number of the events were intra-cloud discharges). Such high discharge rates are not unusual for a large storm, but their occurrence in small, individual cells of normal-sized storms is a new finding. The high-rate discharges have been shown to transfer relatively small amounts of charge (Lhermite and Krehbiel 1979), indicating that the high-rate sequences result from a large number of initiating

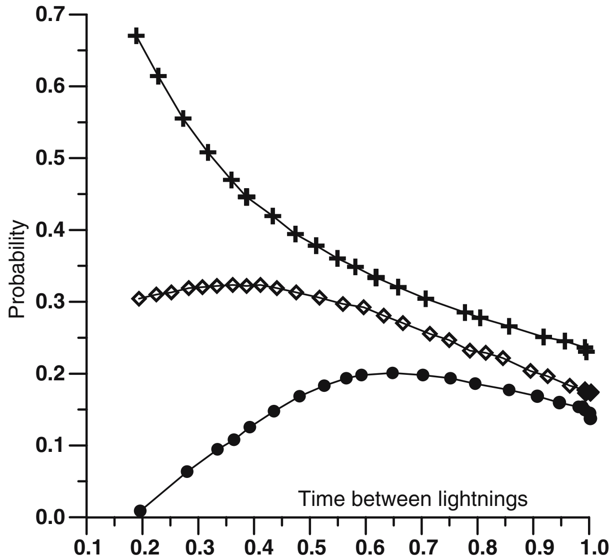


Fig. 4 The probabilities of the appearance of pre-thunder electromagnetic radio emissions with the given pulse duration in intervals between lightning (Adjiev et al. 2001) Pulse duration: *upper curve*—<30 μs, *middle curve*—30–40 μs, *lower curve*—40–50 μs

events rather than from super electrification of the cell. While the high-rate sequences have been observed only in subsequent cells of already electrified storms, it does appear that they are a common feature of such storms. As the band pass of selection was 25 kHz for half-power levels for receivers of the Crete network, indicating that such installations are able to receive the pulses of the first group of radiation emissions, which corresponds to intra-cloud discharges during the development of convective cells. The space monitoring by the radio occultation method will be useful to confirm the atmosphere nature of HF precursors. The payload of the COMPASS space mission included 41/53 MHz receivers for studying global distribution of natural and man-made electromagnetic emissions in the VHF range (Dokukin et al. 2000).

4 Seeps as an active source of gas injection

Using the hypothesis of the convection transport of precursor energy as a starting point (Ruzhin et al. 1999, 2000), we have tried to build a more realistic model. The atmosphere above the sea can be significantly influenced by gas injection during the pre-seismic period. This means that bottom sea gas injection appears to be a source of energy for atmospheric disturbances or earthquake precursors. To support this idea we present examples of sea bottom activity that which illustrate the validity of this assumption on energy transportation. The CRIMEA project (Klerkx 2002) focuses on the transfer of methane from submarine high-intensity methane seeps and outbursts in the sea floor of the Black Sea through the water column and into the atmosphere and aims at evaluating the possible contribution of these seepages and outbursts to changes in atmospheric composition and their possible impact on climate processes. Enormous amounts of methane are continuously being injected into the water of the Black Sea occur at various locations, generating large ascending methane plumes into the seawater. In some cases these methane plumes reach the sea surface and emit methane directly into the atmosphere; in other cases, sporadic huge outbursts have reached the sea surface to be accompanied by fire flashes and explosions (Klerkx 2002). Consequently, this location the perfect area for these studies as such bursts are significant but occur only episodically elsewhere. Near the coast of Georgia, the methane flux at the sea floor ranges between 1700 and 7000 l/m^2 per day. While we have no specific data on gas injection in the sea around Greece, based on the data of Klerkx (2002) gas production via bottom sea emissions may be uplifted to the atmosphere during the earthquake preparation stage (see also Hata et al. 1998). As a result, it can modify the distribution of the horizontal sea surface temperature to create conditions for the development of free sporadic convection cells above the area of the polluted sea. The injected gas components can also change the normal atmosphere composition above the earthquake zone during earthquake preparation.

