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ORIGINAL PAPER

Global regression relations for conversion of surface wave and body wave magnitudes to moment magnitude

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Abstract A homogenous earthquake catalog is a basic input for seismic hazard estimation, and other seismicity studies. The preparation of a homogenous earthquake catalog for a seismic region needs regressed relations for conversion of different magnitudes types, e.g. m_b, M_s, to the unified moment magnitude $M_{w.}$ In case of small data sets for any seismic region, it is not possible to have reliable region specific conversion relations and alternatively appropriate global regression relations for the required magnitude ranges and focal depths can be utilized. In this study, we collected global events magnitude data from ISC, NEIC and GCMT databases for the period 1976 to May, 2007. Data for m_b magnitudes for 3,48,423 events for ISC and 2,38,525 events for NEIC, M_s magnitudes for 81,974 events from ISC and 16,019 events for NEIC along with 27,229 M_w events data from GCMT has been considered. An epicentral plot for M_w events considered in this study is also shown. M_s determinations by ISC and NEIC, have been verified to be equivalent. Orthogonal Standard Regression (OSR) relations have been obtained between M_s and M_w for focal depths ($h < 70$ km) in the magnitude ranges $3.0 \leq M_s \leq 6.1$ and $6.2 \leq M_s \leq 8.4$, and for focal depths 70 km $\leq h \leq$ 643 km in the magnitude range $3.3 \leq M_s \leq 7.2$. Standard and Inverted Standard Regression plots are also shown along with OSR to ascertain the validation of orthogonal regression for M_s magnitudes. The OSR relations have smaller uncertainty compared to SR and ISR relations for M_s conversions. ISR relations between m_b and M_w have been obtained for magnitude ranges $2.9 \leq m_b \leq 6.5$, for ISC events and $3.8 \leq m_b \leq 6.5$ for NEIC events. The regression relations derived in this study based on global data are useful empirical relations to develop homogenous earthquake catalogs in

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the absence of regional regression relations, as the events catalog for most seismic regions are heterogeneous in magnitude types.

Keywords Moment magnitude · OSR relation · ISR relation · Global regression relations

1 Introduction

A number of magnitude scales based on different wave types and/or characteristics of recording instruments are in use for estimating the size of an earthquake. Ever since the first magnitude scale was designed by Richter (1935) for earthquakes in Southern California recorded by a network of Wood Anderson seismometers, the need has been felt by seismologist for its extension to apply to the data produced in various different observational environments e.g. m_b, M_s and M_w magnitudes. These estimates which utilize different information of the seismic source process have variations arising from source.

The concept of a body wave magnitude scale was proposed initially by Gutenberg (Gutenberg 1945a, b) and later reworked by Gutenberg and Richter (1956). m_B determination is based on the ratio of maximum amplitude to period of P or S waves with periods up to about 10 s recorded by intermediate to long period instruments. The body wave magnitudes, $\mathrm{m_b}$, reported by ISC and NEIC bulletins are based on the first 5 s of short period P waves recorded by short period instruments. The period of P waves used in $\mathrm{m_b}$ determinations is around 1 s, whereas the periods used for m_B are several to 10 s. The surface wave magnitude, $M_{s,}$ is estimated using amplitude and corresponding period of Rayleigh waves with periods ranging between 10 and 60 s based on Prague formula (Vanek et al. 1962), for shallow focal depths. This approach is used in M_s magnitude determinations contained in ISC and NEIC data bulletins. Karnik (1973) estimated the following regression relation between m_b and M_s for events with $m_{b,\mathrm{ISC}} \geq 4.5$ and $M_s \leq 6.5$, to overcome the saturation effect.

