Chang et al. Earth, Planets and Space (2016) 68:45
DOI 10.1186/s40623-016-0414-4

Earth, Planets and Space
a SpringerOpen Journal

TECHNICAL REPORT

Open Access

An updated and refined catalog of earthquakes in Taiwan (1900–2014) with homogenized M_w magnitudes

Wen-Yen Chang[1,2], Kuei-Pao Chen[2*] and Yi- Ben Tsai[3]

Abstract

The main goal of this study was to develop an updated and refined catalog of earthquakes in Taiwan (1900–2014) with homogenized M_w magnitudes that are compatible with the Harvard M_w. We hope that such a catalog of earthquakes will provide a fundamental database for definitive studies of the distribution of earthquakes in Taiwan as a function of space, time, and magnitude, as well as for realistic assessments of seismic hazards in Taiwan. In this study, for completeness and consistency, we start with a previously published catalog of earthquakes from 1900 to 2006 with homogenized M_w magnitudes. We update the earthquake data through 2014 and supplement the database with 188 additional events for the time period of 1900–1935 that were found in the literature. The additional data resulted in a lower magnitude from M_w 5.5–5.0. The broadband-based Harvard M_w, United States Geological Survey (USGS) M, and Broadband Array in Taiwan for Seismology (BATS) M_w are preferred in this study. Accordingly, we use empirical relationships with the Harvard M_w to transform our old converted M_w values to new converted M_w values and to transform the original BATS M_w values to converted BATS M_w values. For individual events, the adopted M_w is chosen in the following order: Harvard M_w > USGS M > converted BATS M_w > new converted M_w. Finally, we discover that use of the adopted M_w removes a data gap at magnitudes greater than or equal to 5.0 in the original catalog during 1985–1991. The new catalog is now complete for $M_w \geq 5.0$ and significantly improves the quality of data for definitive study of seismicity patterns, as well as for realistic assessment of seismic hazards in Taiwan.

Keywords: Taiwan earthquake catalog, Homogenized M_w magnitudes, Magnitude conversion equations

Background

Taiwan is located at the juncture of the Philippine Sea plate on the east side and the Eurasian plate on the west side. The Longitudinal Valley in eastern Taiwan marks the suture zone of the two colliding plates. The Philippine Sea plate subducts northwardly under the Eurasian plate along the Ryukyu Trench in the eastern offshore region of Taiwan. Along the Manila Trench in the southern offshore region of Taiwan, the South China Sea Basin on the Eurasian plate subducts eastwardly under the Philippine Sea plate. As a result, earthquakes occur very frequently in this region, many of which are disastrous. Therefore, it is necessary to compile an earthquake catalog with consistent magnitudes to facilitate meaningful delineation of seismicity patterns and reliable assessment of seismic hazards in Taiwan.

A complete catalog of earthquakes with consistent magnitudes can provide necessary data for studying the distribution of earthquakes in a region as a function of space, time, and magnitude. Unfortunately, most catalogs do not determine the magnitude of earthquakes consistently over time. This inconsistency may compromise the usefulness of earthquake catalogs.

Taiwan has a relatively complete catalog of earthquakes since the first seismograph was installed in 1897. However, due to changes in seismographic characteristics, network coverage, and observational practice, the definitions and procedures for determining the magnitude have changed over time. Chronologically, M_H was determined

*Correspondence: chenkueipao@yahoo.com.tw
[2] Eastern Taiwan Earthquake Research Center (E-TEC), NDHU, No. 1, Sec. 2, Da Hsueh Rd., Shoufeng 97401, Hualien, Taiwan, ROC
Full list of author information is available at the end of the article

using intensity data for earthquakes in 1900–1972. $M_{D(A)}$ was determined using the total signal duration on analog seismograms for earthquakes in 1973–June 1987. $M_{D(D)}$ was determined using the total signal duration on digital seismograms for earthquakes in June 1987–February 1991. The local magnitude M_L has been determined using simulated Wood-Anderson seismograms for earthquakes from March 1991–present. Hence, in order to provide good data for meaningful delineation of seismicity patterns and reliable assessment of seismic hazards in Taiwan, we need to convert a raw catalog of earthquakes with magnitudes determined on mixed scales to a modified catalog of earthquakes with internally consistent magnitudes. Toward this end, we develop a catalog of Taiwan earthquakes with homogenized M_w magnitudes covering the time period of 1900–2006 (Chen and Tsai 2008).

Since our previous version of the Taiwan earthquake catalog was published, several developments have motivated us to further update and refine it in this study. We first want to add earthquake data acquired in the last 8 years from 2007 to 2014. Equally significantly, we found in an unpublished report by Hsu (1989) an additional 188 events during the early time period of 1900–1935 that were not included in the previous catalog. The addition of these missing events resulted in a reduction of the lower cutoff magnitude threshold from M_w 5.5 to M_w 5.0 for the time period 1900–1935.

In terms of refining the catalog, we strive to adjust the magnitude to be more compatible with the Harvard M_w using the process described below. In the end, we hope that the newly updated and refined catalog of Taiwan earthquakes (1900–2014) provides a superior database for quantitative seismicity studies.

