Aftershock probability model for Australia

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Abstract

After a main shock, the magnitude and timing of smaller aftershocks follow characteristic distributions known as Gutenberg-Richter and Omori laws, respectively. Based on these empirical laws, Reasenberg and Jones (1989) proposed a model to estimate the probability of earthquakes during an aftershock sequence as a function of time and magnitude. In this study, the parameters of the Reasenberg and Jones aftershock magnitude-time distribution are derived using the Australian instrumental earthquake catalogue (1900-2010). Two sets of model parameters are determined: sequence-specific parameters determined for well recorded aftershock sequences and generic parameters determined for a stack of events with magnitudes larger than or equal to 5. Both sets are found to be comparable to similar studies in other regions of the world. The spatial variation of model parameters is also studied and it is found that aftershock sequences in Southeastern Australia are less productive than sequences in Western Australia. Applicability of the derived generic parameters to forecast aftershock rates in Australia is verified using recent aftershock sequences that were not included in the earthquake catalogue such as the 2012 Gippsland earthquake.

Keywords: Aftershocks probability, Gutenberg-Richter law, Omori law, Reasenberg and Jones model

Introduction

Aftershocks are earthquakes of smaller magnitude that follow a larger main shock. Some definitions of an aftershock encompass all smaller events within a certain distance and timeframe of the main shock. This is the definition implied, for example, by seismic de-clustering routines that remove aftershock sequences from earthquake catalogues for time-independent seismic hazard studies (e.g. Gardner and Knopoff, 1974). Other definitions of aftershocks are more specific in their spatial consideration, restricting aftershocks to the fracture area of the main shock (e.g. Uidas, 1999; Parsons, 2002). A third variation of the aftershock definition is provided by Stein (1999) who states that aftershocks are events that cluster where stress has increased due to the main shock. A further complication in defining aftershocks arises when distinguishing aftershocks from events of an earthquake swarm– which we consider to be a short lived collection of earthquakes that have no clear main shock. Whilst such a distinction sounds clear in principle, applying it may be difficult in practice due to problems with estimating event magnitude and so on. One example of the complexity in identifying aftershocks is the damaging 22 February 2011 Mw 6.2 Christchurch (New Zealand) earthquake which is defined by some authors as an aftershock of

the 4 September 2010 Mw 7.1 Darfield earthquake (e.g. Bannister *et al.*, 2011; Sibson *et al.*, 2011), and by other authors as a main shock triggered (or induced) by the Mw 7.1 Darfield earthquake (Zhan *et al.* 2011; Shcherbakov *et al.*, 2012). Most automatic declustering algorithms would remove the 2011 Mw 6.2 earthquake.
The spatial and temporal concentration of aftershocks present a concentration of data for understanding properties of the Earth such as the geometry of fault planes (Deichmann and Garcia-Fernandez, 1992; Got et al., 1994; Waldhauser et al., 1999; Waldhauser and Ellsworth, 2002; Shearer et al., 2005) and to study rupture mechanics (Rubin et al., 1999; Rubin, 2002). The same spatial and temporal concentration however, leads to heightened seismic hazard around the area of the main shock in the days, months or years following the main shock. If large enough for example, aftershocks have the potential to cause further casualties by damaging buildings and infrastructure already weakened during the main shock thereby putting the safety of rescuers at risk. Aftershock uncertainty also leads to increased psychological trauma of local residents and can adversely influence decisions around the recovery and reconstruction phases following damaging events. Consequently, reliable techniques for forecasting aftershocks have the potential to benefit affected societies by informing emergency management agencies, government departments and the public.

Reasenberg and Jones (1989; 1990) developed an aftershock-forecasting model to quantify the probability of aftershocks of a certain magnitude occurring within a time-frame and region of interest. The Reasenberg and Jones forecasting model is obtained by combining the:

- Gutenberg-Richter Law (Gutenberg & Richter, 1944), an empirical relationship that describes the expected number of earthquakes per unit time as a function of magnitude; and
- the modified Omori Law (Utsu, 1961; Utsu et al. 1995), an empirical relationship that describes the change in the number of expected aftershocks with time.

Reasenberg and Jones (1989, 1990) originally applied this model to California. However, as seismic behaviour differs geographically around the globe, forecasts derived by this model are most accurate once the model parameters are calibrated for the particular location and/or tectonic setting for which the forecast is being derived. Such empirical parameters have been determined for different regions of the world, including California (Reasenberg & Jones 1989; 1990), New Zealand (Eberhart-Phillips, 1998) and Italy (Lolli & Gasperini 2003). The purpose of this paper is to determine empirical constants for the application of the Reasenberg and Jones model in Australia.

The remainder of this paper is structured into four main sections. Firstly, we discuss the Australian earthquake catalogue, describing Australian seismicity and providing details on the techniques we used to identify aftershocks for this study. Secondly, we provide a more detailed overview of the Reasenberg and Jones aftershock-forecasting model and identify the empirical constants that we seek to determine for Australia. Thirdly, we undertake an analysis of the Australian aftershock sequences. Our analysis is undertaken for individual aftershock sequences (case 1), for a compiled set of aftershocks (case 2) and for a regional analysis in western and southeastern Australia (case 3). Finally, we discuss the results and outline areas for future study.

