

Moment Magnitude Estimates for Earthquakes in the Greek Region: A Comprehensive Comparison

by K. I. Konstantinou

Abstract Many different agencies and research groups routinely estimate moment magnitudes (M_w) in the Mediterranean area as a means of offering an unbiased quantitative assessment of earthquake size. In this work, a comprehensive comparison is undertaken of the moment magnitudes estimated for earthquakes in the Greek region by the Global Centroid Moment Tensor (Global CMT) group, Regional CMT group, the Swiss seismological service based in ETH Zürich, Aristotle University of Thessaloniki (AUTH), and the National Observatory of Athens (NOA) Institute of Geodynamics. The orthogonal regression method is applied to obtain the best-fit line between the NOA and the other magnitude estimates. Results show that NOA moment magnitudes are, on average, smaller than Global CMT/Regional CMT/ETH magnitudes by about 0.12–0.19 magnitude units, whereas they agree quite well with AUTH magnitudes. It is also shown that for the calibration of NOA magnitudes relative to the other magnitude estimates, no scaling correction is needed, but only a variable offset correction should be applied. Taking advantage of the fact that Global CMT and Regional CMT magnitudes are fully compatible, it is possible to calibrate NOA magnitudes relative to Global CMT and then merge the moment magnitudes of the three databases. The new catalog compiled in this way is homogeneous with respect to M_w and includes 1966 earthquakes spanning a period from 1976 to 2014.

Online Material: Earthquake catalog.

Introduction

Earthquake magnitude is a fundamental source parameter that allows scientists as well as civil authorities to quickly assess the severity of the resulting ground motion and its potential to cause damage to built structures. Magnitudes are also of primary importance for b -value estimation and seismic-hazard assessment. Over the last century, several definitions of magnitude have been proposed, such as local magnitude (M_L), body-wave magnitude (m_b), and surface-wave magnitude (M_S), each of them having its own advantages (see [Lay and Wallace, 1995](#)). A common disadvantage of all these magnitude scales is that they tend to saturate once the earthquake energy exceeds a specific level, leading to an underestimation of the true magnitude of the earthquake. The introduction of seismic moment by [Aki \(1966\)](#) provided a physically meaningful measure of the strength for a general seismic source; and, when combined with the development of the moment magnitude (M_w) scale ([Hanks and Kanamori, 1979](#)), it removed the problem of saturation. Furthermore, the advent of efficient waveform inversion methods permitted the routine determination of moment tensors and magnitudes, even for small earthquakes ($M_w \sim 3.5$) recorded at local to regional distances.

In the past, the Greek region has suffered large catastrophic earthquakes, and its seismicity levels rank among the highest in the world ([Papazachos and Papazachou, 2003](#)). During the last 15 years, the installation of modern seismological networks in this region has provided a wealth of high-quality waveform data that have been used for investigating the seismotectonics and source processes of several large earthquakes (e.g., [Roumelioti et al., 2004](#); [Konstantinou, Lee, et al., 2009](#); [Konstantinou, Melis, et al., 2009](#)). Since 2005, the National Observatory of Athens (NOA), Institute of Geodynamics, has routinely determined moment tensor solutions of events occurring in Greece and the surrounding areas. Waveform data recorded prior to 2005 have also been analyzed in retrospect, therefore the NOA moment tensor solutions extend back to 2001 ([Konstantinou et al., 2010](#)), now spanning a period of almost 14 years. As a by-product of the moment tensor inversion results, moment magnitude estimates are also listed in the dedicated NOA webpage (see [Data and Resources](#)) along with the other source parameters for each earthquake. Other agencies and research groups have also produced moment tensor solutions and moment magnitudes for the Greek region, such as the Global Centroid

Moment Tensor group (Global CMT, formerly Harvard CMT), the Regional Centroid Moment Tensor (Regional CMT) group based in the Istituto Nazionale di Geofisica e Vulcanologia (INGV), the Swiss seismological service based in ETH Zürich, and the seismological group of the Aristotle University of Thessaloniki (AUTH). However, the exact relationship of all these different M_w estimates is not known, and this makes any attempt to create one homogeneous catalog for the Greek region difficult.

In this work, a systematic comparison between the moment magnitude estimates issued by NOA and the other groups and agencies is performed, with the aim of calibrating the NOA magnitudes against the other estimates and makes the calculation of a homogeneous moment magnitude for the Greek region possible. First, a description of the available data is given, along with an outline of the regression strategy that will be followed. Then the results are examined from a statistical point of view, and they are used to compile a catalog for the Greek region that is homogeneous in moment magnitude. Finally, the variations of the mean difference between NOA magnitudes and the other M_w estimates are investigated, both as a function of moment magnitude and as a function of time.

