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Empirical global relations converting M_S and m_b to moment magnitude

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Abstract

The existence of several magnitude scales used by seismological centers all over the world and the compilation of earthquake catalogs by many authors have rendered globally valid relations connecting magnitude scales a necessity. This would allow the creation of a homogeneous global earthquake catalog, a useful tool for earthquake research. Of special interest is the definition of global relations converting different magnitude scales to the most reliable and useful scale of magnitude, the moment magnitude, M_W. In order to accomplish this, a very large sample of data from international seismological sources (ISC, NEIC, HRVD, etc.) has been collected and processed. The magnitude scales tested against M_W are the surface wave magnitude, M_S, the body wave magnitude, m_b, and the local magnitude, M_L. The moment magnitudes adopted have been taken from the CMT solutions of HRVD and USGS. The data set used in this study contains 20,407 earthquakes, which occurred all over the world during the time period 1.1.1976–31.5.2003, for which moment magnitudes are available. It is shown that well-defined relations hold between M_W and m_b and M_S and that these relations can be reliably used for compiling homogeneous, with respect to magnitude, earthquake catalogs.

Introduction

One of the most important parameters characterizing an earthquake is its "size", which is a measure directly related to the energy released. Since the first work of Richter (1935) when the *local magnitude scale*, M_L, was initially defined using trace amplitudes of local earthquakes recorded on typical Wood Anderson seismographs ($T_0 = 0.8$ s, critical damping 0.8, $V = 2,800$), the earthquake magnitude became the most common measure of the size of an earthquake. Its linear relation with the logarithm of physical quantities characterizing the earthquake (seismic energy, seismic moment) turned it into a tool suitable for solving several important problems of practical and theoretical interest. In the course of time, new seismographs were constructed and different wave types, recorded at various distances, were used for magnitude estimation, which resulted in the definition of new magnitude scales.

Thus, Gutenberg (1945a) defined the *surface wave magnitude scale*, M_S, using the ground amplitudes of surface waves with period 17–23 s measured at epicentral distances 15°–130°. This magnitude could be estimated using the formula:

$$M_S = \log A + 1.656 \log \Delta + 1.818 \quad (1)$$

where A is the ground amplitude in μm and Δ the epicentral distance in degrees.

Gutenberg (1945b,c) and Gutenberg and Richter (1956) introduced the *body wave magnitude scale* based on the recordings of P-waves with periods up to about 10 s by medium to long period instruments. It was denoted as m_B and was originally determined from the ratio of amplitude to period for P or S waves according to the relation:

$$m_B = \log\left(\frac{A}{T}\right) + q(\Delta, h) \quad (2)$$

where A is the maximum amplitude observed, T its respective period and $q(\Delta, h)$ is a calibration function, given in tables for shallow earthquakes (Gutenberg, 1945b) and in charts for all depths of earthquake foci (Gutenberg, 1945c; Gutenberg and Richter, 1956).

The *unified magnitude,* m_b, included in the ISC and NEIC bulletins is estimated using the recordings of the first 5 s of short period ($T \leq 3$ s) P waves by short period instruments, following the procedure proposed by Gutenberg and Richter (1956), by applying the formula:

$$m_b = \frac{\sum_{i=1}^{n} \left[\log \left(\frac{A_i}{T_i} \right) + Q(\Delta_i, h_i) \right]}{n} - 3 \tag{3}$$

where $Q(\Delta_i, h)$ is the depth–distance factor, n is the number of stations (recordings) used and A_i and T_i are the amplitude of the ith station in nm and its respective period in s. This definition (the use of different recordings) resulted in differences between m_B and m_b scales that, in some cases (i.e. earthquakes produced by large faults or earthquakes with complicated rupture process), can be remarkable (Abe, 1981; Kanamori, 1983). Trying to quantify these deviations, Abe (1981) proposed the following relation:

$$m_B = 1.5 m_b - 2.2 \tag{4}$$

connecting m_B with m_b estimated by ISC.

The M_S magnitudes reported in ISC and NEIC bulletins are estimated using amplitudes and respective periods of Rayleigh waves with periods ranging between 10 and 60 s at epicentral distances 20°–160°, applying the *Prague formula* (Vanek et al., 1962):

$$M_S = \log \left(\frac{A}{T} \right)_{\max} + 1.66 \log \Delta + 3.3 \tag{5}$$

where A is the maximum ground amplitude, in μm, observed on horizontal components, T its respective period and Δ the epicentral distance in degrees. The focal depths of the earthquakes for which the M_S is estimated must not exceed 60 km.

