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Effect of Aftershocks on Earthquake Hazard Estimation: An Example from the North Anatolian Fault Zone

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Abstract. In order to investigate the effect of aftershocks on earthquake hazard estimation, earthquake hazard parameters (λ_m, b and $M_{\max}$) have been estimated by the maximum likelihood method from the main shocks catalogue and the raw earthquakes catalogue for the North Anatolian Fault Zone (NAFZ). The main shocks catalogue has been compiled from the raw earthquake catalogue by eliminating the aftershocks using the window method. The raw earthquake catalogue consisted of instrumentally detected earthquakes between 1900 and 1992, and historical earthquakes that occurred between 1000–1900. For the events of the mainshock catalogue the Poisson process is valid and for the raw earthquake catalogue it does not fit. The paper demonstrates differences in the hazard outputs if on one hand the main catalogues and on the other hand the raw catalogue is used. The maximum likelihood method which allows the use of the mixed earthquake catalogue containing incomplete (historical) and complete (instrumental) earthquake data is used to determine the earthquake hazard parameters. The maximum regional magnitude ($M_{\max}$), the seismic activity rate (λ_m), the mean return period (R) and the b value of the magnitude-frequency relation have been estimated for the 24°–31° E, 31°–41° E, 41°–45° E sections of the North Anatolian Fault Zone from the raw earthquake catalogue and the main shocks catalogue. Our results indicate that inclusion of aftershocks changes the b value and the seismic activity rate λ_m depending on the proportion of aftershocks in a region while it does not significantly effect the value of the maximum regional magnitude since it is related to the maximum observed magnitude. These changes in the earthquake hazard parameters caused the return periods to be over- and underestimated for smaller and larger events, respectively.

1. Introduction

One of the debates in the studies of seismic hazard assessment is about the context of earthquake catalogue. The instrumental catalogues involve not only the main shocks but also foreshocks and aftershocks. Existing approaches in the research of seismic hazard assessment are generally based on the Poisson model since seismic activity is considered to be stochastic in nature (Vere-Jones, 1970). Several methods have been suggested for the deletion or separation of aftershocks from the raw earthquake data because aftershocks show a major deviation from a Poisson process (Gardner and Knopoff, 1974; Keilis-Borok *et al.*, 1982; Molchan and Dmitrieva, 1992). Deleting aftershocks and other ‘dependent’ events leads approximately to a Poisson, or random data set for a better estimation of return periods of randomly occurring events (mainshock events) which is an important goal of seismic hazard studies.

The purpose of this paper is to investigate the effect of aftershocks on earthquake hazard estimates. The North Anatolian Fault Zone (NAFZ) is studied as an example. The NAFZ constitutes the northern boundary of the Anatolian block, which moves west due to the northward motion of the Arabian plate with respect to the Eurasian plate. Dextral motion on the NAFZ is known to have taken place since the late Miocene (Sengör, 1979). The central part of the fault zone is well defined morphologically from about 31° E up to its junction with the East Anatolian Fault Zone (EAFZ) at Karliova, at 41° E (Allen, 1969) and has a total length of 1000–1100 km (Ambraseys, 1970; Allen, 1980). A series of six large westward migrating earthquakes between 1939 and 1967 has created a 900 km long surface rupture along the fault zone from Erzincan to the western end of the Mudurnu valley (Ambraseys, 1970; Barka, 1992). The NAFZ spreads into three strands in the Marmara and in the North Aegean Sea regions, beginning from Adapazarı at 31° E (Barka and Kadinsky-Cade, 1988). Several estimates of earthquake hazard on the NAFZ have shown that the western and the central parts of the fault zone are the most active and the most quiescent parts, respectively. The seismicity of the central part differs from the western and eastern parts of the NAFZ since relatively large earthquakes are observed and expected in this part compared to the other parts. Relatively smaller magnitude earthquakes occur more frequently in the western and eastern parts (Öncel et al., 1995; Öncel and Alptekin, 1996). On the other hand, the complexity analysis of seismicity in the NAFZ implies significant variations toward the central part probably due to an underlying tectonic process (Öncel *et al*., 1996). In this study, the fault zone was divided into western, central and eastern subregions with longitudes between 24°–31° E, 31°–41° E and 41°–45° E, respectively, on the basis of seismological and tectonic criteria such as the geometry of surface faults and distribution of seismicity (Öncel, 1992; Alptekin *et al*., 1992).

