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The relationship between local and moment magnitude in Greece during the period 2008–2016

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Abstract—We perform a systematic comparison between local and moment magnitudes in Greece for the period 2008–2016 when both magnitudes have been determined using waveform data recorded by the Hellenic Unified Seismic Network (HUSN). Differences between the two magnitudes scales on average do not exceed $\pm$ 0.2 units as has been found in other regions worldwide. A recalculation of local magnitude using magnitude residuals for each HUSN station shows that station site conditions have very little influence on the difference between local and moment magnitude. It is therefore more likely that wave propagation effects and in rare cases, anomalous source properties are dominant factors in shaping this difference. General orthogonal regression is applied to the whole dataset and also to subsets covering different areas of Greece or different time period to calibrate the one magnitude scale against the other using a linear model. The resulting relationships differ very little, suggesting that there is no significant regional/temporal variation between local and moment magnitudes. While these relationships predict that local magnitude is very close to moment magnitude if both are determined using HUSN data, the comparison with Global CMT moment magnitude (with M_w in the range 4.5–6.2) shows that it is larger than local magnitude by 0.18 units. These results are particularly important for converting local magnitudes to equivalent moment magnitudes and thus homogenize the Greek earthquake catalog.

Key words: Magnitude conversion, regression, homogeneous catalog, seismic hazard, Greece.

1. Introduction

The concept of magnitude has a central role in seismology as a tool to quantitatively understand the size of each earthquake and the severity of its ground motion. Local magnitude (M_L) was first introduced by Richter (1935) as a way to quantify earthquake size by measuring the peak value of ground motion at local to regional distances. The fact that M_L is computationally inexpensive to calculate has made it an indispensable part of routine processing in seismological observatories, even though it may saturate for large (> 6.5) earthquakes. On the other hand, moment magnitude (M_w) is based on seismic moment, which is a physical quantity proportional to the energy released by the seismic source, hence it does not saturate even for very large earthquakes (Aki 1966; Kanamori 1977; Hanks and Kanamori 1979). Unfortunately, the calculation of seismic moment is more demanding computationally and is usually achieved after inversion of regional or teleseismic waveforms of earthquakes exhibiting significant energy in lower frequencies (< 0.1 Hz).

In the past, several authors studied the relationship between local and moment magnitude using data from different areas of the world that spanned periods of several years (Ristau et al. 2003; Braunmiller et al. 2005; Ruppert and Hansen 2010; Gasperini et al. 2013; Ristau et al. 2016). Their results indicated that for earthquakes smaller than 6.5 a difference of about $\pm$ 0.2 units exists between local and moment magnitude values. Deichmann (2006) explained theoretically this good correlation on the basis of the fact that M_L is proportional to the peak of the moment rate function, while M_w is proportional to its integral. However, he also noted that several other factors may strongly affect the accuracy of M_L and as a result they may significantly increase the absolute value of the observed difference with M_w. Some of these factors have to do with the source properties (stress drop, rupture velocity, radiation pattern, faulting geometry) and others have to do with path effects, such as geometrical spreading and inelastic attenuation. This creates a situation where the more accurate magnitudes (i.e., M_w) are relatively few compared to the less accurate ones (i.e., M_L) that are usually plentiful.

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However, for seismic hazard assessment both accurate and numerous magnitude values are needed to provide reliable results, therefore, establishing robust relationships to convert magnitudes from the one scale to the other still remains an outstanding issue in seismology.

In this work we investigate the relationship between M_L and M_w in Greece during 2008–2016 using routine magnitude estimates derived from high-quality data recorded by the Greek national seismic network. First, we give an overview of the available data and of the methodologies used for routine calculation of local and moment magnitudes. We then proceed to describe the variations of their difference as a function of hypocentral depth, moment magnitude and time, also investigating the spatial variations of these differences. A regression analysis is subsequently performed for the purpose of deriving relationships that can be used for magnitude conversion, followed by the main conclusions of this study.

2. Data

In 2008 the four seismological research institutes in Greece, based at the National Observatory of Athens, Aristotle University of Thessaloniki, National Kapodistrian University of Athens and University of Patras, decided to merge their individual seismic networks into one national network which was named Hellenic Unified Seismic Network (HUSN). HUSN consists of about 120 stations equipped with three-component instruments, having a variety of sensor types (CMG-40T, CMG-3ESP, Lennartz Le-3D, STS-1, STS-2, Trillium 120P) and covering the whole of the country (Fig. 1). The National Observatory of Athens (NOA), Institute of Geodynamics, has been performing since 2008 the routine processing of the data recorded by HUSN in terms of location and local magnitude calculation, as well as routine waveform inversion for moment tensor determination of larger ($M > 3.5$) earthquakes. For a description of M_L calculation by NOA prior to 2008 the reader may refer to Roumelioti et al. (2010).

