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# A strategy to build a unified data set of moment magnitude estimates for low-to-moderate seismicity regions based on European–Mediterranean data: application to metropolitan France

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## SUMMARY

Seismic hazard assessment (SHA) requires earthquake events characterized in terms of the moment magnitude ( $M_w$ ) scale both in the earthquake catalogues and in the ground motion databases (SHA data sets). However, published  $M_w$  estimates for the same event may actually differ due to the adoption of different computation methods, input data, or seismic networks. The main objective of this paper is to develop a novel strategy to assign a unique  $M_w$  value for each earthquake and unified to an  $M_w$  reference data set that can be applied to low-to-moderate seismicity regions ( $M_w < 4.5$ ) such as Metropolitan France, the target region of our study. The strategy consists of first collecting all  $M_w$  estimated directly by spectral or temporal inversion in a large area of the European–Mediterranean zone, including regional and specific studies in our target region. Then, the sources of  $M_w$  estimates are ranked in five different categories, from global to specific studies. A GCMT (Global Centroid Moment Tensor project) standard  $M_w$  value is recomputed and a quality flag is assigned depending on the level of the information provided by the sources.  $M_w$  estimates are then compared at the European–Mediterranean scale with those provided by the CMT services, chosen as reference.  $M_w$  estimates are subsequently corrected for their systematic deviations by progressively including lower magnitude estimates as one moves from high ranked categories to lower ones at each step of the unification procedure. In this work, the collected data set contains 6752  $M_w$  estimates of 4454 shallow events (depth < 40 km) that occurred between 1963 and 2019 and computed by 34 sources (bulletins, publications, . . . , etc). A unified  $M_w$  value could be attributed to 185 events ( $2.36 \leq M_w \leq 5.35$ ) in France and neighbouring regions and 3351 events ( $3.06 \leq M_w \leq 7.57$ ) in the European–Mediterranean region. Finally, we showed that this  $M_w$  data set is consistent with European SHA data sets but leads to slightly larger  $M_w$  values compared to the French SHA data sets. We also noted that some variability still subsist in  $M_w$  data set compared to the existing SHA data sets, especially for  $M_w < 5.0$ . This new unified  $M_w$  data set is a first step toward the building of future catalogues. It will contribute to greatly improve the coherence of  $M_w$  definitions in the next generation of SHA data sets for both metropolitan France and Europe.

**Key words:** Europe; Earthquake hazards; Earthquake source observations; Statistical seismology.

## 1. INTRODUCTION

For a coherent application of SHA, it is paramount to dispose of magnitudes ( $M$ ) defined in the same scale and ideally estimated using the same approach in both the earthquake catalogues and in ground motion databases, the two fundamental data sets of any seismic hazard assessment (hereafter referred to as SHA data sets). Introduced by Kanamori (1977), the moment magnitude ( $M_w$ ) is considered today by the community as the magnitude scale of reference for SHA data sets (e.g. Grünthal & Wahlström 2012; Laurendeau *et al.* 2013; Kotha *et al.* 2020). This magnitude has the advantage of not saturating for the largest earthquakes compared to other magnitude scales. In addition,  $M_w$  is directly linked to the source parameters (Aki 1966), especially to the seismic moment ( $M_0$ ). Different methods depending on the target magnitude range have been implemented to estimate  $M_w$  based on waveform inversions in time or in frequency domains (referred to hereafter as the ‘direct’ methods). At the global scale,  $M_w$  are routinely estimated for  $M_w \geq 5.5$  events since 1976 (e.g. Dziewonski *et al.* 1981) and from

$M_w \geq 4.5$  since the end of the 1990s (e.g. Ekström *et al.* 1998).  $M_w$  can be estimated regionally down to  $M_w$  3.5 (e.g. Dreger & Helmberger 1993) and locally to even lower magnitudes if the network allows it (e.g. Godano *et al.* 2013).

The different methods and standard procedures (e.g. IASPEI 2013) used to estimate  $M_w$  do not necessarily lead to the exact same  $M_w$  estimate for an earthquake. For example, Scognamiglio *et al.* (2016) reported for the 2012 May 20 Emilia earthquake  $M_w$  values ranging between 5.63 and 6.12. Several studies have already shown that the  $M_w$  estimated from a regional network are generally smaller than those using teleseismic recordings (Gasperini *et al.* 2012; Konstantinou 2015; Kishida *et al.* 2018). Differences are generally due to a combination of the use of a higher frequency signal, a larger azimuthal gap and the size of the rupture that can exceed the regional network size.

Different strategies are adopted in the literature to define a reference  $M_w$  data set with a ‘unique’  $M_w$  estimate for each event.

A first strategy is to prefer the  $M_w$  estimates given by one source over another following a priority scheme (e.g. Fäh *et al.* 2011; Grünthal & Wahlström 2012). This strategy has the advantage that the original  $M_w$  are kept as they are, but the heterogeneities between the  $M_w$  sources are also kept. The European–Mediterranean Earthquake Catalogue (EMEC, Grünthal & Wahlström 2012) follows this strategy by prioritizing  $M_w$  estimate sources in this way: (1) the specific published studies; (2) the Swiss Moment Tensor Solutions (Braunmiller *et al.* 2005); (3) the European–Mediterranean Regional Centroid Moment Tensor Solutions (Pondrelli 2002; Pondrelli *et al.* 2004, 2007, 2011) and (4) regional catalogues of European countries if they exist. Otherwise, the majority of the  $M_w$  was deduced from empirical magnitudes converted from magnitude scale conversion laws. In this case, the laws are developed from an  $M_w$  reference data set containing events prior to 1993 (Grünthal & Wahlström 2003). Both the Pan-European Engineering Strong Motion data set (ESM, Bindi *et al.* 2018; Lanzano *et al.* 2019) and the recently published GMM of Kotha *et al.* (2020) used the  $M_w$  estimated following the EMEC strategy.

A second strategy is to correct the systematic discrepancies in  $M_w$  estimates relative to a source chosen as reference to achieve ‘unified’  $M_w$  values and then average the estimates for each event (e.g. Gasperini *et al.* 2012; Konstantinou 2015; Kishida *et al.* 2018). In the Italian catalogue, Gasperini *et al.* (2012) chose the  $M_w$  estimates from the Global Centroid Moment Tensor project (GCMT, also known as Harvard  $M_w$ ) as reference and applied offset corrections to the other  $M_w$  sources (up to +0.2 to the Italian regional  $M_w$  estimates). Then, the weighted average ( $W_a$ )  $M_w$  values are used directly in the Italian seismic catalogue (CPTI15, Rovida *et al.* 2016) and to develop magnitude scale conversion laws (Gasperini *et al.* 2013). This unification procedure was also followed in other regions, such as Greece (Konstantinou 2015) and Taiwan (Kishida *et al.* 2018), where discrepancies were found with regional  $M_w$  values up to +0.18 and +0.43, respectively.

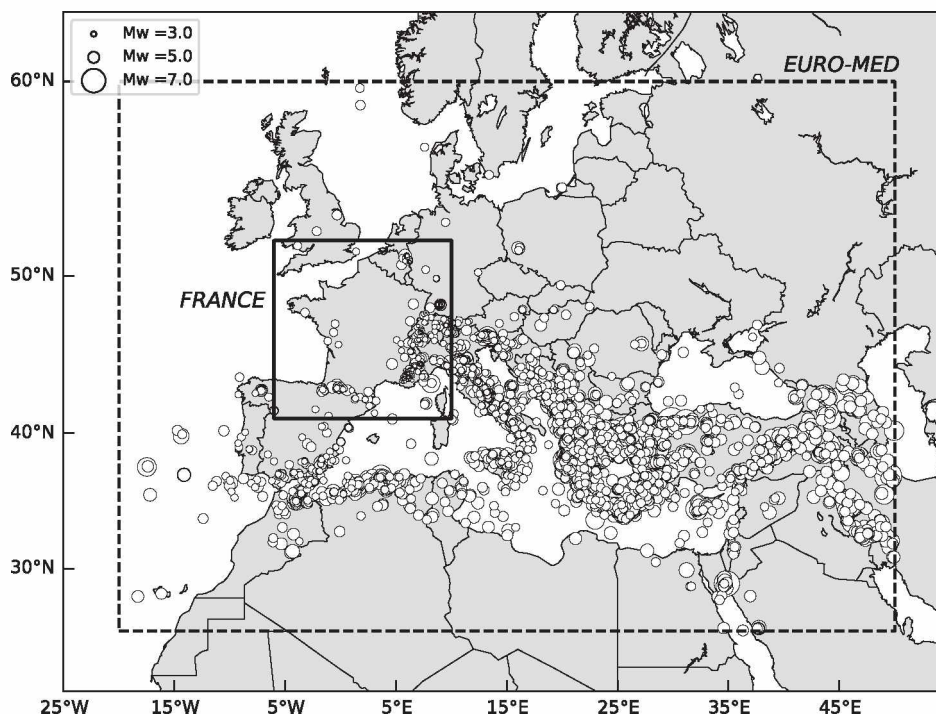
Implementing catalogues following similar strategies would help improving the consistency of the SHA data sets both at regional (e.g. Woessner *et al.* 2015) and national scales (e.g. Drouet *et al.* 2020). Currently, the  $M_w$  unification strategy has only been applied to some moderate-to-high seismicity countries by collecting direct  $M_w$  estimates from a limited number of sources (global and regional approaches). In low-to-moderate seismicity regions there is a need to estimate magnitudes for  $M_w < 4.5$  when performing probabilistic SHA (PSHA). Generally speaking, none or few direct  $M_w$  estimates exist for this magnitude scale range. Thus,  $M_w$  are deduced from other magnitude scales by applying magnitude scale conversion laws established from a reference  $M_w$  data set (referred to hereafter as the proxy  $M_w$ ). SHA data sets are then built from these various heterogeneous magnitude definitions. Heterogeneities can impact both Gutenberg–Richter fitting relationships (Beauval *et al.* 2020; Drouet *et al.* 2020) as well as the standard deviation of GMMs (Kotha *et al.* 2016; Ktenidou *et al.* 2018).