Gutenberg and Richter (1956) defined the following relations connecting the M_L, m_B and M_S magnitude scales:

$$m_B = 0.63 M_S + 2.5 \tag{6}$$

$$M_S = 1.27(M_L - 1) - 0.016 M_L^2 \tag{7}$$

The relation between m_b magnitudes (published by ISC) and M_S was studied by Karnik (1973). He used earthquakes with $m_{b,\mathrm{ISC}} \geq 4.5$ but with $M_S \leq 6.5$, to avoid the saturation effect, finally suggesting the relation:

$$m_{b,\mathrm{ISC}} = 0.46 M_S + 2.74 \tag{8}$$

Recent works (i.e., Murphy et al., 2001; Murphy and Barker, 2003) deal with the reliability of m_b estimated by ISC and/or NEIC. Murphy and Barker (2003) re-estimated the body wave magnitudes for a large number of earthquakes recorded by stations of the International Monitoring System (IMS) at epicentral distances ranging from 23° up to 180° using short period recordings and the corrections for epicentral distance and depth proposed by Veith and Clawson (1972). They also found that the new magnitudes estimated deviated significantly from the m_b magnitudes of ISC and NEIC.

The main problem of all the above magnitude scales is that they do not behave uniformly for all magnitude ranges. Another problem is that the M_L, M_S and m_b scales exhibit saturation effects at different levels for large earthquakes. Both these limitations could result in under- or over-estimation of earthquake magnitudes. These limitations led Kanamori (1977) and Hanks and Kanamori (1979) to propose a new magnitude scale, namely *moment magnitude,* M_W, defined by:

$$M_W = \frac{2}{3} \log M_0 - 10.7 \tag{9}$$

where M_0 is the seismic moment in dyn.cm. From a theoretical point of view, this scale is reasonably reliable since it is controlled by the fault size and the dislocation. The fact that seismic moment estimation is based on spectral amplitudes ensures the robustness of the M_W estimation. M_W does not saturate, since it is directly proportional to the logarithm of seismic moment, resulting in a uniform behavior for all magnitude ranges. For these reasons, M_W is considered as the most reliable magnitude accurately describing the size of earthquakes. However, since it was initially defined for earthquakes of magnitudes $M_S \geq 7.5$ it is of great interest to examine its behavior for weak earthquakes. Recent works revealed possible limitations in the seismic moment magnitude estimation. For example, Patton and Randal (2002) pointed out that for earthquakes of central Asia the seismic moments, M_0, included in the Centroid Moment Tensor (CMT) catalog of Harvard Seismology (2004), HRVD, exhibit

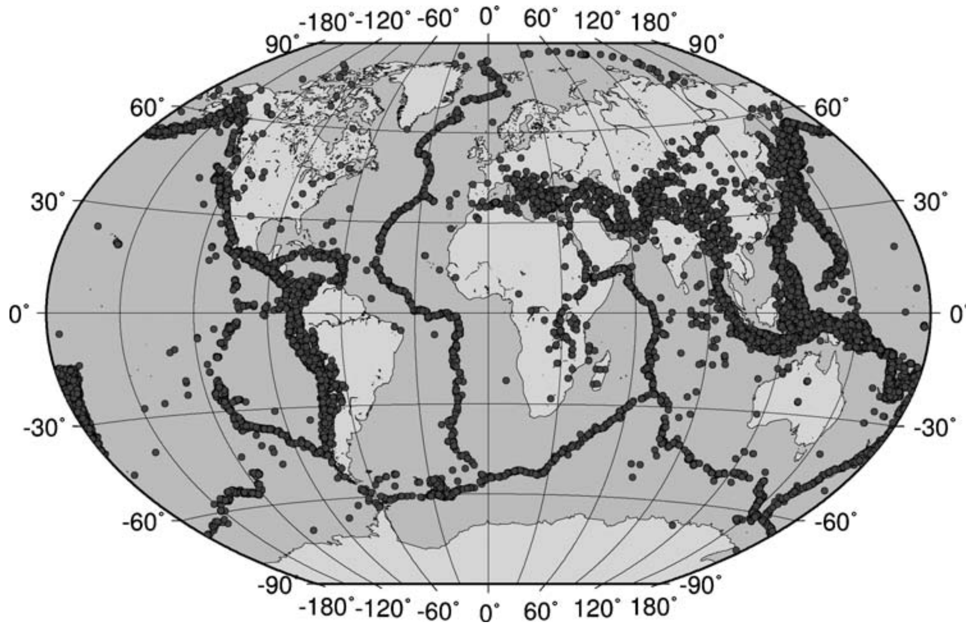

Figure 1. Spatial distribution of 20,407 earthquakes globally, for which M_W values in the range 3.1–8.4 are available.

remarkable deviations from the M_0 estimated from regional surface waves.

Since the M_W scale was first introduced, many studies have been carried out in different regions and seismotectonic environments to establish relations connecting other magnitude scales to M_W (Heaton et al., 1986; Johnston, 1996; Shedlock, 1999; Papazachos et al., 2002; among many others). The most important reason for this was to compile earthquake catalogs with all magnitudes expressed in one common scale (M_W) to solve important practical problems (i.e., seismic hazard assessment), as well as theoretical ones (calculation of crustal deformation, etc.).