2. Earthquake Data and Estimation of Hazard Parameters

2.1. EARTHQUAKE DATA AND IDENTIFICATION OF MAIN SHOCKS

Two types of earthquake catalogues were used in this study. The instrumental part of the catalogue was compiled from the International Seismological Center (ISC) data file for the time period between 1916 and 1992 and Ambraseys and Finkel's (1987) catalogue for the time period between 1899 and 1915. The historical part of the catalogue for the period from 1000 to 1899 was compiled from the Soysal *et al*. (1980) catalogue and the intensities converted to magnitude (Öncel, 1992).

In estimating the earthquake hazard, generally, a Poisson model of earthquake occurrence is assumed. Therefore, the catalogue in use must exhibit random space-time characteristics. As known, the raw earthquake catalogue can not be considered to have ‘random’ or Poisson characteristics due to the existence of fore shock – main shock – after shock sequences and swarms. Therefore, it is necessary to identify and account for these events.

Several methods have been used in the literature to separate main shocks from the aftershocks (Savage, 1972; Gardner and Knopoff, 1974; Reasenberg, 1985; Davis and Frohlic, 1991a, b; Molchan and Dmitrieva, 1992). Dependent shocks as those that fall within the space and time intervals of the main shock and are of smaller magnitudes, are eliminated to obtain a data set of mainshocks which are assumed to show a Poisson distribution. The success of removing aftershocks depends on the criteria used to identify them. An investigation to compare the performance of mainshock identification techniques on the regional catalogues showed no significant differences between various techniques (Davis and Frohlich, 1991a). Among the mainshock identification procedures the method proposed by Gardner and Knopoff (1974) is one of the oldest, but is the easiest to apply to an inhomogeneous catalogue. Results from the application of this method are reported to be very close to the estimates from one of the latest procedures (the Reasenberg method) (Savage and Depolo, 1993). Also, the Gardner–Knopoff method is proposed to be the best technique for removing aftershocks when the earthquake catalogue has variable quality station coverage in different regions and time periods (Savage and Depolo, 1993). Nevertheless, this method is also imperfect and has some disadvantages together with its advantages. One of its advantages is that variable spatial and temporal completeness thresholds of earthquake catalogues do not effect the results (Savage and Depolo, 1993) while it assumes a constant, rectangular, space-time window that is centered on the main shock epicenter. This is not realistic for most earthquakes due to the fact that many main shocks occur at the beginning of one of the aftershock sequences. Therefore, some events may be excluded from the catalogue that should be included, and others will be included that should be excluded (Reasenberg, 1985; Davis and Frohlich, 1991a).

In this study, the window method is used for producing the mainshocks catalogue (Gardner and Knopoff, 1974). Aftershocks of a main shock are identified within space-time windows (t_m, g_m, M_m):

$$t_m < t_a < t_m + Ti, \; |g_a - g_m| < D_i, \; M_a < M_m, \tag{1}$$

where t, g and M are time, epicenter coordinates and the magnitude, respectively, and subscripts a and m identify aftershock and main shock correspondingly. D_i are the distances between the epicenter of a main shock and its aftershocks. Threshold values D_i and T_i of the window method are empirical functions of magnitude and were selected visually for the NAFZ. Values of D_i and T_i for the selection of aftershocks in the space-time domain are given in Table I, and they increase with increasing magnitude of the main shock (Gardner and Knopoff, 1974). With respect to the size of the space-time window of the main shock, the first earthquake in the catalogue is declared as a main shock, then all its aftershocks are eliminated

Table I. Threshold values D_i and T_i for identification of aftershock in the window method (Gardner and Knopoff, 1974)

M	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
D_i, Km	19.5	22.5	26.0	30.0	35.0	40.0	47.0	54.0	61.0	70.0	81.0	94
T_i, days	6.0	11.5	22.0	42.0	83.0	155.0	290.0	510.0	790.0	915.0	960.0	985.0

