Spatial and temporal *b* value anomalies preceding the devastating off coast of NW Sumatra earthquake of December 26, 2004

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[1] Spatial and temporal variations of *b* values are studied by means of 624 earthquakes in the Andaman-Nicobar Islands region during a five-year period preceding the giant shock on December 26, 2004. Sliding time and space windows containing 50 events are used. Temporal variations reveal two significant drops in *b* value which coincide with the occurrence of two large shocks ($M_s \geq 7.0$) towards the end of 2002 and with the M_w = 9.0 event in 2004. The spatial distribution shows accumulation of stresses (low *b*) around the epicentres of the 2002 and 2004 events and an event in North Andaman. The area of high stress around the 2004 epicenter extends in NNW-SSE direction over an area about 450 km long.
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1. Introduction

[2] Although the *b* value in the Gutenberg-Richter relation, log $N = a - bM$, is usually close to 1 over long time periods and large regions, statistically significant variations have been observed for shorter time windows and limited geographical areas. Available observations cover a wide range of magnitudes from micro-earthquakes, such as underground mining triggered rockbursts, $M \leq 4$ [*Nuannin et al.*, 2002] and medium size earthquakes, $M < 7$ [*Wiemer and Wyss*, 1997] to major events, $M \geq 7$ [*Monterroso*, 2003]. There are some explanations for different *b* values. The decrease (increase) of *b* is interpreted in the form of stress increase (decrease) before an approaching seismic event [*Scholz*, 1968; *Wyss*, 1973], as a reflection of the degree of material heterogeneity [*Mogi*, 1962] or as a decrease of thermal gradients [*Warren and Latham*, 1970].

[3] The inverse correlation between the amount of stress accumulated in the hypocentral area and the *b* value is obviously of particular interest in the prediction of major earthquakes. We do not expect fast fluctuations (months, years) to be associated with temperature and/or heterogeneity changes and hence, we accept the interpretation by *Scholz* [1968] and *Wyss* [1973]. Fluctuations of *b* with durations of months and years are known to precede large shocks in various parts of the world [e.g., *Imoto*, 1991; *Jaumé and Sykes*, 1999]. However, to the best of our knowledge, no similar investigation has as yet been made in the region of Andaman-Nicobar Islands.

[4] The incentive for this study is the recent catastrophic earthquake, M_w = 9.0, off coast of NW Sumatra on December 26, 2004 and its brutal aftermath in a form of huge tsunami. We determine the *b* value as a function of space and time for events in the Andaman-Nicobar Islands region during the time period between 2000 and 2004 and try to examine retrospectively the potential of spatial and temporal *b*-variations as a possible precursor heralding an arrival of the December 26 event.

2. The Method

[5] The frequency-magnitude earthquake distribution, FMD, known in the east as *Ishimoto and Iida* [1939] relation and in the west as the *Gutenberg and Richter* [1942] relation defines the distribution of earthquakes with respect to magnitude and represents one of the reliable empirical relations in seismology. For a certain region and time interval, the equation describes the number of events, *N*, with magnitude equal or larger (cumulative distribution) than *M*, where *a* and *b* are positive, real constants.

[6] We made use of a data set reported by USGS, covering a time period of five years, preceding the 2004 earthquake, and the area of Andaman-Nicobar Islands. $b(t)$ is calculated in sliding time-windows containing a constant number, *n*, of events. The window is moved in time by 10% increments of event counts. We prefer a constant number of events in each sample (rather than windows with constant time width) to ensure that a change in sample size does not affect the analysis. A least-squares linear fit and magnitude increment of $\Delta M = 0.1$ is applied throughout the present work. The choice of the number of events in each window is a compromise between the time resolution and the smoothing effect of broad windows. After several tests and also due to experience gained from a similar earlier work [*Monterroso*, 2003], we decided to employ windows with 50 events, with corresponding increments of 5 events.

[7] To examine the spatial distribution of *b*, the study area is subdivided into a 0.5° × 0.5° grid. *b* values are calculated for circular epicentral areas centred at grid nodes. Radii of circles vary along the grid in order to cover the prescribed constant number of events. We chose circle radii including 50 earthquakes. We also map the radii of each circle employed to measure the achieved resolution.

