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TEMPORAL CHARACTERISTICS OF SOME AFTERSHOCK SEQUENCES IN NORTH AEGEAN SEA (GREECE) AND THE SURROUNDING REGIONS

G. Drakatos*, J. Latoussakis* and J. Drakopoulos*

ABSTRACT

The aftershock activities of nine moderate shallow earthquakes in North Aegean Sea and the surrounding regions have been studied quantitatively, by making use of the modified Omori's formula and Akaike's Information Criterion (AIC).

Almost the same seismic patterns before the occurrence of large aftershocks have been observed. The whole aftershock area of the main shock becomes quiescent. Then, the aftershock activity recovers to a normal level or increases beyond it prior to the occurrence of the large aftershock. In such case, the observed pattern may be useful in predicting a large aftershock, if the aftershock activity is observed in the real time check.

ΣΥΝΟΨΗ

Στην παρούσα εργασία γίνεται ποσοτική μελέτη των μετασεισμικών ακολουθιών εννέα (9) επιφανειακών σεισμών, που έγιναν στην ευρύτερη περιοχή του βόρειου Αιγαίου, με την εφαρμογή του νόμου του Omori και του Akaike Information Criterion.

Σε όλες σχεδόν τις περιπτώσεις, πριν από την εκδήλωση του κύριου μετασεισμού παρατηρείται το ίδιο μοντέλο. Η σεισμικότητα της περιοχής αρχικά ελαττώνεται και στη συνέχεια επανέρχεται στα κανονικά επίπεδα ή τα υπερβαίνει λίγο πριν από την εκδήλωση του κύριου μετασεισμού. Εάν η παρακολούθηση της ακολουθίας γίνεται σε πραγματικό χρόνο, τότε τα παρατηρηθέντα μοντέλα είναι δυνατό να συμβάλουν στην πρόγνωση του κύριου μετασεισμού.

ΕΙΣΑΓΩΓΗ - INTRODUCTION

Aftershock activities has been studied intensively (Utsu, 1961, 1969; Mogi, 1962, 1968; Page, 1968; Papazachos, 1974; Karakaisis et al., 1985; Motoya and Abe, 1985; Matsu'ura, 1983, 1986) and it is accepted that the occurrence rate of aftershocks n(t) obeys the Modified Omori formula (Utsu, 1961):

$$n(t) = k/(t+c)^p \qquad (1)$$

where, t is the lapse of time from the main shock.

Aftershocks are usually much smaller than the main shock and they are not followed by secondary aftershocks. However, sometimes a large aftershock occurs in an area adjacent to the rupture zone of the main shock. Such a large aftershock is followed by its own aftershocks and is called secondary after-

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* National Observatory of Athens - Seismological Institute, P.O. Box 20048 GR - 118 10 Athens (Greece)

shock (Matsu'ura, 1986).

Since the temporal characteristics of aftershock sequences is quantitatively represented by the modified Omori formula, it is very interesting to examine whether there is any anomalous change in aftershock activity before the occurrence of a large aftershock. Matsu'ura (1986) proposed a method for a quantitative treatment of aftershock sequences.

In this study, nine earthquake sequences have been studied quantitatively, in order to determine temporal patterns in aftershock activities prior to large aftershocks which are followed by secondary aftershocks. The main shocks have occurred in the same seismotectonic region (North Aegean Sea), which is one of the most active regions of Greece (Papazachos, 1976; Drakopoulos, 1978; Delibassis, 1982; Makropoulos and Burton, 1984; Papazachos et al, 1986; Stavrakakis et al, 1987).

In the data set there are also included two earthquake sequences, which have been analysed by Latoussakis et al. (1991) and occurred in the same region. This study aims to investigate if the observed temporal pattern may be useful in predicting a large aftershock in the investigated area, which might be as large and disastrous as the main shock.