Conversion from original magnitudes to old M_w magnitudes

In the previous study, we converted the original magnitudes of earthquakes that occurred from 1900 to 2006 in the Taiwan region bounded by 21–26°N and 119–123°E to equivalent Harvard M_w using the following procedure:

1. 1900–1972 dataset: As mentioned above, M_H magnitude was determined based on intensity data for this subset of Taiwan earthquakes. For magnitude conversion, we first determined a relationship between M_H and M_S based on common earthquakes in both the Taiwan catalog and the National Earthquake Information Center (NEIC) catalog. We next found a relationship between M_S and M_w based on common earthquakes in the NEIC catalog. We then combined these two relationships to obtain a relationship between M_w and M_H, as follows:

$$M_H = -1.239 + 1.207M_w \quad (1)$$

This relationship is also shown in Fig. 1. From the figure, we can see that M_H is larger than M_w for $M_H \leq 6.0$ and smaller than M_w for $M_H \geq 6.0$. Finally, Eq. 1 was used to convert M_H to M_w for earthquakes that occurred in the Taiwan region from 1900 to 1972.

2. 1973–1987.6 dataset: As mentioned above, the $M_{D(A)}$ magnitude was determined from the total signal duration measured on analog seismograms for this subset of Taiwan earthquakes. For magnitude conversion, we found a relationship between $M_{D(A)}$ and M_w based on common earthquakes in this time period listed in both the NEIC and Taiwan catalogs, as follows:

$$M_{D(A)} = 1.316 + 0.720M_w \pm 0.43 \quad (2)$$

This relationship is also shown in Fig. 1. From the figure, we can see that the $M_{D(A)}$ magnitude is substantially smaller than M_w, and it tends to saturate beyond $M_{D(A)} \geq 6.0$. This phenomenon has resulted in large underestimation of magnitudes of large earthquakes, such as the July 23, 1978, M_w 7.2 and November 14, 1986, M_w 7.3 earthquakes. Finally, Eq. 2 was used to convert $M_{D(A)}$ to M_w for earthquakes from 1973 to 1987.6.

3. 1987.6–1991.2 dataset: As mentioned above, the $M_{D(D)}$ magnitude was determined from the total signal duration measured on digital seismograms for this subset of Taiwan earthquakes. For magnitude conversion, we first found a relationship between $M_{D(D)}$ and M_w based on common earthquakes listed in both the NEIC and Taiwan catalogs. Since the number of $M_{D(D)}$ and M_w values was too small to compare identical events, we adopted the same slope as the relationship between $M_{D(A)}$ and M_w. This resulted in the following conversion formula:

$$M_{D(D)} = 0.758 + 0.720M_w \pm 0.37 \quad (3)$$

This relationship is also shown in Fig. 1. From the figure, we can see that the $M_{D(D)}$ magnitude is much smaller than M_w. Moreover, it tends to saturate beyond $M_{D(D)} \geq 6.0$. This phenomenon may result in great underestimation of magnitudes of large earthquakes. Finally, Eq. 3 was used to convert $M_{D(D)}$ to M_w for earthquakes from 1987.6 to 1991.2.

4. 1991.3–2006 dataset: As mentioned above, the M_L magnitude was determined from simulated Wood-Anderson seismograms for this subset of Taiwan earthquakes. For magnitude conversion, we first found a relationship between M_L and M_w based on common earthquakes listed in both the NEIC and Taiwan catalogs, as follows:

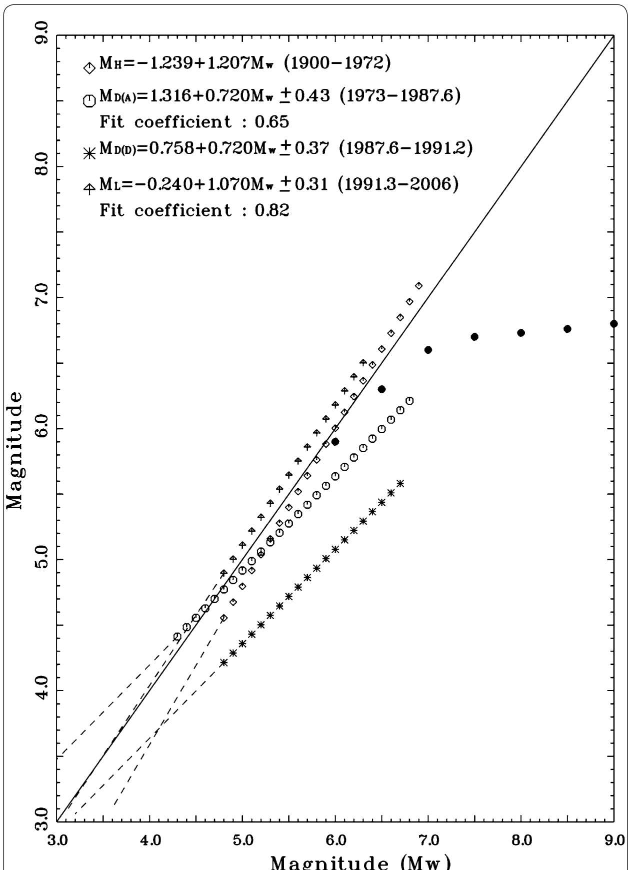

Fig. 1 Empirical relationships used to convert the original magnitudes of earthquakes in Taiwan in different periods since 1900 to a common M_w magnitude scale. The *six solid dots* indicate that the M_L magnitude scale saturates when $M_L > 6.5$

