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SHORT COMMUNICATION

Spatial variation of seismicity parameters across India and adjoining areas

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Abstract An attempt has been made to quantify the variability in the seismic activity rate across the whole of India and adjoining areas (0–45°N and 60–105°E) using earthquake database compiled from various sources. Both historical and instrumental data were compiled and the complete catalog of Indian earthquakes till 2010 has been prepared. Region-specific earthquake magnitude scaling relations correlating different magnitude scales were achieved to develop a homogenous earthquake catalog for the region in unified moment magnitude scale. The dependent events (75.3%) in the raw catalog have been removed and the effect of aftershocks on the variation of *b* value has been quantified. The study area was divided into 2,025 grid points (1°×1°) and the spatial variation of the seismicity across the region have been analyzed considering all the events within 300 km radius from each grid point. A significant decrease in seismic *b* value was seen when declustered catalog was used which illustrates that a larger proportion of dependent events in the earthquake catalog are related to lower magnitude events. A list of 203,448 earthquakes (including aftershocks and foreshocks) occurred in the region covering the period from 250 B.C. to 2010 A.D. with all available details is uploaded in the website http://www.civil.iisc.ernet.in/~sreevals/resource.htm.

Keywords India · Earthquake catalog · Moment magnitude · Seismicity · *b* Value

1 Introduction

A complete and consistent catalog of earthquakes in a region can offer good data for studying the distribution of earthquakes in a region with respect to space, time and magnitude. However, most catalogs do not report the earthquake magnitudes constantly

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over time. This may create obstruction for defining seismicity patterns or for assessing seismic hazards. As earthquake magnitude has become a crucial source parameter of earthquakes since its commencement (Richter 1935), it is essential to convert the original magnitudes based on various scales in different time periods to a common magnitude scale throughout the whole period. The magnitude scales used for the catalogs of earthquakes in India is very heterogeneous. In this study, an attempt has been made to prepare a catalog of earthquakes in and around India (5–40°N and 65–100°E) by compiling all the available data till 2010.

There have been several efforts to estimate seismicity parameters for Indian region based on both the historical as well as the instrumental earthquake catalog (Shanker and Sharma 1998; Iyengar and Ghosh 2004; Raghukanth and Iyengar 2006; Jaiswal and Sinha 2007; Raghukant 2010). These researchers focused on some part of India or used different methodology for homogenization of catalog as well as estimation of seismicity parameters.

Region-specific earthquake magnitude scaling relations correlating different magnitude scales were achieved to develop a homogenous earthquake catalog for the region in unified moment magnitude (M_W) scale. The dependent events in the raw catalog have been removed to ensure the Poissonian distribution of earthquakes. The seismicity analysis was done based on the maximum likelihood method to estimate the seismicity parameters (a and b), and the effect of aftershocks on the same also is presented in the paper.

2 Data and method of analysis

A larger data set provided by various national and international agencies was used in the analysis. Two types of earthquake catalogs were used in this study; historical and instrumental. The historical part of the catalog was compiled from various literatures. The details of earthquake events for the period from 250 B.C. to 1505 A.D. were obtained from Dunbar et al. (1992) except an event (occurred on 5th December 1063) reported by IMD. The catalog given by Dunbar et al. (1992) lists historical earthquakes that have occurred worldwide from 2150 B.C. to 1991 A.D. Later portion of historic earthquakes were compiled from the work of various researchers like Oldham 1883; Basu 1964; Kelkar 1968; Tandon and Srivastava 1974; Rastogi 1974; Chandra 1977, 1978; Kaila and Sarkar 1978; Rao and Rao 1984; Srivastava and Ramachandran 1985; Biswas and Dasgupta 1986; Guha and Basu 1993; Bilham 2004 etc. Major portion of the instrumental catalog was compiled from national to international agencies. The national agencies include Gauribidanur Array (GBA), Indian Meteorological Department (IMD), Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam and National Geophysical Research Institute (NGRI), Hyderabad. International agencies include International Seismological Center (ISC) data file (for the time period between 1964 and 2010), Harvard seismology and USGS/NEIC catalog (for the time period between 1973 and 2010). The earthquakes which are occurring outside the study area will also add to the seismic hazard of the study area (US Regulatory Guide 1997). Hence, the details of the past earthquakes and seismic sources were collected from an area (seismic study area) which extend up to 500 km from the boundary of India.