In this study, an attempt is made to use a very large sample of data (much larger and extended to broader magnitude ranges than previous works) in order to define new empirical relations connecting m_b, M_S and M_L magnitudes with M_W. In particular, the m_b and M_S magnitudes, included in the catalogs of the International Seismological Centre (2004), ISC, and National Earthquake Information Center (2004), NEIC as well as M_S magnitudes included in a broadly used European earthquake catalogue (Karnik, 1996), are correlated with M_W values reported in the CMT catalog of Harvard Seismology (2004), HRVD (Dziewonski et al., 1981 and subsequent papers appeared quarterly on *Phys. Earth Plan. Int.*) and in the United States Geological Survey – Source Parameter Database (2004), USGS – SOPAR, catalog.

The data

To perform this study it was necessary to create an earthquake catalog with information on all earthquakes, for which magnitudes expressed in the scales under examination, estimated by several agencies, were available, and which occurred during the last few decades.

As a reference magnitude we used the moment magnitude estimated by HRVD (CMT solutions – 20,196 events from 1976 up to the end of May, 2003). Moment magnitudes for 212 additional events were taken from USGS. Therefore, the total number of earthquakes with estimated M_W, ranging between 3.1 and 8.4, reached 20,407. Their spatial distribution is shown in the map of Figure 1.

To check the consistency of M_W given by HRVD with M_W given by USGS Figure 2 shows the relation between these two moment magnitudes. 3,756 events with moment magnitudes reported by both sources (time period 1.1.1980–31.5.2003) were used. The relation derived is:

$$M_{W,HRVD} = 1.00(\pm 0.01)M_{W,USGS} + 0.04(\pm 0.09),$$
$$5.0 \leq M_{W,USGS} \leq 8.2,$$
$$R^2 = 0.95, \quad \sigma = 0.11, \quad n = 3,756 \quad (10)$$

This result shows that the differences across the whole magnitude range are negligible (less than 0.05),

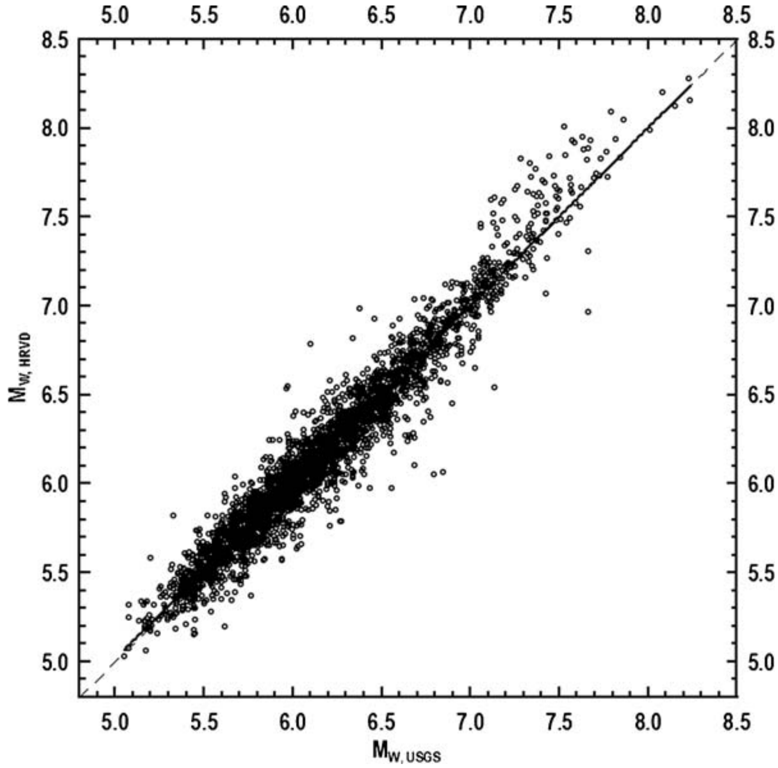

Figure 2. Correlation between M_W given by HRVD and by USGS; 3,756 events. The dashed line is the bisector and the straight line is the best fit. The same line symbols apply to Figures 3–7.

allowing to practically consider them as equivalent. Anyhow, moment magnitudes from USGS were used only for less than 1% of the earthquakes.

To examine the behavior of the body wave magnitude scale, m_b, 284,157 values from ISC and 229,375 from NEIC (for earthquakes occurred during the period 1.1.1965–31.5.2003) have been collected while for the surface wave magnitude scale, M_S, the respective numbers are 56,184 from ISC (time period 1.1.1978–31.5.2003) and 32,464 from NEIC (time period 16.5.1968–31.5.2003).

Surface wave magnitude scale (M_S)

M_S magnitudes reported in the bulletins of ISC and NEIC are all estimated using the Prague formula expressed by Equation (5) (Utsu, 2002). Comparison of relations (1) and (5) shows that they are slightly different. Utsu (2002) noticed that for $T = 20$ s Equation (5) gives M_S values larger by about 0.2 than Equation (1). The M_S overestimation by the Prague formula compared to relation (1) has also been observed by several other authors (Nuttli and Kim, 1975; Thomas et al., 1978; Christoskov et al., 1985; Panza et al., 1989; Herak and Herak, 1993; Rezapour and Pearce, 1998 among others). However, this bias is compensated by the benefit of Equation (5) of using seismic waves with periods between 10 and 60 s recorded at epicentral distances 20°–160°, significantly increasing the number of earthquakes for which M_S estimation is possible.