For the period starting January 2008 until the end of January 2011 the local magnitude was being calculated using data recorded only at station ATH installed at NOA headquarters in Athens. This procedure mimicked the determination of local magnitude prior to 2008, when the actual Wood–Anderson (WA) instrument was in operation and was collocated with station ATH. Such a procedure made possible the comparison of magnitude estimates with those calculated previously using the analog records. Initially, the instrument response of station ATH was removed and the waveforms were convolved with the response of a WA seismometer. The maximum amplitude of the two horizontal components (defined as the peak-to-peak amplitude divided by 2) was then picked and the local magnitude was calculated for each component using the calibration function of Richter (1935). The local magnitude of each event was obtained as the average of these two values. Since early February 2011 synthetic WA amplitudes estimated for other HUSN stations also started being used, while the attenuation function of Hutton and Boore (1987) was utilized in all local magnitude calculations. The local magnitude of an event was then estimated as the 20% trimmed mean of the average M_L values calculated for each station.

NOA moment magnitudes were calculated from seismic moment after determining the moment tensor of each event using linear waveform inversion with a point source approximation in the frequency band 0.04–0.08 Hz (Konstantinou et al. 2010; Konstantinou 2015). At least 4 stations, distributed azimuthally around the earthquake source, were used in each moment tensor inversion. All moment magnitudes used in this work were calculated by utilizing the relationship of Hanks and Kanamori (1979) which is

$$M_w = 2/3\,(\log M_0 - 9.1), \qquad (1)$$

where M_0 is the seismic moment in N-m. For the purpose of our study we focused on the period starting January 2008 until the end of 2016 and searched for events with both M_L and M_w magnitudes. During the period 01/2008–01/2011 when M_L was calculated using only station ATH, we found 269 events with both magnitudes. In the period 02/2011–12/2016 when M_L was calculated using other available HUSN stations, we included events in our analysis that conformed to two criteria: (a) the number of stations used in M_L calculation was at least

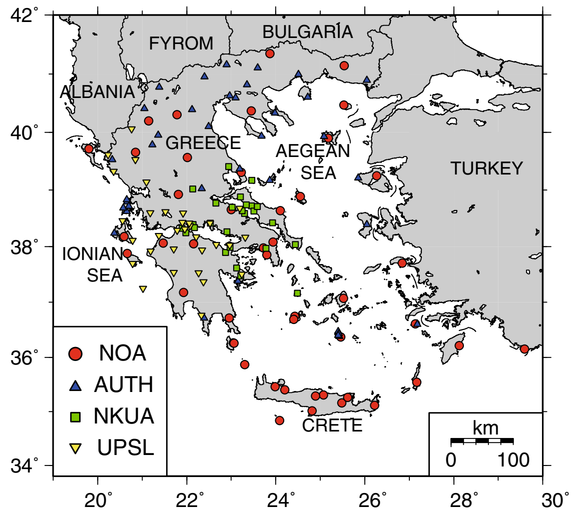

Figure 1
Map showing the locations of the Hellenic Unified Seismic Network (HUSN) stations. The circles represent stations installed by the National Observatory of Athens (NOA), triangles are stations installed by the Aristotle University of Thessaloniki (AUTH), squares are stations installed by the National Kapodistrian University of Athens (NKUA) and inverted triangles are stations installed by the University of Patras Seismological Laboratory (UPSL)

5; and (b) these stations were not clustered in any particular distance or azimuth in which case M_{L} might have been biased. Only 16 events out of 818 did not comply with these requirements and almost all of them were small earthquakes located at the edges of HUSN. Our dataset therefore for the second period consists of 802 events with M_{L} ranging from 3.2 to 6.3 and hypocentral depths smaller than 40 km for about 92% of the selected events.

3. Features of M_L and M_w differences

As a first step towards understanding the relationship between local and moment magnitude we calculated their difference ($M_{\mathrm{L}} - M_{\mathrm{w}}$) and incorporated it on maps showing the locations of the selected events (Fig. 2). During the period 01/2008–01/2011 it can be seen that in many cases the differences exhibit large (± 0.4 units or higher) values, which is reasonable since only one station was used to estimate local magnitude. In particular, moderate to large events (magnitude > 4.5) that occurred near station ATH (distance < 100 km) were causing the recording of large amplitudes thus over-estimating M_{L}. On the other hand, smaller earthquakes that occurred further away from station ATH were recorded with smaller amplitudes which resulted in the underestimation of local magnitude. This wide spreading of the differences around 0.0 can also be clearly seen in the frequency distribution of the ($M_{\mathrm{L}} - M_{\mathrm{w}}$) values (Fig. 3). In the period 02/2011–12/2016 many more events are available; therefore, it is possible to investigate whether other factors (except from distance or size of the events) may be affecting the ($M_{\mathrm{L}} - M_{\mathrm{w}}$) values. It can be seen that based on the spatial distribution of the differences the study area can be divided into three sub-areas. Area 1 covers the northern and central Aegean Sea, as well as northern Greece. In this area the majority of the magnitude differences appear to be slightly above or below 0.0. Area 2 covers the southern Aegean, the area south of Crete island and part of SW Turkey; here differences appear to be larger and they can be positive ($M_{\mathrm{L}} > M_{\mathrm{w}}$) or negative ($M_{\mathrm{L}} < M_{\mathrm{w}}$). Area 3 covers western Greece, the Ionian Sea and SW Albania; in this area the differences appear to be primarily zero or negative with fewer positive ones. This division of the study area is also supported by the fact that these three areas exhibit their own characteristics in terms of prevailing stress field (e.g., Konstantinou et al. 2016), presence or absence of intermediate-depth seismicity, and crustal structure (e.g., Sodoudi et al. 2006). Figure 3 shows the frequency distribution of the ($M_{\mathrm{L}} - M_{\mathrm{w}}$) differences and Table 1 summarizes their statistical properties for all events in each period as well as for each sub-area.

