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New tool for the spatio-temporal variation analysis of seismic parameters

G. A. Papadopoulos[1] **and I. Baskoutas**[2]

[1]Earthquake Planning and Protection Organization, Seismotectonic Division, Xanthou 32, 154 51 Athens, Greece
[2]Institute of Geodynamics, National Observatory of Athens, 118 10 Athens, Greece

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Abstract. In this paper a new research tool called FastBEE (Fast Estimation of Expected Big Earthquake) is proposed, for the analysis of three basic seismic parameters, (the number of earthquakes N, b-value, and the seismic energy released in the form $\log E^{2/3}$), in order to examine their spatio-temporal variation behavior. The developed research tool is suited to analyze earthquake catalogs and it comprise new interactive visualization techniques for the exploration of the results. The tool was tested in several seismic active areas of the Hellenic territory and a case study of its applicability is presented.

It is observed that the results of the seismicity parameters analysis show a clear temporal fluctuation, with respect to their mean values. Such a behavior can be interpreted as the result of the geodynamic process acting in the region. In several cases the observed significant changes can be related to strong earthquakes, so that they can be considered as precursor indicating the preparation stage for an impending strong earthquake activity.

1 Introduction

Extensive researches on the general characteristics of seismicity, in terms of basic characteristics of seismic parameters and in different space and time scale has been presented till now. The importance of the observations and the results obtained for the temporal and spatial characteristics of the seismicity has been examined closely with the combined study of the spatial changes of several basic seismic parameters (Sobolev et al., 1991; Zayvalov, 2002), as well as for the physical modelling of the formation and time evolution of acoustic emission in rocks as a model the natural seismicity (Ponomarev et al., 1997). Spatial and temporal study variability of the seismicity leads also to the development of adequate algorithms like MEE algorithm (Zavialov, 2002) as well as the software package ZMAP (Wiemer, 2001). b-value and seismic energy released, among the basic seismic parameters, seems to be important in order to depict the seismicity characteristics. There is a long number of studies regarding the parameter b and they can be grouped into several categories that include, the study of certain physical properties, such as stress in a tectonic volume (Wyss, 1973); the study of the earthquake evolution process considering its temporal variation as a precursory phenomenon for impending earthquakes (e.g. Smith, 1981; Imoto, 1991; Enescu and Ito, 2003; Monterroso, 2003).

In this paper, a newly developed software tool (FastBEE tool = Fast Big Earthquake Estimation) is proposed, for the contemporaneous qualitative temporal analysis of three basic seismic parameters. In this approach, the visualization of the results refer not only to a graphical images of a set of temporal curves of the seismicity parameters but also to the iterative process of visual inspection and interaction with geotectonic information in the examined region. Changing interactively, the shape and extent of the examined area, as well as the earthquake catalogue parameters, like time window, magnitude and focal depth threshold, the spatio-temporal changes of the seismicity can be more comprehensive, bringing to the light characteristics, which are not immediately apparent in strictly quantitative data analysis methods.

Due to that the Hellenic trench and arc system is seismically the most active region in the whole Mediterranean region (e.g. Papazachos and Papazachou, 1997). Because of this rich earthquake catalogues are available in that region particularly in the time interval from 1990 up to the present. This is absolutely favorable for testing the proposed tool.

Correspondence to: I. Baskoutas
(i.basko@gein.noa.gr)

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2 Seismic parameters and algorithm description

The seismic parameters which are used in the analysis of the temporal variation of the seismicity are the number of earthquakes N, per unit time, the b-value and the seismic energy released in the form $\log E^{2/3}$. The number of earthquakes N is expressed in the form logN, taking into account the magnitude cut-off M_{mi} that characterizes the rate of seismicity in a given area. The choice to express the number of earthquakes in logarithm form permits the better representation of the seismicity time variation according to the data treatment, as it is described below. The estimation of standard error is obtained by the relation σ_N=sqrt(N), which in the present approach was modified as σ_{logN}=0.4343/sqrt(N).