Since both ISC and NEIC estimate M_S using the same technique, it is expected that the magnitudes should be more or less equivalent. To verify this assumption we have plotted M_S given by NEIC versus M_S estimated by ISC for events in 1978–2003. The relations that express the best-fit lines in the least squares' sense are:

$$M_{S,NEIC} = 0.99(\pm 0.003)M_{S,ISC} + 0.05(\pm 0.02),\quad h < 70\,\text{km},\quad R^2 = 0.95,\quad \sigma = 0.16,\quad n = 25{,}960 \tag{11}$$

$$M_{S,NEIC} = 0.98(\pm 0.05)M_{S,ISC} + 0.07(\pm 0.24),\quad 70\,\text{km} \le h \le 640\,\text{km},\quad R^2 = 0.96,\quad \sigma = 0.17,\quad n = 65 \tag{12}$$

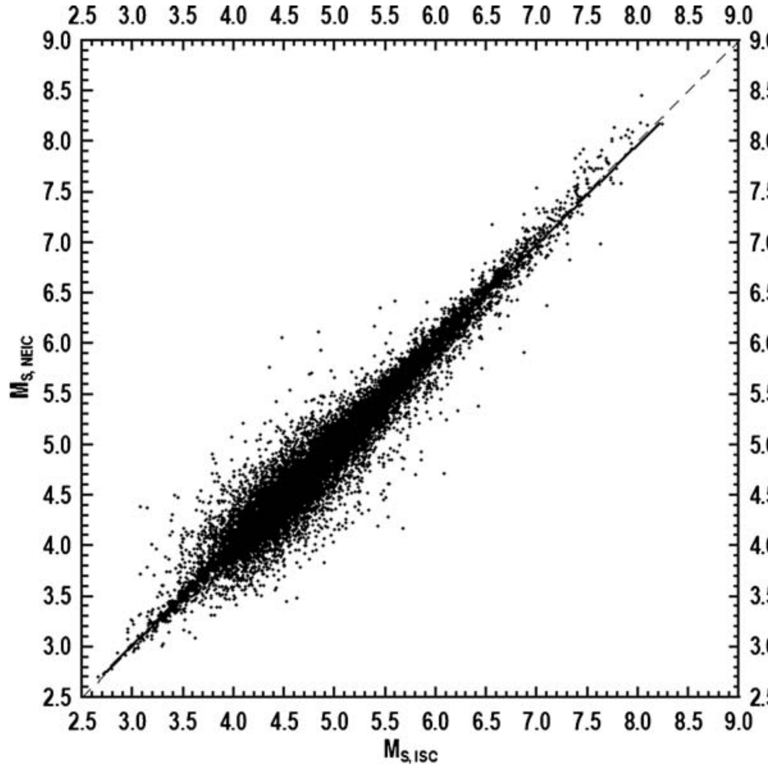

Figure 3. Correlation between M_S values given by NEIC and by ISC for shallow earthquakes ($h < 70$ km); 25,960 events. Similar results are obtained for 65 events in the depth range 70–640 km and for all 26,025 events taken together.

$$M_{S,NEIC} = 0.99(\pm 0.003) M_{S,ISC} + 0.05(\pm 0.02), \quad \text{all } h, \quad R^2 = 0.95, \quad \sigma = 0.16, \quad n = 26{,}025 \tag{13}$$

where h is the focal depth. Equation (11) is shown in Figure 3. It is obvious that throughout a wide range ($2.6 \leq M_{S,ISC} \leq 8.3$), M_S estimated by ISC and by NEIC are practically identical irrespective of focal depth, allowing their consideration as a unified data set.

The distribution of M_W versus M_S for shallow earthquakes, $h < 70$ km, is given in Figure 4 (13,591 points from ISC and 12,714 points from NEIC). Bubbles with size related to the number of points give a clearer picture of the distribution. These plots exhibit a bilinear correlation between M_W and M_S expressed by the equations:

$$M_W = 0.67(\pm 0.005) M_S + 2.07(\pm 0.03), \quad 3.0 \leq M_S \leq 6.1, \quad R^2 = 0.77, \quad \sigma = 0.17, \quad n = 23{,}921 \tag{14}$$

$$M_W = 0.99(\pm 0.02) M_S + 0.08(\pm 0.13), \quad 6.2 \leq M_S \leq 8.2, \quad R^2 = 0.81, \quad \sigma = 0.20, \quad n = 2{,}382 \tag{15}$$

For $M_S < 4.0$ the data are rather poor (Figure 4). However, the relation can give, at least, indicative results for earthquakes of that range of magnitudes.