Data

The moment tensor solutions at NOA for the period January 2001 until October 2012 have been determined using the method of [Herrmann and Ammon \(2002\)](#) as described in [Konstantinou et al. \(2010\)](#); and, from late 2012 until now, inversions are performed using the ISOLA software package ([Sokos and Zahradnik, 2008](#)). Both methodologies assume a point-source approximation and invert regional waveforms to derive the deviatoric part of the moment tensor, with the ISOLA package being adopted by NOA staff because of its user-friendly graphical interface. From 2001 up to the year 2008, station coverage was relatively sparse (interstation distance of about 100 km), and the sensors used were broadband only up to 20 s, limiting the inversion bandwidth to 0.05–0.08 Hz. This situation changed in early 2008, when all seismic networks in Greece were combined into the Hellenic Unified Seismic Network (HUSN) and most of the sensors were upgraded to extend their bandwidth (up to 0.01 Hz). The significant increase in the number of available stations meant that smaller events could be inverted that were occurring outside the political boundaries of Greece, in neighboring areas such as Albania and western Turkey.

On the other hand, the Global CMT group has produced moment tensor solutions since 1976, and the first solution of a Greek earthquake appears in the Global CMT database for an event that occurred on 11 May 1976. The Global CMT algorithm inverts teleseismic waveforms for the deviatoric part of the moment tensor as well as the centroid location and time using body (40–150 s), mantle (125–350 s), and, after 2003, surface waves (passband depends on event size) ([Ekström et al., 2012](#), and references therein). The Regional CMT group

has calculated moment tensor solutions for earthquakes in the Mediterranean region since 1997 using a variation of the CMT algorithm that inverts the first-arriving surface waves with a low-pass cutoff period of 40–60 s ([Pondrelli et al., 2002, 2004, 2011](#)). The Swiss seismological service group in ETH was calculating deviatoric moment tensors for events in the European–Mediterranean region for the period 1999–2005 and fully automatic solutions (i.e., not reviewed by an analyst) for the period 2006–2010. The inversion algorithm used complete three-component waveforms consisting of body and surface waves and applied a cutoff period of 40 s ([Braunmiller et al., 2002](#)). Finally, the seismological group of AUTH has calculated moment tensor solutions since early 2006 using the software package *TDMT_INV* ([Dreger, 2003](#)), which utilizes complete three-component regional waveforms of body and surface waves. It should be noted that the AUTH group initially used only data recorded by their seismic network in northern Greece, whereas after the network unification in 2008, its inversions also included stations from other networks in the region.

The comparison of NOA moment magnitudes versus the other M_w estimates started from identifying common pairs of events across the different catalogs based on the corresponding origin time (acceptable difference should be less than 1 min). For reasons of consistency, moment magnitudes were calculated from the seismic moment values M_0 (in N·m) using the relationship ([Hanks and Kanamori, 1979](#))

$$M_w = \frac{2}{3} (\log_{10} M_0 - 9.1). \quad (1)$$

The value of the seismic moment for Global CMT and ETH events was directly available from each database; however, the Regional CMT database only included an estimate of M_0 with an accuracy of one significant decimal. To remedy this, the value of the seismic moment for each event was calculated from the individual moment tensor elements using the equation ([Silver and Jordan, 1982](#))

$$M_0 = \sqrt{\frac{\sum M_{ij}^2}{2}}, \quad (2)$$

in which M_{ij} symbolizes the moment tensor elements. A cross check was subsequently performed to make sure there were no significant differences between the initial and the new seismic moment values. At this point, it should be noted that only ETH moment magnitudes determined from solutions reviewed by an analyst will be considered in the regression analysis that follows. Figure 1 shows maps of the Greek region, along with the epicenters of the common events among the different databases.

Methodology

Least-squares regression has been a standard method (hereafter referred to as standard regression [SR]) for