3. Data and Analysis

[8] Our study region (Figure 1) is limited by latitudes 2°S–15°N and longitudes 90°W–100°E which covers the

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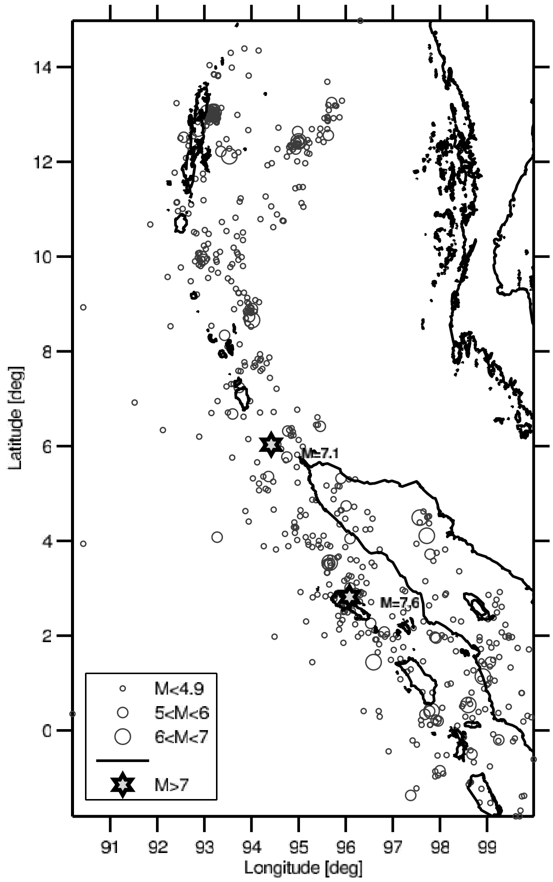

Figure 1. The study region and epicentres of earthquakes (open circles) between January 1, 2000 and December 25, 2004, as reported by USGS. Stars show locations of the two largest shocks (preceding the event of December 26, 2004) on October 24, 2002, M_s = 7.1 (upper star) and on November 2, 2002, M_s = 7.6 (lower star). See color version of this figure in the HTML.

Andaman and Nicobar Islands and the region west of northern Sumatra. It also includes the whole distribution of epicentres of presumed first two-week aftershocks following the M_w = 9.0 main shock. Calculations of b were carried out on data provided by the USGS. During the period of review, i.e. from January 1, 2000 to December 25, 2004, and from the studied region, the USGS reported 624 events within a magnitude interval from 4.0 (m_b) to 7.6 (M_s). Most of the shocks are shallow events (h < 70 km). 128 events occurred at depths 70 $\geq$ km $h \geq$ 250 km. In the USGS event list, most of the reported magnitudes are body-wave magnitudes, m_b, but for several shocks also surface-wave magnitudes, M_s, and/or moment magnitudes, M_w, are given. Parallel observations from the region during the time period from 1973 to 2002, yield magnitude conversion formulae, $M_s - M_w$, $M_s - m_b$ and $m_b - M_w$ so that the event list can be homogenized with respect to any of the magnitudes used, i.e. m_b, M_s or M_w. Body-wave magnitudes were not employed. Due to the effect of saturation, they cannot cope with more energetic earthquakes, say with magnitudes around 6 and larger, while for the M_s-scale, saturation starts first at about 7.0. Moment magnitudes, determined from seismic energy release, should by definition not saturate. Aftershocks (13 shocks) were manually deleted from the list, leaving 611 independent events for analysis. Lower magnitude, proximity to the main shock hypocenter (Δ < 100 km) and short delay time of occurrence (T < one day) were the limits used in the separation. There are two events with magnitude $M_s \geq 7.0$ (October 24, 2002, converted M_s = 7.1 and November 2, 2002, M_s = 7.6) and four events with magnitudes between 6.0 and 6.9. Note that the M_s = 7.6 event lies only about 50 km to the southeast of the December 26 shock. The cumulative number of events as a function of time does not reveal any drastic change in rates, suggesting consistent observation operations during the 5-year period under review.

