Response to Reviewer R.V. Donner

We would like to thank the Reviewer for his efforts in reviewing our article in detail as well as for his constructive comments, which we find helpful in improving the quality of our paper. We will take into account all his comments in the revised version our manuscript by changing appropriately the corresponding parts of text and figures.

In the following we present a detailed report, containing all answers / actions to be taken and references to the intended manuscript changes. Each one of our replies is given in blue-colored fonts, following the corresponding Reviewer's comment (in `black colored fonts`). In the replies text, **bold fonts** indicate text to be inserted / changed.

"The manuscript is based on pre-seismic MHz electromagnetic recordings as well as seismicity data prior to two recent earthquakes at Cephalonia Island (Greece). The systematic existence of distinct electromagnetic signatures prior to at least a certain not yet fully specified class of earthquakes is still a subject of ongoing debates, even though a lot of observational evidence has been provided during the last years. Accepting the latter findings, it is valuable to study the dynamical properties of such emissions and, more precisely, their temporal changes prior to earthquakes in order to contribute to a better understanding of the underlying processes in the solid ground. It is important to note that the present work is far from claiming that relevant dynamical signatures suggested as earthquake precursors can be systematically applied as early warning signals of upcoming events - rather, they should be used as a posteriori diagnostics. In order to avoid possible confusion raised by the utilization of the term "percursor" in the title of the paper, I would recommend to make this point even more explicit in the introduction of the manuscript."

Reply:

As the Reviewer has noticed, we have already pointed out our view that this article, as well as all our previous studies, aims not at EQ prognosis but at a better understanding of the processes preceding a strong EQ. In this direction, we have included the following text in the first version of our manuscript:

"*…However, the understanding of the physical processes involved in the preparation of an EQ and their relation to various available observables is an open scientific issue. Much effort still remains to be paid before one can claim clear understanding of EQ preparation processes and associated possible precursors.*

As it has been repeatedly pointed out in previous works (e.g., Eftaxias et al., 2013; Eftaxias and Potirakis, 2013, and references therein), our view is that such observations and the associated analyses offer valuable information for the comprehension of the Earth system processes that take place prior to the occurrence of a significant EQ. As it is known, a large number of other precursory phenomena are also observed, both by ground and satellite stations, prior to significant EQs. Only a combined evaluation of our observations with other well documented precursory phenomena could possibly render our observations useful for a reliable short-term forecast solution."

However, we will also add text in the first paragraph of the introduction of the revised version of our manuscript in order to make this point even more explicit. The specific part of the text was originally "…The possible relation of the field observed fracture-induced electromagnetic emissions (EME) in the frequency bands of MHz and kHz, associated with shallow EQs with magnitude 6 or larger that occurred in land or near coast, has been examined in a series of publications (e.g., Eftaxias et al., 2001, 2004, 2008, 2013; Kapiris et al., 2004; Karamanos et al., 2006; Papadimitriou et al., 2008; Contoyiannis et al., 2005, 2013, 2015; Eftaxias and Potirakis, 2013; Potirakis et al., 2011, 2012a, 2012b, 2012c, 2013, 2015; Minadakis et al., 2012a, 2012b), while a four-stage model…", it will be changed to "…The possible relation of the field observed fracture-induced electromagnetic emissions (EME) in the frequency bands of MHz and kHz, associated with shallow EQs with magnitude 6 or larger that occurred in land or near coast, has been examined in a series of publications **in order to contribute to a better understanding of the underlying processes** (e.g., Eftaxias et al., 2001, 2004, 2008, 2013; Kapiris et al., 2004; Karamanos et al., 2006; Papadimitriou et al., 2008; Contoyiannis et al., 2005, 2013, 2015; Eftaxias and Potirakis, 2013; Potirakis et al., 2011, 2012a, 2012b, 2012c, 2013, 2015; Minadakis et al., 2012a, 2012b), while a four-stage model…"

"Scientific comments:"

"1. In all applications of MCF, I wonder about the fitting procedure and model selection. Equation (3) presents a statistical model to be fitted to data that does not provide direct access to proper parameter estimates by simple regression in log-log space. Instead, proper parameter estimates for p2 and p3 would require a "clean" maximum likelihood approach. What is the authors take on this? In particular, one could formulate the identification of critical windows as a model selection problem of comparing the statistical models with p3=0 and p3>0 by means of suitable penalized-likelihood criteria or similar approaches. I don't find any details on the parameter estimation in the manuscript, but think that since the distinction between the latter cases is an important part of the present analysis, the best and most robust statistical methodology should be applied at this point."