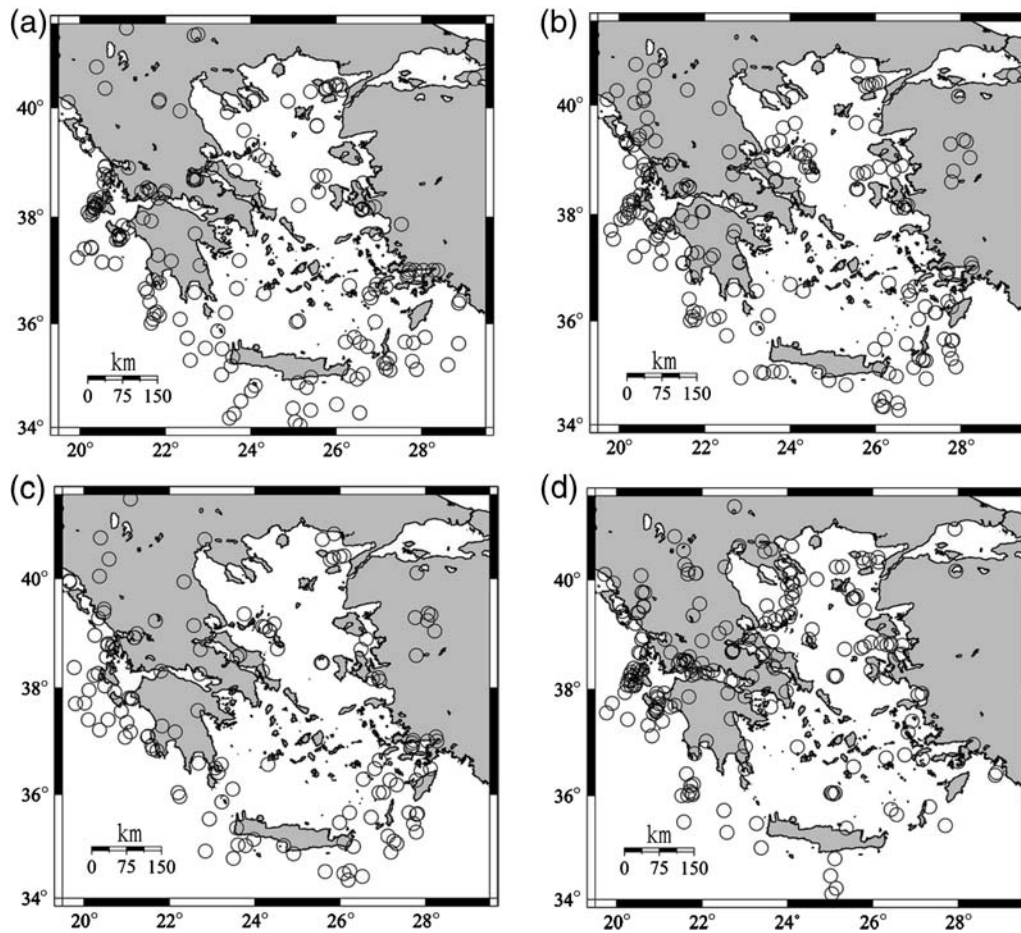


Figure 1. Maps of the Greek region, including the surrounding areas (Albania, western Turkey) showing the epicentral locations of the earthquakes used in this study corresponding to (a) Global Centroid Moment Tensor (Global CMT), (b) Regional Centroid Moment Tensor (Regional CMT), (c) ETH, and (d) Aristotle University of Thessaloniki (AUTH) catalogs.

obtaining an empirical relationship between two variables x and y that are linearly correlated. The model of a line that the two variables follow could then be written as

$$y \leftarrow \beta_{\text{SR}}x + \alpha_{\text{SR}}, \quad (3)$$

in which the arrow symbolizes that the two variables cannot be inverted if the relationship is derived using SR. A basic assumption that underlies SR is that the x variable contains no uncertainties, whereas the uncertainties in variable y are normally distributed. Seismologists are often compelled to derive conversion relationships between two magnitude estimates (of the same or different scale) using SR, ignoring in most cases the fact that both of these estimates are affected by uncertainties. [Castellaro et al. \(2006\)](#) were the first to point out this problem, and, instead of using SR, they advocated the use of general orthogonal regression (GOR). The GOR takes into account uncertainties in both variables by considering the ratio of their variances $\eta = \sigma_y^2/\sigma_x^2$ and fits the line

$$y = \beta_{\text{GOR}}x + \alpha_{\text{GOR}} \quad (4)$$

by minimizing the Euclidean distance between the points and the line (in the special case where $\eta = 1$, this distance corre-

sponds to the orthogonal distance). Empirical relationships derived using GOR can be inverted, hence the arrow has been substituted by the equality symbol. [Castellaro et al. \(2006\)](#) conducted extensive numerical tests using synthetic and real datasets for the purpose of demonstrating the superiority of GOR over SR and showed that the bias of using SR in magnitude conversions can be as high as 0.3–0.4 units. Recently, [Lolli and Gasperini \(2012\)](#) showed that GOR gives almost identical results when compared to regression methods that take into account the variance of the data, such as chi-square regression or weighted total least squares. [Gasperini et al. \(2015\)](#) also showed the superiority of the original GOR over other modified versions of the same method that had been suggested previously.