A catalog of 272,156 earthquakes with magnitudes between M_W 1.0 and 9 since 250 B.C. is the basis of the present study. Since the data were collected from various sources, many of the major events were repeated in the catalog as those were reported by more than one agency/literature. Hence, the duplicate events were identified and removed by comparing the location, time and magnitude of each of the events. About 68,678 events were

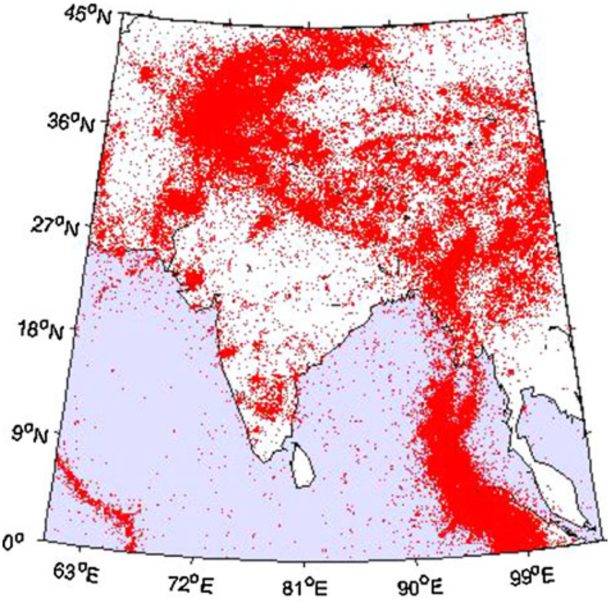


Fig. 1 Spatial distribution of the epicenters of earthquake events (including aftershocks and foreshocks)

found to be duplicate and hence the catalog is refined by considering 203,448 original events only. The spatial distribution of the epicenters of these events is presented in Fig. 1. It is clear that a great majority of earthquakes took place in the Andaman Nicobar regions and North and Northeast India adjoining to Himalayas. The largest event was the one occurred at Sumatra on December 26, 2004, and the latest event is 5.2 m_b earthquake occurred in Western Xizang, Tibet on December 30, 2010.

2.1 Homogenization of earthquake magnitude

It is a prerequisite for complete earthquake catalog to have a uniform magnitude scale for denoting the size of earthquakes, so that a reliable parameterization of the magnitude distribution which is homogeneous and complete with respect to time and size is used in hazard analysis. The earthquake data obtained were in different magnitude scales like body wave magnitude (m_b), surface wave magnitude (M_S), local magnitude (M_L), moment magnitude (M_W) and the earthquake intensity scale (I).

Unfortunately, many of the magnitude scales are all limited by saturation toward large earthquakes with $m_b > 6.0$, $M_L > 6.5$, and $M_S > 8.0$. The existence of different magnitude scales necessitates the conversion of these magnitude scales to a single magnitude scale for the analysis purposes. The moment magnitude M_w (Kanamori 1977) can represent the true size of earthquakes because it is based on seismic moment, which in turn is proportional to the product of the rupture area and dislocation of an earthquake fault (Aki 1966). M_W is defined as

$$M_W = 2/3 \log_{10} M_0 - 6.05 \tag{1}$$

where M_0 is the scalar seismic moment in Nm. The homogenization of earthquake catalog involves expressing the earthquake magnitudes in one common scale. Practical problems,

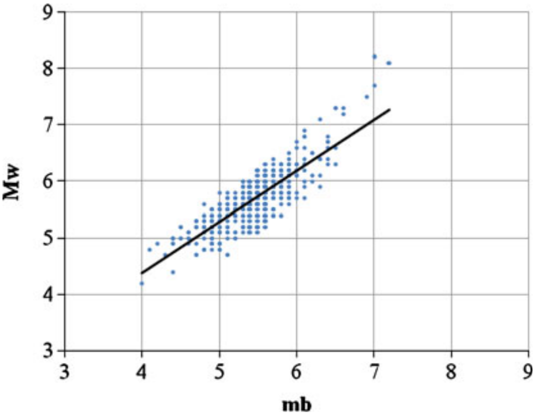


Fig. 2 Relation between m_b and M_W, $R^2 = 0.719$, $n = 1{,}850$

such as seismic hazard assessment, necessitate use of homogenized catalog. Since M_W does not saturate, this is the most reliable magnitude for describing the size of an earthquake (Scordilis 2006). As moment magnitude (M_W) scale is the most advanced and widely used magnitude scale, the original magnitudes of Indian earthquakes in different time periods have been converted to unified M_W magnitudes. Several relations were proposed by different researchers to convert different magnitude scales to M_W (Nuttli 1983; Giardini 1984; Heaton et al. 1986; Patton and Walter 1993; Johnston 1996; Papazachos et al. 2002; Scordilis 2006; Thingbaijam et al. 2008; among many others). In this study, two methods for magnitude conversion were used; one based on Scordilis (2006) and the other using the developed correlations from the data available for the study area (as detailed below).