ΜΕΘΟΔΟΣ - METHOD

The method used in the present study was in details described by Matsu'ura (1986) and by Latoussakis et al. (1991). Here, we only outline the method. Generally, when one aftershock sequence contains some large aftershocks accompanied by their secondary aftershocks, the modified Omori formula is represented by:

$$n(t) = \sum_{i=0}^{M} H(t-T_i) \; . \; k_i/(t - T_i + c_i)^{Pi} \qquad (2)$$

where, H(t) is a unit step function,

M is the number of large aftershocks having their own aftershocks and

$T_o(r_o)$ and T_i are the origin time of the main shock and of the i^{th} large aftershock, respectively.

The estimation of K, P and c parameters of the above mentioned equations is based on the Maximum Likelihood Method, introduced by Ogata (1983). Once the likelihood is obtained, Akaike's Information Criterion (AIC) (Akaike, 1974) defined by

$$AIC = - 2 X [\max \ln(\text{likelihood})] + 2 X(\text{number of parameters}) \quad (3)$$

is used to obtain the model which is best fitted to the data.

ΑΝΑΛΥΣΗ ΔΕΔΟΜΕΝΩΝ ΚΑΙ ΑΠΟΤΕΛΕΣΜΑΤΑ - DATA ANALYSIS AND RESULTS

In the present study, nine (9) earthquake sequences have been analysed. List of aftershocks have been made from the monthly Bulletins of the National Observatory of Athens. Table 1 summarizes their parameters and the epicenters of the same events are plotted in Figure 1.

In order to ensure the homogeneity of the data, a threshold magnitude equal to 3.5 is chosen. The cut-off magnitude is M_L=2.5.

It should be emphasized that for all the cases, the AIC was first tested for the intervals (0.0-S) and (S-T_{max}), where S=i/8 (i=1,2,....,8) and T_{max} the time period that includes all the data. The smaller AIC, in all cases, was found for the whole interval. Probably, this is due to the high threshold magnitude.

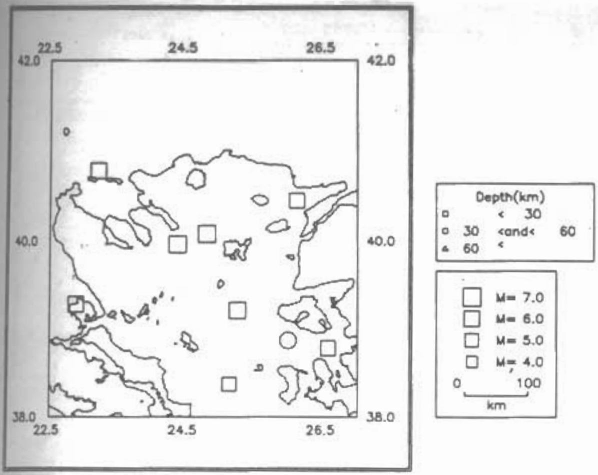


Fig. 1: Map of Epicenters 9 Events
Σχ. 1: Χάρτης Επικέντρων Scale: 1:5.000.000

In the following, a detailed analysis of the earthquake sequence which occurred on August 6, 1983 is given. For the analysis of the other eight sequences the same procedure was followed. Therefore, only the results are tabulated.

Η Μετασεισμική Ακολουθία της 6ης Αυγούστου 1983 (Βόρειο Αιγαίο)

The August 6, 1983, North Aegean Sea Earthquake Sequence

On August 6, 1983 (at 15h 43m), a strong earthquake of local magnitude M_L=6.6 occurred in the northern Aegean Sea. This shock was followed by a considerable number of aftershocks. On August 8, a large aftershock of local magnitude M_L=5.1, occurred.

For studing this sequence a list of aftershocks has been carefully made. In order to ensure the homogeneity of the data, a threshold magnitude equal to 3.5 is chosen.