In practice, the application of GOR to real magnitude data hinges upon the fact that in most cases the value of the variance ratio is not known because the individual variances (σ_y^2, σ_x^2) are not known. In this case, [Castellaro and Bormann \(2007\)](#) propose that the regression can be carried out by assuming that $\eta = 1$ when the GOR becomes an orthogonal regression (OR), because it minimizes the orthogonal distance between the points and the line. The validity of the

assumption of the unit variance ratio can then be tested by calculating the slope of the line using SR and also by determining the slope of the line for inverted variables (y, x), again using SR (hereafter the inverted variables using standard regression is referred to as ISR). If the line with slope β_{OR} is in the angular midst between the other two lines with slopes β_{SR} and β_{ISR} , then the assumption $\eta = 1$ is valid (Castellaro and Bormann, 2007; Gutdeutsch *et al.*, 2011).

The strategy followed for the comparison of moment magnitudes in the Greek region encompasses the assumption that $\eta = 1$ for all pairs of catalogs. The previous assumption appears quite reasonable just by considering the fact that the different moment magnitude estimates have been obtained using similar methodologies (waveform inversion), and any uncertainties owing to other factors (data quality, passband, velocity models) should be approximately of the same order. Nevertheless, the validity of this assumption will be tested by also performing SR and ISR regressions and by estimating the angles that correspond to the arc tangent of the three slopes. In this case, it will be possible to check whether the OR line is close to the angular midst of the other two (SR, ISR) or not. In each comparison, two t -tests will also be conducted. The first test considers the null hypothesis that the OR slope is equal to 1.0 and utilizes a test value

$$t_{\text{sl}} = \frac{\beta_{\text{OR}} - 1.0}{\sigma_{\beta}}, \quad (5)$$

in which σ_{β} is the slope error estimated by OR. This test is performed for the purpose of checking whether or not conversion from one magnitude estimate to the other needs a scaling correction (see also Gasperini *et al.*, 2012). The second test considers the null hypothesis that the mean difference between two moment magnitude estimates is equal to zero, taking the test value as

$$t_{\text{dif}} = \frac{\Delta\bar{M} - 0.0}{\frac{\sigma_{\Delta\bar{M}}}{\sqrt{n}}}, \quad (6)$$

in which $\sigma_{\Delta\bar{M}}$ is the standard deviation of the magnitude difference and n is the sample size. In all cases, the significance level is taken as equal to 0.01, corresponding to a critical value of ± 2.57 for a two-tailed test.

Results

Global CMT Versus NOA

The period considered for the comparison of moment magnitude of the Global CMT–NOA estimates starts from May 2001 up to October 2014, yielding a total of 185 common pairs. The moment magnitude values range from 4.6 to 6.8 and represent both shallow and intermediate depth events with a variety of focal mechanism types. The distribution of the M_{w} differences for all pairs is approximately normal, with a mean of -0.18 signifying an underestimation of NOA magnitudes relative to Global CMT estimates (Fig. 2a).

The t -test regarding the mean magnitude difference shows that the null hypothesis of a zero mean can be confidently rejected ($t_{\text{dif}} = -18.83 < -2.57$). After performing the OR, the following slope and intercept (along with their uncertainties) are obtained (Fig. 3a):

$$M_{\text{w}}^{\text{NOA}} = 1.015(\pm 0.016)M_{\text{w}}^{\text{Global CMT}} - 0.261(\pm 0.085). \quad (7)$$

The t -test regarding the slope of this line shows that the null hypothesis cannot be rejected ($t_{\text{sl}} = 0.93 < 2.57$), therefore the slope is not significantly different from unity. Also the line obtained by OR lies very close to the angular midst (deviation less than 1%) of the lines obtained with SR and ISR, signifying that the absolute variances of the two magnitude estimates are approximately equal.

Regional CMT Versus NOA

The comparison between Regional CMT and NOA magnitudes covers the period from February 2001 until late December 2008, because the finally revised Regional CMT solutions do not extend beyond this time, and a total of 193 common pairs were found. As with Global CMT, both shallow and intermediate depth events are included, and the fact that regional rather than teleseismic waveforms are used in the inversions extends the range of moment magnitudes considered (4.1–6.7). Once more the distribution of the M_{w} differences for all pairs is close to normal, with a mean -0.12 signifying an underestimation of NOA magnitudes with respect to those of the Regional CMT (Fig. 2b). The t -test regarding the mean magnitude difference shows that the null hypothesis of a zero mean can be confidently rejected ($t_{\text{dif}} = -11.11 < -2.57$). The OR slope and intercept, along with their uncertainties, follow the line given by (Fig. 3b)

$$M_{\text{w}}^{\text{NOA}} = 1.024(\pm 0.018)M_{\text{w}}^{\text{Regional CMT}} - 0.246(\pm 0.088). \quad (8)$$

The t -test regarding the slope of this line shows that the null hypothesis cannot be rejected ($t_{\text{sl}} = 1.33 < 2.57$), therefore the slope is not significantly different from unity. The deviation of the OR line from the angular midst of the SR and ISR lines is 1.5%, which again indicates that the assumption of a variance ratio equal to one is acceptable.