Estimates of the b-value of the Gutenberg-Richter (1954) magnitude frequency relationship, are obtained by means of the maximum likelihood estimation method (Gusev, 1976; Van Wormer et al., 1976), and slightly modified by Zavyalov (2002) as:

$$b = \log\left[1 + \frac{N_\Sigma}{\sum\limits_{n=0}^{\infty} nN_{M_{\min+n\Delta M}}}\right] / \Delta M \tag{1}$$

where N_Σ is the total number of earthquakes from $M_{\min}$ to $M_{\max}$, $nN_{\min+n\Delta M}$ is the number of earthquakes in the magnitude range $M_{\min+n\Delta M}$, n=0,1, 2, 3, 4... with magnitude increment Δ_M=0.20. Standard error of b-value determination is given by the relationship σ_b=b/sqrt(N_Σ).

The energy released in the form $\log E^{2/3}$ is derived from the relationship:

$$\bar{E}\,(t) = \sum_{i=1}^{N_t} E_i{}^{2/3} \tag{2}$$

with i=1,2...N_t. Seismic energy E is derived using the relationship, logE=1.5 M_s+4.7, proposed by Papazachos and Papazachou (1997) for the Greek territory. In these estimates the standard error is given by the relationship σ_E=σ_M/sqrt(N), where σ_M=0.2, and σ_E relationship modified as σ_{logE}=0.4343/σ_E.

Temporal variation for each parameter is obtained with a constant time step, e.g. of one month which is our choice in this paper, according to the following relationships:

$$X_t^2 = \sum_{i=1}^{n_t} x_i^2 \qquad n_t = \sum_{i=1}^{n_t} i \qquad X_t = \sum_{i=1}^{n_t} x_i \tag{3}$$

where x_i are unique estimates of the examined data for each parameter, i.e. logN, b-value and energy released E, X_t is the sum of monthly values of data, n_t is the number of earthquakes during one month time interval, where t=1,2...T, with T being the number of months of the total time period of study.

The obtained monthly values, X_t, of the time series are smoothed, with running overlapping time windows shifted by one month, with coefficients derived from the following relationship:

$$\overline{X}(t) = \frac{\sum\limits_{l=1}^{L} X_{t+l} \times \omega_l}{\sum\limits_{l=1}^{L} n_{t+l}} \tag{4}$$

where X_t is the smoothed time series of seismic parameters (logN, b-value and $\log E^{2/3}$), n_t is the number of earthquakes within the time interval of one month, ω_l are the weight coefficients. The time duration of the smoothing window depends on the examined area and the seismicity rate. We found that in our case it varies from 3 to 48 months. Weight coefficients, ω_l, are obtained by the application of a triangular window function of the form:

$$\omega_l = 1 - abs(L - l)L \tag{5}$$

This filter was applied in order to avoid distortion caused by the significant side lobs in the time variation of the parameters. Practically, the applied triangular filter acts as a low pass filter with pass period equal or greater than to the half-time duration width l. Obtained values of the considered seismic parameters are assigned at the end of filter window.

3 FastBEE tool description

FastBEE tool is driven by a graphical user interface (GUI), designed to help seismologists to analyze catalog data and obtain visualization of results through user friendly and interactive menu. The software was developed using Bollard C++ environment.

For a quick and easy data access, FastBEE reads files with the common earthquake catalogs in the standard ASCII HYPO71. FastBEE combines some standard with some advanced seismological analysis functions, aspiring to make data exploration easier and more efficient. With FastBEE the user can explore various seismogenic regions by selecting subsets of events in space, time and magnitude domains, plot seismicity maps, cross-sections and depth distribution histograms. Then, the variations of the three main parameters mentioned above are obtained in different time periods and locations.

Capabilities and applications of FastBEE are summarized in Table 1 of the main Menu (Fig. 1). Functions appear in a separate field with self explanatory subtitles, where the user can set appropriate parameters for input data. Consequently, all information and parameters setting are assigned and saved automatically in an appropriate input file named "region.par".

Table 1. List of the fields and the respective objectives of FastBEE tool capabilities.