5 Power estimation of precursory VHF emission

In this section we attempt to summarize current data on the power of the VHF precursor. Firstly, we estimate the electromagnetic power characteristic of the Crete net situation. If each elementary volume of earthquake precursor in the atmosphere emits the isotropic VHF radio waves, and there is no absorption within the radiated volume V, we can evaluate the radiation power of a single volume taking the value of a signal received by the Crete net monitors. The long-term observations of earthquake VHF precursors by the Crete net monitors have shown that, on an output of receivers (see Fig. 1), the voltage (an average value) reached about 1 V. If we use the actual parameters of the receiver as the starting point, the signal on an aerial (antenna) input should be not less than several micro-volts. Let us allow that the signal reception is implemented on a real design of the aerial (type: the half-wave vibrator, $\lambda/2$), we can then estimate the expected total power that should be radiated by an atmospheric precursor. The value of a signal on a receiving antenna is determined by the product of the strength of an electromagnetic field E at an installation site of the antenna and its effective height h_D:

$$E_A = E * h_D \tag{1}$$

The effective height of a symmetrical half-wave dipole is $h_D = \lambda/\pi$. Therefore, accordingly, we have

$$E_A = E * \lambda/\pi \tag{2}$$

For the point radiation of a precursor signal removed from the antenna on spacing interval R, it is possible to find power P, which provides the strength of an electrical field E in a point of a HF signal reception.

On the distance $R > \lambda$ from a radiation point, the amplitude of the electrical field (E_m) and magnetic field (H_m) components (field strength on the far zone) of a radio wave are presented by the relation $E_m/H_m = \sqrt{(\mu/\varepsilon)}=120\pi$ (for free space propagation, μ and ε are the magnetic and electric permitivity of vacuum constants); a power flux density Π (average value for the one period) is then obtained:

$$\Pi = E_{\mathrm{m}} * H_{\mathrm{m}}/2. \quad (3)$$

The Π is known as the Poynting vector of electromagnetic fields—the EM wave. It is the vector product of the electrical and magnetic fields of an electromagnetic wave, which are orthogonal-related and cophased. If the HF radiation propagates isotropically through a sphere surface of radius R, by equating this flow of power to an absolute value of vector Poynting, which is expressed through amplitude value E_{m} (where $E_{\mathrm{m}} = E * \sqrt{2}$) of the electric field component, we shall write a ratio:

$$P/4\pi R^2 = E_{\mathrm{m}}^2/240\pi \quad (4)$$

The result is an expression of the estimation of the source intensity of a signal E:

$$P = E_{\mathrm{m}}^2 R^2/60 = E^2 * R^2/30 \quad (5)$$

Taking Eq. 5 and substituting spacing interval R = 300 km (up to an epicenter of the earthquake; Fig. 3) and the experimental value of the electric field strength of the precursor signal (on a frequency of 50 MHz) of about 5 μV/m, we find the value of total radiated precursor power, which in our case will be only 0.075 W or 75 mW. The average flux density of the earthquake's HF precursors observed by Crete net receivers is expected to be more than 1.32×10^{-18} $\mathrm{Wm^{-2}\,Hz^{-1}}$. The precursor area with chaotic distribution of convective sources above a zone of pending earthquake is limited by radius R, defined by the classic Dobrovolsky formula (Ruzhin and Depueva 1996):

$$R = \exp M \text{ [km]} \quad (6)$$

Here, M is a magnitude of the future earthquake on a Richter scale.

It is possible to find the volume emissivity of the atmosphere layer and compare it to the radiation of the astronomical sources. If an atmospheric layer, in which the electric charges of mosaic structure are generated, has thickness D (from 100 m up to several kilometers), the radiated volume V of precursor can be written as

$$V = \pi R^2 * D = \pi * D(\exp M)^2 \quad (7)$$

For a future earthquake of magnitude (M) >5.0, an anticipated volume V of a precursor at atmosphere D ~ 1 km (Ruzhin et al. 2000)] will be $V = 6.9 \times 10^4$ km^3, and volume emissivity of the atmosphere layer, based on Eqs. 5 and 7, will be: (P/V) = 1.1×10^{-15} W/m^3 or 1.1×10^{-21} W/cm^3. Let us compare flux density for HF precursors of different earthquake regions. By taking into account the effect of the diffraction and the effective receiving area of the interferometer (44 m^2), the average flux density of the pulsed radiation at NHAO was estimated by Maeda and Tokimasa (1996) to be about 3×10^{-19} $\mathrm{Wm^{-2}\,Hz^{-1}}$. By further assuming that the radiation was emitted over 2π steradian, these same authors estimated that the average pulsed power over the bandwidth of 22.2 MHz must be about 0.20 W. Let us now assume that the emitting area is not shadowed geometrically by a mountain ridge (as supposed Maeda and Tokimasa 1996) and that the observed 22.2-MHz radio emissions constitute a direct signal (or free space propagation) from the atmosphere disturbance region generated above the Kobe or future epicenter, then the total emitted power should be roughly one tenth of the diffraction estimated power, or only about 20 mW. On the basis of data on the Spitak earthquake (Voinov et al. 1992), we conclude that the received pre-seismic signal of 74 MHz was of an atmospheric location, since the antenna beam direction was the local zenith (our calculation shows that sky radio source Swan A passed through the local zenith during the time of VHF observations). The precursor signal of 74 MHz was very high (up to the saturation point of the output level), but estimation of the total source power was non-valid as the geometry is not simple. Nevertheless, the average anomaly of the VHF flux density is comparable with the radio star emission value, or has to be more than 10^{-19} Wm^{-2} Hz^{-1}.