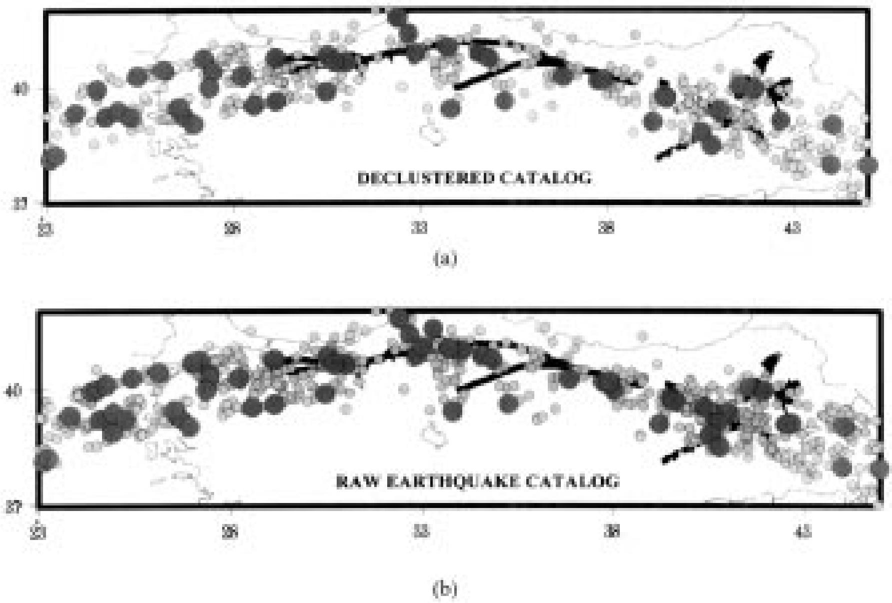

Figure 1. Epicenter coordinates of the NAFZ for instrumental period (1900–1992, $M > 6.5$ ●, $M > 4.5$ ○). (a) Plotted from the mainshock catalogue (declustered). (b) Plotted from the raw earthquake catalogue (clustered).

from the catalogue. The first earthquake in the rest of catalogue is declared as the next main shock and this procedure is continued until the end of the catalogue.

Application of the window method with the parameters given in Table I to the raw earthquake catalogue for the NAFZ reduced the number of events with magnitude $M \geqslant 4.5$ from 851 to 428. The seismic patterns for the raw earthquake catalogue 'clustered' and mainshock catalogue 'declustered' are shown in Figure 1(a) and 1(b), respectively. The declustered catalogue was tested to see it was Poisson distributed.

Magnitude–frequency distributions for the two catalogues are shown in Figure 2. This figure shows that completeness is good for both catalogues for events of $M > 4.5$. In the examination of Figure 2, variation of the proportion of small to large earthquakes between two catalogues is observed to increase towards lower magnitudes. This variation is also demonstrated by the estimated scaling exponents