Reply:

We agree that not enough information is given about the fitting process and this could lead to puzzling the reader. In order to avoid such a situation, we are going to appropriately revise our manuscript. We note that the model of Eq. (3) is adopted following the reasoning described in the already cited reference (Contoyiannis and Diakonos, 2007). In the revised manuscript we will shortly explain why we selected this model rather than just providing a citation to the specific paper. Specifically, we intent to add the following text, shortly after Eq. (3):

"**Note that the choice of the function $\rho(l)$ of Eq. (3), which combines both power-law and exponential decay, to model the distribution of waiting times was deliberately made in order to include both these fundamentally different behaviors, i.e., the critical dynamics (Contoyiannis et al., 2002) and the complete absence of specific dynamics (stochastic processes) (Contoyiannis et al., 2004b), respectively. Of course, the specific function also models intermediate behaviors (Contoyiannis and Diakonos, 2007).**

In applying the MCF the corresponding factors of $\rho(l)$ appear to be competitive: any increase of the p_2 exponent value corresponds to a p_3 exponent value reduction and vice versa. However, this is expected because, for example, any increase of the value of p_3 exponent signifies the departure from critical dynamics and thus the reduction of p_2 exponent value. What is interesting to us is to apply MCF analysis to observe this competition in the case of pre-earthquake EME time-series and see whether the obtained exponent values are consistent with those of MCF analyzes performed on other time-series with large statistics which are considered as references for the application of our method. This competition can be observed even within the critical windows as shown in Figs. 2 (d) and 3 (d)."

Concerning the fitting of the distribution of laminar lengths (waiting times) to the function $\rho(l)$ of Eq. (3), this is directly performed using the Levenberg-Marquardt algorithm, while the fitting criterion is the chi-square minimization. The fitting is not done in log-log space (as for example one does in order to calculate the DFA a-exponent). In order to clarify this issue, the following text will be added in the second paragraph of Section 3 (just before the proposed position for Fig. 2). The specific part of the text was originally "Fig. 2c portrays the obtained laminar distribution for the end point $\phi_l = 655mV$, that is the distribution of waiting times, referred to as laminar lengths l, between the fixed-point ϕ_o and the end point ϕ_l, as well as the fitted function $f(l) \propto l^{-p_2} e^{-p_3 l}$ with the corresponding exponents $p_2 = 1.35$, $p_3 = 0.000$ with $R^2 = 0.999$.", and will be enhanced as: "Fig. 2c portrays the obtained **distribution of laminar lengths** for the end point $\phi_l = 655mV$, that is the distribution of waiting times, referred to as laminar lengths l, between the fixed-point ϕ_o and the end point ϕ_l, as well as the fitted function $f(l) \propto l^{-p_2} e^{-p_3 l}$ with the corresponding exponents $p_2 = 1.35$, $p_3 = 0.000$ with $R^2 = 0.999$. **Note that the distribution of laminar lengths is directly fitted to the specific model using the Levenberg-Marquardt algorithm, while the fitting criterion is the chi-square minimization. The fitting is not done in log-log space; the axes of Fig. 2c are logarithmic for the easier depiction of the distribution of laminar lengths.**"

"2. For a self-sustained description of the NT method in Sect. 2.2, some minor points should be added to this section: (i) What exactly is Phi (p. 1597, l. 12)? I don't find a corresponding explanation. (ii) Please provide an explicit definition (with equation?) of <D>. (iii) The "theoretical estimation"(?) of the normalized power spectrum (p. 1598, l.10) is not fully clear. Please provide a few more details. (iv) The introduction of a magnitude threshold to NT (p. 1598, l.14) comes very ad hoc; some brief motivation/explanation/background would be desirable."

Reply:

Clarifications on all the raised points will be made in the revised manuscript:

(i) The text at the specific point was: "…, $\varpi = 2\pi\varphi$, with φ the natural frequency,…", A clarification will be added to the manuscript and the specific point will read: "…, $\varpi = 2\pi\varphi$, with φ **standing for the frequency in natural time, termed "natural frequency"**, and $p_k = Q_k \big/ \sum_{n=1}^{N} Q_n$ corresponds to the k^{th} event's normalized energy. **Note that, the term "natural frequency" should not be confused with the rate at which a system oscillates when it is not driven by an external force; it defines an analysis domain dual to the natural time domain, in the framework of Fourier–Stieltjes transform (Varotsos et al., 2011b).**"