Metropolitan France SHA data sets are particularly concerned by this issue and the most recent national efforts well illustrate the challenges. On the one hand, Cara *et al.* (2015) built the instrumental SI-Hex (acronym for ‘Sismicité Instrumentale de l’Hexagone’) catalogue covering the period 1962–2009. This catalogue includes only proxy  $M_w$  estimated from various conversion laws established for several magnitude scales and different periods using several inhomogeneous  $M_w$  reference data sets (Cara *et al.* 2017; Laurendeau *et al.* 2019). The majority of the magnitude scale conversion laws are based on the local magnitude ( $M_L$ ) provided by the Laboratory for Detection and Geophysics (LDG). However, several studies (Cara *et al.* 2017; Drouet *et al.* 2020) have shown that SI-Hex  $M_w$  estimates are lower compared to other  $M_w$  estimates that suggest revising the SI-Hex catalogue strategy. On the other hand, the French Seismological and Geodetic network of the European Plate Observing System (Résif-Epos) ground-motion data set published by Traversa *et al.* (2020) containing 468 events recorded in France and surroundings between 1996 and 2016 is also concerned by this issue. In fact, this data set consists of heterogeneous  $M_w$  estimates either taken from the SI-Hex catalogue or from the  $M_L$  provided by the French national seismic network (RéNaSS) converted applying the magnitude scale conversion law of Grünthal *et al.* (2009), developed for EMEC.

In this paper, the main objective is to develop a new strategy to assign a unique and unified  $M_w$  value to seismic events that occurred in low-to-moderate seismic areas ( $M_w < 4.5$ ) with a focus on metropolitan France. We first present the  $M_w$  estimation methods and the sources collected to compile a data set of direct and standard  $M_w$  estimates for the European–Mediterranean region. Then, we introduce the strategy allowing to obtain a data set with a unique and unified  $M_w$  value for each event. Finally, this new unified  $M_w$  data set is presented and the impact of the strategies to build  $M_w$  data sets is discussed by intercomparing our data set with existing SHA data sets in both metropolitan France and Europe.

## 2. COMPILING A DATA SET OF ‘DIRECT’ $M_w$ ESTIMATES

The first step is to collect all ‘direct’  $M_w$  estimated using an inversion in time or in frequency domains. Our target region is an area around the metropolitan France, called hereafter ‘FRANCE’ (6°W–10°E; 41°N–52°N, Fig. 1), corresponding to the SI-Hex extended zone used in Cara *et al.* (2017). We collect instrumental events available since 1962, corresponding to the beginning of the instrumental period for metropolitan France (Duverger *et al.* 2021). In addition, we collect  $M_w$  estimates for events that occurred in a larger area required for the unification of the  $M_w$  estimates discussed later in Section 3.2. This area covers a European–Mediterranean region (20°W–50°E; 25°N–60°N, Fig. 1), called



**Figure 1.** Location map of the 4454 earthquakes with  $M_w$  estimates (from 1963 to 2019) collected in this study (presented in Section 4.1) and of the two regions: (FRANCE), an extended area around metropolitan France [6°W–10°E; 41°N–52°N] and (EURO-MED) the European–Mediterranean area [20°W–50°E; 25°N–60°N].

hereafter ‘EURO-MED’. This area was previously used in the Gasperini *et al.* (2012)’s study. We exclude events deeper than 40 km which are most likely related to subduction events.

In the following subsections, first we introduce the main specificities and nomenclature of the various methods used for estimating  $M_w$  of events collected in this study. Then, we list the sources collected and specify data selection criteria. We review the level of information provided by the different sources, recompute an  $M_w$  value following the GCMT standards and attribute quality flags depending on the level of information provided by the sources. The main characteristics of this data set are finally presented.

## 2.1 Direct $M_w$ estimates: existing methods and associated nomenclatures

Below we briefly recall the difference between the  $M_w$  estimation methods. In order to distinguish them we follow the National Earthquake Information Center (NEIC) three-letter nomenclature.

$Mwc$  identifies  $M_w$  estimates based on centroid inversion of a combination of very long-period body waves, mantle waves and surface waves (e.g. Dziewonski *et al.* 1981; Ekström *et al.* 1998),  $Mwb$  those based on body waves (e.g. Sipkin 1982, 1994) and  $Mww$  those based on ultra-long-period W-phase (e.g. Kanamori & Rivera 2008). These methods were originally developed to estimate  $M_w \geq 5.5$  events based on teleseismic distant stations. Recent developments (Hayes *et al.* 2009; Ekström *et al.* 2012) allowed to consider lower magnitudes ( $M_w \geq 4.5$ ). International agencies such as GCMT, the Regional CMT (RCMT), NEIC and the GEOFON program at the German Research Centre for Geosciences [GeoForschungsZentrums (GFZ)] in Potsdam publish  $M_w$  computed with this kind of methods.

Methods based on the full waveforms from regional distance stations are identified by  $Mwr$  and are usually applied to  $Mwr \geq 3.5$ . The classical tool used to estimate  $Mwr$  is the Time Domain Moment Tensor inversion (TDMT) scheme developed by Dreger (2003) which is based on inversion of the full waveforms mainly of intermediate and long-period surface waves. The solution is determined by fitting the synthetic seismograms to the observed data, with the variance reduction (VR) parameter measuring its quality. This method was initially implemented by the Berkeley Seismological Laboratory in 1992 for the earthquakes in northern California (Dreger & Helmberger 1993) and it is currently used by several regional observatories in Europe such as ETHZ (acronym for ‘Eidgenössische Technische Hochschule Zürich’) in Switzerland (Clinton *et al.* 2006; Baer *et al.* 2007), INGV (acronym for ‘Istituto Nazionale di Geofisica e Vulcanologia’) in Italy (Scognamiglio *et al.* 2009) and IGN (acronym for ‘Instituto Geográfico Nacional’) in Spain (Rueda & Mezcua 2005). GEOFON also estimates  $Mwr < 4.5$  with this method (Saul *et al.* 2011). Based on the work of Clinton *et al.* (2006), a VR threshold larger than 60 per cent is largely used to qualify the solution as reliable. For INGV, Scognamiglio *et al.* (2009) qualify  $Mwr$  as reliable for VR  $\geq 40$  per cent when at least four stations are used. VR will depend on many factors, including the number of stations available, their azimuthal distribution, their proximity to the source, the accuracy of velocity model used, the quality of the recordings. In the literature, similar methods based on the inversion of the full waveforms recorded at regional distance stations are also developed. For example, the FMNEAR method (Delouis

2014) uses both the waveform inversion of near-source seismic recordings and a linear finite source model for moderate-to-large events ( $M_{wr} > 5.5$ – $9.0$ ) or a single point source for  $M_{wr} < 5.5$ .

Finally,  $M_w$  can be computed by measuring the Fourier spectral amplitude of the low frequency plateau of the displacement spectrum of  $P$  and  $S$  waves when a local network exists relatively close to the seismic source (e.g. Lancieri *et al.* 2012; Godano *et al.* 2013), hereafter called  $M_{ws}$ . In this case, an average  $M_0$  value and its standard deviation are estimated from the individual  $M_0$  value deduced for each three component spectrum for each station, while a single  $M_0$  value is determined using the time domain inversion method for the best solution associated to a focal mechanism. The  $M_w$  estimate is finally the average of the different measurements and it is important to have a good azimuthal distribution of the recordings to average the effect of the radiation pattern (e.g. Stork *et al.* 2014).

Finally, for sources that do not specify the approach used, the  $M_{wx}$  notation is used (e.g.  $M_{wx}$  GEOFON).

## 2.2 Compilation of $M_w$ sources and associated metadata

The main characteristics and references of the  $M_w$  estimates given by the different sources used in this study are summarized in Tables 1 and 2.

It should be noted that some institutes publish their  $M_w$  estimates only online through webservices or on their institutional webpage. The webpages/webservices consulted in this study are listed in the Supporting Information S1. Depending on the institute, the level of information published can be heterogeneous and the  $M_w$  estimates and the associated metadata can be more or less easy to collect automatically. For example, NEIC collects and disseminates information from other institutes, such as  $M_{wc}$  GCMT, and provides the results of its own estimations. It is possible to retrieve the event characteristics via a request through the webservices in a quakeml format. In this format, data is grouped into information type blocks, including origins, magnitudes and focal mechanisms. In this study, we have used the preferred origin and the focal mechanism blocks including  $M_0$ , the moment tensor elements and focal mechanism axes, taking care to only extract metadata from a NEIC analysis. However, gathering all metadata from NEIC was challenging due to differences in the quakeml entries throughout the time period covered by the data, the presence of duplicate estimates and the difficulty to merge metadata from different blocks. The reader should thus be aware that in spite of the numerous checks performed mistakes may still persist.

Few institutes have attributed a quality flag to their  $M_w$  estimates and/or have provided the metadata required to be able to qualify an  $M_w$  estimate, such as in particular the azimuthal gap which is generally used to provide a quality to end-users (e.g. Pondrelli *et al.* 2006). In this study, we selected in each source the events for which  $M_w$  were considered reliable by their authors (see Table 1, last column).

SismoAzur (<http://sismoazur.oca.eu>) is the source publishing the most  $M_w$  estimates for French metropolitan events. Its data set is composed of  $M_w$  estimates collected from different origins selected in this order of priority: (i) from manually revised solutions communicated by B. Delouis, part of which is available on the BCSF website (Le Bureau Central Sismologique Français, <http://www.franceseisme.fr/english.php>) (ii) from the SismoAzur website (last version accessed in July 2020), which provided events that occurred since 2019 at the global scale and since 2016 at the regional scale, with automatic solutions associated with a quality A or B that depends on the quality of the focal mechanisms and (iii) from the SismoAzur website (last version accessed in April 2019), which provided  $M_w$  values for events since 2014 independently of the focal mechanism quality and that we consider reliable in terms of  $M_w$  estimate even if the focal mechanism is less reliable.