Another way to depict the differences between local and moment magnitudes is to consider their variation as a function of hypocentral depth and moment magnitude (Fig. 4). We observe that during both periods the majority of differences fall within one standard deviation of the mean, however, the scattering of points during 01/2008–01/2011 is visibly higher. This is again not surprising, since the use of only one station for magnitude estimation makes this estimate sensitive to factors such as radiation pattern or path effects. Unfortunately, the number of intermediate-depth events in both periods is low and it is not possible to confirm a trend of increasing or

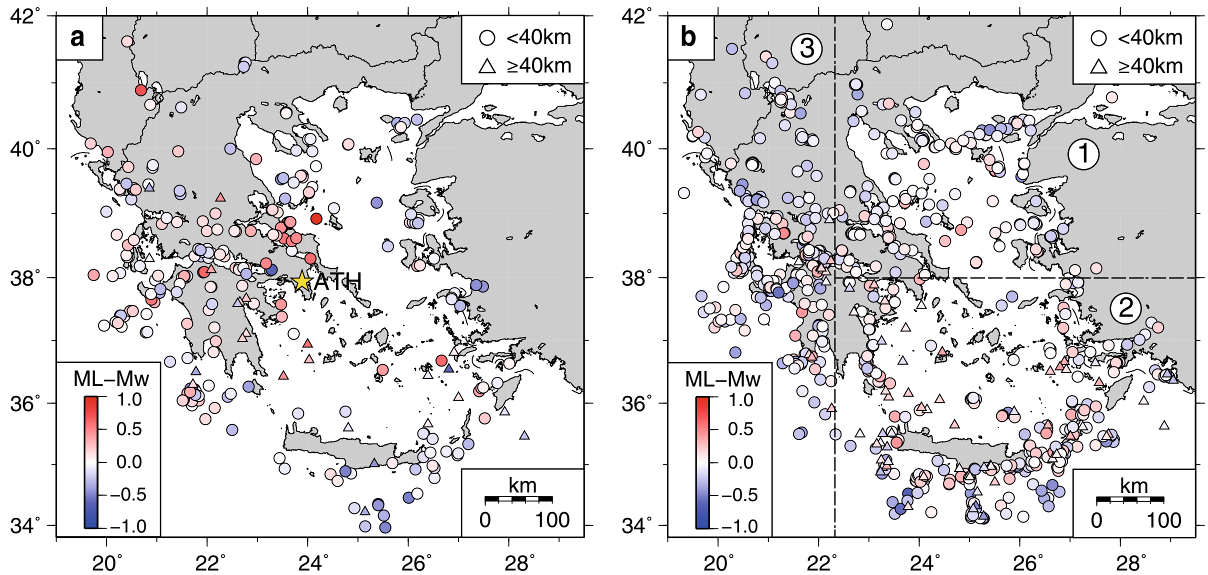

Figure 2

Map showing the epicentral distribution of earthquakes included in this study during **a** 01/2008–01/2011 and **b** 02/2011–12/2016. The color of each point is proportional to the difference between local and moment magnitude given by the scale that is shown in the lower left corner of each map. The circles and triangles represent different ranges of hypocentral depth as shown in the legend at the upper right hand corner of each map. In map **b** dashed lines separate the study area into three sub-areas 1, 2 and 3 (see text for more details)

decreasing difference as a function of their depth or their moment magnitude. Overall the magnitude differences are quite stable as a function of time, even though again the events during 01/2008–01/2011 appear more scattered.

4. *Influence of the station site*

One could argue that during the period 02/2011–12/2016 part of the observed differences may be caused by particular stations that affect the calculation of M_L by over- or underestimating its value owing to geological conditions of the site where the station is installed (hard or soft rock). To investigate this possibility we calculated magnitude residuals for each HUSN station by subtracting single station magnitudes from the M_L value of each event. We then calculated average residuals per station and discarded stations whose residuals were calculated using less than 30 observations. The remaining residuals are added to each single station magnitude and corrected magnitudes are calculated for each event. Figure 5 shows a scatter plot of the original local magnitude M_L (orig) and the corrected one M_L (corr) where a coefficient of determination equal to 0.98 can be observed. It is also possible to statistically compare the difference M_L (orig) $- M_w$ with the difference M_L (corr) $- M_w$. We use a two-tailed *t* test to ascertain whether the two differences come from distributions with the same mean (null hypothesis) or different ones (alternative hypothesis). For a significance level of 0.05 (95% confidence) we cannot reject the null hypothesis, since the *p* value is considerably larger than the significance level we used ($0.314 > 0.05$). We conclude therefore that station site effects have very little influence on the observed $M_L - M_w$ differences and that these are more likely caused by improper correction of wave propagation effects or, less likely, by anomalous source characteristics.