Based on the earthquake data available from the study area, an attempt to develop linear relations connecting various magnitude scales with moment magnitude scale was done. Using the available data, an attempt was done to fit the trend line using polynomial relations also. It was seen that there is not much improvement in the regression compared to linear relation. There were 1,850 sets of data having M_W and m_b, 69 sets of data having M_W and M_L and 1,254 sets of data having M_W and M_S. A relation connecting M_S with m_b was also developed using 16,734 data sets available in the raw catalog.

The distribution of M_W versus m_b obtained for present data is shown in Fig. 2. The correlation of M_W and m_b from 1,850 entries as depicted in Fig. 3 is seen to follow the relation,

$$M_W = 1.08(\pm 0.0152)m_b - 0.325(\pm 0.081) \quad m_b \leq 4 \leq 7.2 \quad R^2 = 0.732 \qquad (2)$$

The distribution of M_W versus M_L is shown Fig. 3 and the correlation is obtained as

$$M_W = 0.815(\pm 0.04)M_L + 0.767(\pm 0.174) \quad 3.3 \leq M_L \leq 7 \quad R^2 = 0.884 \qquad (3)$$

The regression between M_W and M_S as presented in Fig. 4 yield the following relation,

$$M_W = 0.693(\pm 0.006)M_S + 1.922(\pm 0.035) \quad 3.7 \leq M_S \leq 8.8 \quad R^2 = 0.90 \qquad (4)$$

Similarly, the correlation between m_b and M_S as presented in Fig. 5 yield the following relation,

Fig. 3 Relation between M_L and M_W, $R^2 = 0.884$, $n = 69$

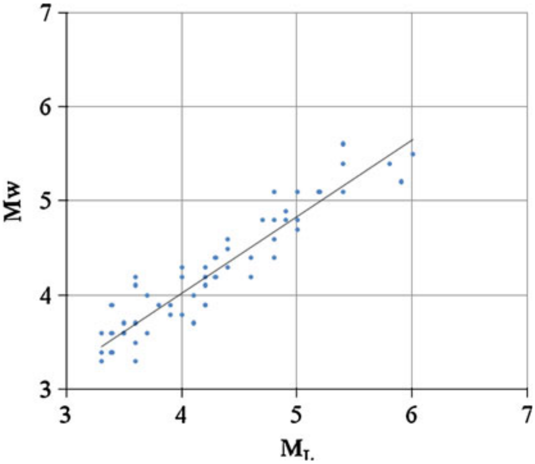
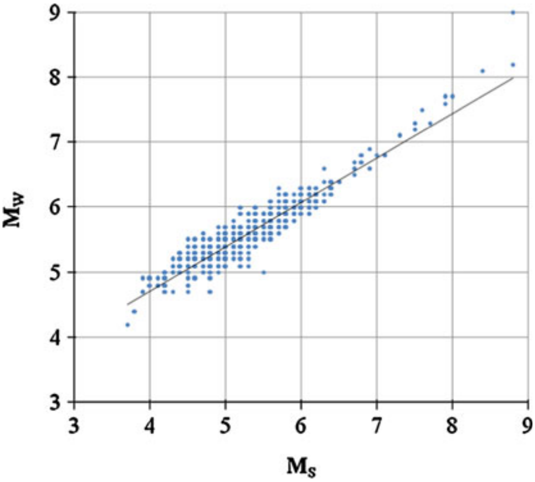


Fig. 4 Relation between M_S and M_W, $R^2 = 0.893$, $n = 1,254$



$$M_S = 1.057(\pm 0.006)m_b - 0.649(\pm 0.028) \; 3.4 \leq m_b \leq 7 \; R^2 = 0.659 \qquad (5)$$

The converted M_W magnitudes obtained from Scordilis (2006) and these methods were compared and both were in good agreement with each other. The comparison of M_W obtained from m_b to M_S using different relations was shown in Tables 1 and 2. The relationships between different magnitude scales will depend on the observation errors, source characters such as stress drop, fault geometry. (Heaton et al. 1986). It is always advisable to use the region specific magnitude conversion relations (Liu et al. 2007). Hence, the M_W values obtained from the correlations developed for the study area were used for homogenization of different magnitude scales. For the conversion of intensity scale to M_W, the relation developed by Menon et al. (2010) was used as commented that the use of relation suggested by Reiter (1990) to convert the intensity scale to moment magnitude may not hold good for Indian conditions. Thus, a consistent catalog with unified magnitude scale is obtained for entire study area (0–45°N and 60–105°E).