TECTONICS, THE EARTHQUAKE CATALOGUE AND DECLUSTERING

Geologically Australia is broadly divided into Proterozoic rocks in the west and Palaeozoic rocks in the east. The Proterozoic region consists of three Archean cratons with extensive areas of reworked Proterozoic crust (1800 – 1500 Ma.) that fuse them together. The Proterozoic crust has, with the exception of a few small areas, not undergone any major tectonic activity in the last ≈1500 Ma. The Adelaide Fold Belt sediments of the Flinders and Mt Lofty Ranges were laid down in a rift complex between 840 – 560 Ma and subject to major uplift during the Delmarian orogeny (520-500 Ma). For simplicity we include them in the Proterozic crust of Australia. The Palaeozoic crust was accreted to the east coast of proto-Australia between 450 and 200 Ma and consists of back-arc and fore-arc sediments, continental fragments, volcanos and island arcs. In the last 200 Ma various intra-continental basins were present but no new crust was formed. Gondwanda broke up between 150 and 80 Ma, with Australia undergoing no significant tectonic activity since then.

Whilst the instrumental period for Australia began in the 1890s, by 1955 there were still only five seismographs in Australia and all were low gain instruments. At this time coverage of Australia for all earthquakes M >5 became possible though in practice it was closer to M 5.5. The 1950s and 1960s saw a rapid expansion of seismic networks in Australia. Local networks were set up by universities in Tasmania and NSW, South Australia and nationally by the Bureau of Mineral Resources (Denham et al., 1979). Five of these stations were part of the World Wide Standard Seismographic Network. During the 1970s, a network was also established in Victoria (Gibson et al., 1981). By 1980, there were about 70 permanent seismic stations operating in Australia. Between the late 1970s and early 1990s, several temporary networks were established to monitor the aftershocks of large earthquakes. The 1990s saw some consolidation of seismic networks and most of Australia’s seismic stations converted from analogue to digital. After the Newcastle earthquake in 1989, the 1990s saw the establishment of strong-motion instruments in Australia’s larger cities. The 2000s saw many short period stations replaced with broadband stations and a modest number of new stations installed.

The catalogue used for this research primarily is the GG-Cat catalogue, compiled by Gary Gibson by merging freely available catalogues: 12 regional catalogues, 1 national catalogue and six international catalogues. These catalogues include earthquakes attributed to over 40 different sources, ranging from national seismic networks down to particular individuals. Where multiple sources are available Gibson has manually chosen preferred location and magnitude and where appropriate reanalysed (location and magnitude) earthquakes from the original phase data. GG-Cat was supplemented by the Geoscience Australia catalogue (QUAKES) for earthquakes from 2010-08-26 up until 2011-01-01.

To identify earthquake clusters within the catalogue, Leonard (2008) proposed a declustering algorithm that was similar to that of Reasenburg and Ellsworth (1982) but had longer time windows. Leonard (2012) and Leonard et al (2013) used the work of Stein and Liu (2009) to lengthen the time window with aftershocks from magnitude 5.0, 6.0 and 7.0 earthquakes considered to last for 1.0, 12 and 150 years respectively. The algorithm treats all earthquakes as potential mainshocks, so aftershocks can have aftershocks. The declustered catalogue closely approximates a temporal Poisson process, so fulfilling the proposal (e.g. Gardner and Knopoff, 1974) that declustered catalogues should be approximately Poissonian in time. For the purpose of this study aftershock sequences are extracted from compiled Australian instrumental earthquake catalogue (1900-2010) following the Leonard (2008) methodology.

METHODOLOGY

The number of aftershocks per unit of time (or rate of aftershocks) decreases as a function of time after the main shock and can be modelled by a seismological model known as the modified Omori's law (Utsu, 1961; Utsu et al., 1995):

$$\lambda(\mathrm{t}) = \frac{k}{(c+t)^p}, \tag{1}$$

where t is the time since the main shock, λ is the rate of aftershocks occurrence, k is a function of the number of events, and c and p are empirically determined constants. Another seismological model, the Gutenberg-Richter recurrence law (Gutenberg and Richter, 1944):

$$log\lambda(M) = a - bM, \tag{2}$$

can be used to model the distribution of earthquake magnitude. In equation 2, M is the magnitude of the earthquake, λ is the rate of earthquakes with magnitude greater than M, and a and b are empirically determined constants. By combining the modified Omori's and Gutenberg-Richter laws, Reasenberg and Jones (1989) developed a model that defines the rate of aftershocks, $\lambda(t,M)$, with magnitude larger than M at a given time t after a main shock of magnitude M_m:

$$\lambda(t,M) = \frac{10^{A+b(M_m-M)}}{(c+t)^p}, \tag{3}$$

where b, c, and p are the Gutenberg-Richter and modified Omori's parameters respectively. The A-value is a measure of seismic productivity independent of the size of the main shock and can be calculated from the b and k values (Lolli and Gasperini, 2003):

$$A = \log(k) - b(M_m - M_c), \tag{4}$$

If the number of aftershocks in a sequence follows a Poisson process, using the Reasenberg and Jones model the probability of at least one aftershock with magnitude larger than given threshold M within a given time interval ΔT can be estimated as:

$$P = 1 - \exp(-\int_T^{T+\Delta T} \lambda(t,M)dt) \tag{5}$$

This model is implemented in several seismic networks around the world to forecast the probability of aftershocks in the days, weeks or months following significant earthquakes (e.g. Reasenberg and Jones, 1990; Pollock, 2007).