Karnik (1968, 1971, 1973, 1996) made a significant attempt to compile an accurate, homogeneous, and complete catalog of earthquakes that occurred during the last two centuries in Europe. In his latest catalog (Karnik, 1996) earthquakes that occurred from 1800 to 1990 in Europe and surrounding areas are included. The converted, or re-estimated, magnitudes are in an M_S scale consistent with the Prague formula (Vanek et al., 1962). Since this catalog is widely used for earthquakes in Europe, it is of interest to see how its magnitudes are related to M_W. The available sample of earthquakes for which both M_W and Karnik magnitude, M_{SK}, are available is rather small (about 280 shocks) and does not include earthquakes with $M_W \leq 4.8$. For this reason,

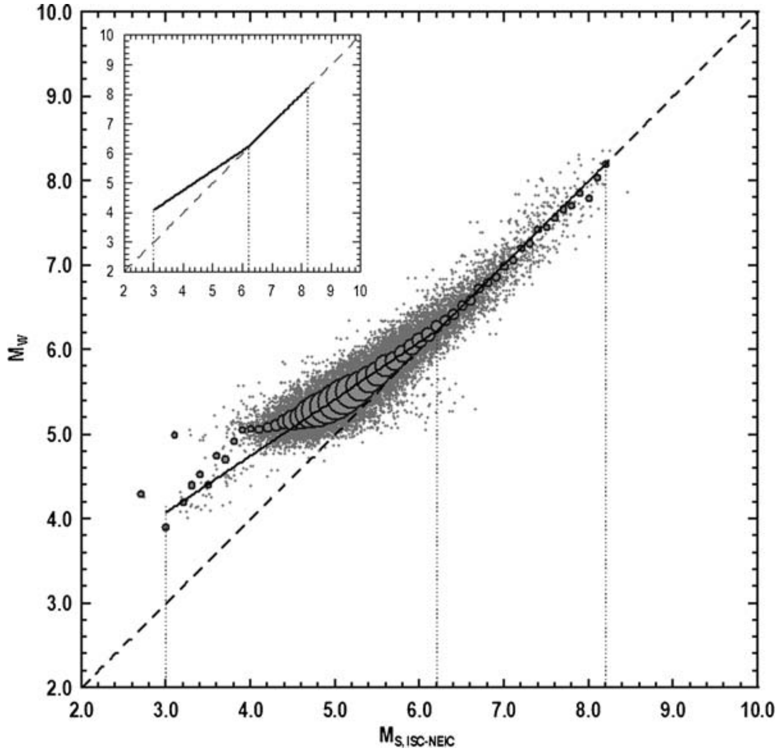

Figure 4. Relation between M_W and M_S for shallow earthquakes; 26,305 points. The bubble size corresponds to the number of values. The same symbols apply to Figures 5 and 7. A break at $M_S = 6.2$ is obvious.

M_{SK} was compared with M_S (from ISC and NEIC) providing a larger sample, 2,149 events, and covering a wider magnitude range, $2.9 \leq M_S \leq 8.0$. Figure 5 shows that for a broad range of magnitudes M_{SK} and M_S are almost identical. Particularly, for the larger earthquakes the relation is:

$$M_S = 1.05(\pm 0.05)M_{SK} - 0.41(\pm 0.31), \quad 5.4 \leq M_{SK} \leq 8.1, \quad R^2 = 0.82, \quad \sigma = 0.27, \quad n = 266 \tag{16}$$

and for the smaller earthquakes the relation is:

$$M_S = 1.19(\pm 0.06)M_{SK} - 1.14(\pm 0.26), \quad 4.0 \leq M_{SK} \leq 5.3, \quad R^2 = 0.53, \quad \sigma = 0.37, \quad n = 1{,}730 \tag{17}$$

The scatter of points for earthquakes with $M_{SK} < 5.4$ shows loose (indicative) correlation between the two magnitude scales. The data are not enough to extend the relation for $M_{SK} < 4.0$.

Comparing the formulae (14), (15), (16), (17) we can extract new relations connecting M_{SK} to M_W. These relations are:

$$M_W = 0.80M_{SK} + 1.31, \quad 4.0 \leq M_{SK} \leq 5.3, \quad \sigma = 0.41 \tag{18}$$

$$M_W = 0.70M_{SK} + 1.80, \quad 5.4 \leq M_{SK} \leq 6.2, \quad \sigma = 0.29 \tag{19}$$

$$M_W = 1.04M_{SK} - 0.33, \quad 6.3 \leq M_{SK} \leq 8.1, \quad \sigma = 0.31 \tag{20}$$

Body wave magnitude scale (m_b)

m_b is one of the most widely used magnitude scales. In the m_B scale definition in Gutenberg's original work (Gutenberg, 1945a,b), intermediate period displacement sensors were used giving peak amplitudes in the 6–12 s period range while a linear attenuation model was adopted. In the present study the magnitudes calibrated are in the m_b scale, as they were reported by ISC and/or NEIC. These centers estimate the m_b