[9] When mapping b values, the completeness of the employed earthquake catalogue, i.e. the estimation of the so-called threshold magnitude, M_c, is critical. M_c magnitudes were estimated from observed FMDs by visual inspections separately for the two types of magnitudes mentioned above. As follows from Figure 2, threshold magnitudes of 3.8 and 4.6 were derived for M_s and M_w magnitudes, respectively.

[10] The present analysis comprises data that span over 3.8 and 2.5 magnitude units with overall b values of 0.71 and 1.21 (Figure 2). The discrepancy between the overall b values is due to the maximum magnitude M_s = 7.6 with an equivalent M_w of only 7.1, to different threshold magnitudes (3.8 and 4.6) and to different number of events employed (317 and 446). All events with magnitudes less than M_c were deleted from the catalogue. The final data lists, for b value determination, comprise 317 and 446 events considering respectively, M_s and M_w. The latter includes about 40% more events and provides higher resolution (lower smoothing). Calculations were performed by making use of the ZMAP software package [*Wiemer*, 2001].

4. Results and Discussion

[11] Diagrams in Figure 3 exhibit calculated b values as functions of time for the two magnitudes considered. Plotted $b(t)$-curves reveal large temporal variations easily discernible by eye in both diagrams, i.e. irrespective of the type of magnitude used. The two curves are in general agreement with each other, revealing a similar pattern, even though the plot for M_s shows more smoothed course. The largest variations of b between 1.15 and 1.78 can be seen in the diagram where M_w has been used. We examined different M_c magnitudes (i.e. lower and higher than those mentioned above) but we could not see any other change than an

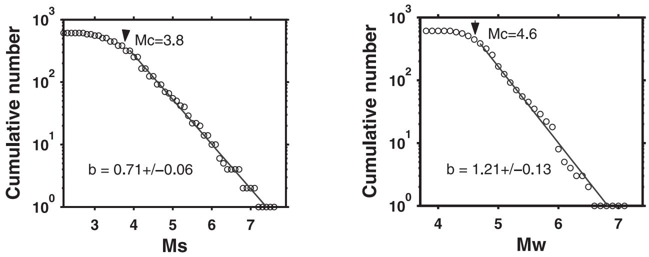

Figure 2. FMD with respect to M_s and M_w. Threshold magnitudes M_c (arrows) and the overall b with standard deviations are also displayed.

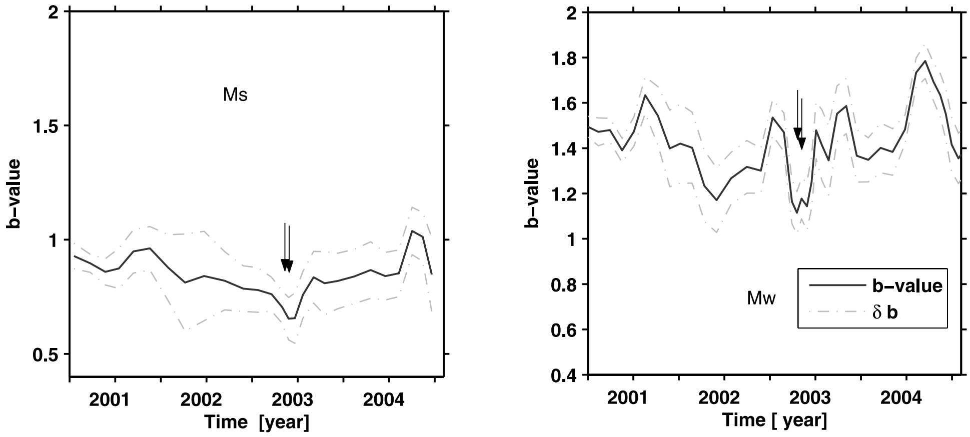

Figure 3. *b* (heavy line) as a function of time for the studied region and the time period from January 1, 2000 to December 25, 2004. USGS catalogue data and (left) M_s and (right) M_w magnitudes are employed. The graphs were calculated by means of sliding time windows comprising 50 events. Dashed lines indicate the standard deviation and arrows mark the times of occurrence of the 2002 earthquakes.

increasing smoothing effect towards larger threshold magnitudes due to a lower number of events (longer time windows) entering the analysis.