(ii) & (iii) The initial text was: "The "average" distance $\langle D \rangle$ between the curves of normalized power spectra $\Pi(\varphi)$ of the evolving seismicity and the theoretical estimation of $\Pi(\varphi)$ for $\kappa_1 = 0.070$ should be smaller than 10^{-2};…";it will be improved as: "The "average" distance $\langle D \rangle$ between the curves of normalized power spectra $\Pi(\varpi)$ of the evolving seismicity and the theoretical estimation of $\Pi(\varpi)$, $\boldsymbol{\Pi_{critical}(\varpi) = (18/5\varpi^2) - (6\cos\varpi/5\varpi^2) - (12\sin\varpi/5\varpi^3)}$, $\boldsymbol{\Pi_{critical}(\varpi) \approx 1 - \kappa_1 \varpi^2}$, for $\kappa_1 = 0.070$ should be smaller than 10^{-2}**, i.e.,** $\boldsymbol{\langle D \rangle = \langle |\Pi(\varpi) - \Pi_{critical}(\varpi)| \rangle < 10^{-2}}$;…"

(iv) The following text will be added at the end of Section 2, to explain the use of magnitude threshold:

"**Note that in the case of NT analysis of foreshock seismicity, the introduction of magnitude threshold,** M_{thres}**, excludes some of the weaker EQ events (with magnitude below this**

threshold) from the NT analysis. On one hand, this is necessary in order to exclude events for which the recorded magnitude is not considered reliable; depending on the installed seismographic network characteristics, a specific magnitude threshold is usually defined to assure data completeness. On the other hand, the use of various magnitude thresholds, M_{thres}, offers a means of more accurate determination of the time when criticality is reached. In some cases, it happens that more than one time-points may satisfy the rest of NT critical state conditions, however the time of the true coincidence is finally selected by the last condition that "true coincidence should not vary upon changing (within reasonable limits) either the magnitude threshold, M_{thres}, or the area, used in the calculation.""

"3. In Sect. 3, the authors study "stationary" time series segments. How has the stationarity been tested? Just by visual inspection or in a strict mathematical sense?"

Reply:

We thank the Reviewer for the opportunity to clarify this point. Stationarity is always tested in a strict mathematical sense before the application of the MCF analysis. A cumulative stationarity test, which to our opinion is a proper and adequate stationarity test for the stationarity requirements of the MCF method, is always performed. Such examples, of executing the specific cumulative stationarity test on time-series excerpts before applying the MCF method, can be found in (Contoyiannis et al., 2004a, 2005, 2010; Contoyiannis and Eftaxias, 2008; Potirakis et al., 2015). In order to clarify this point we will add the following sentence at the end of Section 2.1: "**Note that in order for a time-series to be possible to be analyzed by the MCF, it should at least present cumulative stationarity. Therefore, a cumulative stationarity test is always performed before applying the MCF method; examples can be found in already published articles (e.g., Contoyiannis et al., 2004a, 2005, 2010; Contoyiannis and Eftaxias, 2008; Potirakis et al., 2015).**"

"4. One very interesting fact is the observation of VLF anomalies for the same earthquakes as studied in the present work (Skeberis et al., 2015). I would be curious to learn about the authors' opinion on whether (and how) this kind of signal could be integrated with their four-stage model. Which stage could be accompanied by such seismic-ionospheric disturbances, and under which general conditions?"

Reply:

The VLF anomalies belong to the class of precursors that are rooted in anomalous propagation of EM signals over epicentral regions due to a pre-seismic Lithosphere-Atmosphere-Ionosphere (LAI) coupling (Liu et al., 2000; Ouzounov and Freund, 2004; Uyeda et al., 2009). During quiet periods, there is a standard diurnal variation of the EM data (periodic variation where the main period is ~24h). The records refer to the Earth's ionosphere waveguide propagation of natural EM emissions. Any change in the lower ionosphere due to an induced pre-seismic LAI-coupling may result in significant changes in the signal propagation and consequently in the signal received at a station. Therefore, the emergence of an ionospheric EM anomaly is recognized as a strong perturbation of the characteristic bay-like morphology in the chain of daily data.

According to our view, the observation of VLF anomalies, seems to be associated with the EQ preparation phase happening during the first stage of our proposed four stage model, i.e., during the phase that the critical MHz EME are observed. We focus on the fact that ionospheric precursors appear a few days before the earthquake occurrence and disappear before the earthquake occurrence exactly as it happens in the case of the preseismic MHz EME. Pulinets et al. (2003) have provided a strong evidence for occurrence of ionospheric precursors before the main shock: ionospheric precursors within 5 days before the main seismic shock have been registered in 73% of the cases for earthquakes with magnitude 5, and in 100% of the cases for earthquakes with magnitude 6.