$$M_L = -0.24 + 1.07M_w \pm 0.31 \quad (4)$$

This relationship is also shown in Fig. 1. From the figure, we can see that the M_L magnitude is slightly larger than M_w. However, the M_L magnitude scale tends to saturate beyond $M_L \geq 6.5$, as shown by solid dots in Fig. 1. Finally, Eq. 4 was used to convert M_L to M_w for earthquakes from 1991.3 to 2006.

Figure 2 shows that there are significantly different a and b values in the Gutenberg–Richter relationships among the four periods of time. In order to merge these four different data subsets found in the original catalog of earthquakes in Taiwan into a unified catalog with M_w, we further applied the so-called a-, b-value method (Zuniga and Wyss 1995), which is described as follows:

$$M_w = cM_{\text{ori}} + \text{d}M, \quad (5)$$

$$\text{d}M = c * \left(a' - a\right)/b, \quad \text{and} \quad (6)$$

$$c = b/b', \quad (7)$$

where M_w is the new magnitude; M_{ori} is the original magnitude; a' and b' are the values based on the old M_w, as shown in Fig. 2a; and a and b are the values based on the original M_{ori} magnitude, as shown in Fig. 2b–e. Then, we used the a and b values to convert the original magnitude to the new M_w for different time periods, respectively, from 1900 to 2006. Subsequently, we combined the original catalog with four different types of magnitude into a unified catalog with homogenized M_w magnitudes. This is denoted as the "Converted M_w" in Additional file 1: Table S1 in this study.

Choice of adopted M_w magnitudes for Taiwan earthquakes from 1900 to 2014

This study aims to update and further refine our previous catalog of Taiwan earthquakes (1900–2006) with homogenized M_w magnitudes that were converted from four different types of original magnitude (Chen and Tsai 2008). The original magnitude scales for Taiwan earthquakes from 1900 to present were based on either intensity data or short-period seismograms. As a result, their conversion to the broadband-based moment magnitude M_w will inevitably encounter the saturation problem for large earthquakes. In order to circumvent this obstacle, we use a priority list to adopt a preferred M_w for individual earthquakes in the newly updated catalog from 1900 to 2014.

We apply the same procedure used by Chen and Tsai (2008) to convert the M_H magnitudes of the 188 supplementary earthquakes that occurred from 1900 to 1935 and the M_L magnitudes of the newly acquired earthquake data from 2007 to 2014 to M_w, which are denoted as "Converted M_w" in this study. Subsequently, we find an empirical relationship between the Harvard M_w and the Converted M_w (above) based on earthquakes for which both values are available, as shown in Fig. 3a. This relationship is then used to convert the Converted M_w to the equivalent Harvard M_w, denoted as the "new converted M_w" for all earthquakes from 1900 to 2014. The new converted M_w values are almost the same equivalent to the Harvard M_w values in the selected regression range.

Another moment magnitude, BATS M_w, is also routinely determined using the records of the Broadband Array in Taiwan for Seismology (BATS) operated by the Institute of Earth Sciences of Academia Sinica since July 1995. Although the BATS M_w is determined by a similar procedure as the Harvard M_w, the extracted surface wave period is shorter than that used by the Harvard M_w. This results in a systemic difference between BATS M_w and Harvard M_w, as shown in Fig. 3b. The empirical relationship in the figure is used to convert BATS M_w to Harvard M_w, denoted as "converted BATS M_w." In this study, we also use the United States Geological Survey (USGS) catalog and find that the USGS M is almost the same as the