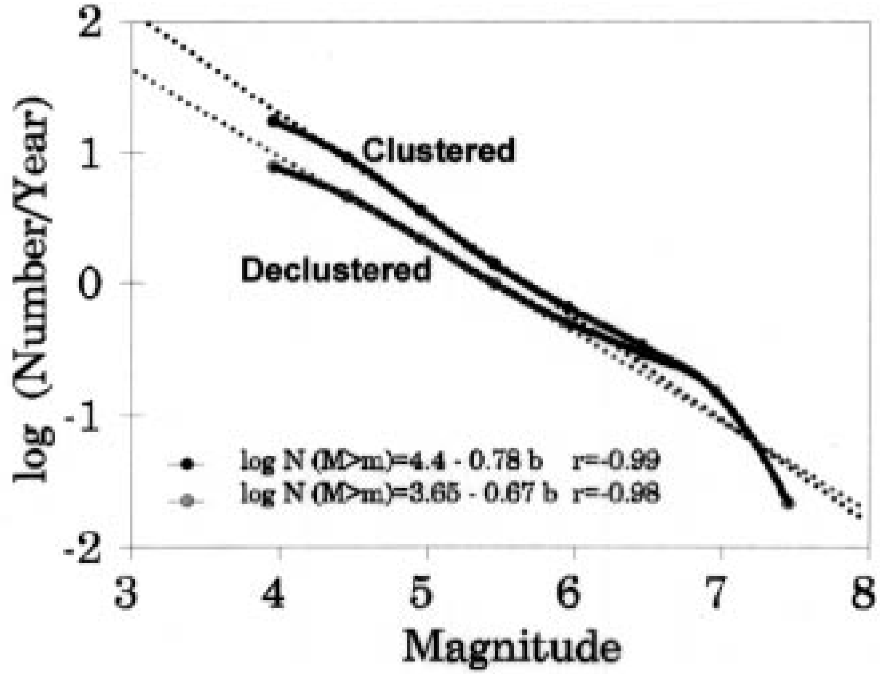

Figure 2. Magnitude–frequency plot for the clustered and declustered earthquake catalogues. The plot shows the number of aftershocks increase for the magnitude range of $M < 7.0$.

(a and b) of the magnitude-frequency distribution. For the region as a whole, scaling exponents a and b are obtained as 4.4–3.65 and 0.78–0.67 for clustered and declustered catalogues, respectively. Temporal changes of seismicity along the fault zone are shown in Figure 3 for both catalogues. It is important to see that the temporal pattern for the mainshock catalogue reflects more stable and Poisson character (Figure 3).

2.2. ESTIMATION OF EARTHQUAKE HAZARD PARAMETERS

The maximum likelihood method was used in the estimation of earthquake hazard parameters (seismic activity rate λ_m and the b-value of the Gutenberg–Richter magnitude-frequency relation and $M_{\max}$ the largest expected magnitude). The method can use a catalogue that has different subcatalogues with different time periods. The historical and instrumental parts of the catalogue represent the incomplete and complete data, respectively. The complete part of the catalogue is allowed to have different subcatalogues with different threshold magnitudes that are related to the quality of station coverage. The method takes account of the artificial seismic gaps in the catalogue that may occur from instrumental or operational problems. Each event is accepted as being in a magnitude interval with lower and upper thresholds (Figure 4). The earthquake occurrence represented by a doubly

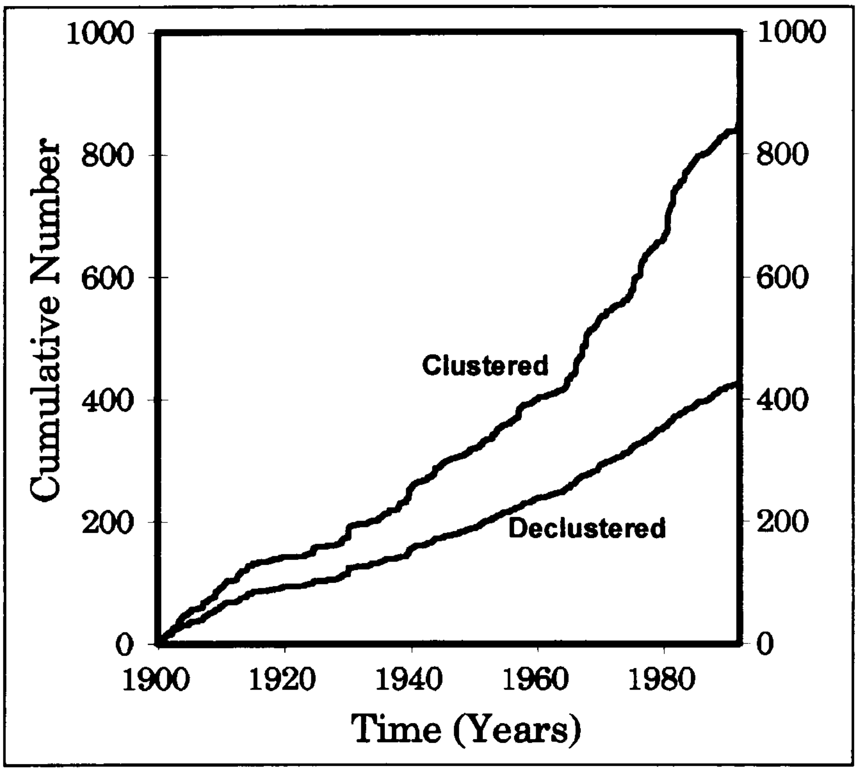

Figure 3. Cumulative number of earthquakes with magnitude of $M \geqslant 4.5$ for clustered and declustered catalogues as a function of time in the study area of Figure 1.

truncated Gutenberg–Richter relation. The largest expected magnitude $M_{\max}$ value is computed with respect to the largest observed magnitude to occur in time period of the used catalogue (Kijko, 1988). Further details of the method were discussed in Kijko and Sellevoll (1987 and 1990).