Fig. 2 displays the number of selected events with an  $M_w$  estimate as a function of  $M_w$  bins and over given periods from the global (called GLOBAL) to regional scales (EURO-MED, FRANCE). For more than 37 700 earthquakes for which  $M_{wc}$  GCMT is available at the global scale, only 11 moderate magnitude earthquakes are associated to an  $M_w$  estimate for the FRANCE zone. Similarly, other international institutes (GEOFON, NEIC) that compute  $M_w$  estimates for a more recent period provide very few events for the FRANCE area. The European RCMT catalogue contains around 1700 events in EURO-MED area, 35 of which are located in the FRANCE area. The regional approaches allow characterizing more events in the FRANCE area. Especially, neighbouring countries of France (Switzerland, Italy and Spain) automatically compute  $M_{wr}$  for  $M_L \geq 3.5$  from their own regional networks which allow having  $M_w$  estimates for some events at the borders of these countries. Fig. 2 highlights the temporal and spatial completeness of the  $M_{wc}$  GCMT data set associated to RCMT on a global and European scale compared to other  $M_w$  sources, particularly the regional methods that have been developed after the deployment of the seismic networks.

The collected  $M_w$  estimates available in specific published studies (see Table 2) can be grouped in five categories. The first one corresponds to a collection of  $M_w$  estimates coming from specific studies with events occurred since the early 1900s compiled to build an earthquake catalogue or to derive magnitude scale conversion laws. The second group is made up of  $M_w$  estimates obtained as part of a regional study using a unique approach. The third category corresponds to  $M_w$  estimated in the context of the development of alternative  $M_w$  estimation methods. A fourth group includes two specific studies in which  $M_w$  were computed for low magnitude earthquake from two local networks: one located in the Sampeyre region in Italy, close to the border of France for which Godano *et al.* (2013) computed  $M_{ws}$  for 730 earthquakes of  $0.7 \leq M_w \leq 3.15$  occurring between 2010/10/13 and 2010/11/12 and another one located around the Middle Durance Fault, France, where IRSN (Nechtschein 2003; Volant *et al.* 2003) computed  $M_{ws}$  ranging between 0.58 and 2.99 for 232 earthquakes that occurred between 1998 and 2007 (Volant *et al.* 2000; Cushing *et al.* 2008). These  $M_w$  estimates, currently only available on request from the authors, will be useful in the future to develop new magnitude scale conversion laws. Finally, the last category includes  $M_w$  estimated for a specific earthquake occurred in metropolitan France or close to the surrounding political border.

**Table 1.** Nomenclature, main characteristics and references of  $M_w$  methods routinely computed for seismic events for each source listed from global to regional scale approaches. The last column indicates if a specific selection is applied to the events of the original collection. When this is the case, the selection is based on quality criteria of the  $M_w$  estimate following the authors' recommendations.

Type	Source	Main references	Time period	Magnitude range	Method	Region	Selection for this study
$M_w$	GCMT	Dziwonski <i>et al.</i> (1981); Ekström <i>et al.</i> (2012)	1976–31/12/2019	$M_w \geq 5.5$ until 2003 and then $M_w \geq 5.0$	Centroid moment tensor inversion using mantle (125–350 s) and body waves (40–125s), and since 2004 intermediate period surface waves (50–150s) in addition	Global	All
$M_w$	NEIC	Sipkin (1982, 1994)	02/03/1996–31/12/2019	$5.5 \leq M_w \leq 7.5$	Centroid moment tensor inversion of long-period body waves (~20–200 s). Applicability limited for larger magnitude than 7.5 due to source complexity	All	All
$M_w$	NEIC	Kanamori & Rivera (2008); Hayes <i>et al.</i> (2009)	28/03/2005–31/12/2019	$5.5 \leq M_w$ ( $4.5 \leq M_w$ if high quality records at a regional scale)	Centroid moment tensor inversion of the W-phase (~50–2000 s)	All	All
$M_w$	NEIC	Dreger & Helmbarger (1993); Dreger (2003)	05/10/2008–31/12/2019	$3.5 \leq M_w \leq 7.0$ (the minimum magnitude depends on the density of stations available)	Moment tensor inversion of the whole seismogram at regional distances (~10–100 s). Applicability limited for larger magnitude than 7.0 due to source complexity	All	All
$M_w$	GEOFON	GEOFON Data Centre (1993); Saul <i>et al.</i> (2011)	27/02/2008–31/12/2019	$4.0 \leq M_w$	$M_w$ estimates from different methods implemented in SeisComp3 that examine different parts of the wave train: teleseismic body waves, mantle and surface waves, and long-period phase waves (W-phase)	All	All
$M_w$	RCMT	Ekström <i>et al.</i> (1998); Pondrelli (2002); Pondrelli <i>et al.</i> (2011)	01/01/1997–31/12/2019	$4.5 \leq M_w \leq 5.5$	Centroid moment tensor inversion using mainly intermediate-period surface waves but also mantle and long period surface waves	Europe	Only definitive solutions <sup>2</sup> of quality A or B
$M_w$	Italian-CMT	Pondrelli & Salimbeni (2006); Pondrelli <i>et al.</i> (2006);	06/05/1976–06/12/2015	$4.0 \leq M_w$	Compilation for Italy of $M_w$ from GCMT and RCMT with new $M_w$ computed for the period 1976–1996	Italy	Solutions of quality A or B and only the events that occurred between 1976 and 1996
$M_w$	SismoAur	Delouis (2014)	07/04/2014–31/12/2019	$2.8 \leq M_w$	The FMNEAR method is based on both the waveform inversion of near source seismic records and on a linear finite-source model	Global but mainly the south of Iberian-Maghrab	All
$M_w$	IAG	Stich <i>et al.</i> (2003, 2006, 2010); Martin <i>et al.</i> (2015)	20/10/1986–19/08/2014	$3.1 \leq M_w$	Full waveform inversion of the size, the depth and the double-couple focal mechanisms from the time domain inversion methodology introduced by Dreger & Helmbarger (1993)	Iberian-Maghrab	when the quality is given selection of a and b
$M_w$	IGN-TDMT	Dreger & Helmbarger (1993); Dreger (2003); Rueda & Mezua (2005)	04/02/2002–31/12/2019	$3.1 \leq M_w$		Spain	if VR $\geq 60$ per cent
$M_w$	INGV-TDMT	Dreger & Helmbarger (1993); Dreger (2003); Scognamiglio <i>et al.</i> (2006); Scognamiglio <i>et al.</i> (2009)	24/11/2004–31/12/2019	$2.8 \leq M_w$		Italy	Solutions of quality Aa, Ab, Ba
$M_w$	SED-TDMT	Dreger & Helmbarger (1993); Dreger (2003); Clinton <i>et al.</i> (2006); Baer <i>et al.</i> (2007)	13/09/1999–28/08/2014	$2.8 \leq M_w$		Switzerland	if VR $\geq 60$ per cent

<sup>1</sup> An estimate of  $M_w$  is given by GCMT for some earlier events (between 1962 and 1976).<sup>2</sup> Reviewed solutions until 31/01/2019.

**Table 2.** List of individual publications used in this study classified according to their main objectives.

Type of study	Application	References of the study
1. Compilation of a large $M_w$ data set from different authors/approaches in the literature	- The ISC-GEM (International Seismological Centre—Global Earthquake Model) catalogue Version 7.0 - $M_w$ used as reference in the EMEC catalogue	- Di Giacomo <i>et al.</i> (2015, 2018); Lee & Engdahl (2015) - Scherbaum & Stoll (1983); Grünthal & Wahlström (2003)
2. Compilation of a regional $M_w$ data set defined by using a unique approach	- $M_w$ used as reference for conversion law of MI for the ECOS catalogue - $M_w$ used as reference to convert $M_s$ for the ECOS catalogue	- Braumiller <i>et al.</i> (2005) - Bernardi (2005)
3. Analysis of a large data set of events for a methodological development	- Catalogue for the Pyrenees - Moment tensor determination at the European scale from regional recordings - Estimation of $M_w$ from the near-field spectra of strong-motion records	- Chevrot <i>et al.</i> (2011) - Braumiller <i>et al.</i> (2002) - Delouis <i>et al.</i> (2009)
4. Low $M_w$ defined from specific local networks	- Swarm of Sampeyre, Italy - IRSN Durance (Volant <i>et al.</i> 2003; Cushing <i>et al.</i> 2008)	- Godano <i>et al.</i> (2013) - Nechtschein (2003)
5. Specific studies around single events		Baer <i>et al.</i> (2007); Diehl <i>et al.</i> (2018); Perrot <i>et al.</i> (2005); Larroque <i>et al.</i> (2009); Larroque <i>et al.</i> (2016); Nechtschein & Lesueur (2011); Courboux <i>et al.</i> (1998); Courboux <i>et al.</i> (1999); Courboux <i>et al.</i> (2001); Courboux <i>et al.</i> (2013); Dufumier <i>et al.</i> (2000); Dufumier (2002)

### 2.3 Recomputing GCMT standard $M_w$ values and assigning quality flags

$M_0$  and  $M_w$  estimates are computed following expert choices that may differ from one institute to another. To have homogeneous  $M_w$  values, our objective was to recompute  $M_0$  and  $M_w$  following the GCMT standard procedure. However, the metadata provided by the different sources collected in this study are heterogeneous (Supporting Information S2) ranging from international institutes furnishing several metadata, allowing to recompute  $M_0$ , to specific studies providing only an  $M_w$  value with one significant digit (SD). Thus we developed a strategy to assign a quality to our standard  $M_w$  estimates.