[12] There are two distinct drops in the *b* value, one during the second half of 2002 and another towards the end of 2004. These drops can be associated with the two large ($M_s \geq 7.0$) shocks in October and November 2002 and with the recent giant earthquake of December 26, 2004. The statistical significance of the difference in *b* is examined by means of the F-distribution. For moving time windows with 50 events, both major troughs in Figure 3 (M_w magnitudes), i.e. that around October–November 2002 and that towards the end of 2004, are statistically significant to a 90% confidence level. We performed the calculations also with windows comprising 75 and 100 events. While the former still reveal weak troughs in the $b(t)$ diagrams coinciding with the 2002 and 2004 events, the latter, with strong smoothing effects, make these no more discernible. The broad trough at the end of 2001 correlates well with the occurrence of more than 10 events ($5 \leq M_s \leq 6$) during the period from October 2001 to January 2002.

[13] To investigate the spatial distribution of *b*, we used circular areas (with different radii but constant number of events) centred at grid nodes. Figure 4 shows the resolution map. As follows from the figure, resolution is high (small radii) around the epicentre of the giant 2004 earthquake, i.e. roughly south of 6°N, and north of 9°N (North Andaman). In the centre of the reviewed area, between 6°N and 9°N, resolution becomes poor (large radii). There is good agreement between resolution maps made with M_s and M_w magnitudes (Figure 4). Figure 5 exhibits the spatial distribution of *b* in the studied region. Two distinct areas of low *b* (high stress) can be seen in the figure, one in the south, say, between 1°S and 6°N (off coast of northern Sumatra) and the other in the north, approximately north of 11°N, in North Andaman. The former is centred around the epicentre of the M_w = 9.0 event and includes also the M_s = 7.6 earthquake in 2002. The second largest event in the present catalogue (M_s = 7.1, October 24, 2002) took place at the northern edge of the southern low *b* anomaly. The northern anomaly is centred around the epicentre of the M_s = 6.7 event of September 13, 2002. This is the third largest shock in our event list (i.e. prior to December 26, 2004).

[14] The spatial distribution of *b* was studied with respect to both the M_s and M_w magnitudes (Figures 4 and 5). It

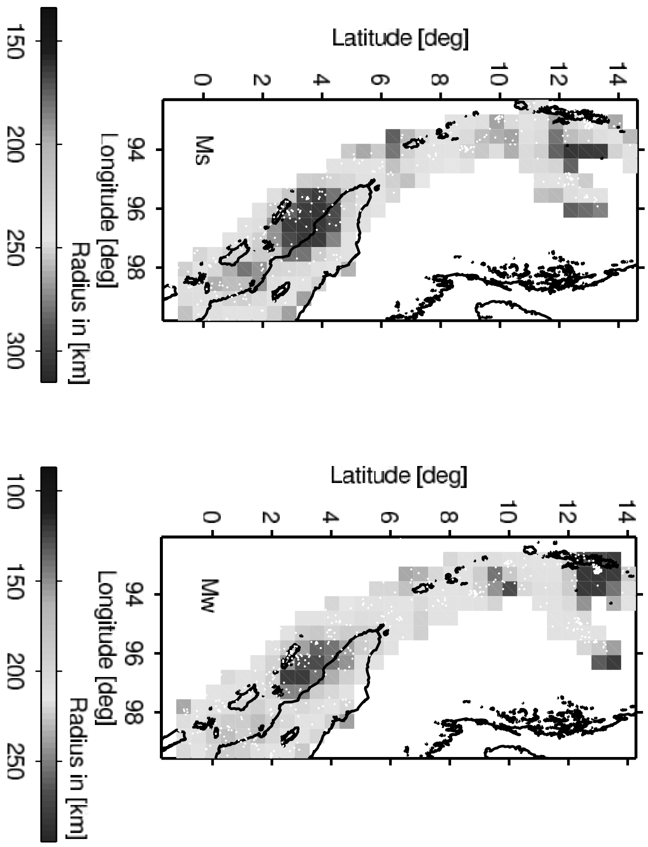

Figure 4. Resolution maps for the studied region, for (left) M_s and (right) M_w magnitudes. In both diagrams sliding circular windows contain 50 events. Red indicates low resolution, while blue shows areas with high resolution. White dots represent epicentres used. See color version of this figure in the HTML.