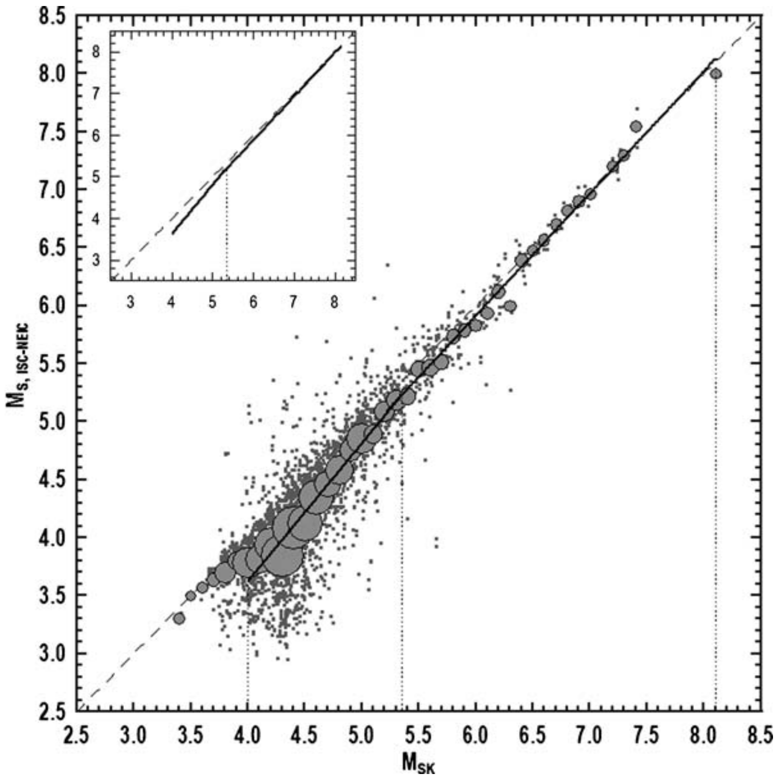

Figure 5. Correlation between M_S (from ISC and NEIC) and M_{SK} (from Karnik, 1996) for earthquakes which occurred in the broader area of Europe between 1965 and 1990; 2,149 events.

magnitudes of the earthquakes which occurred since the early 60's using the first 5 s of P-waves recorded on short period instruments.

To check how the m_b reported by ISC is correlated with the m_b reported by NEIC, 215,163 earthquakes which occurred globally between 1.1.1965 and 31.5.2003 with m_b magnitudes ranging from 2.5 up to 7.3 were used. The diagram of Figure 6 shows the variation of m_b ISC versus m_b NEIC (least-squares' fit). The relation is:

$$m_{b,\mathrm{ISC}} = 1.02(\pm 0.003)m_{b,\mathrm{NEIC}} - 0.18(\pm 0.01), \quad 2.5 \leq m_{b,\mathrm{NEIC}} \leq 7.3, \quad R^2 = 0.99, \quad \sigma = 0.20, \quad n = 215,163 \tag{21}$$

This relation indicates that the m_b magnitudes given by ISC and NEIC are, practically, equivalent. The slight bias between them has been also observed by other researchers (e.g., Utsu, 2002).

Considering m_b given from ISC and NEIC as a unified magnitude scale it is of great interest to examine its behavior against M_W. For this reason a data set consisting of 20,870 earthquakes with both m_b (from ISC and/or NEIC) and M_W values available (40,580 pairs) was prepared, covering the time period 1965–2003.

The plot of M_W against m_b (Figure 7) clearly shows that m_b values are consistently lower than those of M_W, as has been shown in several previous studies (e.g., Nuttli, 1983, 1985; Giardini, 1984; Kiratzi et al., 1985; Heaton et al., 1986; Patton and Walter, 1993, 1994; Johnston, 1996; Papazachos et al., 1997 among others). The data show an approximate linear distribution up to an m_b value of about 6.2 which is expressed by the relation:

$$M_W = 0.85(\pm 0.04)m_b + 1.03(\pm 0.23), \quad 3.5 \leq m_b \leq 6.2, \quad R^2 = 0.53 \quad \sigma = 0.29, \quad n = 39,784 \tag{22}$$

For $m_b < 4.5$ the data are rather poor (Figure 7). However, relation (22) can give, at least, indicative results for earthquakes of that range of magnitudes. For $m_b > 6.2$ (approximately) the relation increases its slope showing an unstable behavior that could be