3. Results and Discussion

In this study, the effect of dependent events 'aftershocks' on earthquake hazard parameters (λ_m, B, $M_{\max}$) and the recurrence times of large events are examined. Two kinds of catalogues called as clustered and declustered catalogues (1900–1992) are used in this investigation. The historical catalogue (1000–1899) is used for reliable return period estimates. Historical catalogue is used as an independent data set together with clustered and declustered catalogues since the methodology used in the analysis use complete and incomplete catalogues together (Figure 4). So, we compute the earthquake hazard parameters using both clustered and declustered catalogues together with the historical data in the time interval (1000–1992), but classification is done only for the catalogues of instru-

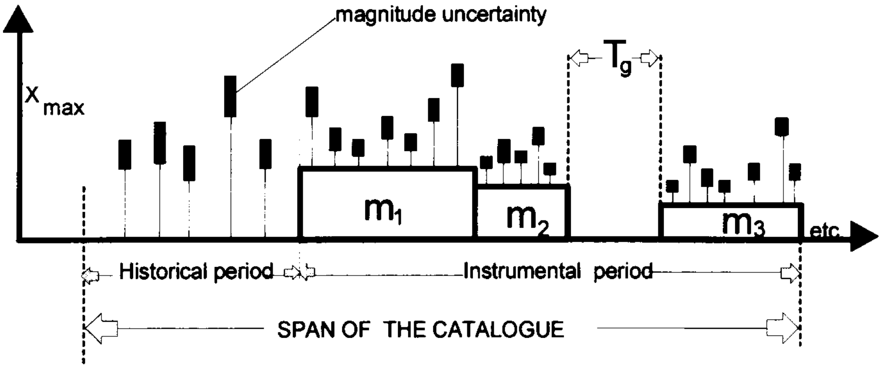

Figure 4. An illustration of the properties of the earthquake catalogue (Kijko and Sellovoll, 1987, 1989). This approach allows us to combine historical catalogue and instrumental catalogues with variable threshold magnitudes.

Table II. Earthquake hazard parameters (λ_m, b, $M_{\max}$) computed from the raw earthquake data and the main shock catalogue for the studied regions are given. λ_m is the number of annually occurring earthquakes with magnitude 4.5 or larger

Area	n_{main}	N_{whole}	b_{main}	λ_{whole}	λ_{main}	λ_{whole}	$(M_{\max})_{\text{main}}$	$(M_{\max})_{\text{whole}}$
24°–31° E	172	375	0.51	0.73 ± 0.0	0.526	0.718	7.56 ± 0.34	7.64 ± 0.3
31°–41° E	150	275	0.65 ± 0.02	0.71 ± 0.03	0.461	0.489	8.02 ± 0.45	8.20 ± 0.5
41°–45° E	106	201	0.64 ± 0.04	0.71 ± 0.03	0.375	0.46	7.69 ± 0.039	7.71 ± 0.4

mental period. Thus, we have clustered and declustered catalogues both including historical data.

Seismic b value and the activity rate λ_m computed from the declustered and clustered catalogues for the three seismic subregions along the NAFZ are listed in Table II. Seismic b values computed from the declustered and clustered catalogues for the western part of the NAFZ differ significantly while those for the other two subregions differ slightly. Similarly significant changes are observed in seismic activity rates λ_m. The reason for a significant decrease in seismic b value and activity rate λ_m in the western part of the NAFZ is related to the larger proportion of aftershocks (54%) in the catalogue. The proportion of aftershocks in the earthquake catalogue is inversely correlated with earthquake magnitude as emphasized in Figure 2. It means that a larger proportion of dependent events in the earthquake catalogue is related to lower magnitude events. The inclusions of dependent events in the catalogue affect the relative abundance of low and high magnitude earthquakes as shown in Figure 2. Thus, greater inclusion of dependent events leads to higher b-values and higher activity rate λ_m as seen in the results given in Table II.