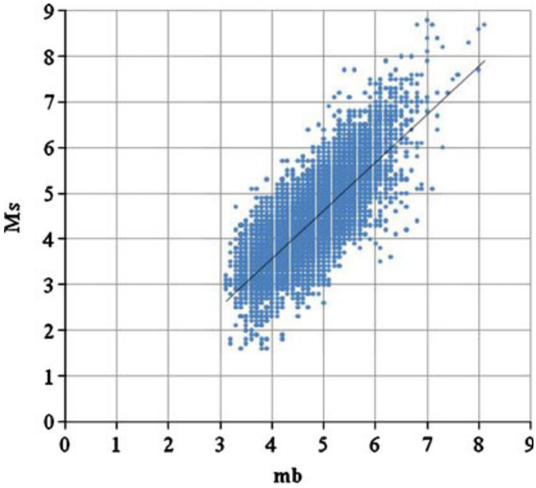


Fig. 5 Relation between m_b and M_S, $R^2 = 0.659$, $n = 16{,}734$

Table 1 Comparison of magnitude conversion relations relating m_b with M_W

m_b	Present relation	Scordilis (2006)	Thingbaijam et al. (2008)
3.5	3.9	4.0	3.0
4.0	4.4	4.4	3.7
4.5	4.8	4.9	4.4
5.0	5.3	5.3	5.1
5.5	5.7	5.7	5.8
6.0	6.2	6.1	6.4

Table 2 Comparison of magnitude conversion relations relating M_S with M_W

M_S	Present relation	Scordilis (2006)	Thingbaijam et al. (2008)
3.0	4.0	4.1	3.9
4.0	4.7	4.8	4.6
5.0	5.4	5.4	5.3
6.0	6.1	6.1	6.0
7.0	6.8	7.0	6.7

2.2 Identification of main shocks

The instrumental catalogs involve not only the main shocks but also foreshocks and aftershocks. In estimating the earthquake hazard, generally, a Poisson model of earthquake occurrence is assumed. Therefore, the catalog in use must exhibit random space time characteristics. Aftershocks and foreshocks show a major deviation from a Poisson process and several methods have been suggested for the separation of aftershocks from the raw earthquake data (Savage 1972; Gardner and Knopoff 1974; Reasenberg 1985; Davis and Frohlich 1991; 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 which is an important goal of seismic hazard studies.

Table 3 Statistics of earthquake events in the declustered catalog

Magnitude (M_W)	No. of events
4–4.9	16,079
5–5.9	9,879
6–6.9	1,036
7–7.9	129
8–9	22

Declustering is the separation of the dependent events (i.e., foreshocks, aftershocks and clusters) from the background seismicity (Reasenberg 1985). For seismicity rate studies (Wiemer and Wyss 1994, 1997) as well as hazard-related studies (Frankel 1995), declustering is often considered necessary to achieve better results.

Knopoff (1964) introduced a declustering algorithm to count earthquakes in successive 10 days intervals and to prepare a histogram showing the traits of a Poisson distribution. Gardner and Knopoff (1974) introduced a procedure for identifying aftershocks within earthquake catalogs using their distances in time and space. They also provided specific space–time distances as a function of the mainshock magnitude to identify aftershocks. They ignored secondary and higher order aftershocks (i.e., aftershocks of aftershocks). They also did not consider fault extension for larger magnitude earthquakes by assuming circular spatial windows. Reasenberg (1985)'s algorithm allows to link up aftershock triggering within an earthquake cluster. In this approach, the largest earthquake in a cluster is identified as mainshock. Another crucial development in this method is that the space–time distance is based on Omori's law (for its temporal dependence): as the time from the mainshock increases, the time one must wait for the next aftershock also increases in proportion (Stiphout et al. 2010).