The generation of a preseismic ionospheric anomaly is rooted in physical and chemical transformations that occur in the preparation (activation) zone of an impending earthquake. Its observation implies that the preparation zone is extended up to the surface of the Earth in an extensive spatial region. We recall that we refer to the surface earthquakes which occur on land with magnitude 6 or larger. For such events the aforementioned requirement is valid during the first stage of our proposed four-stage model. Indeed, the conception of the earthquake “preparation zone” was developed by different authors (Pulinets and Boyarchuk, 2004 and references there in). In general, this is an area, where local deformations connected with the source of the future earthquake are observed. According to the dilatation theory (Scholz et al., 1973; Myachkin et al, 1975), formation of the cracks happens within the preparation zone and will be accompanied by physical and chemical changes (Rikitake, 1976; Mogi, 1985; Sobolev 1993; Pulinets and Boyarchuk, 2004). According to Dobrovolsky’s formula, the earthquake preparation zone radius is of the order of 380 km for magnitude 6. Kossobokov et al. (2000) obtained the value of the preparation zone through a new formula that leads to estimations that is in agreement with that performed by Dobrovolsky’s formula. The theory of criticality has been also accepted as an approach concerning the scale of earthquake preparation (or activation in other publications) zone. This approach leads to the same scale parameters as the dilatation (Kossobokov et al., 2000). An approach in terms of criticality leads to the conclusion that for an earthquake with magnitude 6 the foreshock activity is extended up to a critical radius of ~ 120 km (Bowman et al., 1998). Please note that the specific mechanism of Levy flight that the MHz EM precursor follows (Contoyiannis, and Eftaxias, 2008) “has no characteristic scale”. This means that the microcracking process is expected to extend to very long distances, up to the limits of the system. In our case this means that microcracking propagates up to the surface of the Earth.

The disappearance of both MHz and ionospheric anomalies before the earthquake occurrence is also in agreement with the proposed four-stage model. The appearance of “symmetry breaking” at the tail of the first stage reveals the transition from the phase of non-directional, almost symmetrical, cracking distribution in an extensive area to a directional localized cracking zone; the completion of the “symmetry breaking” implies that the rupture process has already been obstructed along the backbone of strong asperities distributed across the surfaces of the main fault. The ‘’siege” of asperities has started. The strong localization of fracture process leads to the corresponding localization of the induced physical and chemical transformations which justifies the disappearance of both MHz and ionospheric anomalies before the earthquake occurrence.

Finally, we should also note that the beyond VLF anomalies, the observed prseismic ULF anomalies are also associated with the EQ preparation phase corresponding to the first stage of our proposed four-stage model (Hayakawa et al., 2015a,b; Contoyiannis et al., 2016).

"Technical comments:"

"1. The third and second last paragraphs of the Introduction provide a very (probably unusually) detailed summary of the findings of the present paper, which would better fit to the conclusions section. In the introduction, much less details should be given."

Reply:

The specific part of the Introduction will be significantly shortened (from 16 lines to 6 lines), while parts of it will be moved to the Discussion – Conclusions section. The specific part in the revised form will read: "Moreover, we analyzed the foreshock seismic activity using the NT method; the obtained results indicate that seismicity also presented critical characteristics before each one of the two important events. This result implies that the observed EM anomaly and the associated foreshock seismic activity might be considered as "two sides of the same coin". Last but not least, one day before the occurrence of EQ2, and five days after the corresponding critical EME signal, tricritical characteristics were revealed in the EME recorded by the Cephalonia station.
The remainder of this manuscript is organized as follows: …"

"2. p.1593, l.5: Terming "critical phenomena" as a "model" might be a wording that one could discuss about. Some minor rephrasing of the corresponding sentence would help avoiding possible misunderstandings."

Reply:

We will rephrase this point. In the first version of our manuscript it was: "Critical phenomena have been proposed as the likely model to study the origins of EQ related EM fluctuations,…" and in the revised it will be: "Critical phenomena have been proposed as the likely **framework** to study the origins of EQ related EM fluctuations,…"

"3. p.1593, l.13: What exactly is meant by "multiply" here?""