$$m_{\mathrm{b,ISC}} = 0.46\,M_s + 2.74, \tag{1}$$

The m_b and M_s magnitude scales suffer from a major shortcoming that they do not behave uniformly for all magnitude ranges and, in addition, also exhibit saturation effects for large earthquakes at different thresholds. This can cause under or over-estimation of earthquake magnitudes in certain magnitude ranges. To get rid of these limitations, Kanamori (1977) and Hanks and Kanamori (1979) proposed a new magnitude scale, called moment magnitude, M_w, defined by

$$M_w = \frac{\log M_0}{1.5} - 10.7 \tag{2}$$

where M_0 is the seismic moment in dyn-cm. The M_w scale defined above does not saturate for large earthquakes as it is directly proportional to the logarithm of seismic moment which in turn is related to earthquake source physics (slip, fault area, rigidity) depicting a uniform behavior for all magnitude ranges. Hence M_w is considered as the most reliable magnitude to describe the size of earthquakes. Due to the advantages of the M_w magnitude scale, it is preferred to compile earthquake catalogs with all magnitudes expressed in this unified scale M_w for the purposes of seismic hazard assessment and other important seismological problems having engineering applications.

A homogeneous earthquake catalog is of basic importance for studying the earthquake occurrence pattern in space and time and also for many engineering applications including assessment of seismic hazard, estimation of peak ground accelerations and determination of long-term seismic strain rates etc. In order to prepare homogeneous earthquake catalog for different seismic regions, various regression relation procedures have been used in various studies to convert different magnitude types to a preferred magnitude scale. The regression relations used for conversion of magnitudes, hence, is of basic importance since any bias introduced at conversion leads to errors in the parameters of the Gutenberg Richter frequency-magnitude distribution and consequently in the seismic hazard estimates (Castellaro et al. 2006).

For seismological applications including homogenization of earthquake catalogs, it is important to know how different magnitude determinations and their associated measurement errors compare with each other. It is common to derive magnitude conversion relations considering either only one of the magnitudes to be in error or the order of the error is taken to be very small relative to the dependent variable measurement errors. It is observed that most of the existing regression relations used for converting different earthquake magnitudes to the unified magnitude M_w are based on standard regression relation which is not a good estimator as both the variables contain measurement errors.

In case both the magnitudes have measurement errors, due to saturation or otherwise, the use of least-squares linear regression procedure may lead to wrong results. In such a situation, it is appropriate to use Orthogonal Standard Regression (OSR) procedure which takes into account the errors on both the magnitudes (Stromeyer et al. 2004; Castellaro et al. 2006, 2007; Joshi and Sharma 2008; Thingbaijam et al. 2008; Ristau 2009). This regression procedure requires the knowledge of the error variance ratio for the two magnitudes. The case of $\eta = 1$, may not be always proper as significant disparity exists in the accuracies of magnitudes estimated by different catalogs (Kagan 2003). The error ratio is infinite in standard least squares regression because the independent variable is taken to be fixed and free from error. In an orthogonal fit with a large error ratio, the fitted line approaches the standard least-squares line of fit.

Qualitatively, the magnitude conversion relationships should be based on the OSR relation (Castellaro et al. 2006) provided error variance values are known. When square root of the error variance ratio is less than 0.7 and greater than 1.8 either ISR or SR relations is better than OSR relation (Castellaro and Bormann 2007). An advantage of the OSR approach is that the computations give us predicted values for both the variables. The predicted values specify the point on the line that is closest to the data point.

In the present study global magnitude data for 81,974 M_s events from ISC, 16,019 M_s events from NEIC, 3,48,423 m_b events from ISC and 2,38,525 m_b events from NEIC along with 27,229 events from GCMT during the period 01.01.1976–31.05.2007 has been considered. Earthquake epicenters for M_w events considered in this study are shown in Fig. 1. An attempt has been made to find empirical relationships between M_s and M_w and m_b and M_w considering the magnitudes to be in error. M_s determinations by ISC and NEIC, have been verified to be equivalent. OSR relations have been obtained between M_s and M_w for different magnitude ranges and focal depths. Standard and Inverted Standard Regression plots are also shown along with OSR (Fig. 3) to ascertain the validation of orthogonal regression for M_s magnitudes. Further, ISR relations have been proposed between m_b and M_w for magnitude ranges $2.9 \leq m_b \leq 6.5$, for ISC events and $3.8 \leq m_b \leq 6.5$ for NEIC events.

2 Methodology for orthogonal standard regression relationship

General orthogonal regression is designed to account for the effects of measurement error in both the variables. The procedure for general orthogonal regression is described in detail

Fig. 1 Epicentral plot of 27,229 earthquakes with M_w values in the range 4.6–9.0

in the literature (Madansky 1959; Fuller 1987; Kendall and Stuart 1979; Carrol and Ruppert 1996; Castellaro et al. 2006) and a brief description is given below.