The GCMT standard (Method1) is based on the Hanks & Kanamori (1979) and IASPEI (2013) formula:

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

where  $M_0$  is the moment tensor in N m, is computed from the principal axes of the moment tensor solution as the average of the modulus of the two largest eigenvalues ( $\lambda_1$  and  $\lambda_2$ ) of the moment tensor:

$$M_0 = \frac{1}{2}(|\lambda_1| + |\lambda_2|) \quad (2)$$

In the case of NEIC,  $M_0$  is estimated by the Silver & Jordan (1982) formula based on the individual moment tensor elements (Method2). Differences up to 0.1 units of  $M_w$  between these two methods can be observed (Fig. 3, left-hand panel). Because the choice of the  $M_0$  computation formula may be a first source of discrepancy, we also traced the origin of the discrepancies between the original published  $M_w$  values and the ones from the GCMT standard procedure. We also found discrepancies due to the accuracy of published  $M_0$ , that is the number of SD used to compute  $M_w$ . In Fig. 3 (right-hand panel),  $M_w$  collected on the GCMT websites are compared to  $M_w$  values obtained from  $M_0$  which has been rounded from four to one SD. This comparison reveals that four SD are necessary to reproduce the  $M_w$  value published by GCMT. With three and two SD, we can still retrieve the  $M_w$  GCMT value for the majority of the events with a maximum deviation of 0.01. However, when only one SD is provided the error could be larger than 0.1  $M_w$  unit. Finally, a third reason for  $M_w$  discrepancies, already pointed out by Kagan (2003), is the application of a slightly different formula to compute  $M_w$  from  $M_0$  (such as eq. 1), mainly due to different round numbers if the 2/3 factor is already applied. For example, Gasperini *et al.* (2012) found  $M_w$  values 0.03 unit lower than the original ones in the ETHZ collection due to the use of a slightly different formula.

Thus, depending on the level of metadata available from each source, an information quality flag, called ‘FLAG quality standard  $M_w$ ’, ranging from A to E was assigned to qualify it with respect to the standard procedure as follows:

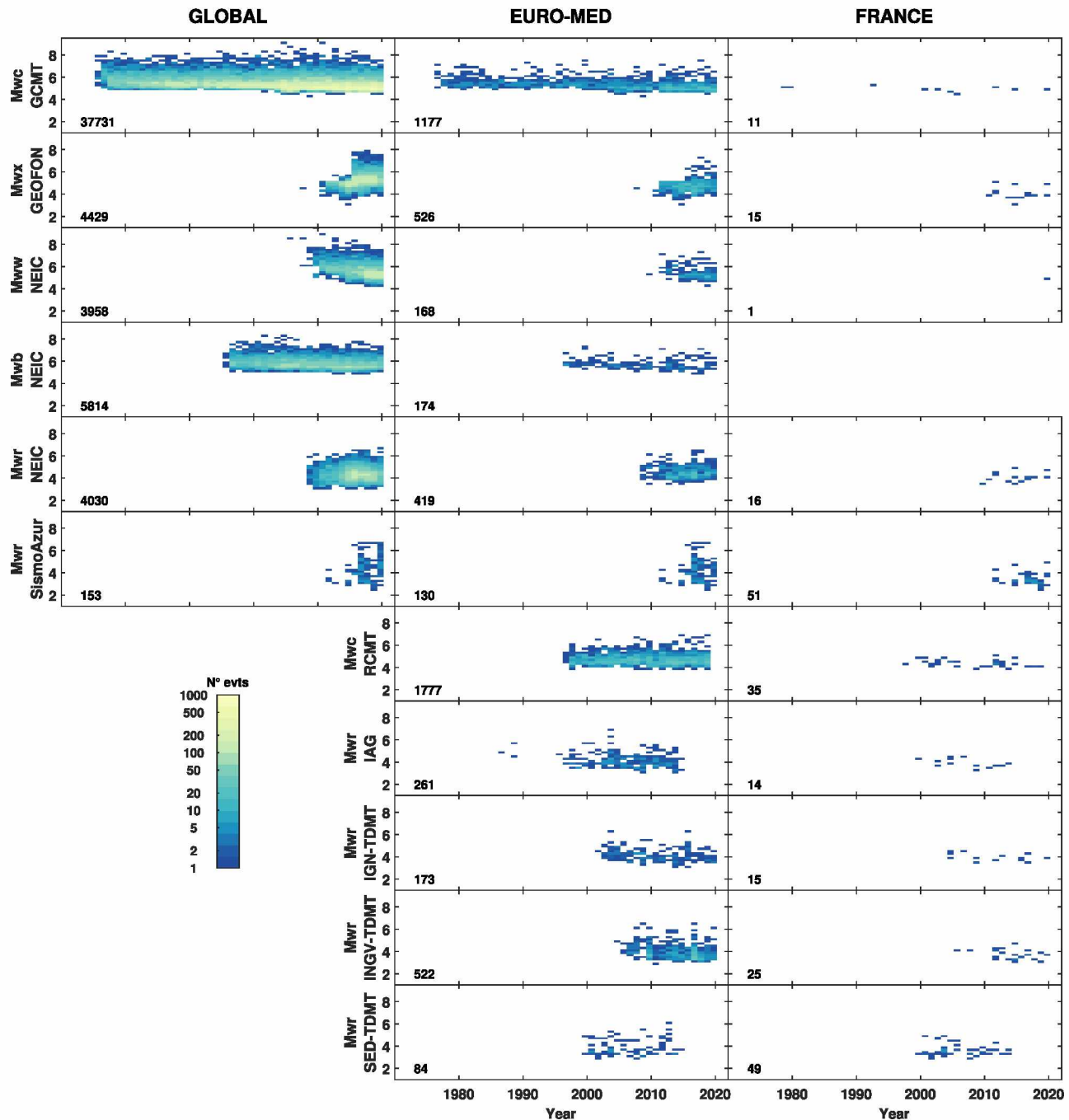
A. GCMT standard procedure: the principal axes of the moment tensor are available with sufficient SD allowing to recompute  $M_0$  (Method1) and then  $M_w$  following the IASPEI (2013)’s recommendations (eq. 1).

B.  $M_0$  is given with at least two SD and other information, such as the individual moment tensor elements (Method2) allows to check the  $M_0$  value or if  $M_0$  is computed from the spectral method ( $Mws$ ).

C.  $M_0$  is given with at least two SD but no information is available to check  $M_0$ .

D.  $M_0$  is not available,  $M_w$  is available with at least three SD and the equation used to compute  $M_w$  is known ( $M_w$  can thus be corrected for discrepancies by using eq. 1).

E. Only  $M_w$  is available without information about its computation or if  $M_w$  is available with less than three SD.



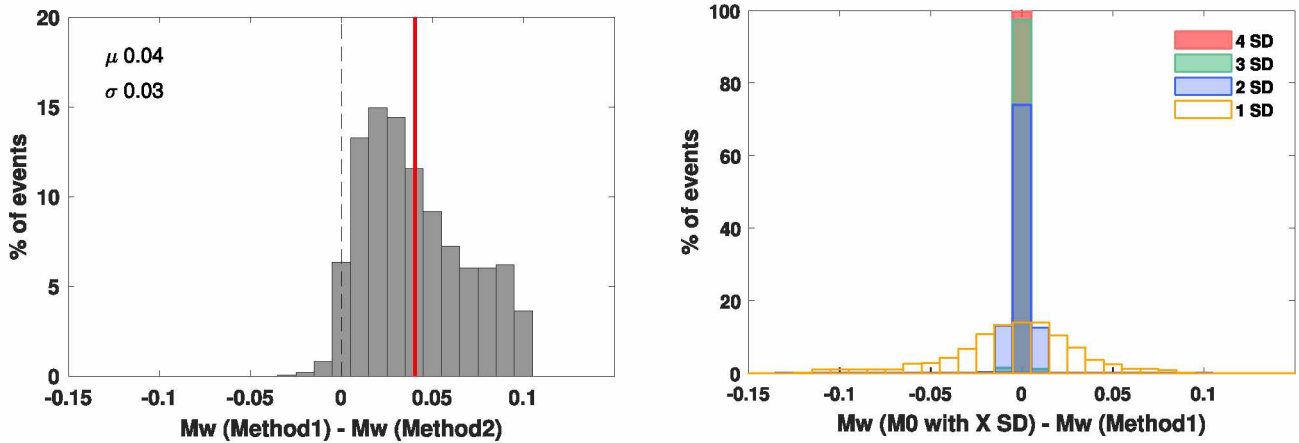
**Figure 2.** Temporal distribution of earthquakes in terms of  $M_w$  estimates provided by the institutes listed in Table 1 for the three geographic areas (GLOBAL, EURO-MED and FRANCE). The magnitude and time bins are of 0.2 and 1 yr, respectively. The total number of earthquakes is indicated at the bottom left and the colourbar indicates the number of events for each bin.

#### 2.4 Merging the compiled $M_w$

We collected in the EURO-MED region all  $M_w$  values given by the different sources mentioned in Section 2.2, with the exception of (i) events for which the solutions were not considered reliable by the authors (see last column of Table 1) and (ii) events with significant differences between the  $M_0$  values published and recomputed by us [difference of  $\log_{10}(M_0) > 0.4$ ].

The different  $M_w$  sources were then merged. However, merging two data sets can be a challenging task due to possible large differences in the time origins and the epicentral locations between two solutions or on the contrary when these parameters are too close due to sequences of events. We developed an automatic merging procedure that allows identifying duplicate events between two collections mainly using the differences in time ( $\Delta t$ , s) and in distance ( $\Delta d$ , km). Details of the processing applied for each event is described in the Supporting Information S3.

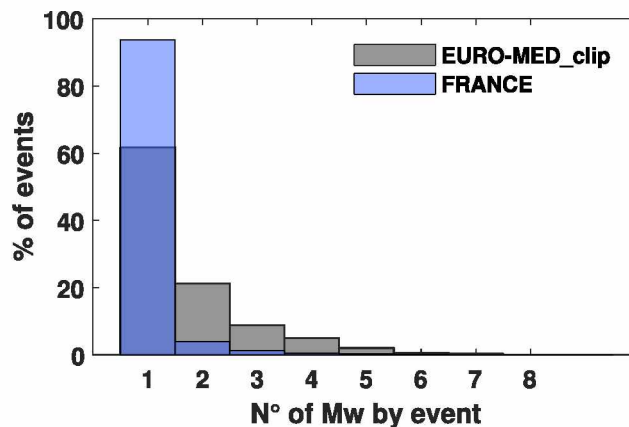




**Figure 3.** Comparison of  $M_w$  values from the GCMT collection defined with three significant digits (SD) and computed from different  $M_0$  values. Left-hand panel:  $M_0$  is computed from the principal axes (Method1) and from the moment tensor elements (Method2). Right-hand panel:  $M_0$  is the value provided by GCMT and rounded to 4/3/2/1 SD (with  $X$  the number of digits) and  $M_0$  is computed from Method1. For this example, the GCMT collection is used for earthquakes occurred at the global scale since 2003 for which  $M_0$  is given with four SD.