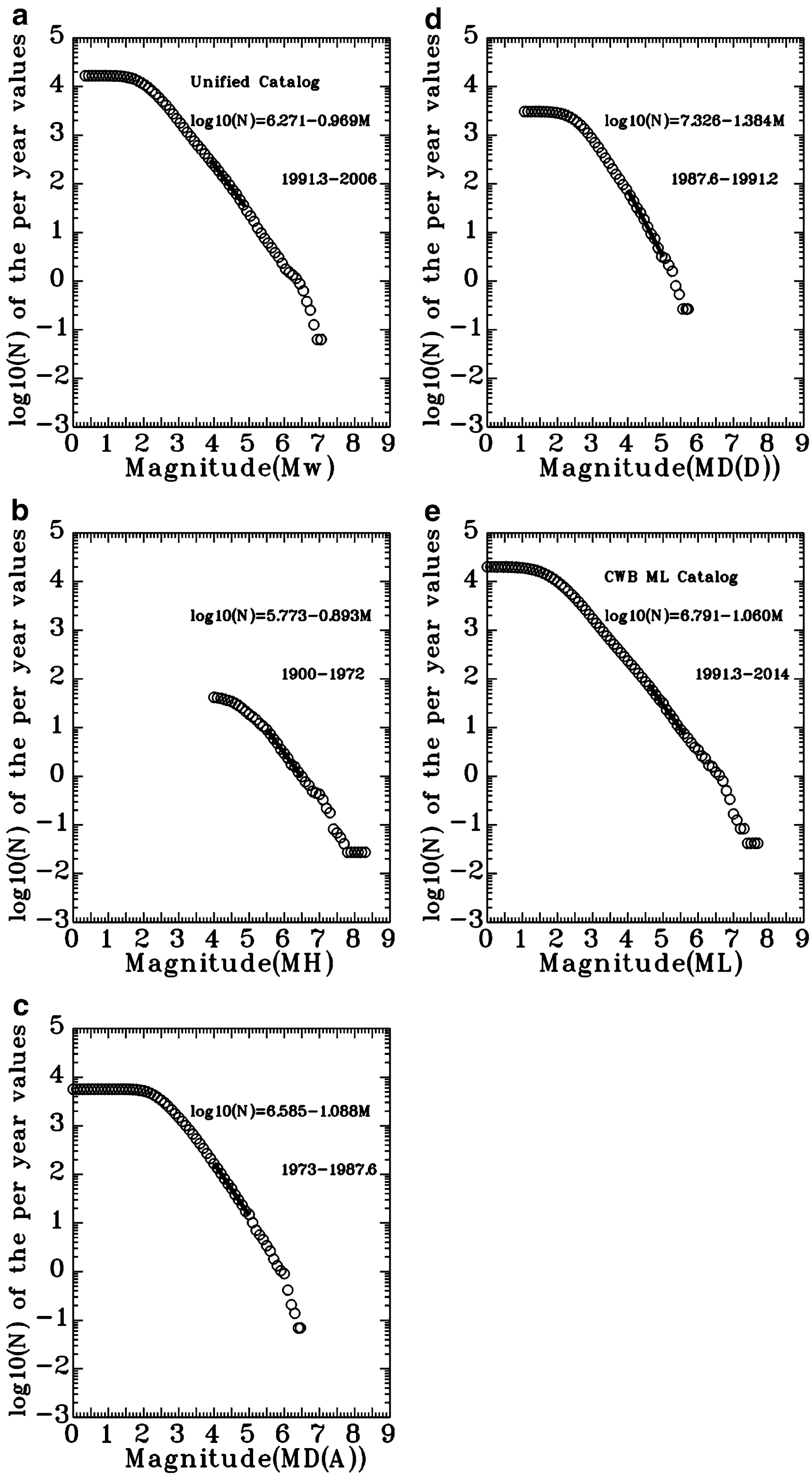

Fig. 2 Logarithmic plots of the cumulative number of earthquakes in Taiwan per year versus magnitude. For each, we selected **a** $3.9 \leq M_w \leq 4.9$, **b** $5.5 \leq M_H \leq 6.5$, **c** $4.0 \leq M_{D(A)} \leq 5.0$, **d** $4.0 \leq M_{D(D)} \leq 5.0$, and **e** $4.6 \leq M_L \leq 5.6$ as the critical magnitude ranges to calculate the values of *a* and *b*. We then used these values to derive the relationships used to convert the original magnitudes from different time periods to a common M_w magnitude scale