Let us assume that two variables M_y and M_x are linearly related and that their measurement errors ε and δ are independent normal variates with variances σ_ε^2 and σ_δ^2. Therefore, we can write

$$m_y = M_y + \varepsilon, \tag{3}$$

$$m_x = M_x + \delta, \tag{4}$$

$$M_y = \alpha + \beta M_x + \hat{\varepsilon}, \tag{5}$$

where

$$\hat{\varepsilon} = \varepsilon + \delta. \tag{6}$$

The error variance ratio

$$\eta = \frac{\sigma_\varepsilon^2}{\sigma_\delta^2}, \tag{7}$$

where

$$\sigma_\varepsilon^2 = \sigma_{m_y}^2 \quad \text{and} \quad \sigma_\delta^2 = \sigma_{m_x}^2, \tag{8}$$

when σ_ε^2 and σ_δ^2 are constants.

The general orthogonal estimator of slope is then

$$\hat{\beta} = \frac{s_{m_y}^2 - \eta s_{m_x}^2 + \sqrt{\left(s_{m_y}^2 - \eta s_{m_x}^2\right)^2 + 4\eta s_{m_x m_y}^2}}{2 s_{m_x m_y}}, \tag{9}$$

where $s_{m_y}^2, s_{m_x}^2$, and $s_{m_x m_y}$ denote the sample variance of the M_y and M_x and the sample covariance and the intercept is

$$\hat{\alpha} = \bar{m}_y - \hat{\beta}\bar{m}_x, \tag{10}$$

where $\bar{m}_y$ and $\bar{m}_x$ denote the average values.

As demonstrated in Fuller (1987), The errors on the regression parameters will be

$$\hat{\sigma}_\beta = \frac{\hat{\sigma}_{m_x}(n-1)(n+\hat{\beta}^2)\hat{\sigma}_\delta + (\sigma_\delta)^2(n-1)(\eta+\beta^2)^2 - (n-2)(-\hat{\beta}\hat{\sigma}_\delta)^2}{(n-2)(n-1)\sigma^2_{m_x}}, \tag{11}$$

and

$$\hat{\sigma}^2_\alpha = \frac{(n-1)(\eta+\hat{\beta}^2)\hat{\sigma}_\delta}{n(n-2)} + \bar{m}^2_x\hat{\sigma}^2_\beta, \tag{12}$$

where

$$\hat{\sigma}m_x = \frac{\sqrt{\left(s^2_{m_y} - \eta s^2_{m_x}\right)^2 + 4\eta s^2_{m_x m_y}} - \left(s^2_{m_y} - \eta s^2_{m_x}\right)}{2\eta}, \tag{13}$$

and

$$\hat{\sigma}_\delta = \frac{\left(s^2_{m_y} + \eta s^2_{m_x}\right) - \sqrt{\left(s^2_{m_y} - \eta s^2_{m_x}\right)^2 + 4\eta s^2_{m_x m_y}}}{2\eta}. \tag{14}$$

2.1 Inverted standard least-squares regression (ISR)

Inverted standard least-squares regression is similar to the standard least -squares regression but minimizes the horizontal offsets to the best fit line. In this regression the role of the two variables gets reversed; thus M_y is taken as the independent variable without error and M_x is the dependent variable having some error. The procedure for ISR is given in literature (e.g., Draper and Smith 1998), and is not described here.

A computer C++ code has been developed in this study for deriving OSR, SR, ISR regression relations and the quality of regression fits obtained have been tested with the examples given by Fuller (1987).

3 Data

In this study, events data for the whole globe during the period 01.01.1976–31.05.2007, has been compiled from International Seismological Center (ISC), U.K. (http://www.isc.ac.uk/search/Bulletin), National Earthquake Information Center (NEIC). USGS, USA (http://neic.usgs.gov/neis/epic/epic-global.htm) and HRVD (since 1976 now operated as Global Centroid-Moment-Tensor projectat Lamont Doherry Earth Observatory (LDEO) http://www.globalcmt.org/CMTsearch.html) earthquake data bulletins.