Figure 6 shows a map of the spatial distribution of these local magnitude residuals for stations with 30 or more observations. Several HUSN stations exhibit non-zero, positive or negative residuals and the exact causes of these residuals are most likely not only related to the geological conditions underneath each station, but are also the result of installation and

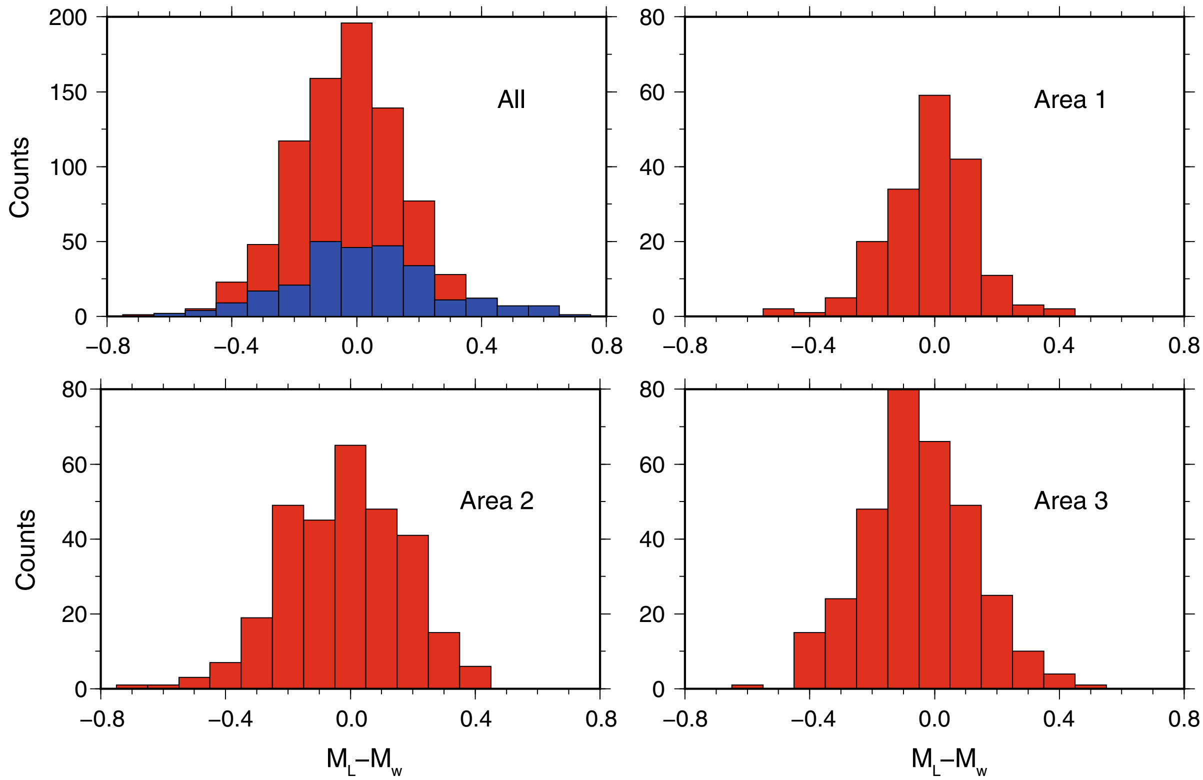

Figure 3
Histograms depicting the frequency distribution of the difference between local and moment magnitude during 02/2011–12/2016 for the whole dataset (all) and each of the sub-areas defined in Fig. 2. Also shown as blue bars is the frequency distribution of the magnitude difference during the period 01/2008–01/2011

Table 1

Summary of statistical properties of the difference between local and moment magnitudes for the two time periods and different areas considered in this study

	N	Mean ($M_L - M_w$)	SD ($M_L - M_w$)	SD ($M_L - M_w$)/$\sqrt{N}$
02/2011–12/2016				
All	802	− 0.02	0.17	0.006
Area 1	178	− 0.009	0.13	0.009
Area 2	300	− 0.01	0.19	0.01
Area 3	323	− 0.05	0.17	0.009
01/2008–01/2011				
All	269	0.02	0.24	0.014

N is the number of earthquakes in each group and SD is the standard deviation of the differences

operational conditions. As an example that illustrates this combination of factors, we refer to stations ATH located at NOA headquarters in Athens, and ATHU located at the University of Athens. The residual of ATH is very close to zero (− 0.01 units) representing the mean value of 221 observations. Such a low residual value is very likely linked to the installation site that is comprised of hard rock (Cretaceous limestone), as well as the placement of the sensor inside a vault which was built under the 1964 WWSSN standards. On contrary, station ATHU exhibits a residual of + 0.45 units which is the mean