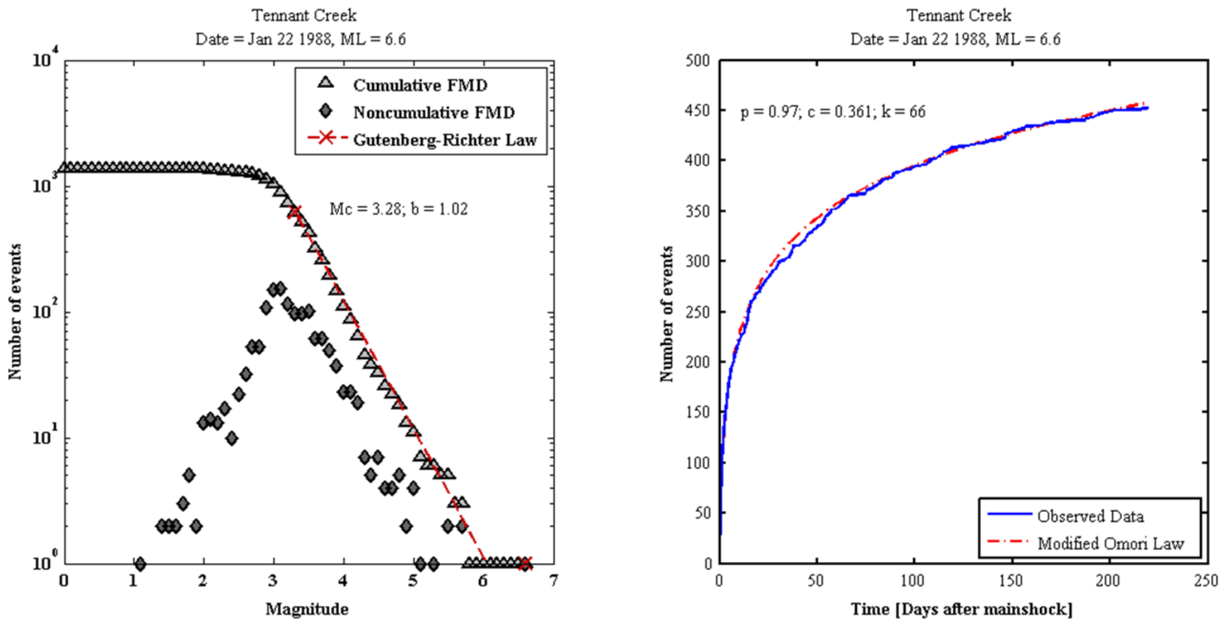
AFTERSHOCK SEQUENCE PARAMETERS

In this section we analyse Australian earthquake sequences in three cases. In case 1 we consider individual aftershock sequences. In case 2 we stack all aftershock sequences together. In case 3 we repeat the analysis of case 2 after separating the aftershock sequences regionally according to whether they are located in western or southeastern Australia (Table 1).

Table 1: List of sequences included in the stack of events. ML is the magnitude of the mainshock. The epicentres of the mainshocks are also listed. # are the well recorded sequences. * are the events used in the southeast stack.

Name, Region	Longitude	Latitude	Year	ML
Gayndah, Queensland *	151.7	-25.5	1883	5.2
Warrnambool, Victoria *	142.533	-38.433	1903	5.2
Gunning, New South Wales *	149.2	-34.8	1934	5.2
Meeberrie, Western Australia	116.197	-26.791	1941	6.8
Simpson Desert, Northern Territory	136.9	-25.3	1941	5.8
Simpson Desert, Northern Territory	137.34	-25.95	1941	6.4
Gabalong, Western Australia	116.4	-30.7	1955	5.1
Robertson, New South Wales *	150.606	-34.564	1961	5.3
Meckering, Western Australia #	116.98	-31.62	1968	6.7
Boolarra, Victoria *	146.3	-38.47	1969	5.0
Calingiri, Western Australia	116.512	-31.093	1970	5.7
Canning Basin, Western Australia	126.673	-22.059	1970	6.2
Wilpena Pound, South Australia	138.619	-31.578	1972	5.1
Picton, New South Wales* #	150.34	-34.187	1973	5.2
Cadoux, Western Australia #	117.104	-30.821	1979	6.1
Wonnangatta, Victoria *	146.972	-37.211	1982	5.1
Marryat Creek, Northern Territory	132.734	-26.31	1986	5.7
Tennant Creek, Northern Territory #	133.855	-19.896	1988	6.6
Broome, Western Australia	122.407	-17.666	1989	5.5
Newcastle, New South Wales *	151.61	-32.952	1989	5.4