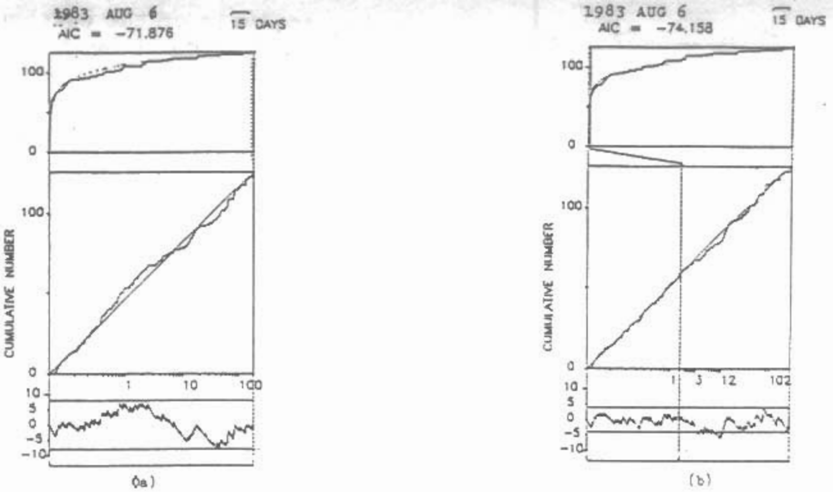
For the time interval 0-184.0 days, which includes the whole aftershock activity, the modified Omori formula (AIC=-71.876) is represented by the relationship:

$$n(t) = 16.446/(t+0.0706)^{1.021}, \text{ for } 0.0 \le t \le 184.0 \text{ days} \quad (4)$$

and is shown in Figure 2(a), which corresponds to all data. Top and middle figures show the cumulative number of aftershocks against ordinary time and Frequency-Linearized Time (Ogata and Shimazaki, 1984), respectively. The calculated cumulative number, represented by dashed lines (Fig. 2), is calculated using Omori's parameters which are obtained by the maximum-likelihood method from data in the range designated by a horizontal bracket at the right top. Figures

Table 1

No	Date	h:m	Φ_N	λ_E	Depth (Km)	M_L
1	1975 MAR 27	05:15	40.45	26.12	15	5.7
	1975 MAR 27	19:42	40.48	26.08	5	4.5
2	1978 JUN 20	20:03	40.78	23.24	3	6.0
	1978 JUL 4	22:23	40.75	23.06	10	4.7
3	1979 JUN 14	11:44	38.79	26.57	6	5.5
	1979 JUN 16	18:41	38.72	26.64	11	4.8
4	1980 JUL 9	02:11	39.29	22.91	7	6.0
	1980 JUL 10	19:39	39.32	22.93	22	5.4
5	1981 DEC 19	14:10	39.22	25.25	16	6.3
	1981 DEC 27	17:39	38.91	24.92	16	6.0
6	1982 JAN 18	19:27	39.96	24.39	5	6.4
	1982 JAN 19	12:18	39.72	24.34	10	4.8
7	1983 AUG 6	15:43	40.08	24.81	22	6.6
	1983 AUG 8	08:09	40.39	25.51	5	5.1
8	1984 JUN 17	07:48	38.88	25.99	41	5.3
	1984 JUN 26	19:48	38.81	25.87	39	4.8
9	1986 MAR 25	01:41	38.38	25.13	16	5.2
	1986 MAR 26	18:36	38.37	25.18	16	5.3



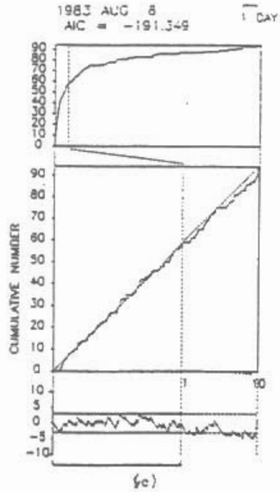


Fig. 2: Top and middle figures show the cumulative number of aftershocks against ordinary time and FLT respectively. The bottom of the figure magnifies the difference of the observed cumulative number from the calculated one, on the same time scale as the middle. (a) The FLT from all data (b) The best fitted model from all data, (c) FLT from data until t = 15 days.