FIELD	OBJECTIVE
Region Name	Set new conventional file name for a region or select existing one from the list (which following is used for the creation of all output or plot files names).
Map Coordinates	Set geographical coordinates for the region map creation.
Seismic Source Par	Set area geographical coordinates to obtain subset of earthquake catalogs. Set the width of the defined area. Distance of the greater order magnitudes to appear in the temporal variation output as well as on created seismicity maps.
Time window	Set time window to create new subset of earthquake catalog and then perfom the temporal variation analysis of seismic parameter.
Seis Catalog Parameters	Cut in magnitude threshold and depth range. Define the strong earthquake magnitude, in the subfield "Earthq Predict", to appear on the final temporal variation output (chronologically numbered arrows perpendicular to the time axis), as well as, on the seismicity map (chronologically numbered stars).
Seismic Catalog Treatment	Set parameters, for a draft earthquake catalogue declustering from aftershocks, in a given time and space span, for additional testing of results.
Filter Parameters	Set filter width, in months, to smooth the temporal variation of seismic parameters.
Trend Correction	Activate the base line correction.
Fourier filter	Set start and end periods for the spectral FFT approximation.

Figure 2, shows a snapshot of the typical visualization output window of the FastBEE tool. In this figure, the output curves of the temporal variation estimates of the seismic parameters, logN, b-value and logE$^{2/3}$, are shown from the top to the bottom, respectively. Filtered time series are displayed superposed to the estimates as red curves. Vertical scales for all drawings are self adjusted, to facilitate visual inspection. In addition, the mean values of seismic parameters (parallel lines to the time axis), as well as standard error estimations of logN and logE$^{2/3}$ and standard error estimations, 1σ, of the monthly b-value estimates can be shown, respectively. Large standard errors of b-value estimates due to the data absence can be considered within accepted limits, because of the qualitative character of the results. In the same graph, the numbered arrows perpendicular to the time axis, shows the origin time and the magnitude of the main strong earthquakes. Magnitude and origin time of the displayed earthquake can be adjusted in the appropriate field of the main menu and saved in the "TempBigE.dat" file. This choice is useful for the comparison of the strong seismic activity with observed temporal variation changes. For instance, in the presence of an anomaly the absence of strong earthquake, let's say of magnitude 6.0 or so, may be associated to a couple of smaller size events, say 5.8 each. The results are displayed in the monitor and can be saved in appropriate data and image files, e.g. jpg format.

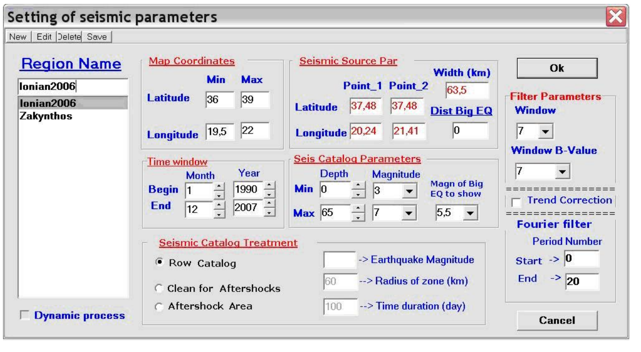

Fig. 1. The FastBEE tool main input menu for the parameters setting.

4 Case study

In this section the results of the FastBEE tool application in the Ionian Sea region, western Greece (see rectangular area in Fig. 3), are presented as a case study. The seismic data

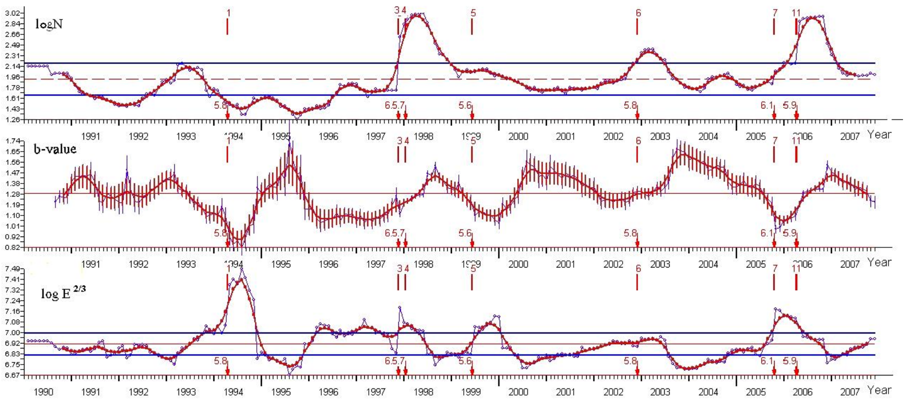

Fig. 2. Temporal variation curves of logN, b-value and log$E^{2/3}$ and their respective estimation errors, in the time period 1990–2007. Numbered arrows show the origin time of the strong events occurred in the area, greater than 5.7.