For case 1 we must first identify the aftershock sequences that are well recorded. Klein et al. (2006) demonstrated that a good parameter fitting requires a “well-recorded sequence” with a magnitude range of at least 3 to 4 between the main shock magnitude and the completeness magnitude. The magnitude of completeness (M_c) indicates the lowest magnitude above which all earthquakes in the sequence are recorded (Wiemer and Wyss, 2000). The level of M_c is mainly controlled by the performance of the operational seismic network, and the method of analysis. There are several techniques proposed to assess the level of M_c (Woessner and Wiemer, 2005). In this study we automatically determine M_c using the “maximum curvature” technique as proposed by Wiemer and Wyss (2000). In this technique the point where the first derivative of the Frequency-Magnitude Distribution (FMD) curve of the sequence becomes zero, determines the magnitude of completeness. For example, Figure 1.a shows the FMD of the 1988 Tennant Creek’s sequence (main shock magnitude: M_L 6.6), together with the estimated magnitude of completeness (M_c 3.3). In this example, the difference between the main shock magnitude and the completeness magnitude is around 3 and the Tennant Creek’s sequence is flagged as a “well-recorded sequence”.



(a) (b)

Figure 1: Case 1 (a) Cumulative and non-cumulative numbers of observed earthquake magnitudes in 1988 Tennant Creek's sequence. Fitted Gutenberg-Richter law to the observations along with the estimated parameters are also shown. (b) Cumulative numbers of observed aftershocks of 1988 Tennant Creek earthquake versus time (in days) elapsed from the main shock. Fitted modified Omori law to the observations along with the estimated parameters are also shown.

Applying the Klein et al. (2006) criterion to all clusters in the Australia earthquake catalogue identifies 5 sequences as well-recorded sequences. The spatial distribution of these sequences is shown in Figure 2. For each of the 5 identified aftershock sequences, we determine the best fitting empirical constants k, c and p in the modified Omori's law using the method of maximum likelihood proposed by Ogata (1983). Similarly, we determine the best fitting empirical constants a and b for the Gutenberg-Richter law using the method of maximum likelihood proposed by Aki (1965). Finally, we calculate the A-value in the Reasenberg and Jones model based on the estimated b and k values.

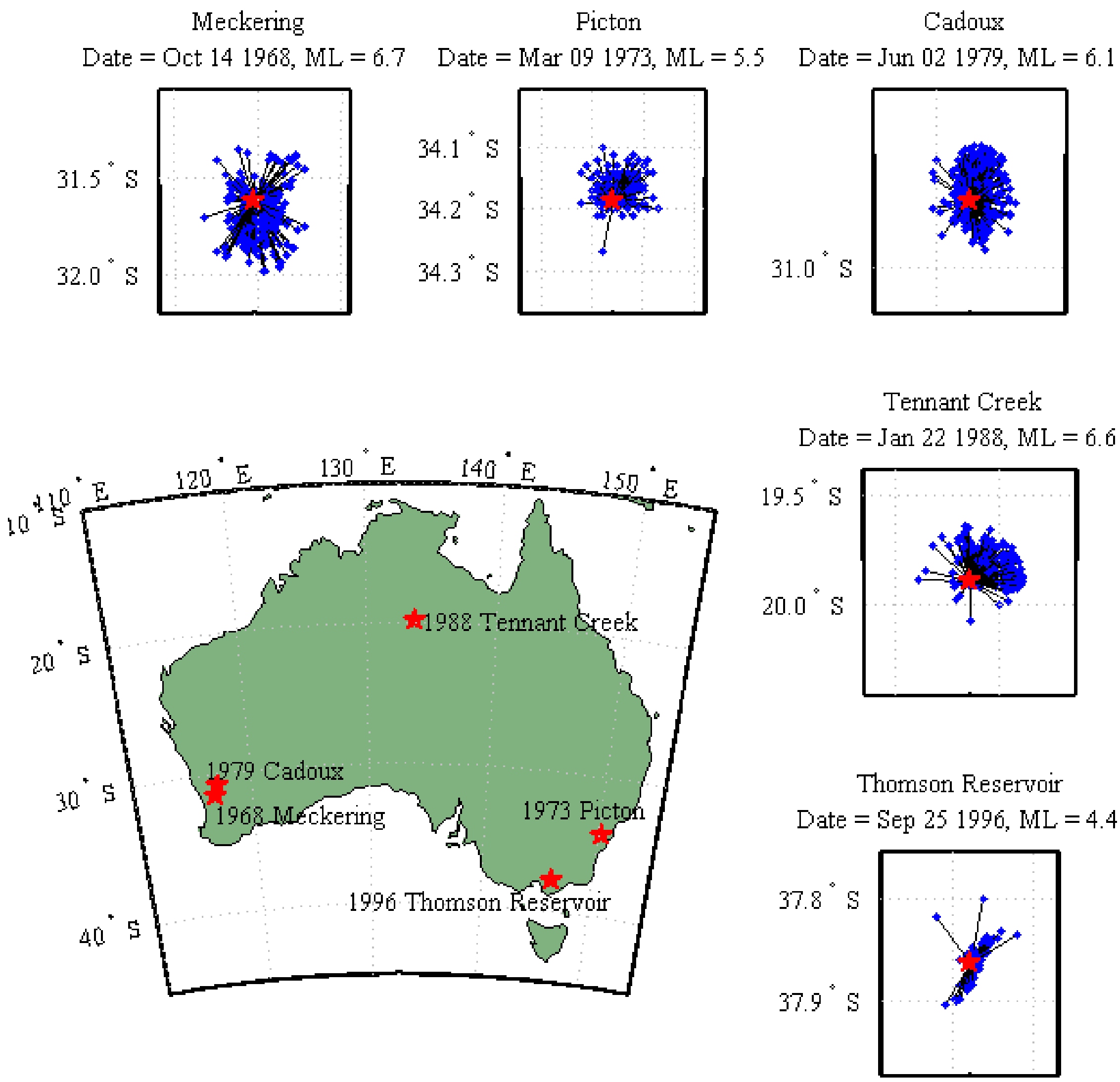
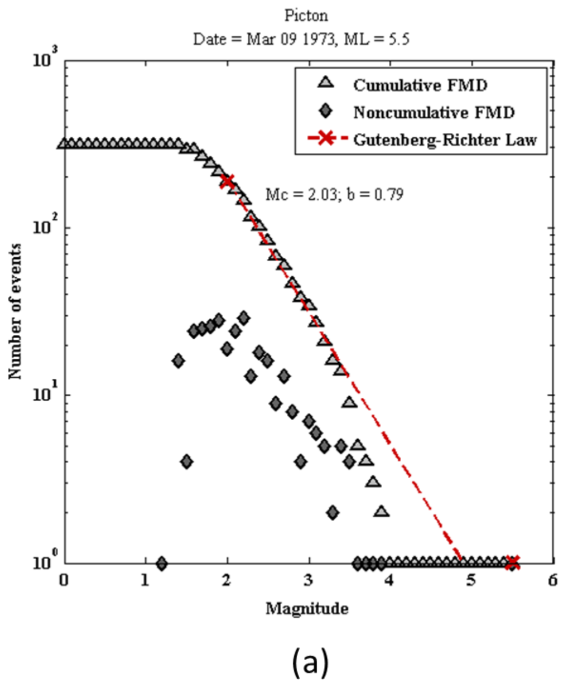