**Table 3.** Number of ‘direct’  $M_w$  collected and percentage of associated ‘standard’  $M_w$  quality factors estimated in this study shown separately for earthquakes located in the FRANCE region and those located outside in the so-called EURO-MED\_clip region (cf. Supporting Information S4, sheet ‘ $M_w$ \_sources\_used’).

Region	Number of $M_w$ estimates	Number of events	Range of $M_w$	Number (per cent) of $M_w$ estimates associated with the following standard $M_w$ quality				
				A	B	C	D	E
FRANCE	1425	1288	0.12–6.30	237 (17)	988 (69)	90 (6.3)	54 (3.8)	56 (3.9)
EURO-MED_clip	5327	3166	2.82–7.62	3509 (66)	1636 (31)	62 (1.2)	70 (1.3)	50 (0.9)



**Figure 4.** Histogram of the percentage of events as a function of the number of  $M_w$  sources available for each event for FRANCE and EURO-MED\_clip regions.

The collection of 34 sources allowed identification of 6752 ‘direct’  $M_w$  estimates (sheet ‘ $M_w$ \_sources\_used’ in Supporting Information S4) concerning 4454 events that occurred between 1963 and 2019 in the EURO-MED region. Table 3 lists the number of events and the percentage of ‘standard’  $M_w$  estimates for each quality level by distinguishing those within the FRANCE region from those outside in the so-called EURO-MED\_clip region.  $M_w$  estimates are computed for a large majority of events applying the standard procedure (A: 66 per cent) or with a procedure close to the standard one (A + B: 97 per cent) for the EURO-MED\_clip and for FRANCE region (A + B: 86 per cent). Many events of the EURO-MED\_clip data set (62 per cent) are associated to an  $M_w$  value from only one source (Fig. 4); only four events are associated to a maximum of eight sources. In the FRANCE area, 94 per cent of the events are associated to only one source and three events are associated to a maximum of six sources (Table 4). Table 4 illustrates well the range of discrepancies in  $M_w$  estimates that can exist among sources (ranging from 0.14 to 0.42 unit of  $M_w$ ).  $M_w$  GCMT is the source which always estimates the highest  $M_w$  value in this case, but the  $M_w$  of these earthquakes are below the validity threshold value of this method. Conversely, the  $M_w$  ING-V-TDMT or an equivalent regional study such as the one of Chevrot *et al.* (2011) provide the lowest  $M_w$  values. In addition,  $M_w$  estimates based on equivalent methods can lead to significant differences: for example, the  $M_w$  values range from 4.16 to 4.42 for the Vallorcine earthquake. Table 4 also presents

**Table 4.** Examples of  $M_w$  estimates collected in the case of four earthquakes that occurred in or close to metropolitan France.  $\Delta M_w$  indicates the difference between the largest and the lowest ones.

$M_w$ sources	$M_w$ types	Event 1366	Event 1481	Event 3423	Event 4432
		2004/09/18 12:52:18 Spanish Basque region	2005/09/08 11:27:17 Vallorcine	2014/04/07 19:27:00 Barcelonette	2019/11/11 10:52:46 Le Teil
GCMT	$M_{wc}$	4.68	4.58	4.95	4.91
RCMT	$M_{wc}$	4.52	4.51	4.93	
GEOFON	$M_{wx}$			4.86	4.87
NEIC	$M_{ww}$				4.84
NEIC	$M_{wr}$			4.82	4.77
INGV-TDMT	$M_{wr}$		4.16	4.71	
IGN-TDMT	$M_{wr}$	4.45			
IAG	$M_{wr}$	4.49			
SismoAzur	$M_{wr}$			4.79	4.86
SED-TDMT	$M_{wr}$		4.42		
Chevrot <i>et al.</i> (2011)	$M_{wr}$	4.36			
Delouis <i>et al.</i> (2009)	$M_{ws}$		4.47		
IRSN-RAP	$M_{ws}$	4.50	4.31		
$\Delta M_w$		0.32	0.42	0.24	0.14

the five  $M_w$  values currently collected for the recent 11 November 2019 Le Teil earthquake, for which the  $M_w$  estimates seem more stable, with discrepancies of 0.14 unit of  $M_w$ .

### 3. A STRATEGY TO UNIFY $M_w$ ESTIMATES

In this section, a new strategy is implemented to assign a unique and unified  $M_w$  value to each earthquake event by adapting the unification procedures previously proposed in the literature (Gasperini *et al.* 2012; Konstantinou 2015; Kishida *et al.* 2018) in order to integrate lower  $M_w$  events, essential for low-to-moderate seismicity countries. We developed a hybrid strategy combining (i) a priority scheme of sources classified in five categories ranging from global to specific analyses and (ii) a unification of the  $M_w$  estimates with a reference, which is a combination of the  $M_w$  values given by the CMT services. In this strategy, the definition of the  $M_w$  reference data set progressively evolves by including lower  $M_w$  estimates as one moves to lower categories. In this way, the majority of sources can be unified. Unfortunately, the last category includes  $M_w$  estimates that cannot currently be unified. The hybrid strategy is summarized in Fig. 5 and more details will be given in the following paragraphs.

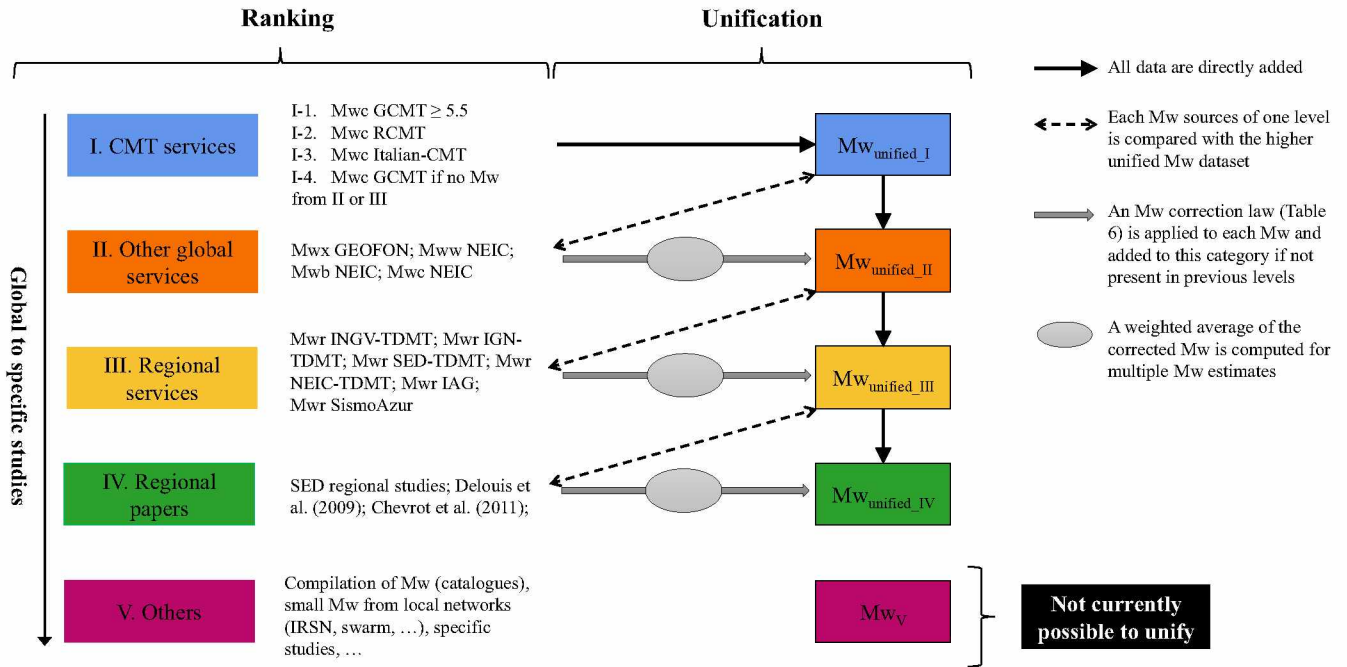
#### 3.1 Ranking of the sources

Ranking (left part of Fig. 5) of the different sources of  $M_w$  (from global to specific published studies) depends on the method used to estimate  $M_w$  (see Section 2.1), the standard  $M_w$  quality of the published data set (see Section 2.3) and the number of earthquakes with an  $M_w$  estimate in each data set for the EURO-MED region (Fig. 2). Indeed, to estimate homogeneous  $M_w$  on a larger scale than our target area and over a longer period of time, we have favoured sources estimating  $M_w$  on large data sets.

The first category ('I. CMT services') constitutes our first reference  $M_w$  data set to which the other  $M_w$  sources are unified. The  $M_{wc}$  GCMT are considered as the reference by the seismological community due its large spatial, temporal and magnitude range coverage (Fig. 2). Several authors have chosen  $M_{wc}$  GCMT as the prime reference in their catalogues (e.g. CPT15; ISC-GEM). Following the strategy of Pondrelli *et al.* (2006) for the Italian-CMT catalogue, we constituted this first category, referred to as  $M_{w,unified,I}$ , as a combination of centroid moment tensor solutions selected according to the following priority scheme:

- (1)  $M_{wc}$  GCMT  $\geq 5.5$ ;
- (2)  $M_{wc}$  RCMT;
- (3)  $M_{wc}$  Italian-CMT (for earthquakes occurring between 1976 and 1996 new  $M_{wc}$  were computed in a similar way to RCMT for Italy);
- (4)  $M_{wc}$  GCMT  $< 5.5$  if no  $M_w$  estimate provided by sources of categories II and III (as the quality of the  $M_w$  estimate is lower in the low  $M_w$  range, we preferred to use  $M_w$  from lower categories when available).