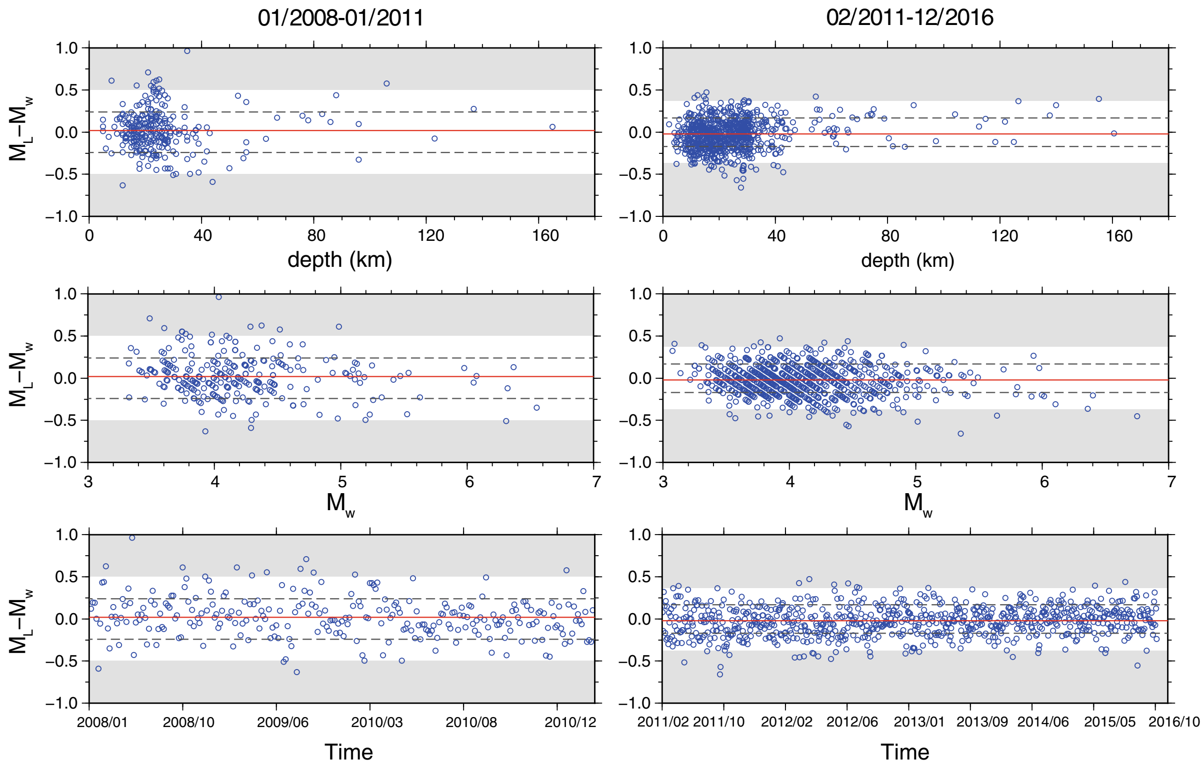

Figure 4

Diagrams showing the variation of the difference between local and moment magnitude of events during the two time periods as a function of hypocentral depth, moment magnitude, and time. Solid lines indicate the mean value of the difference; dashed lines indicate one standard deviation and gray shaded areas signify differences with more than 2 standard deviations of the mean

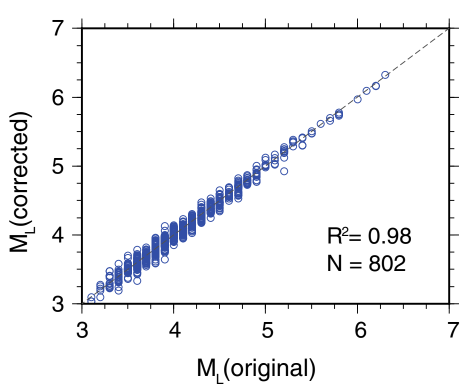

Figure 5

Scatter plot showing the correspondence between original and corrected local magnitudes after subtracting station residuals. R^2 is the linear correlation coefficient, while N is the number of events. The dashed line signifies the 1:1 slope

value of 134 observations. The distance between the two stations is only a few kilometers and ATHU is founded also on hard (metamorphic) rock; however, we do not know the exact details of its installation settings. It is beyond the scope of this work to investigate the causes of large residuals at other HUSN stations; nevertheless, this study highlights the need that the institutes operating HUSN investigate which of these factors (station site, installation settings) are responsible for anomalously large (> 0.2 units) residuals.

5. *Empirical calibration*

As mentioned earlier, the establishment of robust relationships that can be used for converting from local to moment magnitude is of crucial importance

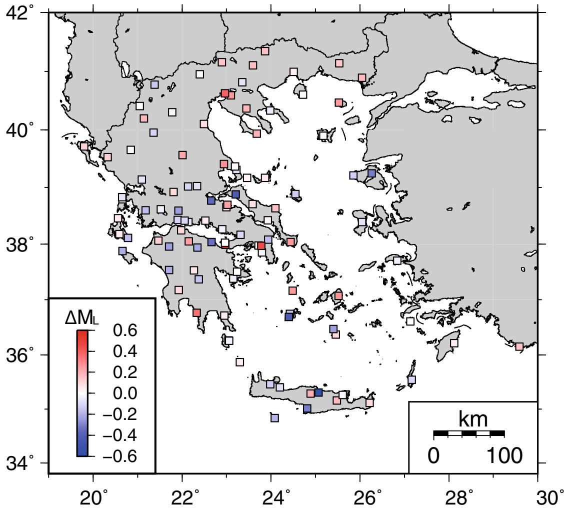

Figure 6
Map showing the average M_L residuals for HUSN stations calculated using more than 30 observations. The color of each symbol represents the value of the magnitude residual and follows the scale shown in the lower left corner of the map