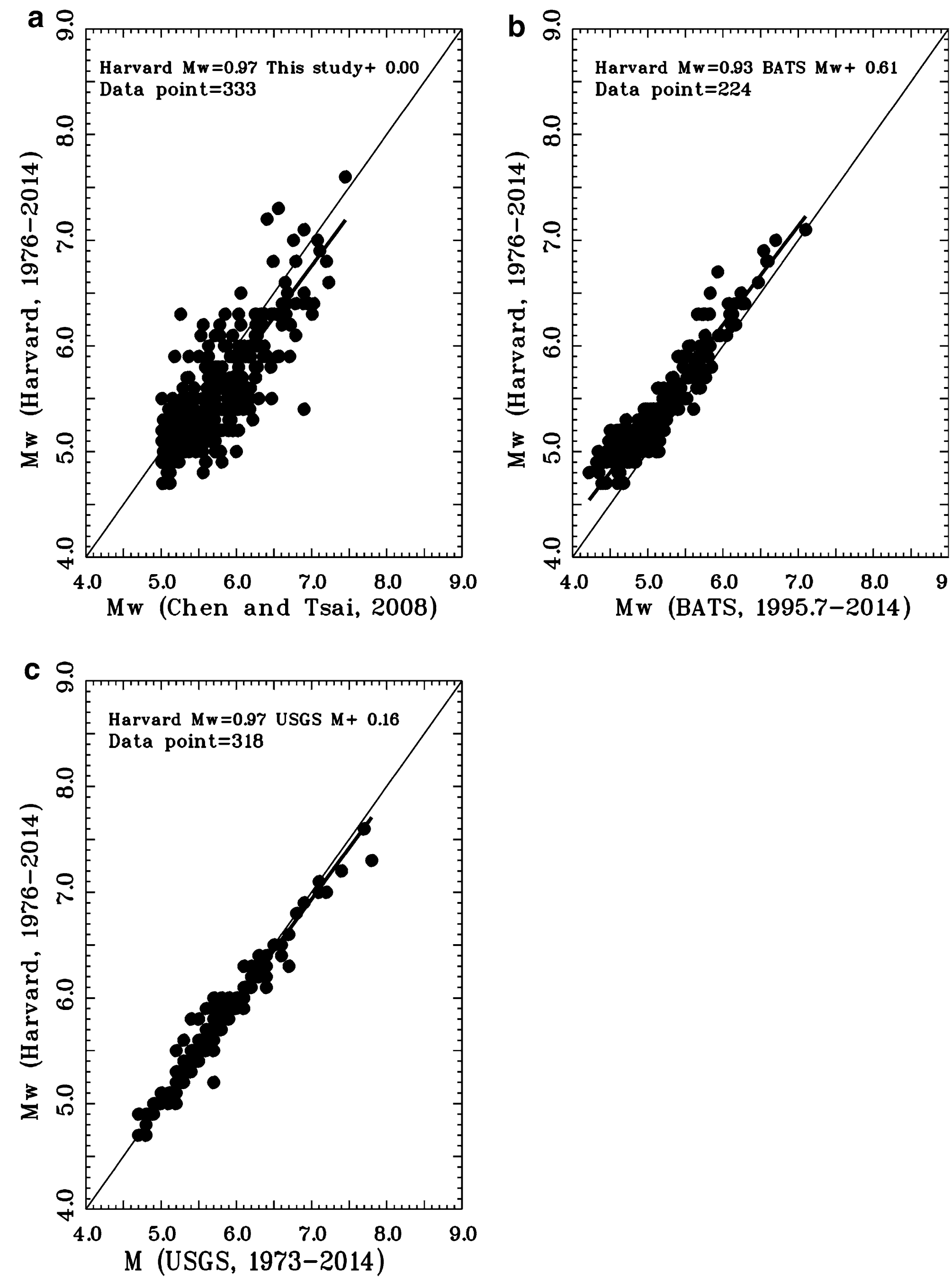

Fig. 3 Relationship between Harvard M_w and other magnitude scales: **a** Harvard M_w versus our old converted M_w, **b** Harvard M_w versus Broadband Array in Taiwan for Seismology (BATS) M_w, and **c** Harvard M_w versus United States Geological Survey (USGS) M

Harvard M_w, as shown in Fig. 3c. Thus, the original USGS M is retained.

Finally, we use a priority list to adopt preferred M_w magnitudes for all Taiwan earthquakes in the new catalog. The priorities in descending order are as follows:

1. The Harvard M_w is adopted whenever available.
2. Available USGS M is adopted when the Harvard M_w is not available.
3. Available converted BATS M_w is adopted when neither Harvard M_w nor USGS M is available.

4. New converted M_w is adopted when none of the above three M_w is available.

The preferred M_w chosen according to the list above is denoted as the "adopted M_w." Additional file 1: Table S1 lists a total of 1989 earthquakes with adopted $M_w \geq 5.0$ that occurred in the Taiwan region from 1900 to 2014.

Merits of the 188 supplementary events and new adopted M_w

Here we show the merits of the updated and refined catalog of Taiwan earthquakes with homogenized M_w magnitudes by comparing its histogram of occurrences from 1900 to 2014 with that of the original magnitudes, as shown in Fig. 4. From Fig. 4a, b, we see that addition of 188 supplementary events significantly enriches $M_w \geq 5.0$ events from 1900 to 1935. Moreover, the new adopted M_w apparently fills the gap from 1985 to 1991. It also lowers the magnitudes of more small earthquakes after 1996 to 0.0.

Next, we plot the Gutenberg–Richter (G–R) relationship of earthquake data from different time periods (Fig. 5). Figure 5a shows a significant difference in G–R relationships for different time periods using the original magnitudes. This suggests that serious problems could be encountered if the catalog with original magnitudes is used to study the distribution of earthquakes or to assess seismic hazards in Taiwan. From Fig. 5b, we see that the addition of the 188 supplementary events lowers the cutoff threshold magnitude from about M_w 5.5 to 5.0 for the time period of 1900 to 1935. Comparing Fig. 5a, b shows that the additional data increases the annual rate of earthquakes with a magnitude ≥5.0 for the whole