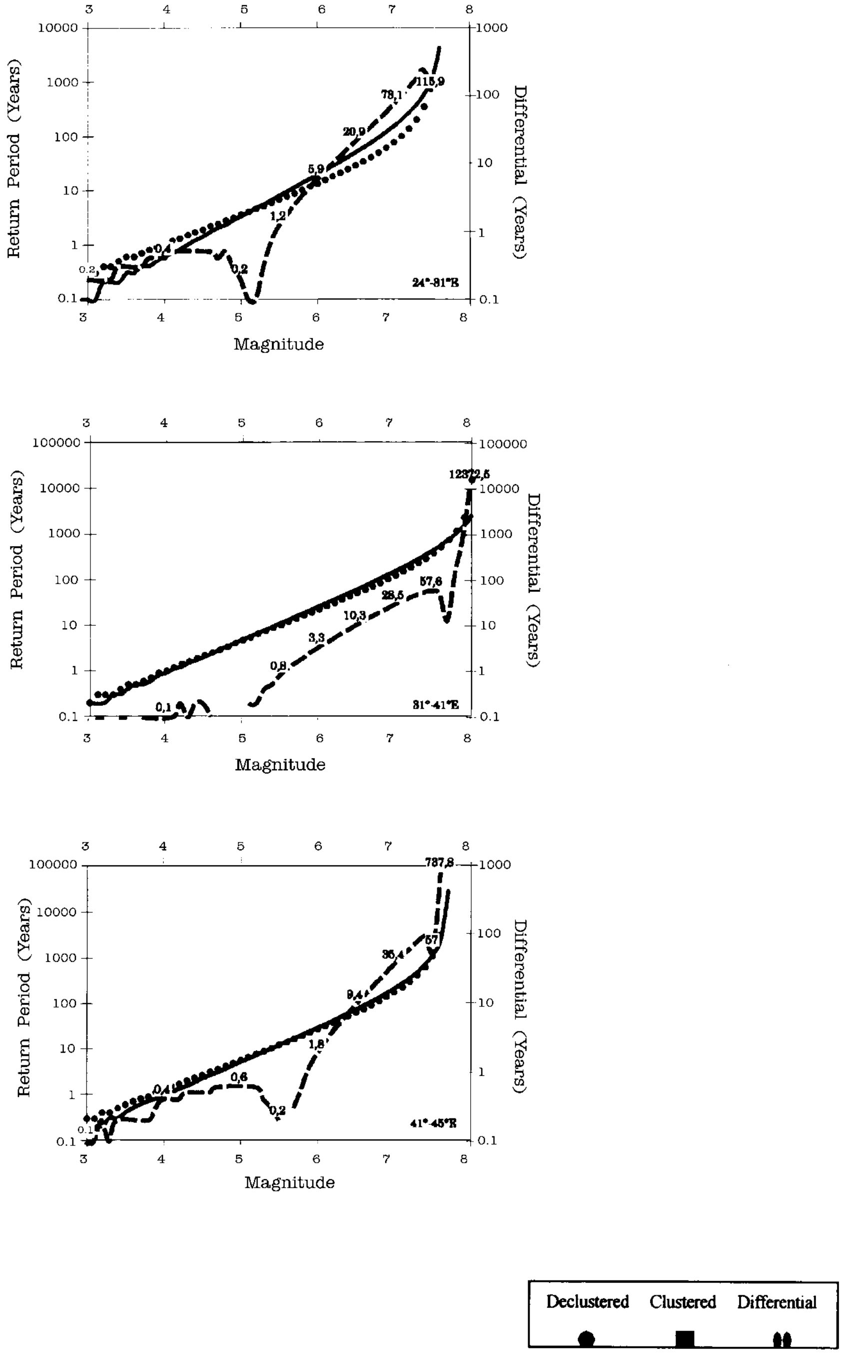

Figure 5. Mean return times for two catalogues and differential return periods for three sub-regions of the North Anatolian Fault Zone. Solid line and dotted line show the raw earthquake catalogue and mainshock catalogue respectively. Dashed line shows the absolute difference of return periods computed from clustered and declustered catalogues.