for regional seismic hazard assessment. In this respect we use general orthogonal regression (GOR) to fit to our magnitude data a relationship of the form (Castellaro et al. 2006; Lolli and Gasperini 2012)

$$y = \beta x + \alpha. \quad (2)$$

The advantage of GOR over the ordinary least-squares method is that it takes into account the fact that both regressed variables are affected by errors. This means, however, that to apply GOR the ratio of the error variances $\eta = (\sigma_y/\sigma_x)^2$ of the two variables has to be known. It is relatively easy to estimate the average error variance of M_w (σ_{Mw}) from the standard deviations of the differences of NOA moment magnitudes with moment magnitudes estimated by other agencies (GCMT, RCMT, ETH see Konstantinou 2015). This gives an average standard deviation of the error equal to 0.12 units which is slightly higher than the estimate of Gasperini et al. (2012) ($\sim$ 0.07 units) for earthquakes in the Mediterranean region. The approximation of the error standard deviation for M_L is not as straightforward, especially for the period 01/2008–01/2011 when magnitude determination was based on only one station. We therefore carry out our regression analysis in two steps; during the first step we make an approximation of the standard deviation of local magnitude error (σ_{ML}), perform the regression and obtain the slope β. We then calculate the a priori standard deviation σ_a of the regression which is given by (Gasperini et al. 2013)

$$\sigma_a = \sqrt{\left(\sigma_{Mw}^2 + \beta^2\sigma_{ML}^2\right)}. \quad (3)$$

The value of σ_a is subsequently compared to the empirical standard deviation (σ_{ee}) of the regression. If σ_a is close to σ_{ee} we consider that our σ_{ML} approximation is sufficiently close to the true uncertainty. On the other hand, if σ_a and σ_{ee} are different, we re-size our σ_{ML} approximation and recompute the regression. We also exclude from our analysis events that show clear signs of local magnitude saturation compared to moment magnitude and this typically occurs when M_w is larger than 6.5.

We first perform a regression using all the available data for period 02/2011–12/2016 and separate regressions for each of the sub-areas shown in Fig. 2b, to check whether there are any regional variations in the $M_L - M_w$ relationship. The initial value of σ_{ML} in each regression was computed as the standard deviation of the mean value of each M_L divided by the square root of the number of stations used to estimate it. Except from the regression of Area 1 in all other regressions the σ_{ML} uncertainty had to be re-sized (cf. Table 2); however, its value after re-sizing never exceeded 0.15 units. Regression results are shown in Fig. 7 along with the corresponding coefficient of determination (R^2) and number of events used. From the resulting regression lines there is very little evidence to suggest that the $M_L - M_w$ relationship shows significant regional variations in Greece. The maximum difference of the predicted M_w for $M_L = 6.0$ using the regression line for all events and the predicted M_w using the lines for the three sub-areas is 0.08 units becoming even smaller for smaller local magnitudes. For the regression corresponding to the period 01/2008–01/2011 the σ_{ML} uncertainty was initially considered as equal to σ_{Mw} and then re-sized (cf. Table 2). As expected, the re-sized uncertainty (0.22 units) is larger than that during 02/2011–12/2016 when the

Table 2

Summary of the local magnitude uncertainties that were utilized during the empirical calibration for the different datasets considered (see text for a description of the regression procedure)

	σ_{ML} (initial)	σ_{ee}	σ_a	σ_{ML} (re-sized)	η
02/2011–12/2016 (NOA)					
All	0.07	0.17	0.13	0.13	0.85
Area 1	0.07	0.13	0.13	–	2.93
Area 2	0.08	0.18	0.14	0.15	0.64
Area 3	0.06	0.17	0.13	0.13	0.85
01/2008–01/2011 (NOA)					
All	0.12	0.24	0.16	0.22	0.29
02/2011–12/2016 (GCMT)					
All	0.07	0.17	0.09	0.18	0.15

determination of local magnitude was based on many stations. Despite the fact that the M_L values correspond to measurements only from station ATH, the predicted M_w values from this regression are very close to those predicted by the previous four regressions.

In the final regression we calibrate the local magnitude during the period 02/2011–12/2016 against the moment magnitude of Global CMT (Ekström et al. 2012 and references therein). The uncertainty of σ_{Mw} is taken as 0.07 units (Gasperini et al. 2012), while the σ_{ML} uncertainty is considered initially equal to this value and later re-sized to 0.18 units (cf. Table 2). The regression line predicts that the calculated values of M_w will be larger than M_L by about 0.18 units. Taking into account that previous regressions showed that M_w(NOA) is almost equal to M_L this agrees well with the results of Konstantinou (2015) where the difference of M_w(NOA) and M_w(GCMT) was found to be on average 0.17 units.