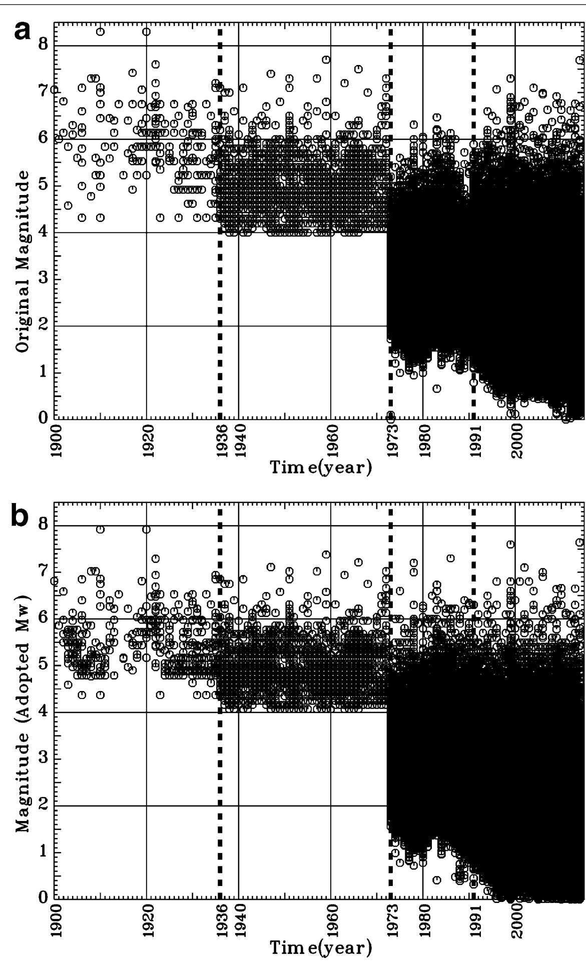

Fig. 4 a Relationship between the original magnitudes and time. There is a gap for magnitudes ≥5.0 during 1973–1991. **b** The relationship between our new converted M_w magnitude and time. The gap present in the *plot* of original magnitudes during 1973–1991 is improved

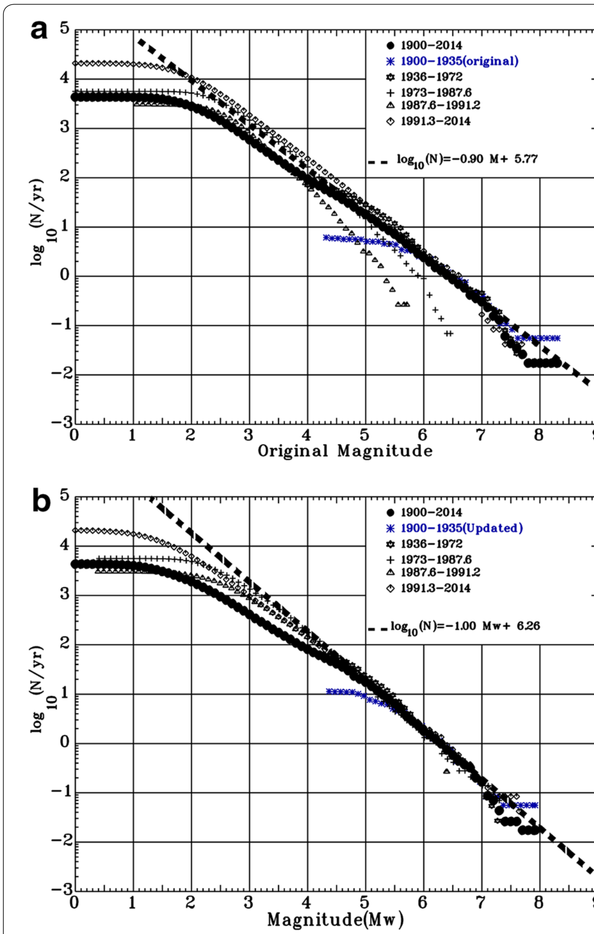

Fig. 5 a Logarithmic plots of the cumulative number of earthquakes per year in Taiwan versus the original magnitudes (M_H, $M_{D(A)}$, $M_{D(D)}$, M_L) over different time periods. **b** Logarithmic plots of the cumulative number of earthquakes in Taiwan per year versus our new converted M_w magnitude over different time periods since 1900. The regressive slope is 1.0, indicating that our new converted M_w values are the same as the Harvard M_w values in the regression range catalog. From Fig. 5b, we also see that the annual rates of earthquakes for different time periods overlap each other for $M_w \geq 5.0$, and the gap between 6.5 and 7.0 (Cheng and Yeh 1989) is eliminated. In addition, in Fig. 5b we see that the slope of regression is equal to 1.0, which indicates that the b value of the adopted M_w approaches our final goal of the Harvard M_w values. In summary, we have successfully converted various original magnitudes to a homogenized M_w that is closely compatible with the Harvard M_w.

Distribution of earthquakes in Taiwan

In order to develop a more complete catalog of Taiwan earthquakes with magnitude $M_w \geq 5.0$, we have merged the four subcatalogs with mixed magnitude scales. Taking the Harvard M_w as our final goal, we have chosen the adopted M_w for individual earthquakes according to the following order: Harvard M_w > USGS M > converted BATS M_w > our new converted M_w.