Body wave magnitude values for 3,48,423 events from ISC and 2,38,525 events from NEIC and surface wave magnitude values for 81,974 events from ISC and 16,019 events from NEIC have been compiled for examining the behavior of the two magnitude scales.

As a reference magnitude, we used the moment magnitude estimated by HRVD (CMT solutions) for 27,229 events during the same period. Epicenters plot of the GCMT moment magnitudes has been shown in Fig. 1.

4 Magnitude conversion relations

OSR relation for conversion of surface and body wave magnitudes to moment magnitudes requires the value of the error variance ratio η. However, if the square root of the error variance ratio is less than 0.7 and greater than 1.8, then either ISR or SR relation is better than OSR relation (Castellaro and Bormann 2007). For the events data considered in this study, the comparative standard deviations associated with different magnitude types have been estimated to be 0.09, 0.12 and 0.2 for M_w, M_s and m_b, respectively. The values obtained in this study are of similar order as estimated by Thingbaijam et al. (2008) and Kagan (2003).

4.1 Conversion of surface wave magnitudes to $M_{w,\mathrm{HRVD}}$

The surface wave magnitudes estimated by ISC and NEIC have been compared in various studies and are found to be similar, as both the databases determine M_s using the same technique (Utsu 2002; Das and Wason 2010). In the present study, the equivalence of M_s values has been verified by deriving an OSR relation between the two magnitudes for the range $2.8 \le M_{s,\,\mathrm{NEIC}} \le 8.8$, which is given below

$$\begin{aligned} M_{s,\mathrm{ISC}} &= 0.99\,(\pm.00003)\,M_{s,\mathrm{NEIC}} + 0.012\,(\pm.00009)\,, \\ R^2 = 0.97,\ \sigma = 0.12,\ n &= 14,323, \quad \text{for } h < 70 \text{ km}\ ,\ \eta = 1 \end{aligned} \tag{15}$$

The above OSR relationship between $M_{s,\mathrm{ISC}}$ and $M_{s,\mathrm{NEIC}}$ shows that both the M_s determinations can be taken as equivalent (Fig. 2) and it can be considered as a unified data set.

Through computer search routine developed in C++ as well as manual inspection, the authors were able to access 18,264 events having both $M_{s,\mathrm{ISC}}$ and $M_{w,\mathrm{HRVD}}$ values and 9,191 events having both $M_{s,\mathrm{NEIC}}$ and $M_{w,\mathrm{HRVD}}$ values. Combining these two data sets, we derived OSR relations between $M_{w,\mathrm{HRVD}}$ and M_s for different magnitude ranges and focal depths. The OSR relations obtained are given below

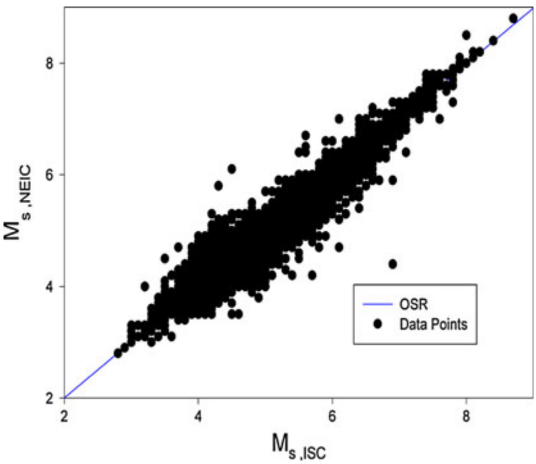


Fig. 2 Correlation between M_s values given by ISC and NEIC for all depths

$$
\begin{gathered}
M_{w,\mathrm{HRVD}} = 0.67\,(\pm.00005)\,M_s + 2.12\,(\pm 0.0001), \\
3.0 \le M_s \le 6.1,\ R^2 = 0.83,\ \sigma = 0.12,\ n = 24807,\ h < 70\,\mathrm{km}\ ,\ \eta = 1
\end{gathered} \tag{16}
$$