ETH Versus NOA

A total of 140 common pairs were found spanning the period between February 2001 until July 2005, after which point the ETH manual solutions become sparse because the implementation of the automatic solutions had started. Both shallow and intermediate depth events are included while magnitudes are in the range 4.0–6.2, indicating a somewhat smaller upper magnitude compared to the Regional CMT. The distribution of the M_{w} differences for all pairs is approximately normal, with a mean of -0.19 signifying an under-

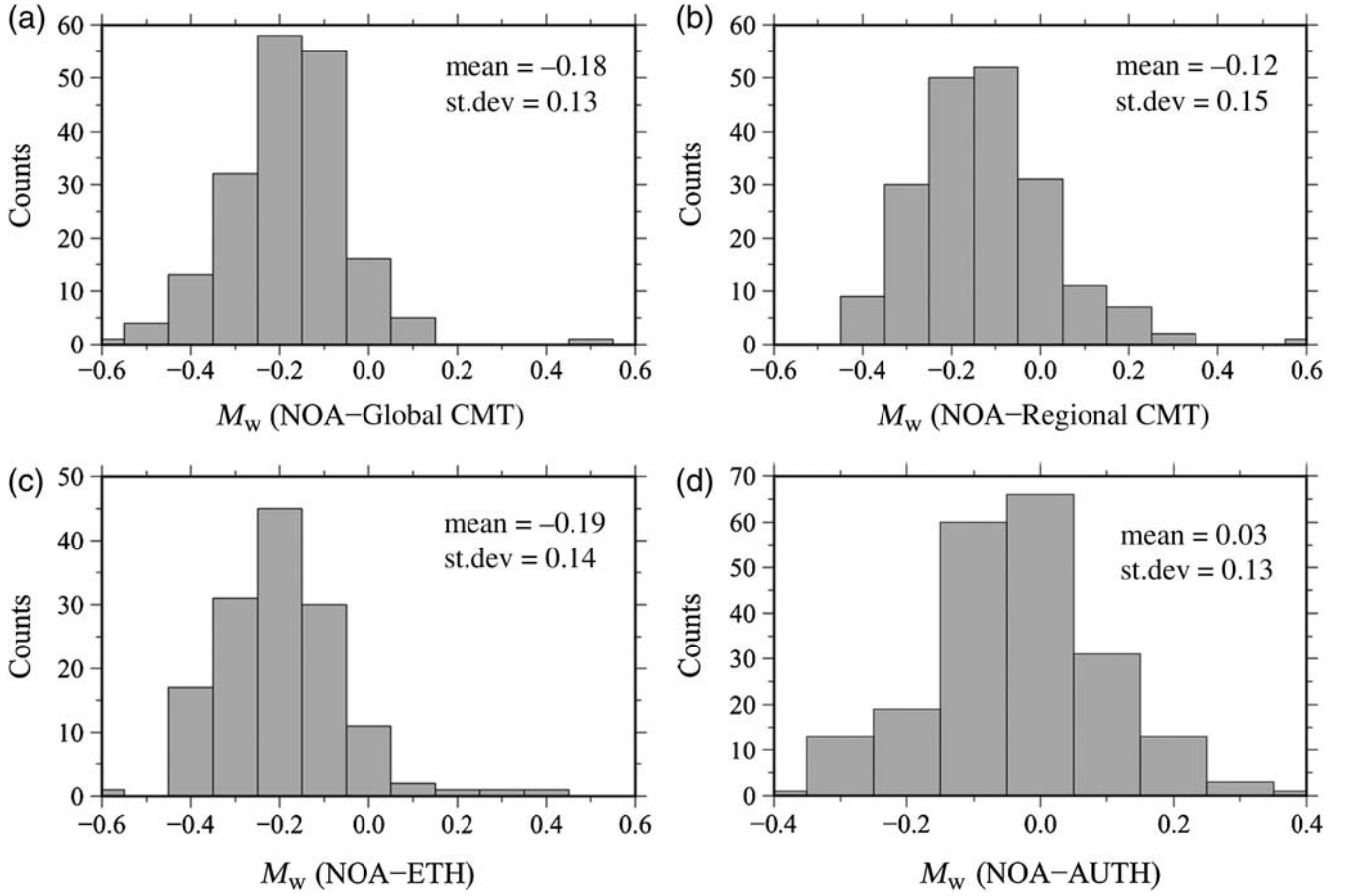


Figure 2. The distribution of the magnitudes differences for (a) National Observatory of Athens (NOA)–Global CMT, (b) NOA–Regional CMT, (c) NOA–ETH, and (d) NOA–AUTH. All histograms are calculated using a bin width of 0.1 magnitude units. The mean and standard deviation (st. dev.) of each distribution is shown in the upper right corner of each plot.