Reply:

We will rephrase this point. In the first version of our manuscript it was: "…which, then, progressively grow and multiply, leading to cooperative effects." and in the revised it will be: "…which, then, progressively grow and **proliferate**, leading to cooperative effects."

"4. p.1593, l.16: The terms short vs. long range correlations are typically related to a distinction between exponential and algebraic (power-law) decay of correlations with increasing distance. Is this what is meant here, or do the authors simply refer to increasing spatial correlation lengths?"

Reply:
Yes, we refer to the distinction between exponential and power-law decay of correlations with increasing distance, which actually corresponds to the critical phase.

"5. p.1595, ll.17-18: "forming the distribution" sounds a bit strange."

Reply:
We will rephrase this point. In the first version of our manuscript it was: "…can be estimated by forming the distribution of laminar lengths and fitting it to a function $\rho(l)$…", and in the revised it will be: "…can be estimated by **fitting the distribution of waiting times (laminar lengths)** to a function $\rho(l)$…"

"6. The term "laminar distribution" (p. 1599, l. 13, as well as several figure captions) is short but rather imprecise. I recommend using a longer but precise term here."

Reply:
We will substitute the term "laminar distribution" with the term "**distribution of laminar lengths**" throughout the manuscript. For example, a part of the text that initially was "Fig. 2c portrays the obtained laminar distribution for the…", in the revised it will be: "Fig. 2c portrays the obtained **distribution of laminar lengths** for the…"

"7. The fourth paragraph of Sect. 3 is an almost literal repetition of the second one with just numbers changed. Just concentration on the differences between the two signals would allow shortening the results on the second one (Fig. 3) considerably. In the same spirit, it is not necessary to have almost identical figure captions in all figures using the MCF. Just give all details once and then refer to the caption of the first of these figures, emphasizing only the differences."

Reply:
The fourth paragraph will be considerably shortened (from 13 lines to 4 lines) by revising it in the direction pointed out by the Reviewer, and will reads: "The **application of the** MCF analysis on the specific time series (cf. Fig. 3), revealed that the criticality conditions, $p_2 > 1$ and $p_3 \approx 0$, are satisfied for a wide range of end points ϕ_l**, for this signal too. In other words, this signal has also embedded the power-law decay feature that indicates intermittent dynamics, rendering it a CW.**".
The figure captions of Figs. 3, 4, 5 and 7 will be shortened as advised by the Reviewer. For example, the caption of Fig. 5, in its revised version will reads: "**Figure 5.** (a) The 18,000 samples long critical window of the MHz EME that was recorded before the Cephalonia $M_w = 5.9$ EQ at the Zante station**; (b), (c), and (d) are similar to the corresponding parts of Fig. 2. In Fig. 5c, the distribution of laminar lengths corresponds to the end point** $\phi_l = 400mV$"

"8. Some sentences in the conclusions are literal repetitions from the introduction (e.g., the disclaimer regarding the four-stage conceptual model). I strongly recommend avoiding such self-repetitions. Content-wise recapitulation of results is okay, but just copy and paste sentences should be avoided."

Reply:

The Discussion - Conclusions as well as the Introduction will be revised so as to limit the self-repetitions. For instance, the phrase: "Note that the specific four-stage model is a suggestion that seems to be verified by the up to now available MHz-kHz observation data and corresponding time-series analyzes, while a rebuttal has not yet appeared in the literature." that has been used as an example by the Reviewer will be deleted from the Introduction. Please also refer to our reply to technical comment 1.

"9. In Fig. 1, it is really hard to see the different symbols in front of the green background. Just using the land contours without filling would present a much better visualization option. The same also applies to Figs. 8, 9 and 11."

Reply:

We will improve Figs. 1, 8, 9 and 11 by removing the green filling from the land parts of the maps. The revised Figures will be:

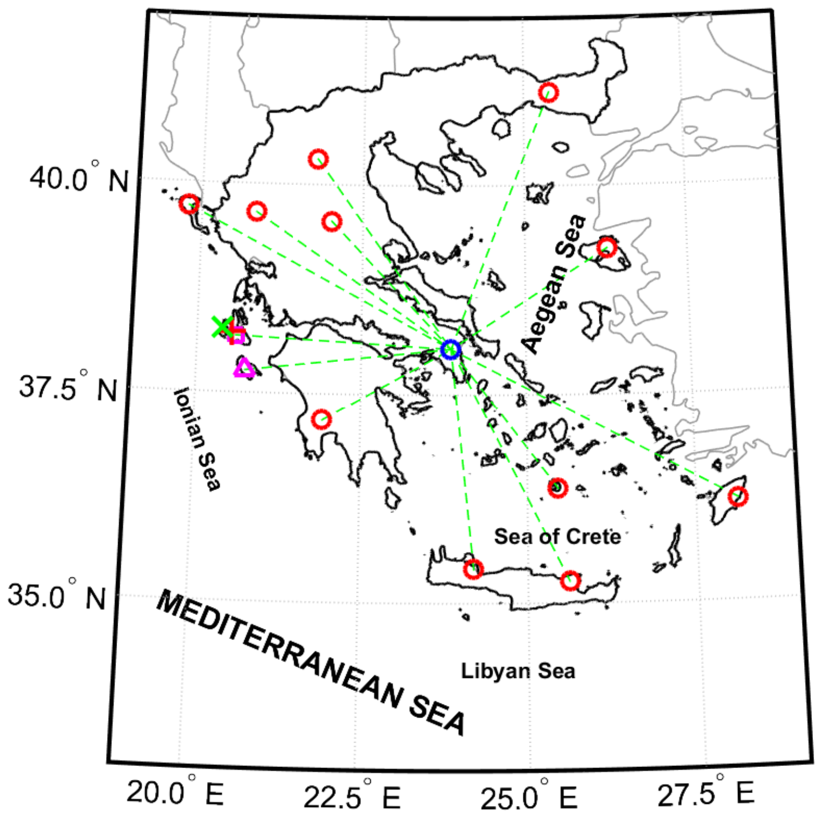

40.0° N
37.5° N
35.0° N
20.0° E
22.5° E
25.0° E
27.5° E
Aegean Sea
Ionian Sea
Sea of Crete
MEDITERRANEAN SEA
Libyan Sea

Fig. 1:

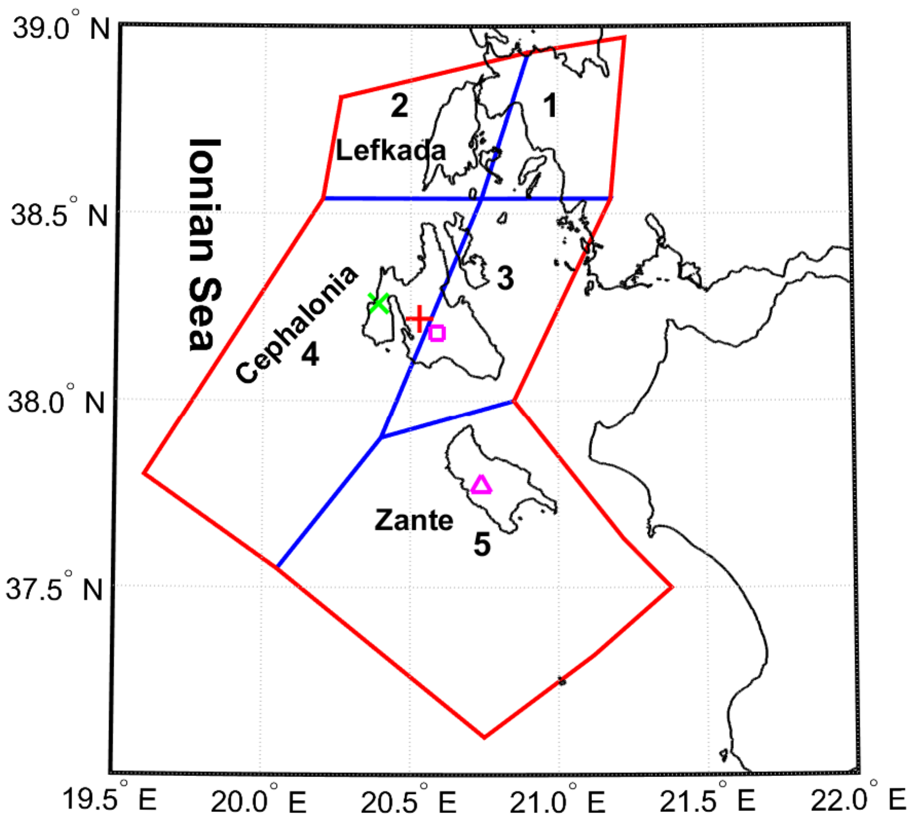

39.0° N
38.5° N
38.0° N
37.5° N
19.5° E
20.0° E
20.5° E
21.0° E
21.5° E
22.0° E
Ionian Sea
Lefkada
Cephalonia
Zante
1
2
3
4
5