Figure 2: Spatial distribution of the mainshocks with sufficient number of aftershocks that are classified as well-recorded sequences. Spatial distribution of aftershocks within each sequence is also shown.

The Frequency-Magnitude distribution (the number of events versus magnitude), as well as frequency-time distribution (the number of events versus time after the main shock) of 4 out of 5 of the "well-recorded sequences" closely follow the Gutenberg-Richter and modified Omori's laws. For example, Figure 1 shows the model-fit of the Gutenberg-Richter and modified Omori's laws to the aftershocks in Tennant Creek's sequence. Both the number of aftershocks for a given magnitude and the cumulative number as a function of elapsed time from the main shock are well represented by the Gutenberg-Richter and modified Omori's laws, respectively. In contrast, Figure 3 shows the model-fit to the number of aftershocks in the 1973 Picton earthquake sequence. It can be seen that the numbers of aftershocks with magnitudes larger than ~3.5 are clearly over-estimated by the fitted Gutenberg-Richter law. This is due to the automatic process underestimating the M_c value. This example clearly shows the importance of manual checking the automatic estimates of M_c. Note that due to the overestimation of M_c the Picton sequence is not classified as a “well recorded sequence”.



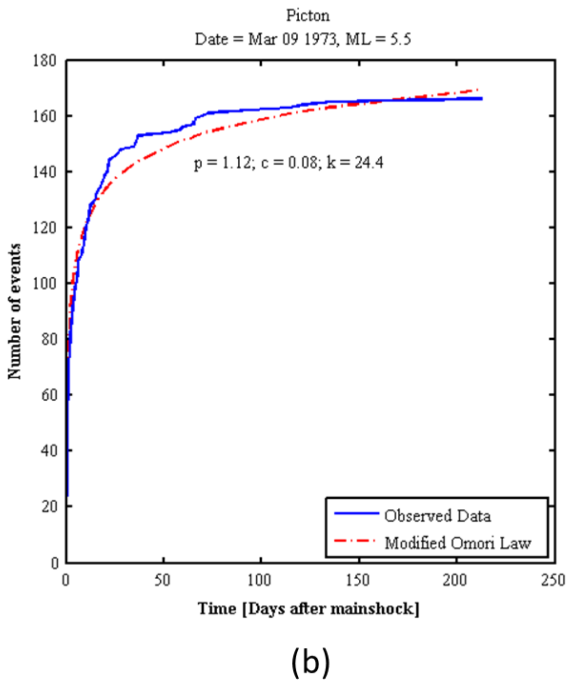


Figure 3: Case 1 (a) Cumulative and non-cumulative numbers of observed earthquake magnitudes in 1973 Picton’s sequence. Fitted Gutenberg-Richter law to the observations along with the estimated parameters are also shown. (b) Cumulative numbers of observed aftershocks of 1973 Picton earthquake versus time (in days) elapsed from the mainshock. Fitted modified Omori law to the observations along with the estimated parameters are also shown.