estimation of NOA magnitudes relative to ETH estimates (Fig. 2c). The t -test regarding the mean magnitude difference shows that the null hypothesis of a zero mean can be confidently rejected ($t_{\text{dif}} = -16.05 < -2.57$). The line that describes the OR results between the two magnitude estimates is given by (Fig. 3c)

$$M_w^{\text{NOA}} = 0.980(\pm 0.033)M_w^{\text{ETH}} - 0.099(\pm 0.160). \quad (9)$$

The t -test regarding the slope of this line shows that the null hypothesis cannot be rejected ($t_{\text{sl}} = -0.60 > -2.57$), therefore it is concluded that the slope is not significantly different from unity. The deviation of the OR line from the angular midst of the SR and ISR lines is slightly larger than 1%, which confirms the validity of the assumption that $\eta = 1$.

AUTH Versus NOA

A total number of 207 common pairs are found, spanning the time period between March 2006 and December 2014, and the magnitude range has a lower limit of 3.3 and an upper limit of 6.6, covering three orders of magnitude. The distribution of the M_w differences for all pairs is approximately symmetric,

including both negative ($M_w^{\text{AUTH}} > M_w^{\text{NOA}}$) and positive ($M_w^{\text{AUTH}} < M_w^{\text{NOA}}$) values and exhibiting a mean value slightly above zero (~ 0.03) (Fig. 2d). The t -test regarding the mean magnitude difference shows that the null hypothesis of a zero mean can be confidently rejected ($t_{\text{dif}} = 3.32 > 2.57$). The line that corresponds to the OR results is (Fig. 3d)

$$M_w^{\text{NOA}} = 0.991(\pm 0.017)M_w^{\text{AUTH}} + 0.003(\pm 0.08). \quad (10)$$

Once more, the t -test regarding the slope of this line shows that the null hypothesis cannot be rejected ($t_{\text{sl}} = -0.52 > -2.57$), therefore it is concluded that the slope is not significantly different from unity. The deviation of the OR line from the angular midst of the SR and ISR lines is approximately 0.5%, which is the lowest value in all four regressions. This means that the two variances ($\sigma_{\text{AUTH}}^2, \sigma_{\text{NOA}}^2$) are practically the same and that η is indeed equal to unity.

Conclusions

The results of this work indicate that, for all comparison pairs, no scaling correction is needed; however, an offset (the amount of which depends on which catalog is used) should