6. Conclusions

Greece experiences every year numerous small or moderate earthquakes and occasionally a few larger ones that can cause damage to buildings as well as casualties (e.g., Papazachos and Papazachou 2003). The creation of an earthquake catalog that is homogeneous in magnitude is an essential step for assessing seismic hazard in the Greek region. To create such a catalog, however, the numerous, but possibly inaccurate local magnitude estimates should be converted to equivalent moment magnitudes. This can only be achieved by understanding the relationship between the two magnitude scales and using the appropriate statistical tools to calibrate the one against the other. In the last 8 years (2008–2016) local magnitude calculation in Greece has improved considerably by incorporating synthetic WA amplitudes initially from one and then from many HUSN stations. At the same time, routine moment tensor determination even for relatively small events has also provided a good sample of earthquakes that have both M_L and M_w values. Using this sizable sample we were able to confirm that the overall difference between local and moment magnitude determined using HUSN stations has a mean very close to zero and an empirical standard deviation which varies between 0.13 and 0.24 units. We also showed that any differences between M_L and M_w are unlikely to have been caused by localized station conditions, but rather stem either from improper correction of propagation effects, or less likely, from anomalous source properties. Nevertheless, we find that the attenuation function of Hutton and Boore (1987) used currently in M_L determination provides acceptable results in the moment magnitude range 3.4–6.2. Our regressions for the whole dataset as well as for regionally defined subsets of the data suggest that the linear relationship between M_L and M_w varies very little

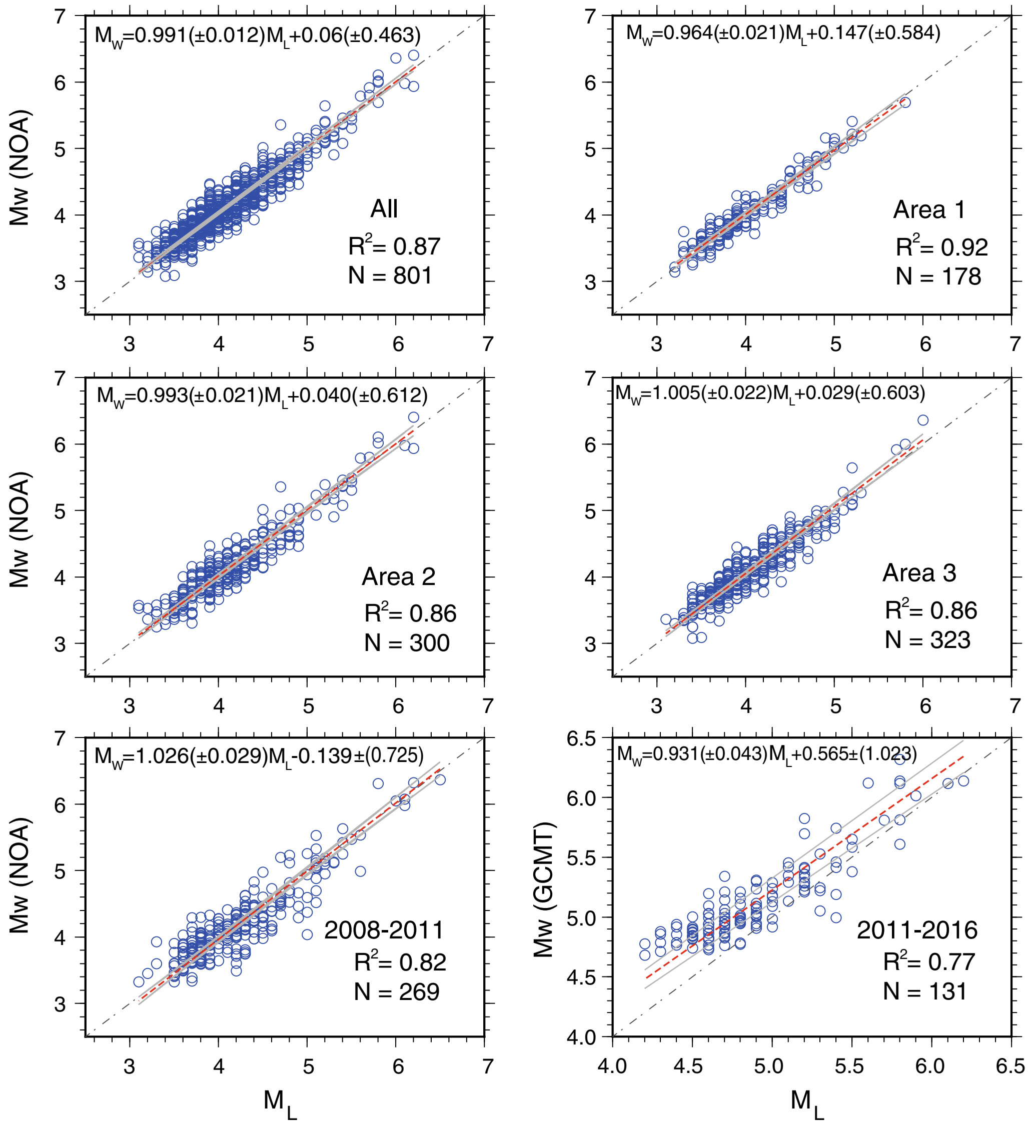

Figure 7

Diagrams summarizing the results of the application of GOR to the whole dataset (all) and each of the three sub-areas defined in Fig. 2. Also shown is the regression for the period 01/2008–01/2011 and the regression using GCMT moment magnitudes. The red dashed lines represent the regression lines; the gray lines indicate the 95% confidence limits and the dashed-dotted lines are the 1:1 slope. The obtained regression lines in terms of slope, intercept and their uncertainties are shown at the upper left corner of each plot

throughout Greece and that the two magnitude scales are reasonably close.