In the present study, dependent shocks as those falls within the space and time intervals of the main shock are eliminated to obtain a data set of mainshocks which are assumed to show a Poisson distribution. The declustering was done following the algorithm developed by Gardner and Knopoff (1974) modified by Uhrhammer (1986). Out of 203,448 events in the raw catalog, 75.3% were found to be dependent events and remaining 50,317 events were identified as mainshocks of which 27,146 events were of $M_W \geq 4$. The number of earthquake events in the declustered catalog for different magnitude range is shown in Table 3 ($M_W \geq 4$). The details of major earthquakes in the region are listed in Table 4. Temporal changes of instrumental seismicity of both clustered and declustered catalog is shown in Fig. 6. In recent years, a rapid increase is seen in the number of earthquakes which reflects the capability of advanced seismic recording instruments to record even smaller magnitude earthquakes in India.

3 Estimation of seismicity parameters

The size distribution of earthquakes in a seismogenic source can often be adequately described over a large range of magnitudes by a power law relationship. This was explained by Gutenberg and Richter (1944) using the earthquake data of California. The commonly used form of the power law is given as

$$\log N = a - bM \tag{6}$$

Table 4 Details of major earthquakes ($M_W > 7.5$) occurred in and around India

Year	Month	Date	Longitude (°)	Latitude (°)	M_W
1668	5	1	68	25	7.6
1737	5	11	88.4	22.6	7.7
1816	5	26	86.5	30	8
1819	6	16	69.6	23.6	8.3
1833	8	26	86.5	27.5	8
1897	6	12	91	26	8.1
1902	8	22	77	40	8.5
1902	8	30	71	37	7.7
1905	4	4	76	33	7.8
1908	10	23	70.5	36.5	7.6
1908	12	12	97	26.5	8.2
1911	7	4	70.5	36.5	7.6
1916	8	28	81	30	7.7
1918	7	8	91	24.5	7.6
1921	11	15	70.5	36.5	8.1
1931	1	27	96.8	25.6	7.6
1932	12	25	96.5	39.2	7.6
1934	1	15	86.5	26.5	8.1
1937	1	7	98	35.5	7.6
1941	6	26	92.5	12.5	8.5
1947	3	17	99.5	33	7.7
1949	3	4	70.6	36.6	7.7
1950	8	15	96.5	28.6	8.6
1951	11	18	91	30.5	8
1956	6	9	69.1	34.3	7.6
1965	3	14	70.8	36.6	7.8
1983	12	30	72	34.5	7.7
1988	11	6	99.6	22.8	7.6
1997	11	8	87.325	35.069	7.6
2001	1	26	70.232	23.419	7.7
2001	11	14	90.541	35.946	7.8
2004	12	26	94.26	3.09	9
2005	10	8	73.588	34.539	7.6

where N is the cumulative number of earthquakes, and a and b are constants. The parameter "a" describes the productivity of a volume, and b, the slope of the frequency–magnitude distribution (FMD), describes the relative size distribution of events. Spatial mapping of b values has been proven as a rich source of information about the seismotectonics of a region. The ample, high-quality earthquake catalogs collected primarily over the past two decades, and the availability of increased computing power, have enabled researchers to investigate spatial variations in b with high precision. The strong difference in b is simply a reflection of the heterogeneity of the earth that emerges on all scales, once suitable datasets become available (Wiemer and Wyss 2002). The maximum likelihood method was used in the estimation of seismicity parameters. In this study, the effect of

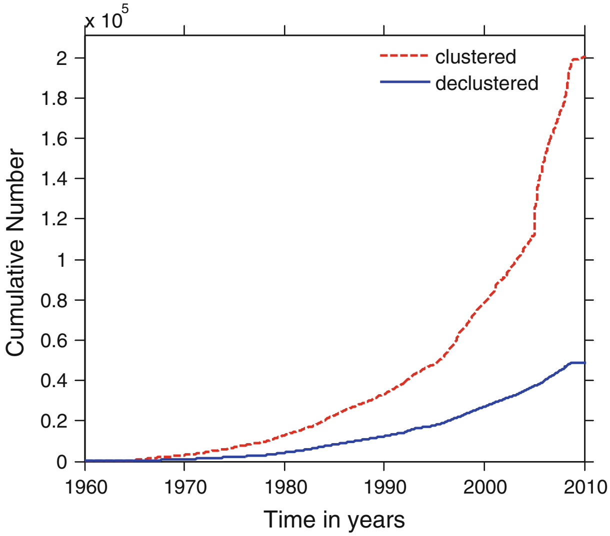


Fig. 6 Cumulative number of earthquakes in instrumental part of the catalog

dependent events (aftershocks) on earthquake hazard parameters is also examined. Two kinds of catalogs i.e., clustered and declustered catalogs (250 B.C. to 2010 A.D.) were used in this investigation.