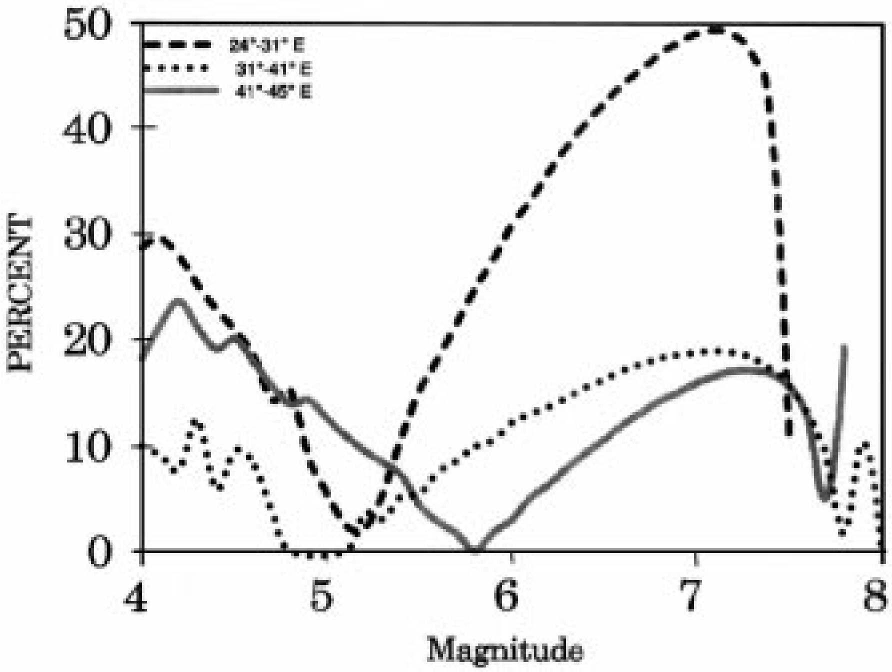

Figure 6. The percent of change of return periods for the three subregions of NAFZ as the inclusion of aftershocks to earthquake catalogue.

The other earthquake hazard parameter M_{max} does not significantly change for all three subsections along the NAFZ, since its size depends upon the largest observed magnitude rather than inclusion of dependent events.

Variations of the mean recurrence time with magnitude for the clustered and declustered catalogues are plotted in Figure 5. The certain magnitudes (5.1, 4.8, 5.8) divide the plots into two parts. Left and right parts of these plots are related to underestimated and overestimated values, respectively. The discrepancies between the return times for larger events of magnitude $M > 7.5$ are about 115 years in western, 58 years in central and 57 years in eastern sections of the NAFZ. Discrepancies in mean return periods for larger earthquakes of $M > 7.5$ increase for the central part (12,000 years) and eastern part (738 years) but these dramatic changes may not be realistic due to lack of macroseismic data. The percent changes of mean return periods for the three subregions of the NAFZ are plotted in Figure 6. The maximum discrepancies in mean return periods as 30 and 50% are observed for the western part while it is about 20% for the other parts (Figure 6). Note that the maximum discrepancies of 30 and 50% show the shifting of mean return periods in terms of underestimation for smaller events and overestimation for larger events respectively due to the effect of aftershocks for the western part of NAFZ. Similar but lower variations in mean return periods for other parts of NAFZ exist.

4. Conclusion

In this study, an earthquake catalogue for the NAFZ covering the time interval between 1000 and 1992 is used to study the effect of aftershocks in earthquake hazard estimation. Maximum likelihood estimations of the b value and the λ_m seismic activity rate from the raw and declustered earthquake catalogues show significant changes leading to discrepancies of about 57 to 115 years in return period estimates. $M_{\max}$ does not significantly change, since it depends on the largest observed magnitude rather than the inclusion of dependent events (aftershocks). In conclusion, we can state that for a more realistic hazard estimation aftershocks should be removed from the earthquake catalogue.

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