The distribution of epicenters of 1989 earthquakes in Taiwan with magnitudes $M_w \geq 5.0$ is shown in Fig. 6. Detailed information for these earthquakes is listed in Additional file 1: Table S1, where the star symbol indicates a supplementary event. From Fig. 6, it is evident that most earthquakes were located in eastern Taiwan and its offshore region. Table 1 shows a comparison for magnitudes ≥7.0 among our new converted M_w, USGS M, and Harvard M_w values for identical events. From Table 1, we can see that our new converted M_w values are generally smaller than the Harvard M_w and USGS M values, and with the largest difference value reaching 1.0 for our new converted M_w is smaller than Harvard M_w and USGS M. This is primarily due to saturation of the original magnitude scales above a certain magnitude. Although we have tried to convert the original magnitudes of large earthquakes to Harvard M_w, the saturation problem has not been overcome. We circumvent this limitation by adopting the broadband-based Harvard M_w, USGS M, or converted BATS M_w whenever available.

Conclusion and discussion

A complete catalog of earthquakes with homogenized moment magnitude M_w can provide indispensable data for studying the distribution of earthquakes in a region as a function of space, time, and magnitude. With this in mind, the present study aims to convert mixed original magnitude values of Taiwan earthquakes from 1900 to 2014 to a homogenized M_w that is closely compatible with the Harvard M_w. Before 1973, graphical methods were used to locate earthquakes in Taiwan using smoked paper records with manual timing from pendulum clocks at individual seismic stations. In order to recover missing earthquake data from this early period, we conducted a literature search. Fortuitously, we found data on 188 additional earthquakes from 1900 to 1935 in an unpublished report by Hsu (1989). These supplementary events have enriched the catalog with earthquakes with a magnitude ≥5.0 during the time period 1900–1935. New events from 2007 to 2014 were also added to bring the catalog of earthquakes in Taiwan up to date.

Recognizing that our new converted M_w values from previous study are based on old intensity data or recent short-period seismograms, either the broadband-based Harvard M_w, USGS M, or converted BATS M_w is chosen as the adopted M_w for individual events in the following order: Harvard M_w > USGS M > converted BATS M_w > our new converted M_w.

After converting the original magnitudes of earthquakes in Taiwan to new converted M_w values, the gap in the data for earthquakes with magnitudes ≥5.0 from 1985 to 1991 is eliminated. In the meantime, the new converted M_w values approach the Harvard M_w values. We also compare our new converted M_w with USGS M and Harvard M_w for identical events with magnitudes ≥7.0 and find that our new converted M_w values are often smaller than the Harvard M_w or USGS M values, with the largest difference reaching 1.0. This is primarily due to saturation of the original magnitude scales above