Σχ. 2: Το επάνω και το μεσαίο τμήμα της εικόνας δείχνουν την αθροιστική συχνότητα των σεισμών σε συνάρτηση με τον κανονικό χρόνο και τον FLT, αντίστοιχα. Το κάτω τμήμα δείχνει τη διαφορά μεταξύ παρατηρηθέντος και υπολογισθέντος αριθμού σεισμών (a) Ο FLT από όλα τα δεδομένα, (b) Το μοντέλο που ανταποκρίνεται καλύτερα στα δεδομένα, (c) Ο FLT έως t = 15 ημέρες.

on the FLT axis show lapse of time in days from the left end. The bottom of Figure 2 illustrates the difference of the observed cumulative number from the calculated one on the same time scale as in the middle. The double standard deviation of the difference in the designated range is also shown by the two parallel lines.

In order to investigate the seismic patterns of the sequence, various models have been tested in terms of AIC. Figure 2(b) illustrates the best fitted model, including also all data. This model corresponds to AIC=-74.158 and the modified Omori formula is expressed by the relationship:

$$n(t) = \begin{cases} 29.798/(t+0.415)^{2.014} & \text{, for } 0.0 \le t \le 1.6 \text{ days} \\ 2.325/(t+0.001)^{0.542} & \text{, for } 1.68 \le t \le 184.0 \text{ days} \end{cases} \qquad 5)$$

Figure 2(c) illustrates the practical meaning of the current analysis for earthquake prediction purposes. Suppose that the aftershock activity were