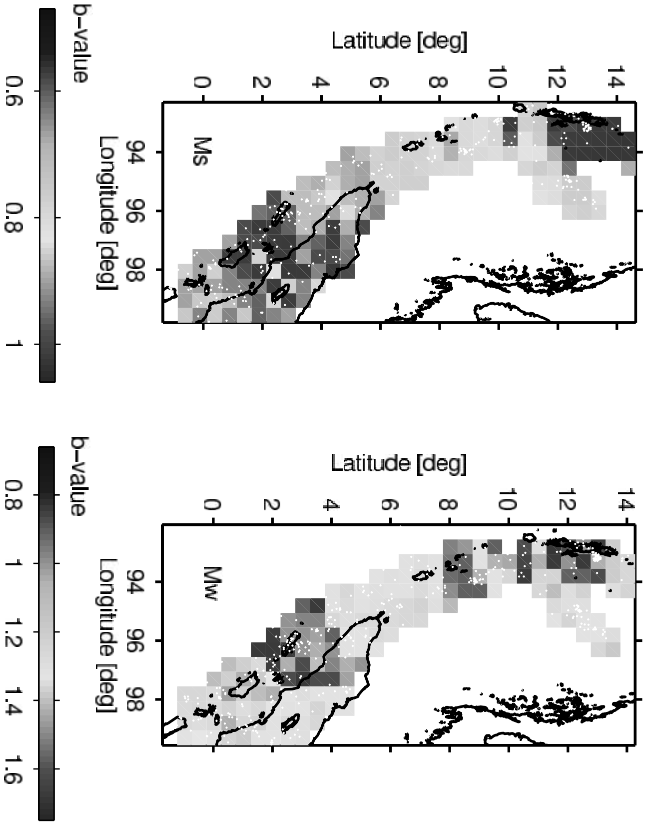

Figure 5. Spatial b distribution within the studied region. M_s (left) and M_w (right) magnitudes were used. Blue indicates low b, whereas red shows high b. White dots show the epicentral locations. See color version of this figure in the HTML.

follows from the figures that in general there is good agreement between maps derived for the two magnitude scales. There are no discernible differences in the northern low b value area. In the south, the anomalous low b extends up to about 6°N and 4°N for the M_s and M_w magnitudes, respectively. The demarcation is more distinct when the moment magnitude is applied. This implies that accumulation of high stresses prior to the giant M_w = 9.0 shock extends approximately over an area of 450 km (M_w diagram) and 700 km (M_s diagram) in length. Since the resolution in the M_w map is better than that in the M_s map it seems that an extension of the stressed region of the order of 450 km oriented NNW-SSE is more plausible. It is also clear from Figure 5 that in spite of the fact that low b values surround the epicentre area, i.e. with extension to both north and south from the epicenter, no first two-week aftershocks were located south of the M_w = 9.0 main shock. Differences between low and high b values in Figure 5 are statistically significant to a 99% confidence level.

5. Conclusions

[15] The present study includes 624 earthquakes in the Andaman-Nicobar Islands region which occurred during a five-year period preceding the giant event of December 26, 2004. Achieved results can be summarized as follows:

[16] • Calculated b values show temporal variations in a broad range from 1.10 to 1.78 (M_w magnitude). Statistically significant drops in b can be associated with the time of occurrence of two large ($M_s \geq 7.0$) events in 2002 and with the devastating shock towards the end of 2004.

[17] • Significantly low b value indicates two regions of stress concentration. One around the epicentre of the 2004 event and the other in North Andaman.

[18] • The low b value anomaly, around the 2004 epicenter, extends over an area approximately 450 km long oriented in the NNW-SSE direction.

[19] • Observed variations in b reveal a precursory potential which could be used in medium-term (months, years) earthquake prediction.

[20] **Note added in proof.** After this manuscript had been submitted for publication, another giant event (M_w = 8.7) occurred on March 28, 2005, off the coast of NW Sumatra, about 200 km southeast of the December 26 earthquake. The location of the most recent event correlates well with the distribution of high stresses exhibited in Figure 5.

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