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References

Aki, K. (1966). Generation and propagation of G waves from the Niigata earthquake of June 16, 1964. 2. Estimation of earthquake movement, released energy, and stress-strain drop from G wave spectrum. *Bulletin of the Earthquake Research Institute, University of Tokyo, 44,* 23–88.

Braunmiller, J., Deichmann, N., Giardini, D., & Wiemer, S. (2005). Homogeneous moment magnitude calibration in Switzerland. *Bulletin of the Seismological Society of America, 95,* 58–74. https://doi.org/10.1785/0120030245.

Castellaro, S., Mulargia, F., & Kagan, Y. Y. (2006). Regression problems for magnitudes. *Geophysical Journal International, 165,* 913–930. https://doi.org/10.1111/j.1365-246X.2006.02995.x.

Deichmann, N. (2006). Local magnitude, a moment revisited. *Bulletin of the Seismological Society of America, 96,* 1267–1277. https://doi.org/10.1785/0120050115.

Ekström, G., Nettles, M., & Dziewonski, A. (2012). The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors, 200–201,* 1–9. https://doi.org/10.1016/j.pepi.2012.04.002.

Gasperini, P., Lolli, B., & Vannucci, G. (2013). Empirical calibration of local magnitude data sets versus moment magnitude in Italy. *Bulletin of the Seismological Society of America, 103,* 2227–2246. https://doi.org/10.1785/0120120356.

Gasperini, P., Lolli, B., Vannucci, G., & Boschi, E. (2012). A comparison of moment magnitude estimates for the European-Mediterranean and Italian regions. *Geophysical Journal International, 190,* 1733–1745. https://doi.org/10.1111/j.1365-246X.2012.05575.x.

Hanks, T. C., & Kanamori, H. (1979). A moment magnitude scale. *Journal of Geophysical Research, 84,* 2348–2350.

Hutton, L. K., & Boore, D. M. (1987). The M_L scale in southern California. *Bulletin of the Seismological Society of America, 77,* 2074–2094.

Kanamori, H. (1977). The energy release in great earthquakes. *Journal of Geophysical Research, 82,* 2981–2987.

Konstantinou, K. I. (2015). Moment magnitude estimates for earthquakes in the Greek region: A comprehensive comparison. *Bulletin of the Seismological Society of America, 105,* 2555–2562. https://doi.org/10.1785/0120150088.

Konstantinou, K. I., Melis, N. S., & Boukouras, K. (2010). Routine regional moment tensor inversion for earthquakes in the Greek region: The National Observatory of Athens (NOA) database (2001–2006). *Seismological Research Letters, 81,* 738–748. https://doi.org/10.1785/gssrl.81.5.738.

Konstantinou, K. I., Mouslopoulou, V., Liang, W.-T., Heidbach, O., Oncken, O., & Suppe, J. (2016). Present-day crustal stress field in Greece inferred from regional-scale damped inversion of earthquake focal mechanisms. *Journal of Geophysical Research: Solid Earth*. https://doi.org/10.1002/2016JB013272.

Lolli, B., & Gasperini, P. (2012). A comparison among general orthogonal regression methods applied to earthquake magnitude conversions. *Geophysical Journal International, 190,* 1135–1151. https://doi.org/10.1111/j.1365-246X.2012.05530.x.

Papazachos, B. C., & Papazachou, K. (2003). *The earthquakes of Greece*. Thessaloniki: Ziti editions.

Richter, C. F. (1935). An instrumental earthquake magnitude scale. *Bulletin of the Seismological Society of America, 25,* 1–31.

Ristau, J., Harte, D., & Salichon, J. (2016). A revised local magnitude scale for New Zealand earthquakes. *Bulletin of the Seismological Society of America, 106,* 398–407. https://doi.org/10.1785/0120150293.

Ristau, J., Rogers, G. C., & Cassidy, J. F. (2003). Moment magnitude–local magnitude calibration for earthquakes off Canada's west coast. *Bulletin of the Seismological Society of America, 93,* 2296–2300.

Roumelioti, Z., Kiratzi, A., & Benetatos, C. (2010). The instability of the Mw and M_L comparison for earthquakes in Greece for the period 1969–2007. *Journal of Seismology, 14,* 309–337.

Ruppert, N. A., & Hansen, R. A. (2010). Temporal and spatial variations of local magnitudes in Alaska and Aleutians and comparison with body-wave and moment magnitudes. *Bulletin of the Seismological Society of America, 100,* 1174–1183. https://doi.org/10.1785/0120090172.

Sodoudi, F., Kind, R., Hatzfeld, D., Priestley, K., Hanka, W., Wylegalla, K., et al. (2006). Lithospheric structure of the Aegean obtained from P and S receiver functions. *Journal of Geophysical Research, 111,* B12307. https://doi.org/10.1029/2005JB003932.

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