The category II includes additional global sources that provide moment tensor solutions estimated in a uniform way at the global scale and with information allowing  $M_0$  to be defined accurately (see Section 2.3). For this category II, the solutions however are provided with a smaller temporal window than I (Fig. 2). All regional services that systematically furnish  $M_{wr}$  since 2000–2010 are included in the category III. Then, the category IV includes publications that provide  $M_w$  estimates computed using the same method for a collection of events but



**Figure 5.** Scheme of the hybrid strategy used to build a reference data set of unique and unified  $M_w$  estimates. The colours chosen to differentiate the categories will be used in the following figures.

**Table 5.** Number and percentage of earthquakes with an  $M_w$  estimate for the five categories of sources for FRANCE and EURO-MED\_clip.

Category	FRANCE		EURO-MED_clip	
	Number	Per cent	Number	Per cent
I	51	4	3004	56
II	16	1	838	16
III	170	12	1408	26
IV	70	5	77	1
V ( $M_w \geq 2.5$ )	80	6	-	-
V	1118	78	-	-
Total	1425	100	5327	100

not estimated with this method in a systematic way over time (see Table 2). In the case of Switzerland, we combined the  $M_w$  values available within different publications in a unique data set called hereafter ‘SED regional studies’ following a priority scheme similar to ECOS-09 (Fäh *et al.* 2011):

- (1) Bernardi (2005).
- (2) Baer *et al.* (2007).
- (3) Braunmiller *et al.* (2005).
- (4) Braunmiller *et al.* (2002).

Finally, all the other  $M_w$  estimates are integrated into the last category V.

For the II to IV categories, the different  $M_w$  sources in each category were considered as equivalent. For earthquakes associated to several  $M_w$  estimates, an average  $M_w$  value is thus computed. Indeed, it is difficult to give a preference to a source within a category; it would be better to individually analyse each event, but this task is too time-consuming when building a large data set.

The resulting classification for each earthquake in our data set is reported in the Supporting Information S4 (sheet ‘ $M_w$ \_sources\_used’, field ‘ $M_w$ \_ranking’). Table 5 indicates the number of  $M_w$  for each of the five categories of sources. For EURO-MED\_clip area, 56 per cent of earthquakes were described by an  $M_w$  value provided by the category I, conversely for the FRANCE area, 12 per cent are from the category III including the regional approaches and 78 per cent from category V. It should be noted however that only 6 per cent of the category V earthquakes have magnitudes values  $M_w \geq 2.5$ .

### 3.2 Unification of the $M_w$ values

The second step (right-hand part of Fig. 5) is to unify the  $M_w$  values to be consistent with a reference. Thus, the  $M_w$  values from one source (X) have to be compared with an  $M_w$  data set chosen as reference (Y) and then eventually corrected to be unified with this reference.

#### 3.2.1 Choice of statistical tools to perform regressions

In the literature, different regression techniques are implemented to compare magnitudes considering the associated uncertainties (e.g. Stromeyer *et al.* 2004; Bethmann *et al.* 2011; Gasperini *et al.* 2012, 2013). Lolli & Gasperini (2012) found comparable results from these techniques. When monitoring services do not report an uncertainty associated with the  $M_w$  estimates, ordinary orthogonal regression (OOR) are often performed (e.g. Grünthal *et al.* 2009; Gasperini *et al.* 2012) under the assumption of equal variances for the two magnitudes [ $\eta = \sigma^2(Y)/\sigma^2(X) = 1$ ]. Castellaro & Bormann (2007) and Gutdeutsch *et al.* (2011) recommended in such cases to compare OOR results with the ordinary linear least square regression (OLS) ( $Y \rightarrow aX + b$ ) and the inverted OLS\_inv ( $X \rightarrow cY + d$ ) technique. This ensures that the  $\eta = 1$  hypothesis can be considered reasonable (i.e. the OOR line is close to the angular midst formed by OLS and OLS\_inv lines).

In this study, we used the OOR technique with the hypothesis of  $\eta = 1$ . The OLS techniques were used as a tool to quantify the variances. We also checked two hypothesis: (i) that the mean difference between two magnitudes estimates,  $\overline{\Delta M}$  is equal to zero can be rejected and thus an offset correction is required and (ii) that the slope of the linear conversion law is equal to unity ( $Y = X + b$ ) can be rejected and thus a scaling correction is needed. The two statistical tests were rejected if the  $p$ -value, computed as described in Konstantinou (2015), is lower or equal to 0.01, that is if the mean difference is significantly different from zero and the slope is significantly different from unity. Thus, if only the first test is rejected, only an offset correction is applied such as  $Y = X + b$ . If the second test is rejected (whatever the result of the first test), a complete scaling correction such as  $Y = aX + b$  is applied.

#### 3.2.2 Implementation of the unification procedure

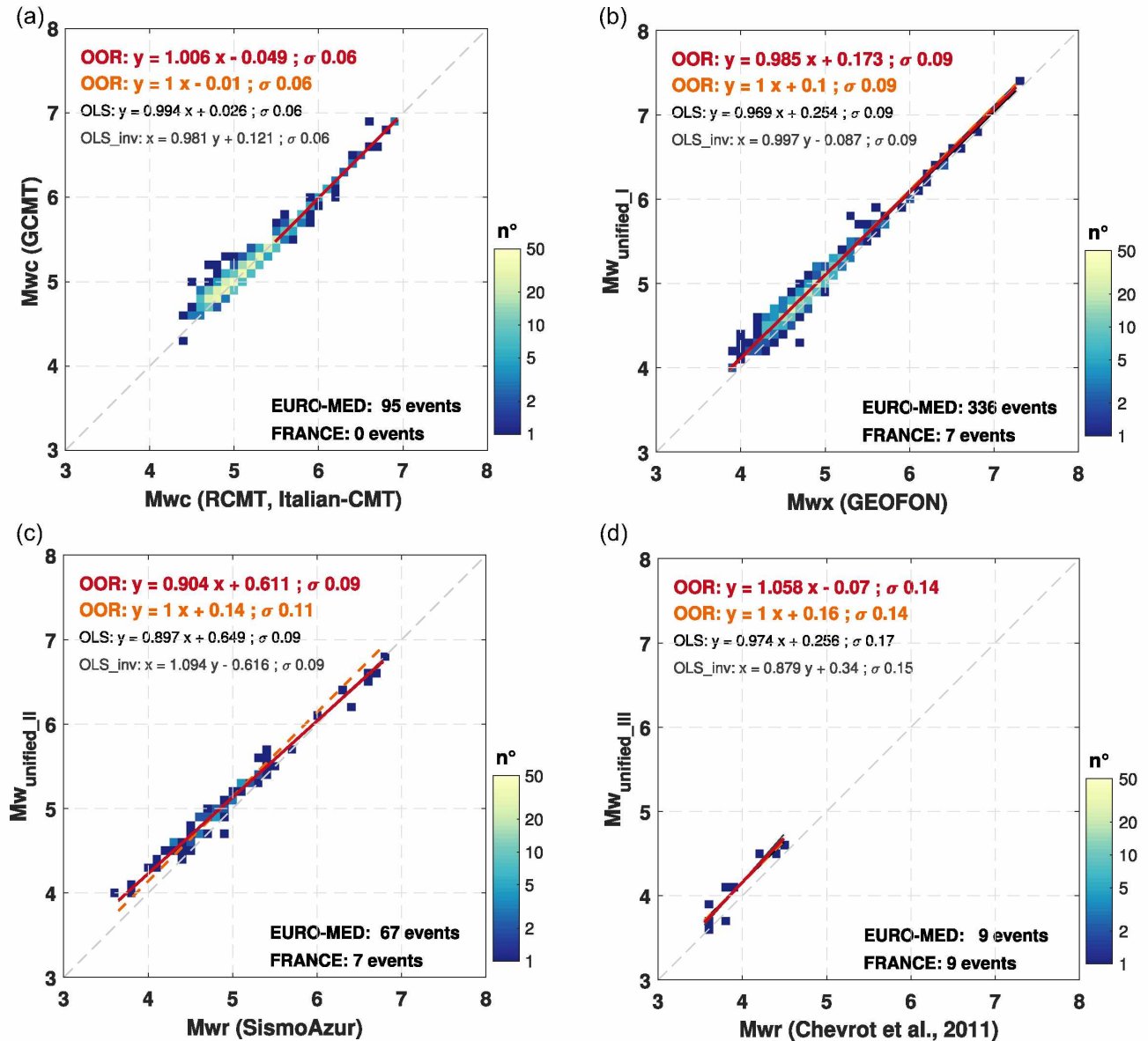
The  $M_w$  value intercomparisons were carried out progressively following the proposed ranking by setting up for each category of sources a new data set, called  $Mw_{unified,X}$  (with X for the category number), which serve as a reference for the lower category (see Fig. 5). Table 6 presents the  $M_w$  correction laws obtained for all sources and Fig. 6 displays four intercomparison examples of  $M_w$  sources from category I to IV compared with their own reference. Figures showing the intercomparisons for all sources are included as Supporting Information S5. For each  $M_w$  intercomparison, the four conversion laws obtained from the different regression techniques discussed before are presented. We find that the  $\eta = 1$  hypothesis is reasonable and that the variances associated to the  $M_w$  values are relatively low given the small angle observed between OLS and OLS\_inv laws (explaining why the OLS and OLS\_inv lines are overlying in Fig. 6).

For the category I, the  $Mw_{unified,I}$  data set is directly built following the priority scheme of the three CMT sources. Fig. 6a displays the comparison between  $Mwc$  GCMT and a combination of  $Mwc$  from RCMT (1997–2019) and Italian-CMT (1976–1996 only for Italy). The similarity of the OOR, OLS and OLS\_inv laws and a low standard deviation ( $\sigma$ ) of 0.06 attest to the compatibility of these  $Mwc$  values for  $Mwc \geq 5.5$ . For lower  $Mwc$  values, the dispersion is larger ( $\sigma$  of 0.08) and a scaling bias can be observed with increasingly higher  $Mwc$  GCMT values compared to  $Mwc$  (RCMT, Italian-CMT) with decreasing  $Mwc$  values. As already mentioned by Gasperini *et al.* (2012), GCMT tends to overestimate  $Mwc$  for  $M_w < 5.5$ , that is why we preferred  $M_w$  from other CMT services or lower categories (II, III) for  $Mwc$  GCMT  $< 5.5$  when estimates are available.