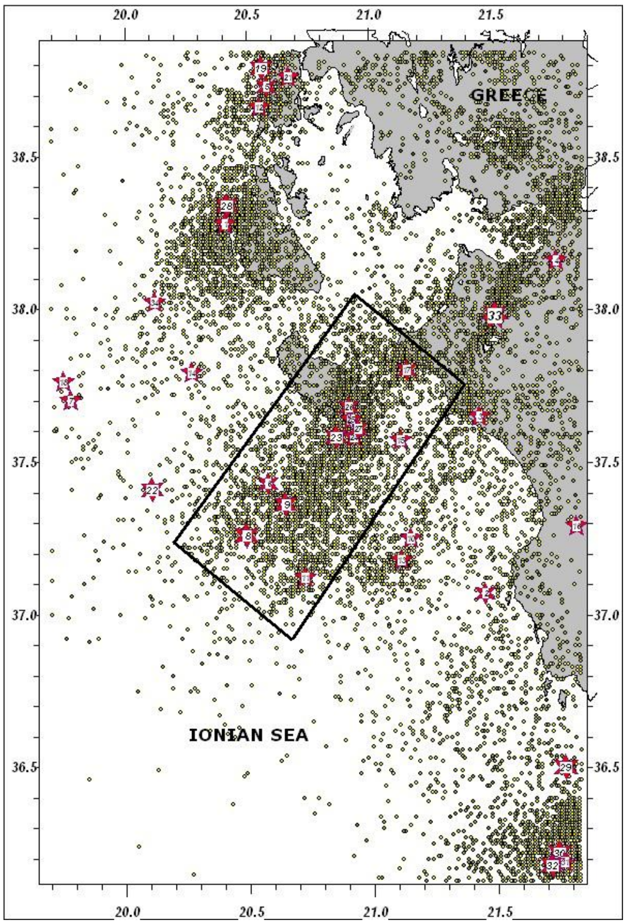

Fig. 3. Seismic epicentre map with magnitude $M_l \geq 3.0$, for the time period 1990–2007, in the Ionian Sea region. The rectangle shows the study area. (Dots show all events independently from their magnitude, for the better spatial distribution and density display.)

Table 2. List of the strong earthquakes for the study area appearing on Fig. 2.

Year	Month	Day	hhmmsec	Lat	Lon	Depth	Ms
1994	APR	16	23 09 36.4	37.43	20.58	30	5.8
1997	NOV	18	13 07 36.9	37.26	20.49	5	6.6
1997	NOV	18	13 13 48.3	37.36	20.65	5	6.2
1998	JAN	10	19 21 54.3	37.12	20.73	5	5.7
1999	JUN	11	07 50 15.4	37.57	21.12	55	5.6
2002	DEC	2	04 58 56.4	37.80	21.15	17	5.8
2005	OCT	18	15 25 59.5	37.58	20.86	22	6.2
2006	APR	4	22 05 3.3	37.58	20.93	18	5.7
2006	APR	11	00 02 41.5	37.64	20.92	18	5.7
2006	APR	11	17 29 28.4	37.68	20.91	18	5.9
2006	APR	12	16 52 1.2	37.61	20.95	19	5.9

used, in this analysis have been taken from the Bulletins of the Geodynamic Institute, National Observatory of Athens, for the time period from 1990 to 2007 inclusive.

Figure 3 shows the seismicity map of the area with M_L magnitude greater than 3.0. In this map, all events are plotted as equal size dots independently from their magnitude, with the aim to display better the epicentre spatial distribution and density. Exception has been made for the strong events which are illustrated as numbered stars in chronological order. The same strong events appear also in the output graphs of Fig. 2, as numbered arrows perpendicular to the time axis, thus showing their origin time and the respective magnitude. Table 2 shows the list of the above mentioned strong earthquakes, with $M_s \geq 5.8$ which have been occurred in the examined area.