The study area is spread over a vast region and the earthquake pattern obtained from the past earthquake data (Fig. 1) clearly indicates the nonuniformity in the seismic activity. To study the spatial variation of the seismicity parameters, *a* and *b* values, the study area was divided into small grids of size $1^\circ \times 1^\circ$ and the seismicity parameters were evaluated at the center of each of these grid cells. The evaluation of these values was done based on the magnitude of completeness (*Mc*) of the catalog (Reasenberg 1985). The magnitude of completeness (*Mc*) is defined as the lowest magnitude at which 100% of the events in a space–time volume are detected (Rydelek and Sacks 1989). Below this magnitude, a fraction of events is missed by the network because they are either too small to be recorded by enough stations, or because they are below the magnitude of interest or because they are mixed with the coda of a larger event and therefore, they passed undetected. The value of *Mc* was calculated at the center of the grid points by considering the events within a radius of 300 km. The evaluation of *b* value was done based on the maximum likelihood method (Aki 1966). For this calculation, only those earthquake events which are higher than the magnitude of completeness *Mc* for each grid points were considered. In order to get better estimates of *b* values, the values were evaluated for those grid points which were having at least 50 events with magnitude equal to or greater than *Mc*. This criterion is very essential for getting a good statistical analysis (Utsu 1999). The uncertainties involved in evaluating *b* value were calculated using the boot strap method with 100 bootstraps (Chernick 1999). The spatial and temporal variations of seismic activity across the country are investigated based on the seismic tool ZMAP (Wiemer 2001).

4 Results and discussion

The correct estimate of the *a* and *b* values depends critically on the completeness of the sample under investigation. The FMD deviates from a linear power law fit increasingly for

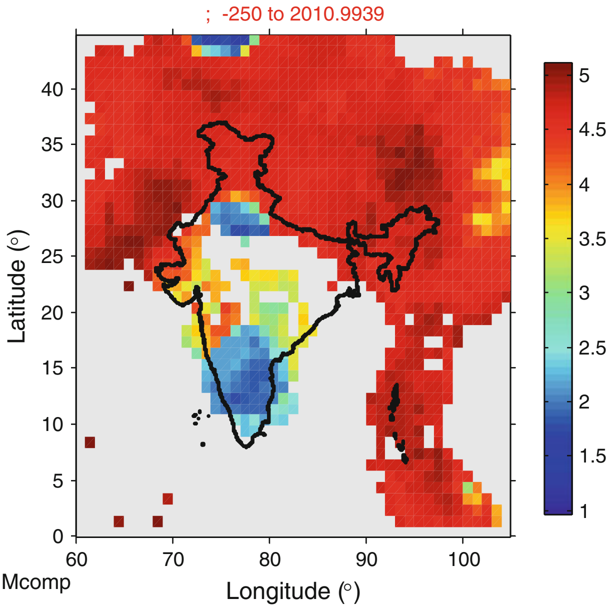


Fig. 7 Spatial variation of magnitude of completeness (from declustered catalog)

smaller magnitudes which is caused by the fact that the recording network is only capable of recording a fraction of all events for magnitudes smaller than the magnitude of completeness, *Mc*. If *Mc* is raised to large values, the uncertainty in the *b* value estimate increases strongly. The situation is complicated by the fact that *Mc* varies as a function of space and time throughout all earthquake catalogs, hence estimating the correct *Mc*, while maximizing the available number of earthquakes, becomes difficult. The method suggested by Wiemer and Wyss (2000) is adopted to estimate *Mc* in the present study. The variation of *Mc* with space is shown in Fig. 7.

The *b* value at each grid point was estimated considering the events within a radius of 300 km from center of the grid. The spatial variation of *b* value across the study area obtained from clustered to declustered catalogs is shown in Figs. 8 and 9, respectively. It is seen that the declustered catalog is giving a lower *b* value in most of the regions (Koyna region, North and Northeast India and Andaman Nicobar Islands). The reason for a significant decrease in seismic *b* value in declustered catalog compared to raw catalog is related to the larger proportion of foreshocks and aftershocks in the raw catalog. The proportion of foreshocks and aftershocks in the earthquake catalog is inversely correlated with earthquake magnitude. It means that a larger proportion of dependent events in the earthquake catalog are related to lower magnitude events. The inclusions of dependent events in the catalog affect the relative abundance of low and high magnitude earthquakes. Thus, greater inclusion of dependent events leads to higher *b* values and higher activity rate as is evident from Figs. 8 and 9. Hence, the seismicity parameters obtained from the declustered catalog is valid as they follow a Poisson distribution.