In order to demonstrate the applicability of Reasenberg and Jones model, for each of the “well-recorded sequences”, a 1-month forecast of the expected numbers as well as probabilities of aftershocks following the main shock of the sequence are generated based on sequence specific parameters. For all of the selected well-recorded sequences there is a very good agreement between the expected numbers of aftershocks calculated based on Reasenberg and Jones model and observed ones. Figure 4 shows such comparison for Tennant Creek’s sequence. It can be seen that, as expected, the probability of an aftershock occurring decreases as the corresponding magnitude increases (Figure 4.a). It can be also seen that, the predicted numbers of aftershocks with different magnitudes (Figure 4.b) are in good agreement with the actual observed numbers (Figure 4.c).

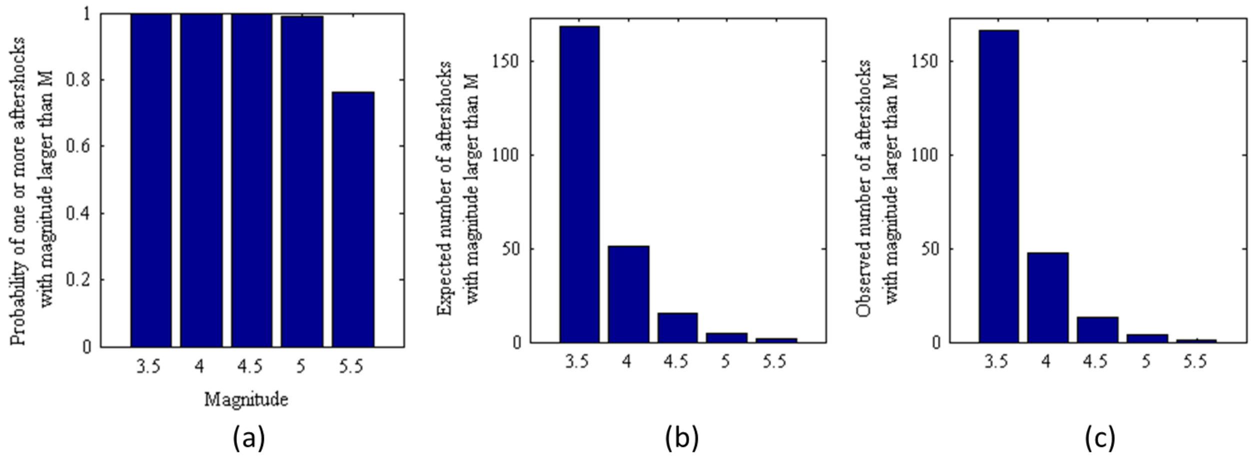


Figure 4: Case 1 (a) Estimated probabilities for the aftershocks of the 1988 Tennant Creek earthquake. Each bar indicates the probability for the occurrence of at least one aftershock with magnitude equal to or greater than the given magnitude. (b) Expected numbers of aftershocks with magnitudes equal to or greater than the given magnitudes. (c) Observed numbers of aftershocks with magnitudes equal to or greater than the given magnitudes.

Using only well-recorded sequences to estimate aftershock parameters may cause overestimates of A-value: a function of productivity of the sequence. To avoid overestimating the A-value and also considering the fact that there are only very few well-recorded sequences, aftershock data from all identified sequences with corresponding main shock magnitude larger than 5 are stacked to form a single average sequence. This stacked collection of aftershocks from 20 main shocks (Table 1) forms the basis of analysis for case 2. The Frequency-magnitude and frequency-time distributions for the stacked sequence are shown in Figure 5. Fitted Gutenberg-Richter and modified Omori's models are also presented as dashed lines. We observe that the models fit the observed data well. The estimated parameters of the fitted models are also indicated in this figure. To verify the applicability of the Reasenberg and Jones model using "generic parameters" derived for the stacked sequence, a 1-month forecast is generated for two aftershock sequences that are not originally included in the earthquake catalogue used in this study. The aftershocks sequences that we use for this test are those from the 2011 Bowen earthquake's sequence (main shock magnitude: M_L 5.3) and the 2012 Moe earthquake's sequence (main shock magnitude: M_L 5.4). The expected numbers of aftershocks and their corresponding probabilities are illustrated with the observed aftershocks in Figure 6. In this case, the inherent uncertainty of the estimated numbers of aftershocks is also calculated and a range for expected numbers of aftershocks is provided in parentheses. The observed aftershocks for both of these sequences fall within the forecasted range using the fitted parameters determined for case 2 with the stacked aftershock sequences.