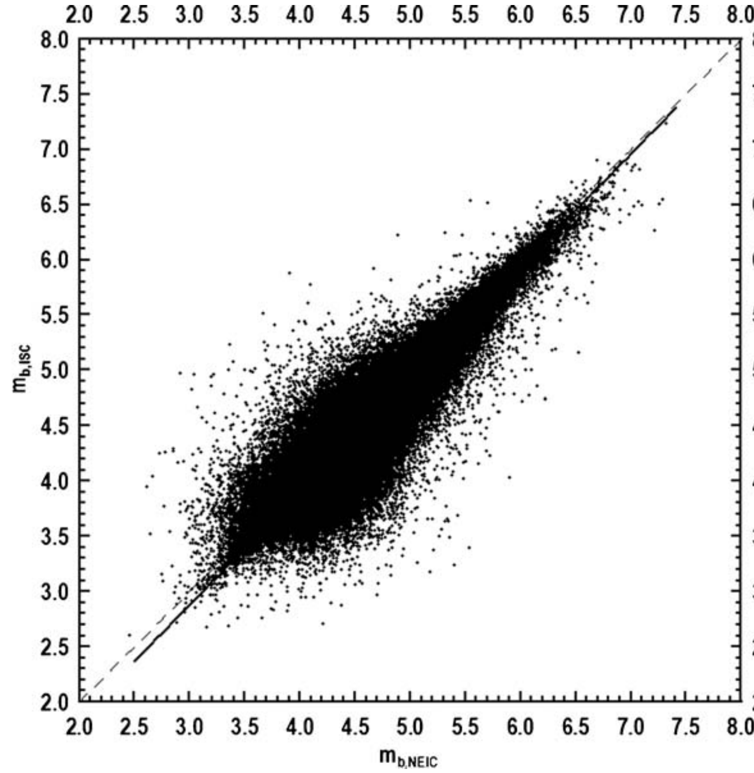

Figure 6. Correlation of m_b from ISC and from NEIC for earthquakes which occurred globally from 1965 up to the end of May, 2003 with m_b magnitudes ranging from 2.5 to 7.3; 215,163 events.

considered as saturation. This is expected because the m_b magnitudes are estimated from the amplitudes of the first 5 s of short period recordings. Consequently, in many cases of strong earthquakes the maximum amplitudes occur later, a fact that leads to underestimation of magnitudes.

Local magnitude scale (M_L)

Several authors have defined relations between M_W and M_L using data from earthquakes occurring in different regions of the world (e.g., Kim et al., 1989; Uhrhammer et al., 1996; Papazachos et al., 1997, 2002; Wahlström and Grünthal, 2000; Grünthal and Wahlström, 2003 among others). These relations show a linear, bilinear or quadratic connection between these two magnitude scales.

However, there is confusion regarding the magnification of the Wood Anderson seismographs which were used to estimate the original M_L magnitudes. According to Richter (1935), the typical Wood Anderson (WA) seismograph used in the definition of the M_L scale had a magnification of 2,800 (Anderson and Wood, 1924, 1925). More recent studies by Uhrhammer and Collins (1990) and Uhrhammer et al. (1996) have pointed out that the effective magnification of the typical WA seismograph is around 2,080, leading to systematic errors in M_L estimations. The magnification is often different for different WA instruments. For instance, Papazachos et al. (1997) and Margaris and Papazachos (1999) showed that the Wood Anderson seismograph, still operating at the National Observatory of Athens, Greece, has an even lower magnification (~1,000) resulting in systematic underestimation of M_L, which has systematically affected local magnitude estimations for the southern Balkan area. Moreover, "equivalent" M_L magnitudes are also calculated by using recordings of several short-period instruments (i.e., Kiratzi, 1984; Kiratzi and Papazachos, 1984; Scordilis, 1985; Papanastasiou, 1989; Uhrhammer and Collins, 1990; Uhrhammer et al., 1996) calibrated against (possibly incongruous magnification) Wood Anderson seismographs.

As a result of this confusion, the M_L magnitudes reported by several seismological stations cannot be considered as equivalent and, therefore, regional

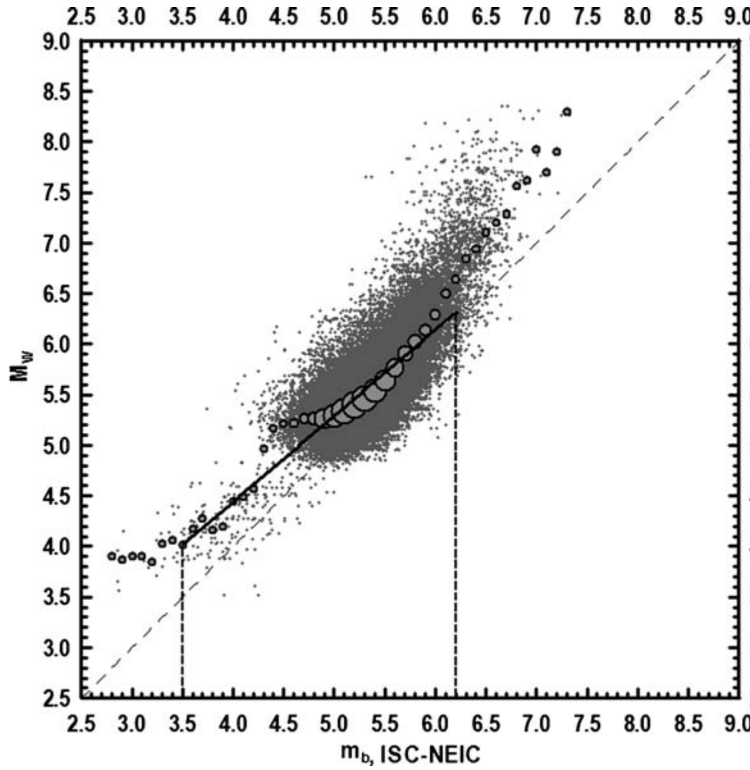

Figure 7. Correlation between M_W and m_b (from ISC and NEIC) for earthquakes which globally occurred since 1965 up to the end of May, 2003; 40,580 points.

relations connecting them with M_W are required. For this reason it is not possible to define unique global relations connecting M_L to M_W or to other magnitude scales.