The spatial variation of *b* value using the declustered catalog was studied by considering both constant radius and constant numbers of earthquakes. The *b* value map obtained using a constant radius of 300 km is given in Fig. 9 and that obtained using nearest 200 events are shown in Fig. 10. Both approaches are equally valid, and from the comparison of both

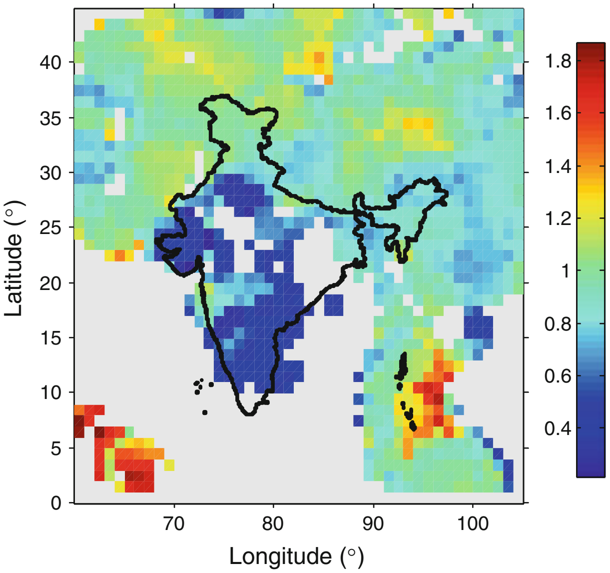
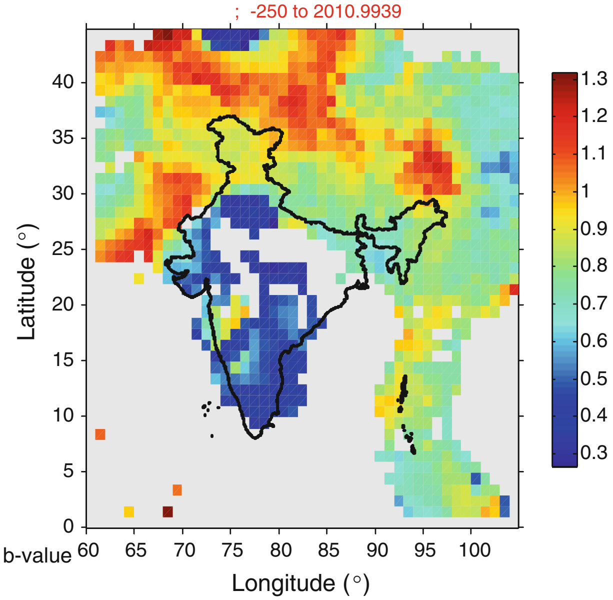


Fig. 8 Spatial variation of *b* value from the clustered catalog considering events within a radius of 300 km from the center of each grid point

Fig. 9 Spatial variation of *b* value from declustered catalog considering events within a radius of 300 km from the center of each grid point



the results, it is seen that seismicity parameters are almost independent of the choice of sampling method. By sampling a constant number of events at each node, the sample size, and hence uncertainty, is approximately constant, and the best spatial resolution possible at each node is achieved (Wiemer and Wyss 2002). In this case, the radii of sampling volumes, or resolution, are inversely proportional to the local density of earthquakes and

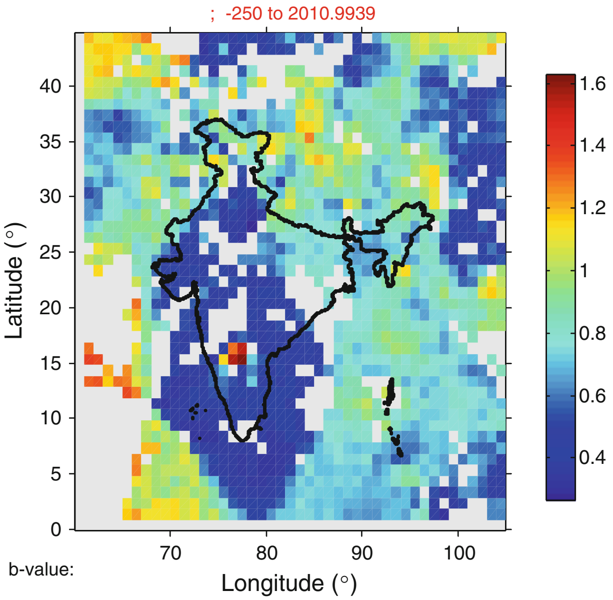


Fig. 10 Spatial variation of *b* value from declustered catalog considering nearest 200 events from a grid point