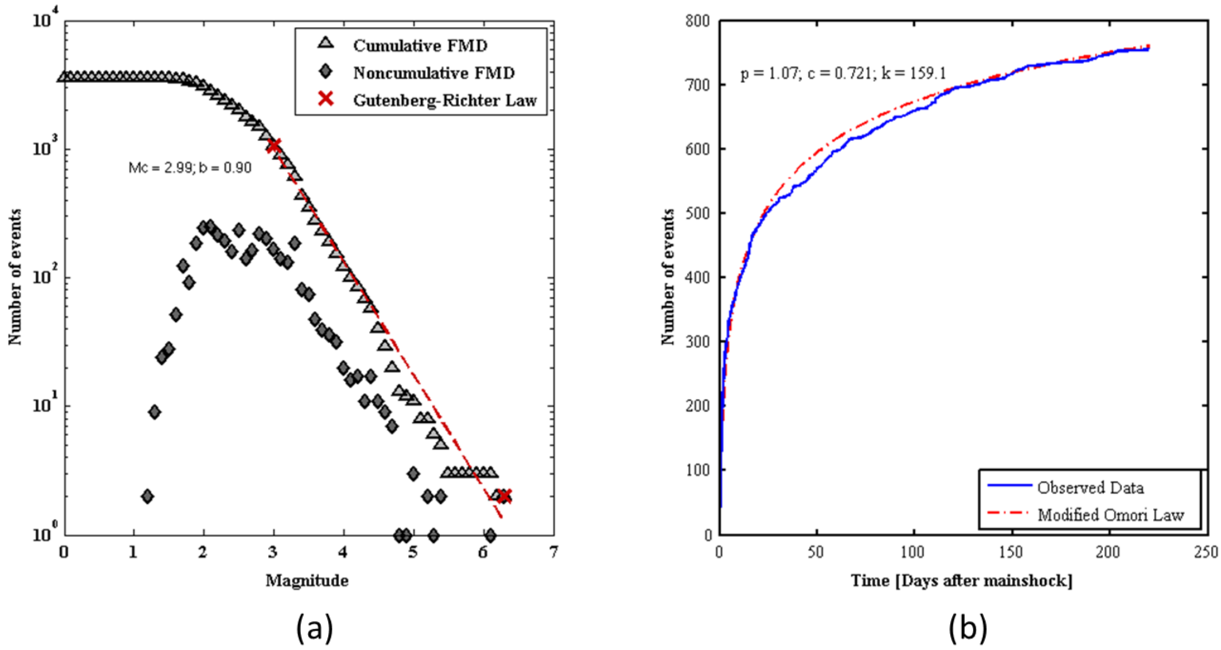


Figure 5: Case 2 (a) Cumulative and non-cumulative numbers of earthquake magnitudes in the stacked sequence. Fitted Gutenberg-Richter law to the observations along with the estimated parameters are also shown. (b) Cumulative numbers of aftershocks in the stacked sequence versus time (in days) elapsed from the mainshock. Fitted modified Omori law to the observations along with the estimated parameters are also shown.

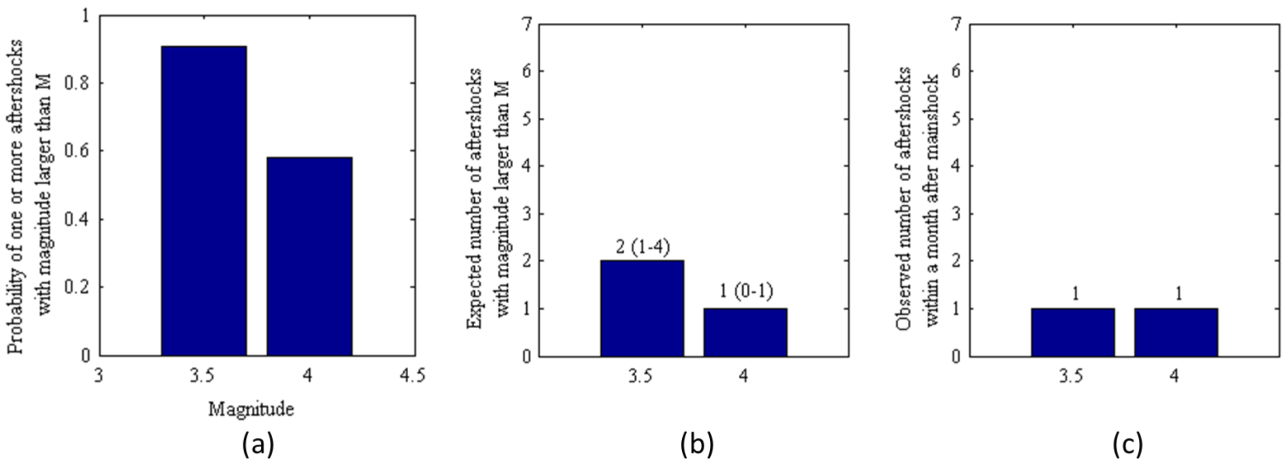


Figure 6: Case 2 (a) Estimated probabilities for the aftershocks of the 2012 Moe earthquake. Each bar indicates the probability for the occurrence of at least one aftershock with magnitude equal to or greater than the given magnitude. (b) Expected numbers of aftershocks with magnitudes equal to or greater than the given magnitudes. The numbers in parentheses indicate the estimated range for expected numbers of aftershocks. (c) Observed numbers of aftershocks with magnitudes equal to or greater than the given magnitudes.