For the categories II to IV, the  $M_w$  values of each source were compared with its  $M_w$  of reference,  $Mw_{unified,X}$ , defined at the level of the higher category (see Table 6 and Fig. 5). According to the results of the statistical test, an offset or a scaling correction was defined and applied to each source (see Table 6). Then, a weighted average (Wa) is computed when more than one  $M_w$  estimate is available for one event inside a category, using the standard deviations of the laws as a weight (Table 6). We verified the agreement between the new unified  $M_w$  values with their reference by confirming that corrections are no longer necessary (see Table 7). Finally, the  $M_w$  estimates from a category were used when the corresponding events were not already associated with an  $M_w$  estimate from the higher levels. These different steps are represented schematically in Fig. 5.

For category II, a simple offset correction is required for the different sources (see Table 6). Using events occurring from 2011 to 2019, we defined an offset correction of +0.1 for  $Mwx$  GEOFON compared to the reference  $Mw_{unified,I}$  (Fig. 6b). This result is stable regardless of the  $M_w$  range: similar tendencies are observed for earthquake of  $M_w < 5.5$  (offset of +0.1) and of  $M_w \geq 5.5$  (offset of +0.09).

Concerning the sources of category III,  $Mwr$  SED-TDMT is the source of  $M_w$  with the most dispersion ( $\sigma$  of 0.14) but not requiring offset correction.  $Mwr$  IGN- and INGV-TDMT required an offset correction of +0.1 and +0.24, respectively. For the other sources of this category III, the statistical tests revealed that a scaling correction is required. In fact, in the case of  $Mwr$  INGV-TDMT, the  $p$ -value from the scaling test (hypothesis of  $a = 1$  in the law  $Y = aX + b$ ) was close to the chosen threshold value of 0.01. The intercomparisons of  $Mwr$  SismoAzur with the reference  $Mw_{unified,II}$ , presented in Fig. 6(c), shows that a scaling correction is required and the dispersion of the  $M_w$  values is low ( $\sigma$  of 0.09), indicating a clear trend. In the case of  $Mwr$  NEIC and IAG, a scaling correction was applied in spite of the  $p$ -value being close to the threshold of 0.01.



**Figure 6.** Selection of intercomparisons between the  $M_w$  estimates of the different sources with the corresponding data set of reference. The data are represented in terms of density of events indicated by the colourbar for bins of 0.1 unit of  $M_w$ . Different regression techniques are computed for events occurring in the EURO-MED zone: OOR is represented in case of a classical linear regression ( $Y = aX + b$ ) (red line) and for a linear regression for which the slope is fixed to one ( $a = 1$ ;  $Y = X + b$ ) (orange line); OLS (dark grey line) and OLS\_inv (grey line). The light grey dashed line corresponds to  $Y = X$ . The number of events included in EURO-MED and FRANCE zones are indicated at the right bottom of each subplot.

For category IV, we found an offset correction of  $-0.04$  for the  $Mwr$  of the SED specific studies. The most important offset correction was applied to the  $M_w$  values from the specific study of Chevrot *et al.* (2011) for earthquakes of the Pyrenees region. We define a clear correction of 0.16 but only from nine events (Fig. 6d). Note that for this category IV, the restricted data sets available limits the robustness of the regression. The estimated corrections are still in the same range as those of other sources with larger data sets.

Finally, for category V, with the exception of 20 earthquakes out of 1118 (Table 5), already characterized by other sources of the previous categories (see Supporting Information S5), no comparisons could be performed and therefore these  $M_w$  values were not unified.

## 4. RESULTS AND DISCUSSION

### 4.1 A data set of direct, unique and unified $M_w$ estimates

The resulting data set contains 4454 shallow seismic events (depth  $< 40$  km) occurred from 1963 to 2019 in the European–Mediterranean region associated to a direct and unique  $M_w$  value (table given as Supporting Information S4, sheet ‘ $Mw_{unified}$ ’). For 3351 earthquakes, a unified  $M_w$  value based on a ‘CMT services’ reference is provided. For the remaining 1103 earthquakes, the  $M_w$  estimate of the original study

**Table 6.** Intercomparisons of  $M_w$  estimates, from the different sources used in this study and ranked by category, with the  $M_w$  values of reference ( $M_{w_{\text{reference}}}$ ) defined at the level of the higher category. The corresponding number of data used for the comparisons coming from EURO-MED (FRANCE) is indicated.  $M_w$  correction laws were established with their corresponding standard deviations ( $\sigma$  intersources) for each source according to the  $p$ -value results.  $P$ -values in bold indicate that offset and/or scaling corrections are needed ( $p < 0.01$ ).

$M_{w_{\text{reference}}}$	$M_w$	Number of data in EURO-MED (FRANCE)	$p$ -Value ( $\Delta M = 0$ )	$p$ -Value ( $a = 1$ )	Mw correction laws	$\sigma$ Inter sources
$M_{w_{\text{unified_I}}}$	$M_{wx}$ GEOFON	336 (7)	<b>&lt;0.01</b>	0.15	$M_{w_{\text{reference}}} = Mw + 0.10$	0.09
	$M_{ww}$ NEIC	124 (0)	<b>&lt;0.01</b>	0.27	$M_{w_{\text{reference}}} = Mw + 0.04$	0.09
	$M_{wb}$ NEIC	162 (0)	<b>&lt;0.01</b>	0.65	$M_{w_{\text{reference}}} = Mw + 0.09$	0.11
$M_{w_{\text{unified_{II}}}}$	$M_{wr}$ NEIC	299 (13)	<b>&lt;0.01</b>	<b>&lt;0.01</b>	$M_{w_{\text{reference}}} = 0.952.Mw + 0.342$	0.09
	$M_{wr}$ SismoAzur	67 (7)	<b>&lt;0.01</b>	<b>&lt;0.01</b>	$M_{w_{\text{reference}}} = 0.904.Mw + 0.611$	0.09
	$M_{wr}$ INGV-TDMT	219 (10)	<b>&lt;0.01</b>	0.02	$M_{w_{\text{reference}}} = Mw + 0.24$	0.11
	$M_{wr}$ IAG	69 (3)	0.03	<b>&lt;0.01</b>	$M_{w_{\text{reference}}} = 0.911.Mw + 0.46$	0.12
	$M_{wr}$ IGN-TDMT	52 (3)	<b>&lt;0.01</b>	0.44	$M_{w_{\text{reference}}} = Mw + 0.1$	0.11
	$M_{wr}$ SED-TDMT	27 (10)	0.18	0.07	$M_{w_{\text{reference}}} = Mw$	0.14
$M_{w_{\text{unified_{III}}}}$	$M_{wr}$ of SED specific studies	61 (13)	<b>&lt;0.01</b>	0.61	$M_{w_{\text{reference}}} = Mw - 0.04$	0.11
	$M_{ws}$ of Delouis <i>et al.</i> (2009)	7 (4)	0.28	0.72	$M_{w_{\text{reference}}} = Mw$	0.12
	$M_{wr}$ of Chevrot <i>et al.</i> (2011)	9 (9)	<b>0.01</b>	0.73	$M_{w_{\text{reference}}} = Mw + 0.16$	0.14

**Table 7.** Comparison between the unified  $M_w$  values at one level (after applying the  $M_w$  correction laws presented in Table 6) with the unified  $M_w$  values of the category defined at the higher level.