$$
\begin{gathered}
M_{w,\mathrm{HRVD}} = 1.06\,(\pm.0.0002)\,M_s - 0.38\,(\pm.0.006), \\
6.2 \le M_s \le 8.4,\ R^2 = 0.89,\ \sigma = 0.16,\ n = 2250,\ h < 70\ \mathrm{km}\ ,\eta = 1
\end{gathered} \tag{17}
$$

$$
\begin{gathered}
M_{w,\mathrm{HRVD}} = 0.67\,(\pm 0.0004)\,M_s + 2.33\,(\pm 0.01), \\
3.3 \le M_s \le 7.2,\ R^2 = 0.81,\ \sigma = 0.15,\ n = 396,\ 70\ \mathrm{km} \le h \le 643\ \mathrm{km}\ ,\eta = 1
\end{gathered} \tag{18}
$$

The above relationships have been plotted as shown in Fig. 3a, b and c, respectively.

4.2 Conversion of body wave magnitudes to $M_{w,\mathrm{HRVD}}$

Body wave magnitudes for 3,48423 of ISC and 2,38,525 of NEIC have been considered during the period 01.01.1976–31.05.2007. Out of all, 2,14,404 events have m_b values both from ISC and NEIC. The OSR relation between them is

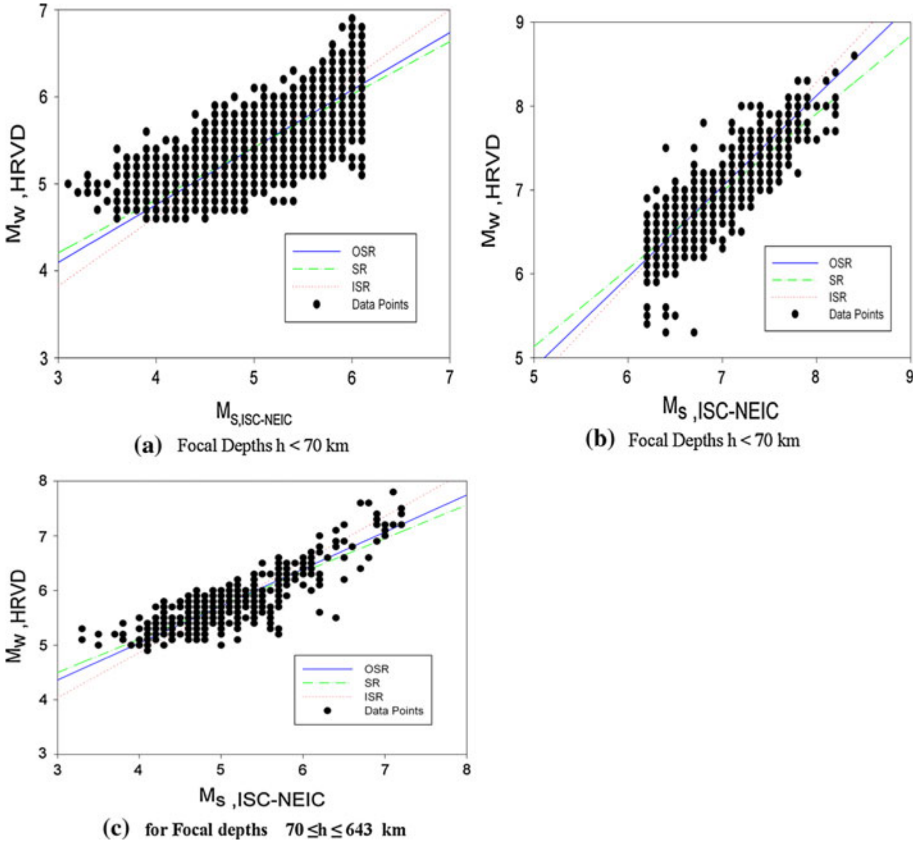


Fig. 3 Plots of regression relations between M_s and $M_{w,\mathrm{HRVD}}$ magnitudes: **a** for magnitude range $3.0 \le M_s \le 6.1$ and focal depths $h < 70$ km; **b** for magnitude range $6.2 \le M_s \le 8.4$ and focal depths $h < 70$ km; **c** for magnitude range $3.3 \le M_s \le 7.2$ and focal depths $70\ \mathrm{km} \le h \le 643$ km

$$m_{b,\mathrm{ISC}} = 1.04\,(\pm 0.000001)\, m_{b,\mathrm{NEIC}} - 0.29\,(\pm 0.00002), \quad R^2 = 0.91, \sigma = 0.2, n = 2,14,404, \eta = 1 \tag{19}$$