In case 3 we re-determine the empirical constants at the regional scale for western and southeastern Australia separately by stacking the events for these regions separately. Figure 7 shows the forecasted number of aftershocks with magnitude larger than 3.5 for a hypothetical main shock with magnitude equal to 6.0. We observe that the expected number of aftershocks in a western-Australian sequence is significantly larger than that expected for a sequence in southeastern–Australia.

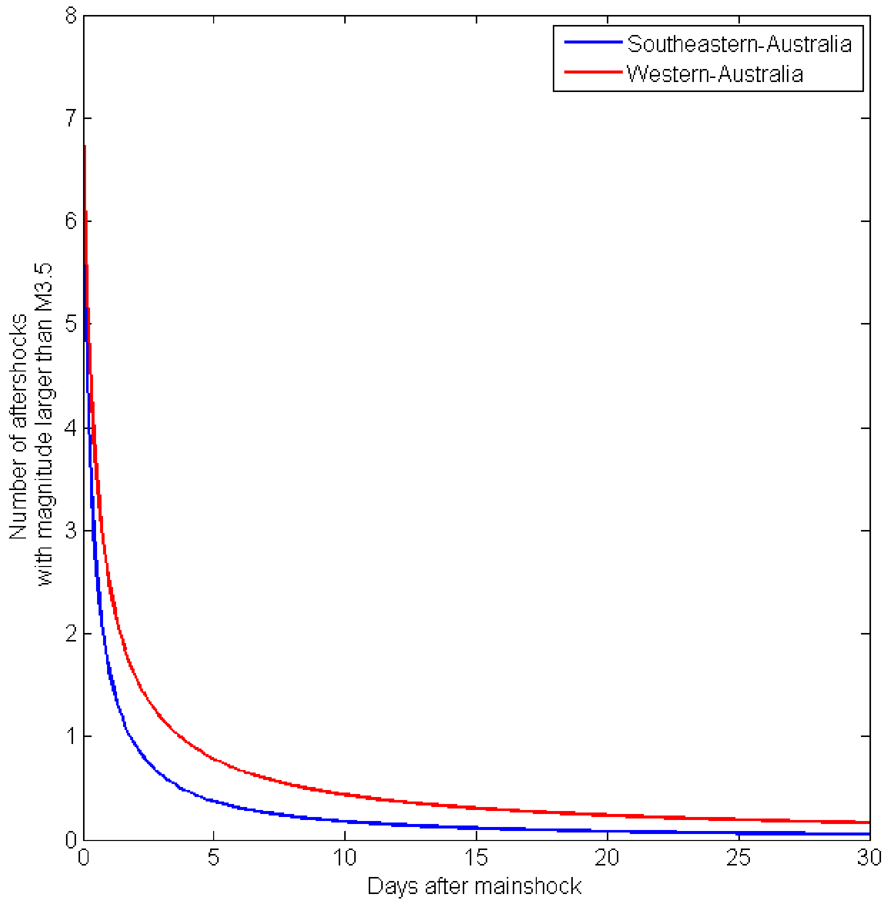


Figure 7: Case 3. Comparison of the rates of aftershocks in western and southeastern-Australia with magnitudes larger than 3.5 in numbers per day following a hypothetical earthquake with magnitude equal to 6.0.

Discussion and concluding remarks

In this study we calibrate the Reasenberg and Jones model for Australia using aftershock sequences extracted from the Australian instrumental earthquake catalogue (1900-2010). The applicability of the adjusted model is verified using two recently recorded aftershock sequences in Australia: 2011 Bowen earthquake's sequence (mainshock magnitude: M_L 5.3) and 2012 Moe earthquake's sequence (mainshock magnitude: M_L 5.4). It is shown that the numbers of observed aftershocks during these sequences are within the range of model forecasts. Although the results are promising, we emphasise that the model parameters should be continuously updated as new aftershock sequences occur in Australia.

Another possible modification to the methodology applied in this study could be implementing better constraints on the spatial distribution of aftershocks. Currently the only spatial constraint is a simple circular-space-window, with the radius proportional to the magnitude of the event, as implemented in the de-clustering algorithm used in this study. However, as shown by previous studies, a better constraint on the location of aftershocks could be applied by considering dynamic and static stress transfer due to an earthquake occurrence (e.g. Stein, 1999). We have observed the potential for this improved definition through preliminary analysis of the correlation of aftershock locations with the regions of static stress increase for the 1988 Tennant Creek sequence (results not presented herein).

In practice, a near real-time aftershock forecast can be made using derived "generic parameters" for Australia, as soon as a significant event occurs. Then the "generic parameters" can be updated as new data becomes available following, for example, the Bayesian approach as suggested by Reasenberg and Jones (1989). Although this process can be performed in a fully automatic manner, the operators should be aware of possible limitations. One inherent limitation of modified Omori's law that is also echoed in Reasenberg and Jones model is that the occurrence of strong aftershocks with the magnitude comparable to the main shock has no effect on the sequence productivity rate. However, it is well understood that occurrence of strong aftershocks may indeed increase the rate of aftershock occurrence of the overall sequence. To overcome this problem, one simple solution would be to treat such strong aftershocks as a new main shock and generate aftershock forecasts independently.

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