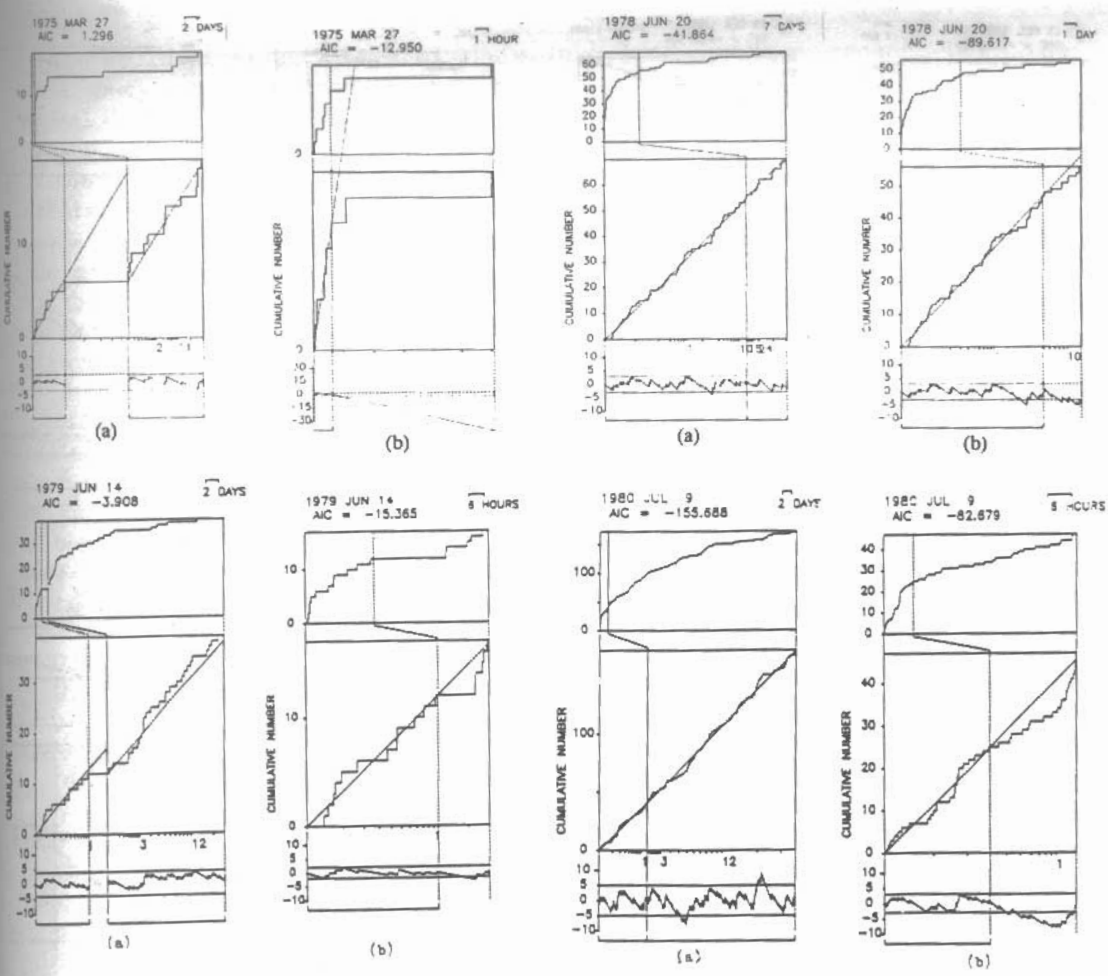


Fig. 3: (a) The model which best fits the data is shown, for each aftershock sequence. (b) The case in which the aftershock activity was observed in real time is shown. (Further explanations are given in the caption of Fig. 2).

Σχ. 3: (a) Το μοντέλο που ανταποκρίνεται καλύτερα στα δεδομένα, χωριστά για κάθε μετασεισμική ακολουθία. (b) Η περίπτωση κατά την οποία η ακολουθία θα καταγράφετο σε πραγματικό χρόνο.

observed in real time ($0.0 \le t \le 15.0$ days) and the cummulative number as well as the difference Äí of the observed cummulative number from the calculated one were also plotted in real time. Then, from Figure 2(c)one would observe that after the time period t=1.0 days a remarkable quiescence is observed, which could be considered as an anomalous pattern of the sequence. Actually, this pattern was followed by the aftershock of $M_L=5.1$ on August 8, 1983, exactly 1.684 days after the main shock.

For the analysis of the other eight sequences the same procedure was followed. The results of the analysis of the events No 5 and No 9 (Table 1) are according to Latoussakis et al., (1991). The results are shown in Figure 3. For each event, the model which best fits the data and corresponds to the smallest AIC's value is shown in Figure 3(a), while Figure 3(b) illustrates the case in which the aftershock activity was observed in real time.