Conclusions

The main target of the present work is to derive globall valid empirical relations converting magnitudes expressed in widely used magnitude scales to equivalent moment magnitudes. Such relations could become a very useful tool in compiling homogeneous earthquake catalogs.

The M_S magnitudes estimated by ISC and NEIC applying the Prague formula (Vanek et al., 1962) are equivalent throughout a wide magnitude range (M_S = 2.6–8.3). New relations connecting M_S with M_W have been defined for earthquakes with foci not exceeding a depth of 70 km. It has been shown that for strong earthquakes ($6.2 \leq M_S \leq 8.2$) these magnitude scales are practically equivalent (relation 15), while for weaker events ($3.0 \leq M_S \leq 6.1$) the M_S values are significantly lower than M_W (relation 14).

The magnitude M_{SK} reported in Karnik (1996) estimated for earthquakes covering the broader area of Europe, is, according to the author, equivalent to M_S. However, its comparison with M_S estimated by ISC and NEIC shows a clear bilinear correlation (relations 16, 17).

The consistency between m_b magnitudes estimated by ISC and NEIC has been demonstrated throughout a wide magnitude range ($2.5 \leq m_b \leq 7.3$), although there is a slight bias observed (Figure 6, relation 21). The relation between m_b and M_W clearly reveals linear dependency up to $m_b \leq 6.2$ expressed by relation (22). The m_b magnitude scale exhibits an unstable behavior that could be considered as saturation for earthquakes with $m_b > 6.2$ (or its equivalent $M_W > 6.3$) – see Figure 7.

The main reasons for the inconsistency of M_L estimated by several seismological centers are: (a) they are calculated based on Wood Anderson seismographs (or their simulated) with different effective magnification, usually smaller than the nominal one (~2,800), (b) the distance corrections applied are often adopted from the original M_L definition and not estimated for

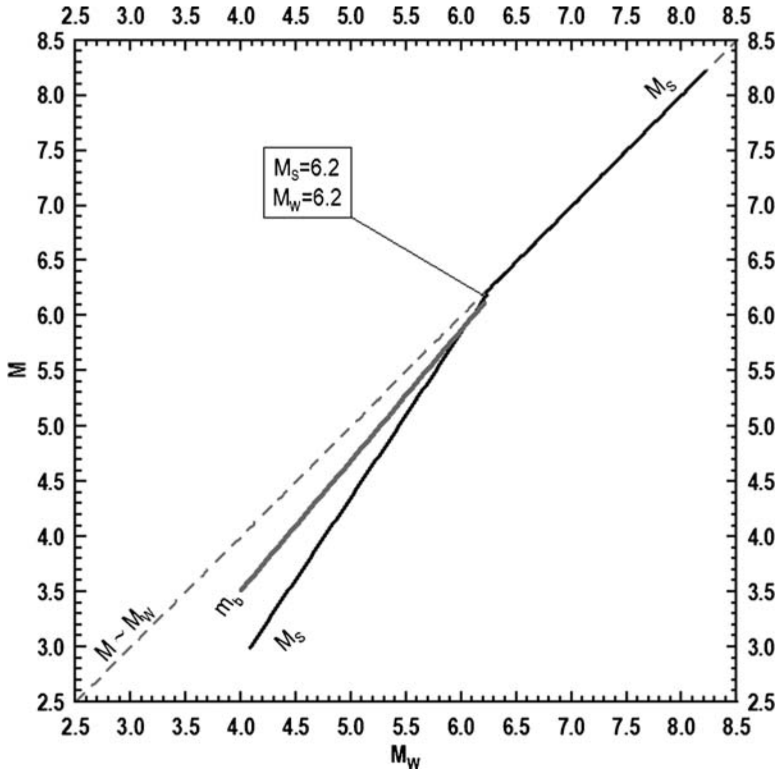

Figure 8. Summary plot of the final results for the comparison between m_b and M_S, and M_W, derived using the global earthquake catalogue developed in the present work.

the local region. For these reasons, no general globally valid relation between M_L and M_W magnitudes can be proposed and such relations must be derived for each group of Wood-Anderson seismographs and possibly for each seismotectonic region.

The results of the present work are summarized in the diagram of Figure 8 showing the variation of M_S and m_b with M_W. It is important to notice that no magnitude other than M_W is capable to express the "size" of earthquakes with $M_W > 8.2$ and that the available data do not permit for weak earthquakes ($M_W < 4.0$) the implicit estimation of moment magnitudes from magnitude measurements in other scales. The M_S-M_W relation is bilinear changing slope at $M_S = 6.2$ and the uncertainties of both branches are reasonable ($\sigma \sim 0.19$). The m_b-M_W relation is linear for $3.5 \leq m_b \leq 6.2$ but the uncertainties are rather high ($\sigma = 0.29$).

It must be clearly stressed that all the relations derived in the present work are valid only for large-scale studies. For regional studies new and more detailed relations connecting M_W or M_S or m_b with magnitudes from local agencies should be derived.

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