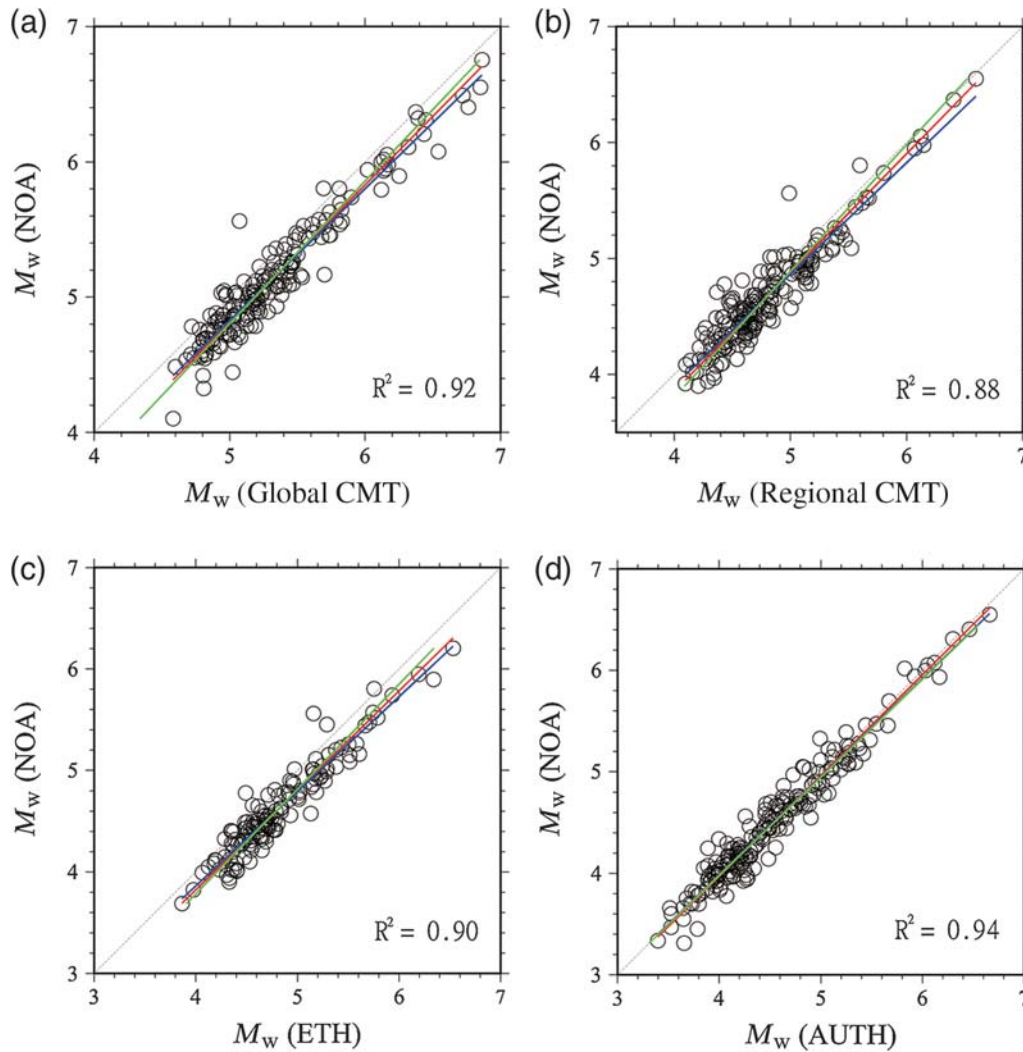


Figure 3. Regression results for moment magnitudes of (a) Global CMT–NOA, (b) Regional CMT–NOA, (c) ETH–NOA, and (d) AUTH–NOA. The red line corresponds to orthogonal regression (OR), the blue to standard regression (SR), and the green to inverted variables using SR (ISR) (see text for more details). The dotted line corresponds to the line with slope of unity. R^2 is the coefficient of determination for each case.

be applied. The homogenization of Global CMT and NOA magnitudes requires the addition of a positive offset to M_w^{NOA} estimates to compensate for the underestimation because of the limited bandwidth of the NOA inversions. As shown in Figure 4, this offset depends on the magnitude of each earthquake, being in the order of 0.15–0.19 magnitude units for $M_w \leq 6.2$ and about 0.25 magnitude units for larger events. The offset for calibrating NOA magnitudes relative to Regional CMT ranges between 0.1 and 0.2 magnitude units, exhibiting some fluctuations for moderate events, in which case it would be convenient to use a value of 0.12 equal to the mean magnitude difference. On the other hand, the mean difference of NOA–ETH magnitudes shows a progressive increase from 0.15 for $M_w \leq 5.0$ to about 0.3 magnitude units for larger events. Because this large difference is observed only for ETH estimates, it is quite possible that it not only stems from bandwidth limitations of NOA inversions, but also from the waveform inversion practices of the ETH

group. The AUTH moment magnitudes are the closest estimates to M_w^{NOA} , with the mean difference fluctuating between +0.01 and –0.05 for earthquakes with magnitudes ranging from 3.5 to 5.5.

Recently, Gasperini *et al.* (2012) conducted a similar calibration study for moment magnitudes of events in the European–Mediterranean region estimated by Global CMT, National Earthquake Information Center (NEIC), Regional CMT, ETH, and INGV (which specifically provides moment tensor solutions for earthquakes in Italy). The authors showed that no scaling correction was needed in any of the comparison pairs, but rather a variable (0.02–0.20) positive offset should be applied to all other estimates to calibrate them relative to Global CMT. These results are in good agreement with the findings of this study and highlight the underestimation of regional M_w estimates over the teleseismic ones provided by Global CMT or NEIC. Gasperini *et al.* (2012) also showed that there is an exact correspondence

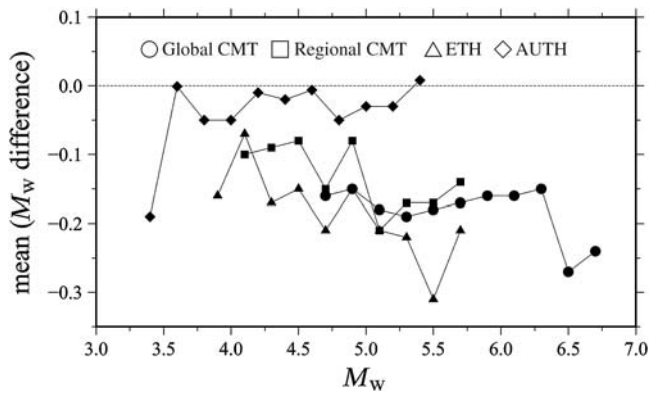


Figure 4. Variation of the mean of M_w differences for each comparison pair as a function of moment magnitude. Mean values were calculated in bins having a width of 0.2 magnitude units and were plotted in the midpoint of each bin.

between Global CMT and Regional CMT moment magnitudes, thus no scaling or offset correction is needed to create a joint Global CMT/Regional CMT catalog. It therefore is possible to compile a composite catalog for the Greek region that would consist of (a) Global CMT magnitudes for moderate and large events for the period 1976–2001, (b) Regional CMT magnitudes for smaller events for the period 1997–2001, and (c) NOA magnitudes covering the period 2001–2014 after an offset correction is applied to calibrate them relative to Global CMT (for $4.5 \leq M_w \leq 6.2$ offset is +0.17, whereas for $M_w > 6.2$ the offset is +0.25 magnitude units). This catalog is homogeneous in moment magnitude, contains 1966 events, and can be found in (E) Table S1 (available in the electronic supplement to this article).