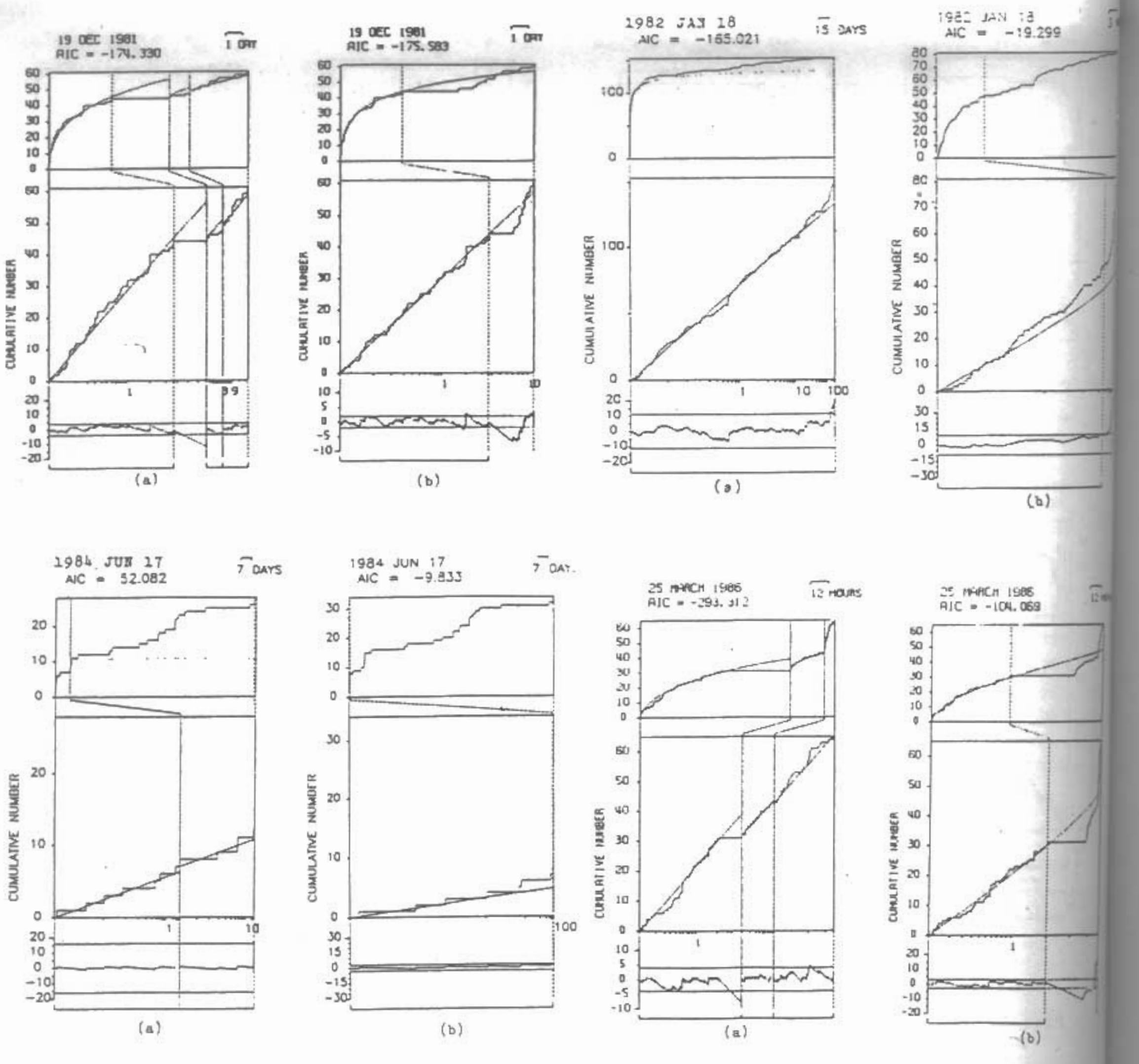


Fig. 3: continue
Σχ. 3: συνέχεια

ΣΥΜΠΕΡΑΣΜΑΤΑ - DISCUSSION AND CONCLUSIONS

Temporal features of the aftershock activities following nine moderate earthquakes in North Aegean Sea and the surrounding regions have been studied quantitatively, following the method of Matsu'ura (1986). The earthquakes concerned were accompanied by large aftershocks which triggered their own aftershock activities.

Seismicity pattern brings information about physical conditions such as the state of stress or the degree of strain concentration in and around the source region of an impeding large eartquake. Therefore, almost the same seismic patterns before the occurrence of large aftershocks have been observed.

The whole aftershock area of the main shock becomes quiescent. Then, the aftershock activity recovers to the normal level or increases beyond the normal level prior to the large aftershock. The same pattern was determined also by Matsu’ura (1986) and by Latoussakis et al. (1991).

The observed temporal pattern may be usefull in predicting a large aftershock which might be as large and destructive as the main shock, if the aftershock activity is monitored immediately after the occurrence of the main shock. The rough location of this aftershock can be estimated by checking the location of the aftershocks during the recovered stage. Therefore, the observed patterns may be useful in predicting a large aftershock.

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