We considered 23,281 and 22,960 m_b events data from ISC and NEIC, respectively during the period 01.01.1976–31.05.2007, which have also M_w,HRVD values assigned. It is observed a slight bias between the two m_b determinations Utsu (2002), we considered the two sets of data separately to check how they are correlated with each other. It is seen that the average difference between $m_{b,\mathrm{ISC}}$ and $m_{b,\mathrm{NEIC}}$ is of the order of ±0.04 m.u, but the absolute average difference is found to be ±0.2 m.u. Therefore, we use separate relations for ISC and NEIC m_b data sets.

If $\sqrt{\eta} < 0.7$, ISR is found to perform better compared to OSR and SR relations (Castellaro and Bormann 2007) We, therefore, prefer ISR relations for conversion of m_b to M_w,HRVD. ISR relationships have been derived for conversion of $m_{b,\mathrm{ISC}}$ to $M_{w,\mathrm{HRVD}}$ in the magnitude range $2.9 \le m_{b,\mathrm{ISC}} \le 6.5$ with 23,245 events data and for $m_{b,\mathrm{NEIC}}$ to $M_{w,\mathrm{HRVD}}$ in the magnitude range $3.8 \le m_{b,\mathrm{NEIC}} \le 6.5$ using 22,883 events data and are given in Eqs. (20) and (21).

$$m_{b,\mathrm{ISC}} = 0.65\,(\pm 0.003)\, M_{w,\mathrm{HRVD}} + 1.65\,(\pm 0.02), \quad 2.9 \le m_{b,\mathrm{ISC}} \le 6.5,\ R^2 = 0.54,\ \sigma = 0.27,\ n = 23,245 \tag{20}$$

$$m_{b,\mathrm{NEIC}} = 0.61\,(\pm 0.005)\, M_{w,\mathrm{HRVD}} + 1.94\,(\pm 0.02), \quad 3.8 \le m_{b,\mathrm{NEIC}} \le 6.5, R^2 = 0.56,\ \sigma = 0.29,\ n = 22,883 \tag{21}$$

The plots of the above regression relations are shown in Fig. 4a, b, c, respectively.