The comparison presented here spans several years, and this also puts forward the question of how the magnitude differences vary as a function of time. Figure 5 shows the temporal variation of the mean and standard deviation of the magnitude differences for each comparison pair. The Global CMT–NOA differences span the longest time period (2001–2014) and also exhibit the largest variations of the mean value, from 0.14 to about 0.23 magnitude units. It is followed by the Regional CMT–NOA differences that cover a period of seven years (2001–2008), and their mean varies from 0.07 to 0.18 magnitude units. The five years (2001–2005) of available data for ETH seem to indicate very small variations in the order of 0.18–0.22 magnitude units. The pair AUTH–NOA spans nine years (2006–2014), and its mean difference is below 0.1 magnitude units, fluctuating from year to year around zero. On the other hand, the standard deviation of the differences for all pairs follows a very similar trend of initially increased values (~ 0.23 magnitude units) that progressively approach or fall below the level of 0.1 magnitude units. An additional characteristic is that the mean of magnitude differences for Global CMT, Regional CMT, and AUTH is increasing in the years 2007 and 2008, whereas the mean difference for Global CMT exhibits significant fluctuations after the year 2010. The cause of the observed increase

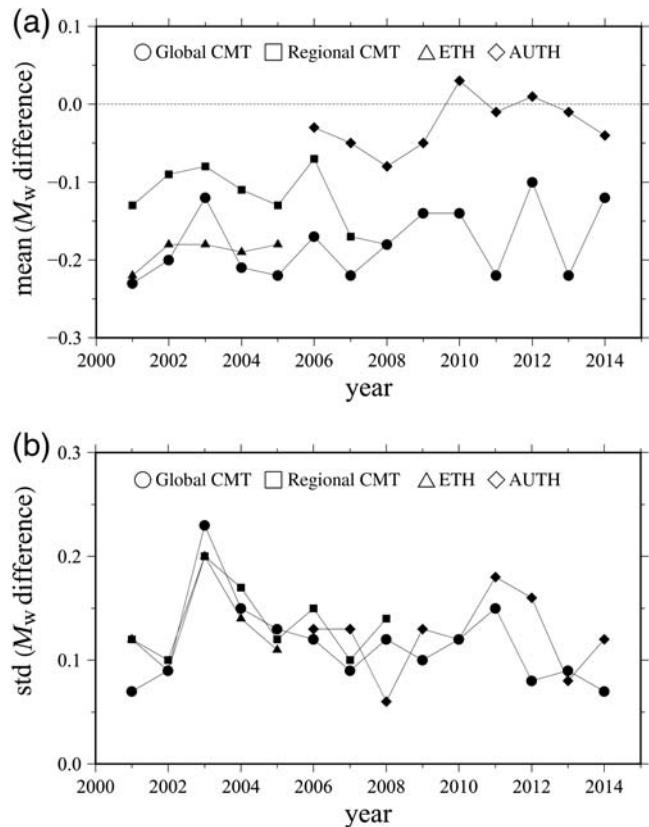


Figure 5. (a) The variation as a function of time (in years) of the mean of M_w differences between different catalog pairs and (b) the same for the standard deviation.

during 2007–2008 is not known; however, the period of fluctuating values roughly coincides with the change of the moment tensor inversion method implemented by NOA staff. Therefore, it is recommended that this variation in mean magnitude differences between NOA and Global CMT is monitored in the future for the purpose of finding its exact causes.

Data and Resources

The values of seismic moment were adopted from each moment tensor database for the Global Centroid Moment Tensor (www.globalcmt.org; last accessed February 2015), Swiss Seismological Service (http://www.seismo.ethz.ch/prod/tensors/index_EN; last accessed February 2015), and Aristotle University of Thessaloniki (www.geophysics.geo.auth.gr; last accessed February 2015). The components of the moment tensor elements for the Regional Centroid Moment Tensor are adopted from the corresponding database (www.bo.ingv.it/RCMT/; last accessed February 2015). The event locations and National Observatory of Athens seismic moments have been obtained from Konstantinou *et al.* (2010) and, after 2006, from the online database of the Institute of Geodynamics (bbnet.gein.noa.gr; last accessed February 2015).

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