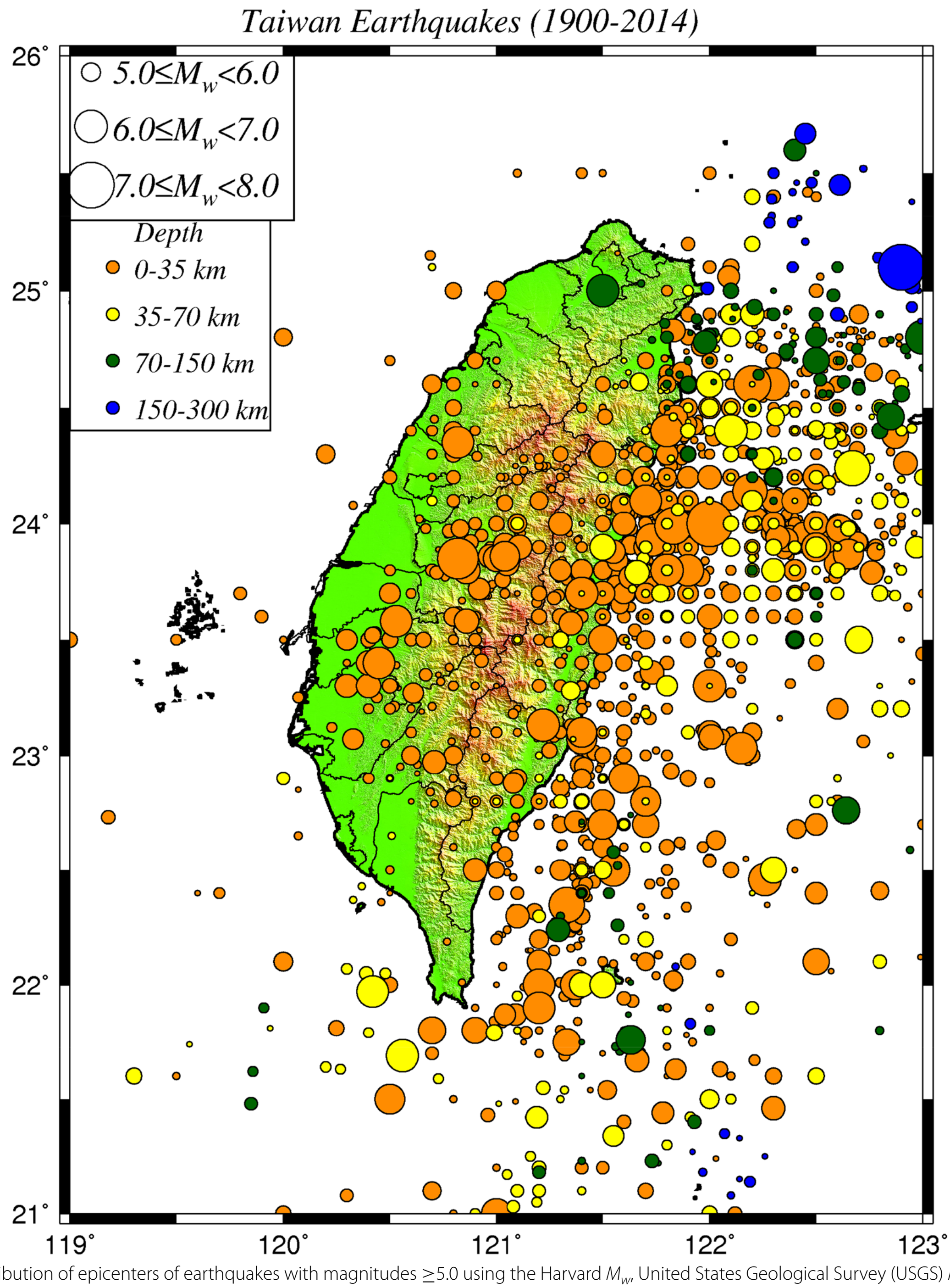

Fig. 6 Distribution of epicenters of earthquakes with magnitudes ≥5.0 using the Harvard M_w, United States Geological Survey (USGS) M, converted Broadband Array in Taiwan for Seismology (BATS), and our new converted M_w

Table 1 List of earthquakes with a magnitude ≥7.0 for comparison among our catalog M_w, Harvard M_w, and the United States Geological Survey (USGS) catalog during 1973–2014

Date	Time (UTC)	Lat. (N)	Long. (E)	Depth (km)	USGS (M)	New converted (M_w)	Harvard (M_w)
1978/07/23	14/42/38.18	22.35	121.33	6.10	7.4	>6.2<	7.2
1978/12/23	11/23/11.67	23.30	122.00	4.12	7.2	>6.6<	7.0
1986/11/14	21/20/04.52	23.99	121.83	15.00	7.8	>6.4<	7.3
1996/09/05	23/42/07.88	22.00	121.37	14.76	6.8	<7.0>	6.8
1999/09/20	17/47/15.85	23.85	120.82	8.00	7.7	>7.3<	7.6
2002/03/31	06/52/49.95	24.14	122.19	13.81	7.1	>6.7<	7.1
2004/10/15	04/08/50.18	24.46	122.85	91.03	6.7	<7.0>	6.6
2006/12/26	12/26/21.00	21.69	120.56	44.11	7.1	>6.9<	7.0

Symbols "<" and ">" indicate that our magnitude ("new converted M_w") is, respectively, greater than or smaller than Harvard M_w or USGS M

certain magnitudes. Although we try to convert the original magnitudes to new converted M_w values, this shortcoming is still not overcome.

Additional file

Additional file 1: Table S1. A list of earthquakes in Taiwan with Mw ≥ 5.0 in the period of 1900–2014.

Authors' contributions
W-YC dealt with data processing, K-PC provided the text and illustrations of the manuscript, and Y-BT set the key themes of the manuscript. All authors read and approved the final manuscript.

Author details
[1] Department of Natural Resources and Environmental Studies, NDHU, Shoufeng, Taiwan. [2] Eastern Taiwan Earthquake Research Center (E-TEC), NDHU, No. 1, Sec. 2, Da Hsueh Rd., Shoufeng 97401, Hualien, Taiwan, ROC. [3] Pacific Earthquake Science Associates, Los Altos, CA 94022, USA.

Acknowledgements
The authors wish to express their sincere appreciation to the Central Weather Bureau and Institute of Earth Sciences for providing the original catalog of earthquakes in Taiwan. This study was supported by Grant NSC101-2116-M-259-006-MY4.

Competing interests
The authors declare that they have no competing interests.

Received: 22 October 2015 Accepted: 13 February 2016
Published online: 17 March 2016

References

Chen KP, Tsai YB (2008) A catalog of Taiwan earthquakes (1900–2006) with homogenized M_W Magnitudes. Bull Seismol Soc Am 98:483–489

Cheng SN, Yeh YT (1989) Earthquake catalogues in Taiwan from 1604 to 1988. Institute of Earth Sciences, Academia Sinica, Taipei

Hsu MT (1989) Estimation of magnitude of earthquakes in Taiwan from 1900 to 1935. Sinotech Foundation for Research and Development of Engineering Sciences and Technologies, SFRDEST R-89-EQ-01-1, 1–30

Zuniga F, Wyss M (1995) Inadvertent changes in magnitude reported in earthquake catalogs: their evaluation through b-value estimates. Bull Seism Soc Am 85:1858–1866