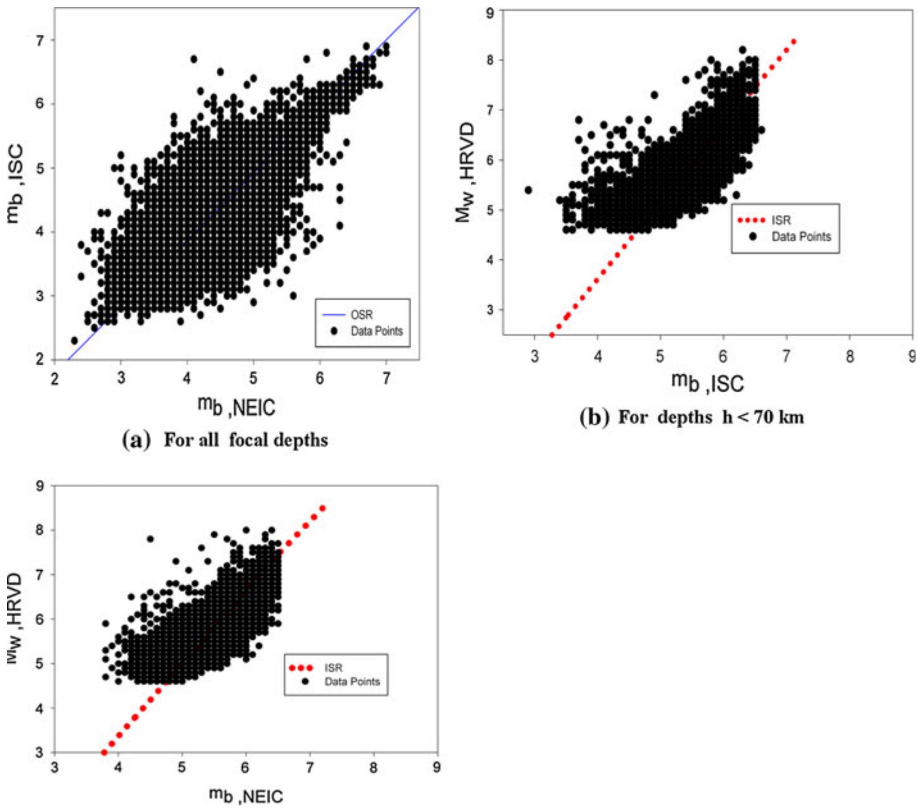
5 Summary and conclusions

The main objective of the present study is to derive global regression relations for conversion of M_s and m_b magnitudes to the unified moment magnitude $M_{w,\mathrm{HRVD}}$. M_s magnitudes data for 81,974 events from ISC and 16,019 events from NEIC, m_b magnitudes data for 3,18,423 events from ISC and 2,38,525 events from NEIC, along with M_w values for 27,229 events from GCMT during the period 01.01.1976–31.05.2007 has been considered. A world seismicity map has been prepared with the Arc GIS software depicting the epicenters of the M_w events used in this study (Fig. 1).

As surface wave magnitude determinations both by ISC and NEIC employ the same technique, it is expected that the magnitude estimates from these databases should be more or less equivalent (Utsu 2002; Das and Wason 2010). For the data considered in the present study, this equivalence between the two M_s estimates has been verified for the magnitude range $2.8 \le M_{s,\mathrm{NEIC}} \le 8.8$ through an OSR relation. This equivalence allows the consideration of M_s estimates by ISC and NEIC as a unified data set.

OSR relationships have been derived for conversion of M_s estimates to $M_{w,\mathrm{HRVD}}$, as the square root of the error variance ratio between M_s and $M_{w,\mathrm{HRVD}}$ measurements is found to lie between 0.7 and 1.8. But, we prefer OSR relationships with $\eta = 1$, which yields better results as suggested by Castellaro and Bormann (2007) and Ristau (2009). The OSR regression relations derived (Eqs. 16–18) have lower uncertainties compared to the corresponding SR relation obtained by Scordilis (2006).

It is observed that absolute average difference between $m_{b,\mathrm{ISC}}$ and $m_{b,\mathrm{NEIC}}$ differs by 0.2 m.u where as their average difference is 0.04 m.u. Similiar bias between these have



(a) For all focal depths

(b) For depths h < 70 km

(c) For depths h < 70 km

Fig. 4 The plots of regression relations between **a** OSR relation between $m_{b,\mathrm{ISC}}$ and $m_{b,\mathrm{NEIC}}$; **b** ISR relation between $M_{w,\mathrm{HRVD}}$ and $m_{b,\mathrm{ISC}}$; **c** ISR relation between $M_{w,\mathrm{HRVD}}$ and $m_{b,\mathrm{NEIC}}$

also been found in earlier studies (e.g., Utsu 2002). In the case of $m_{b,\mathrm{ISC}}$ and $m_{b,\mathrm{NEIC}}$ conversion to $M_{w,\mathrm{HRVD}}$, ISR relations have been derived. For $m_{b,\mathrm{ISC}} < 3.9$ and $m_{b,\mathrm{NEIC}} < 4.3$, the data are rather scarce for the purpose of conversion relations. It can be seen from Fig. 4b, c that $m_{b,\mathrm{ISC}}$ and $m_{b,\mathrm{NEIC}}$ estimates are generally lower compared to $M_{w,\mathrm{HRVD}}$ values as has been observed earlier by many other researchers (e.g., Nuttli 1983, 1985; Giardini 1984; Kiratzi et al. 1985; Heaton et al. 1986; Papazachos et al. 1997).

C++ code has been developed for calculating the OSR, SR and ISR relations. The regression relations derived in this study based on global data are useful to develop homogenous earthquake catalogs for seismic regions in the absence of regional regression relations, as the events catalog for most seismic regions are heterogeneous in magnitude types. The smaller uncertainties in the OSR relations compared to SR relations are preferred for surface wave magnitudes conversions as they propagate lower uncertainty levels in the seismic hazard estimation.

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