Fig. 8:

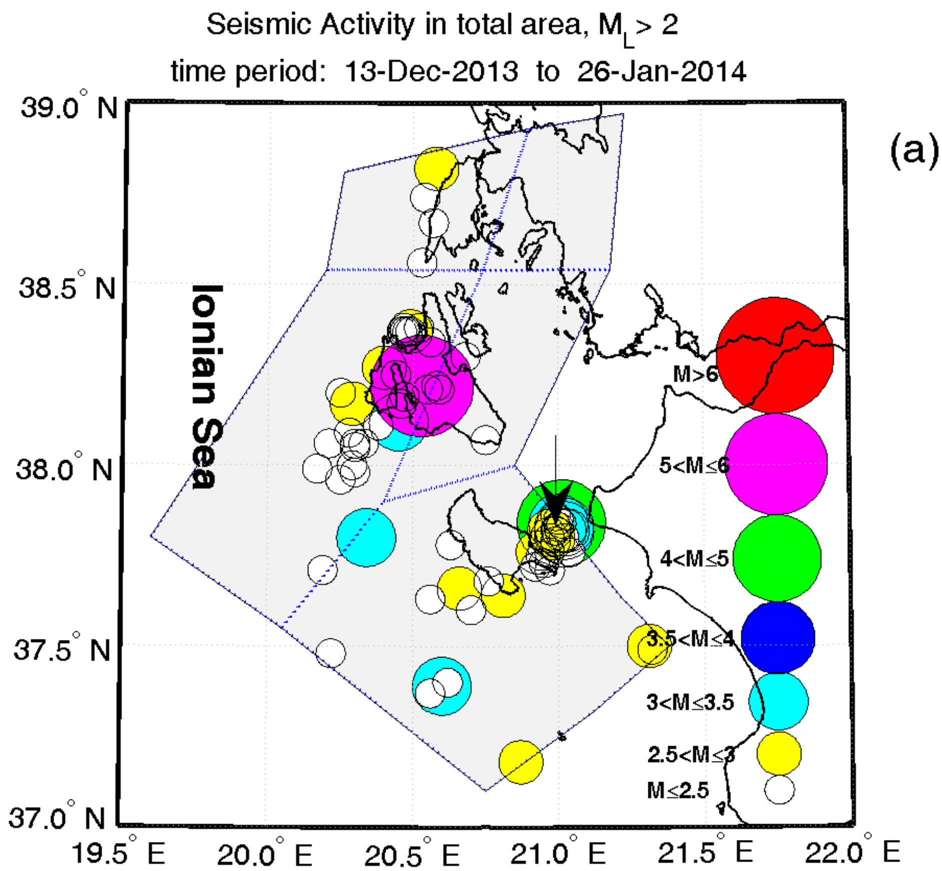

Seismic Activity in total area, $M_L > 2$
time period: 13-Dec-2013 to 26-Jan-2014
(a)
Ionian Sea
39.0° N
38.5° N
38.0° N
37.5° N
37.0° N
19.5° E
20.0° E
20.5° E
21.0° E
21.5° E
22.0° E
M>6
5<M≤6
4<M≤5
3.5<M≤4
3<M≤3.5
2.5<M≤3
M≤2.5

Fig. 9a:

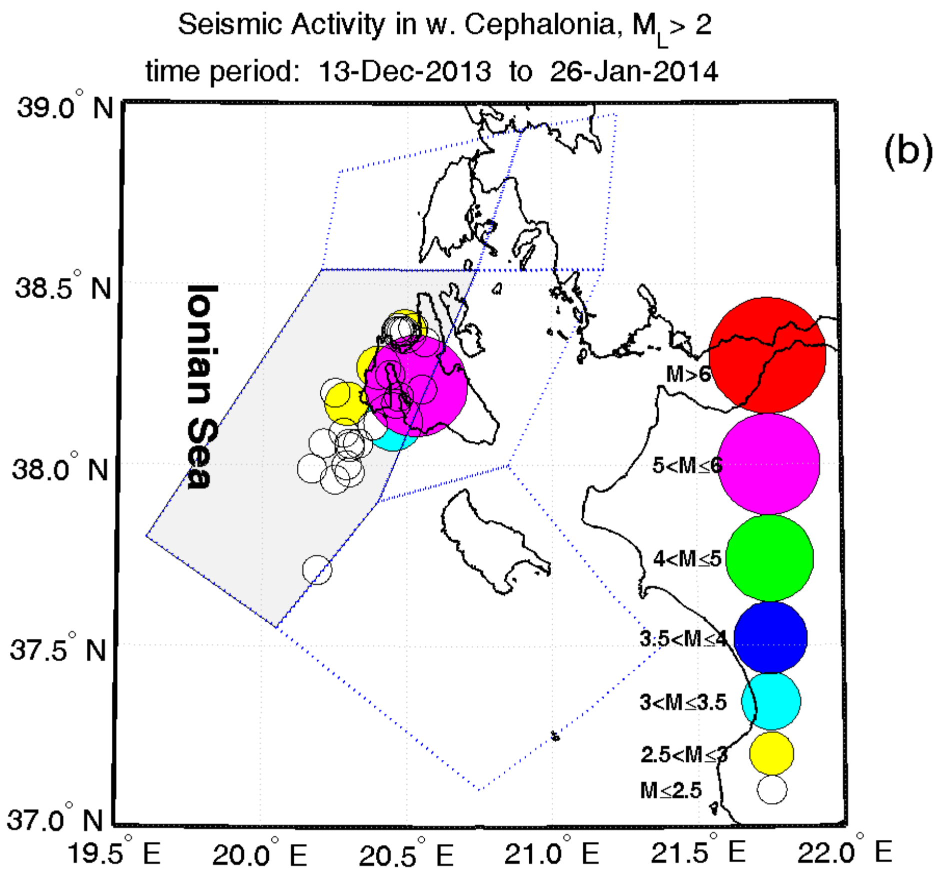
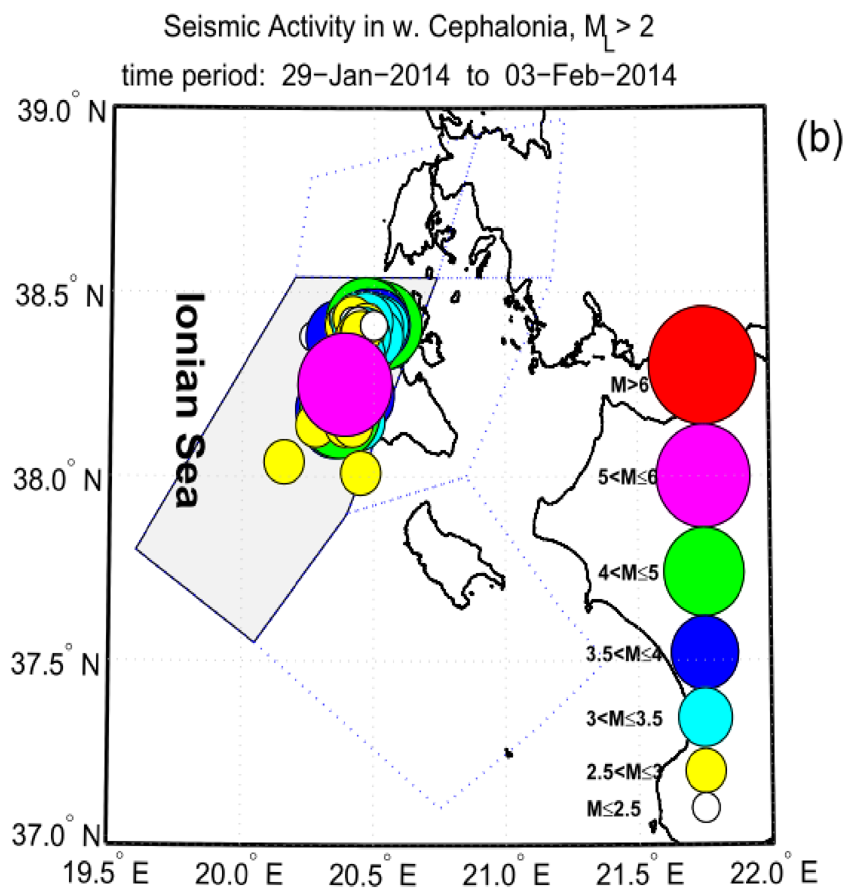

Seismic Activity in w. Cephalonia, $M_L > 2$
time period: 13-Dec-2013 to 26-Jan-2014
(b)
Ionian Sea
39.0° N
38.5° N
38.0° N
37.5° N
37.0° N
19.5° E
20.0° E
20.5° E
21.0° E
21.5° E
22.0° E
M>6
5<M≤6
4<M≤5
3.5<M≤4
3<M≤3.5
2.5<M≤3
M≤2.5

Fig. 9b:

Fig. 11b:



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