A careful visual inspection of Fig. 2 shows that the temporal fluctuations form consecutive relative minima and maxima in all three curves. Exceeding significantly of the minima and maxima around the relative mean value could be considered as anomalies. The comparison of the foresaid

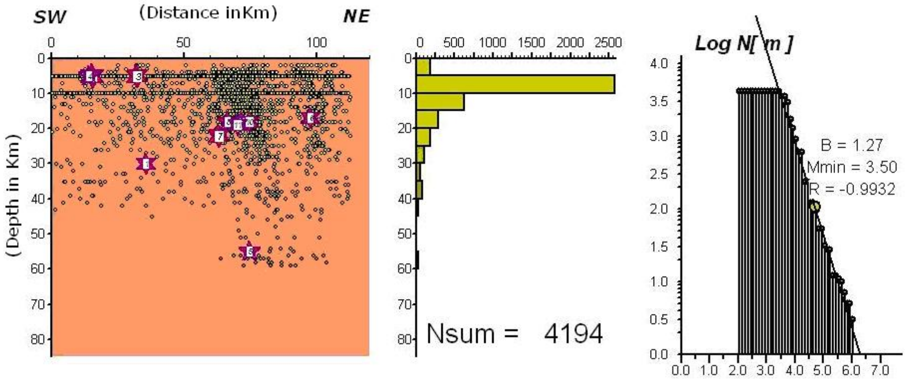

Fig. 4. Seismic epicentre distribution cross section, in SW–NE direction, depth magnitude distribution histogram, and b-value, respectively for the study area of Fig. 3. *N*sum is the total number of events within the examined area.

temporal anomalies shows a clear relation, especially for the b-value and $\log E^{2/3}$ curves, with the observed strong earthquakes occurrence, reported in Table 2. Namely, in the case of b-value, the strong earthquakes occurrence coincide with its decreasing phase after it has passed a relative maxima. On the contrary, in the case of $\log E^{2/3}$ such a coincidence is observed during the increasing phase after the relative minima, which expresses a deficit of the seismic energy released.

5 Discussions and conclusions

The finding that the b-value decreases prior to the occurrence of an earthquake is not new. Fielder (1974), Smith (1986), Voidomatis et al. (1990), Imoto (1991), and Monterroso (2003), among others, have shown that significant changes of b-value precede large earthquakes. In this study, it is shown that the analysis of seismic parameters with FastBEE tool and the visualization of the results can spotlight very distinct temporal changes not only for b-value but also for seismic energy released. In this respect, some specific phases of the temporal changes can be related to the strong earthquake activity in a quick, easy and efficient way.

Nevertheless, in some other cases the foresaid anomalies can not be related to a particular strong earthquake within the limits of the examined area, but they can be associated with another strong earthquake located outside the area of study or they can be related to a cluster of smaller size earthquakes within the area. In few other cases, it is observed that a weak correlation between seismicity anomalies and the occurrence of particular strong earthquakes can be improved by considering larger areas of study. This is consistent with the concept that long-range correlation of the basic premonitory phenomena that precede an approaching earthquake may come from an area which is much wider than the source area (e.g. Keilis-Borok and Soloviev, 2003). There are also cases with absence of sharp or significant changes in seismic parameters temporal behaviour, despite the presence of the strong earthquakes occurrence, which is common in areas with low seismic activity rate or even with lack of data (e.g. Baskoutas and Papadopoulos, 2006). Nevertheless, repeated steps of the trials and error technique for the elaboration of the seismic data and of the filtering window can depict the temporal profile of the seismicity in a given area, which can be useful for further consideration.

The above findings encourage to suppose that the temporal fluctuations of the seismic parameters, as obtained by the FastBEE output, reflect the influence of the geodynamic regime, because of the accumulation or redistribution of the energy in the study area and/or in adjacent areas.

As a conclusion, we may suggest that FastBEE tool permits the dynamic elaboration of the seismic data so that the visualization of the results can help seismologists to depict the temporal variation profile of the seismicity at any region. To bring in light subtle temporal characteristics of the seismicity that may not be immediately apparent in strictly quantitative data analysis methods. Moreover results permit to investigate the geodynamic process acting in a region, in respect to the temporal variation of the seismicity, and finally contribute to the assessment of impending strong earthquakes.

The results obtained with FastBEE tool may be useful not simply to arrive at a specific "solution", but also to help to extract some physical meaning from data, stimulating hypotheses or to test existing ones (e.g. Papadopoulos and Baskoutas, 2008). It is hoped also that the results will raise questions about the possible interaction between adjacent areas and the value of the mid-term seismicity variations as potential precursory phenomena.

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