6 Discussion: Mechanism of pre-seismic thunder-like electricity and VHF radiation

The proposed model of VHF radiation that occurs on the eve of an earthquake (Ruzhin et al. 2000) is based on natural processes of convective transportation and charge separation that result in the generation of cloud electricity. This convection is generated by the mosaic distribution of temperatures of the sea bottom surrounding the future epicenter position (source of convection in sea water) and on the sea surface (source of convection in atmosphere). Tronin (1999) demonstrated that seismic activity is accompanied by anomalies in the Earth's infrared radiation (detected by satellites in some seismically active regions). Observations show that these anomalies have an irregular spatial (mosaic) and temporal (twinkle) structure. Sporadically generated convective cells, which are distributed inside of an earthquake preparation zone, create the electrical active volumes in the atmosphere in a manner similar to the simulation of natural thunder/lightning. However, the observed differences are significant with respect to both the horizontal scale and the lifetime scale. For seismogenic convection, the horizontal size of the area occupied by the mosaic cells depends upon the magnitude of imminent the earthquake and exceeds the thunderstorm region (sometime it is more than 1000 km). The lifetime of seismogenic anomalies significantly exceeds the duration of a thunderstorm (which is usually no longer than 1–2 h). The seismogenic thunderstorm activity reported first by Voinov et al. (1992) was observed by meteo-radar (in the direction of the future epicenter of the Spitak earthquake) and lasted for a few hours each day in the period preceding the earthquake (1–3 days). The height range of the target reflections was 5–15 km. This long-term atmosphere phenomenon was accompanied by VHF radiation at 75 MHz. The Crete VHF net observations (Nomicos et al. 1995) also showed a similar long lifetime (Fig. 1) in comparison with the duration of a typical thunderstorm. It is important to note that pre-seismic thunder electricity is not always accompanied by lightning. This is a stage of convective cloud development when the conditions for leader discharges may be not realized. For normal lightning the length of the leader jumps must be in range of 30–90 m.

Beituganov (1990) has recently presented the final results of his investigation on non-lightning radio emission of convective clouds in the 0.1- to 300-MHz frequency range. Such radio emissions were occasionally observed even earlier than the first lightning discharge. Moreover, the generation of radio emissions inside the electrical active volumes in the atmosphere was found not to provide a condition that would enable the convective cloud to develop up to the thunder (lightning) stage. It was shown that the power of pre-lightning radioemission or continuous EM noise could be result of the additive effect of the line currents that are generated by different types of corona discharge:

- Avalanche corona;
- Streamer corona.

The latter produces more intensive currents (up to three or four orders of magnitude), and so appears to be a more effective source to generate high-power radioemissions. Therefore, the corona discharge produces maximum currents if it has the streamer form – the longer the streamer, the more intensive the current. An example of continuous EM noise generation is the radioemissions of the hail cloud reported by Stenford et al. (1973). In our opinion, the assumed source of EM radiation of the meter-length band (VHF) could be the line discharge currents (in convective clouds these are generated above the EQ) of a scale that corresponds to a quarter or a half of the radiated wavelength. A more probable candidate is the streamer electric discharge that does not reach the minimum length of the stable leader discharge or the length scale that does not exceed 5–6 m. Streamers are effective at the pre-breakdown stage of spark or corona discharges. The total radiated power increases proportionally to the relation between the size of the region occupied by convective cells and their characteristic scales.

7 Conclusion

All of the results discussed in this article support the interpretation of the VHF data of the Crete net stations as being signals received from that atmosphere that appear 1–3 days prior to imminent earthquakes. The average anomaly of the VHF flux density is comparable with the emissions of the radio stars, or more than 10^{-19} Wm^{-2} Hz^{-1}. We have made an attempt to explain the published data on VHF precursors from one (definite) position, and in doing so we have reached a different conclusion as that discussed by Kapiris et al. (2002). In our model, due to convective transportation and the separation of charges, the local conditions promoting the generation of thunder electricity are created, with the processes that occur in both the lithosphere and in an atmosphere defining its occurrence and time of life. With respect to the relation between an earthquake and normal lightning, Oike and Yamada (1994) find a tendency for lightning to be correlated with shallow inland earthquakes. The time sequence of earthquakes, especially the shallow earthquakes in the Wakayama region, coincides with that of lightning in and around the region. The space monitoring by the occultation method will be useful to confirm the atmosphere nature of VHF precursors. The payload COMPASS mission included 41/53 MHz receivers aimed at studying global distribution of electromagnetic emissions in VHF range.

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