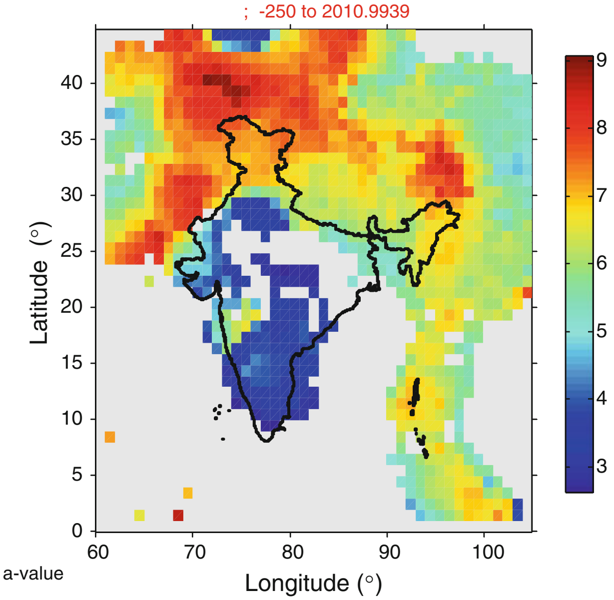


Fig. 11 Spatial variation of *a* value from declustered catalog considering events within a radius of 300 km from the center of each grid point

consequently variable across a region. When using constant radii for sampling, the resolution does not vary spatially, but the sample size, and hence the uncertainty varies. The constant radius method seems to be more valid as it characterizes the seismicity of a region with respect to a defined space limit.

The *b* value in the region varies from 0.5 to 1.5 and for the majority of the study area the value is around 1. The *a* values for the study area varies from a lower value of 3 to a higher value of 10 and are shown in Fig. 11. The *a* and *b* values were not evaluated for some of the regions (shown as void regions in Figs. 8, 9, 10 and 11) as those cells were not having adequate number of earthquake events (50) with magnitude equal to or greater than *Mc*. Higher *b* values are observed for North and Northeast India and for Andaman Nicobar Islands. The lower *b* values obtained in shield regions imply that the energy released in these regions are mostly from large magnitude events. The *b* value for Northeast India and Andaman Nicobar region is around unity which implies that the energy released is compatible for both smaller and larger events.

5 Conclusion

An updated earthquake catalog that is uniform in moment magnitude and fairly complete at the $M_W \geq 4.8$ level, has been prepared for India and adjoining area for the period till 2010. Region-specific magnitude scaling relations have been established for the study region, which facilitated the generation of a homogenous earthquake catalog. By carefully converting these original magnitudes to unified M_w magnitudes, we have removed a major obstacle for consistent assessment of seismic hazards in India. The details of the earthquake events are uploaded in the website http://www.civil.iisc.ernet.in/~sreevals/resource.htm.

A quantitative study of the spatial distribution of the seismicity rate across India and its vicinity has also been performed. The lower *b* values obtained in shield regions imply that the energy released in these regions are mostly from large magnitude events. The *b* value for Northeast India and Andaman Nicobar region is around unity which implies that the energy released is compatible for both smaller and larger events.

The effect of aftershocks in the seismicity parameter was also studied. Maximum likelihood estimations of the *b* value from the raw and declustered earthquake catalogs show significant changes leading to larger proportion of low magnitude events as foreshocks and aftershocks. The inclusions of dependent events in the catalog affect the relative abundance of low and high magnitude earthquakes. Thus, greater inclusion of dependent events leads to higher *b* values and higher activity rate. Hence, the seismicity parameters obtained from the declustered catalog is valid as they follow a Poisson distribution. $M_{\max}$ does not significantly change, since it depends on the largest observed magnitude rather than the inclusion of dependent events (foreshocks and aftershocks). The spatial variation of the seismicity parameters can be used as a base to identify regions of similar characteristics and to delineate regional seismic source zones which is an inevitable input to seismic hazard analysis.

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