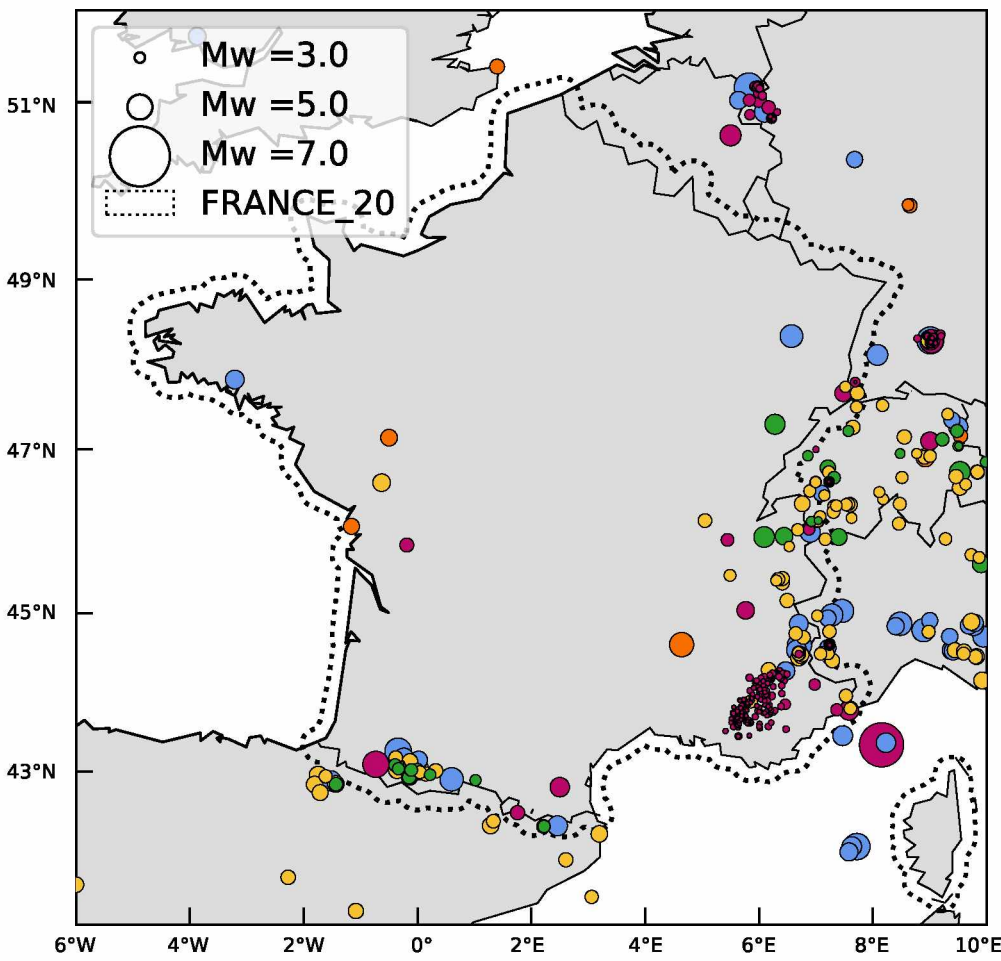
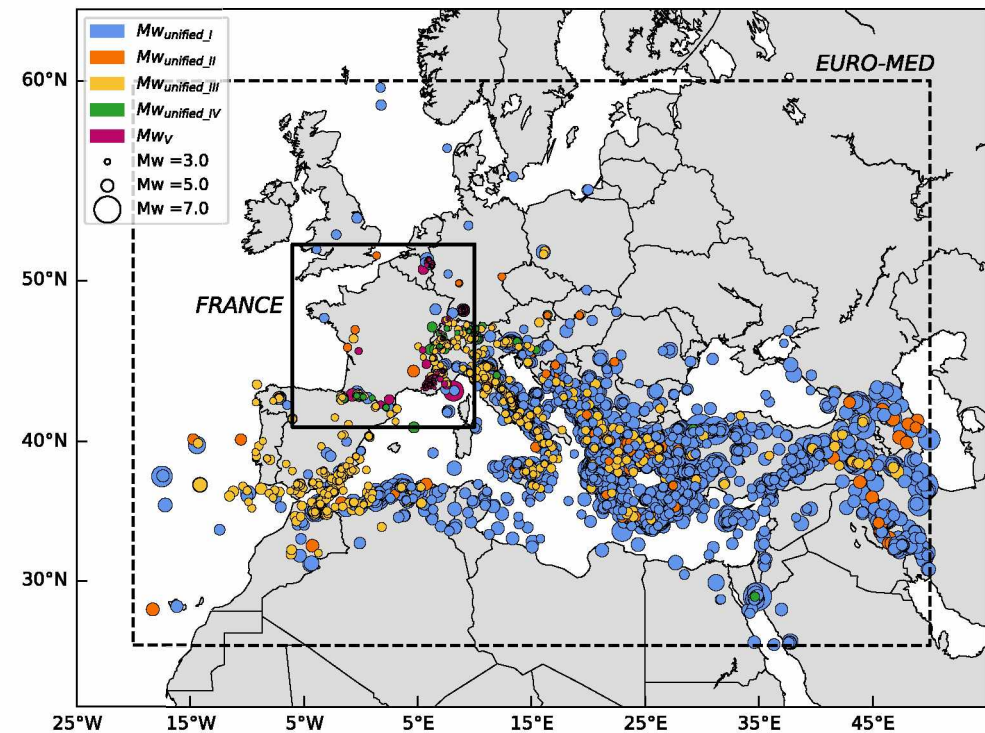
$M_{w_{\text{reference}}}$	$M_w$	Number of data in EURO-MED (FRANCE)	$p$ -Value ( $\Delta M = 0$ )	$p$ -Value ( $a = 1$ )	$\sigma$ inter sources
$M_{w_{\text{unified_I}}}$	$M_{w_{\text{unified_{II}}}}$	481 (7)	0.85	0.47	0.09
$M_{w_{\text{unified_{II}}}}$	$M_{w_{\text{unified_{III}}}}$	549 (30)	0.83	0.04	0.10
$M_{w_{\text{unified_{III}}}}$	$M_{w_{\text{unified_{IV}}}}$	73 (24)	0.45	0.30	0.11

is reported (all in category V). It should be noted that in this data set, we have reported the location given by the source providing the  $M_w$  estimates. However, for the building of an earthquake catalogue, a more regional location would be preferable.

This data set was compiled with a focus on metropolitan France, which means that not all data sources were collected at the European scale. For this reason, for easier distinction, the events were classified according to EURO-MED, FRANCE and an additional FRANCE\_20 geographical region (see Fig. 7, bottom), corresponding to a zone extended up to 20 km beyond the borders of metropolitan France (similar to the definition used in the SI-Hex catalogue, Cara *et al.* 2015). Table 8 provides the number of events for each of the three geographic areas and for the different categories. Fig. 7 displays the geographic distributions of all earthquakes and Fig. 8 provides the temporal limits of each subset.

For the FRANCE region, unified  $M_w$  values are provided for 185 earthquakes (Table 8) with magnitude ranging from  $M_w$  2.36 to 5.35. The majority are located in the southwest and southeast of France (Fig. 7, bottom panel), the most seismically active regions, and also in the neighboring countries for which the  $M_w$  computed from regional approaches are collected (such as Switzerland, Italy and Spain). On the contrary, only five earthquakes (including four with unified  $M_w$  estimates) are currently associated to a direct  $M_w$  value in the western part of France. As shown in Fig. 8, it was only from the late 1990s that our data set for the FRANCE\_20 area began to include  $M_w$  estimates in a more systematic way, which is also concomitant with the development of the French accelerometric network (Péquegnat *et al.* 2008).

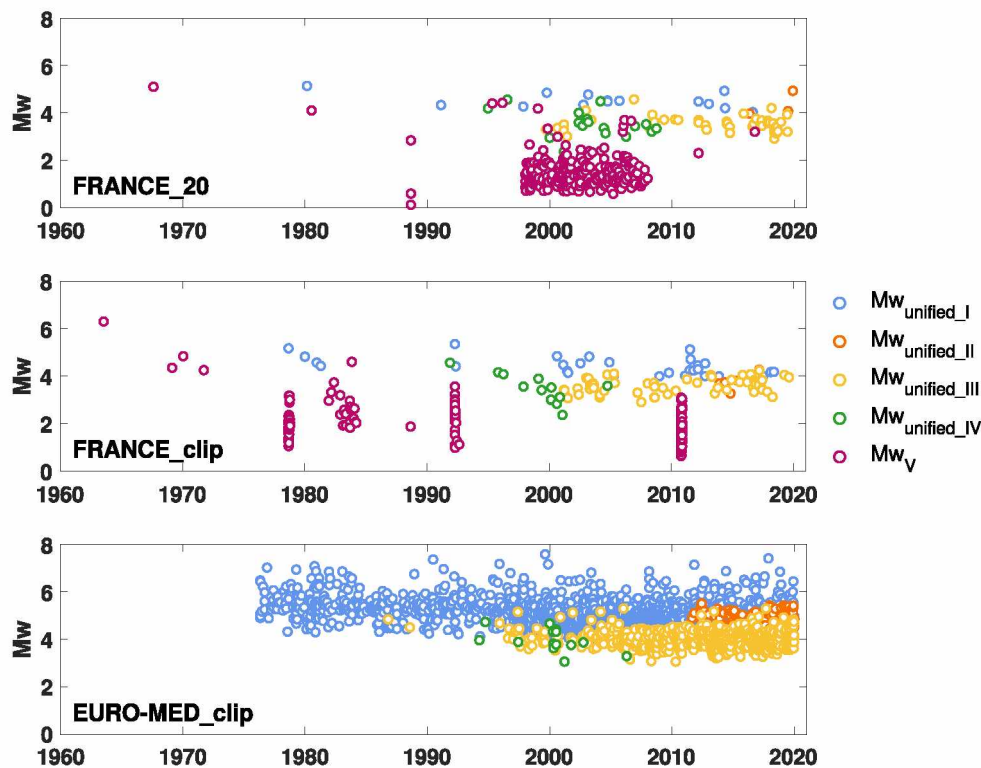
Concerning the EURO-MED\_clip region, the methodology consists of collecting all  $M_w$  estimates from categories I and II but for categories III and IV, only sources concerning the FRANCE region were collected. This data set contains mainly earthquakes with magnitude ranging from  $M_w$  3.06 to 7.57 located in Italy, Greece, Turkey and at the Iberian-Maghreb boundary (Fig. 7, top panel). Most earthquakes are characterized in category I (CMT services) since 1976 (Fig. 8, top panel). From 2010, some  $M_w$  estimates from category II are provided by other global networks, particularly GEOFON (Table S4). Concerning the category III,  $M_w$  estimates are mainly provided since 1995 by the Italian, Swiss and Spanish regional networks with also a contribution coming from  $M_{wr}$  NEIC and SismoAzur for Greek and Turkish events.



**Figure 7.** Location maps of the seismic events included in our resulting data set represented according to the categories of the  $M_w$  sources for EURO-MED, FRANCE (top panel) and FRANCE\_20 (bottom panel). The colours indicate the category of the  $M_w$  origin ( $M_w$  values represented in purple are not unified).

**Table 8.** Number of earthquakes with an  $M_w$  estimate from the five categories of sources shown separately for earthquakes located in a zone extended up to 20 km beyond the borders of metropolitan France (FRANCE\_20), located in the FRANCE\_clip region and then in the EURO-MED\_clip region.

Category	FRANCE_20	FRANCE_clip	EURO-MED_clip
I	14	29	2336
II	3	5	181
III	47	56	635
IV	18	13	14
V	247	856	0
V ( $M_w \geq 2.5$ )	16	49	0
Total	<b>329</b>	<b>959</b>	<b>3166</b>
Range of $M_w$	0.12–5.14	0.63–6.30	3.06–7.57
Number ( <i>per cent</i> ) of earthquakes with an unified $M_w$ value	<b>82 (25)</b>	<b>103 (11)</b>	<b>3166 (100)</b>
Range of unified $M_w$	2.36–5.14	2.36–5.35	3.06–7.57



**Figure 8.** Temporal distribution of  $M_w$  estimates for earthquakes represented for the three geographic zones; the colours indicate the different categories of the  $M_w$  estimates.

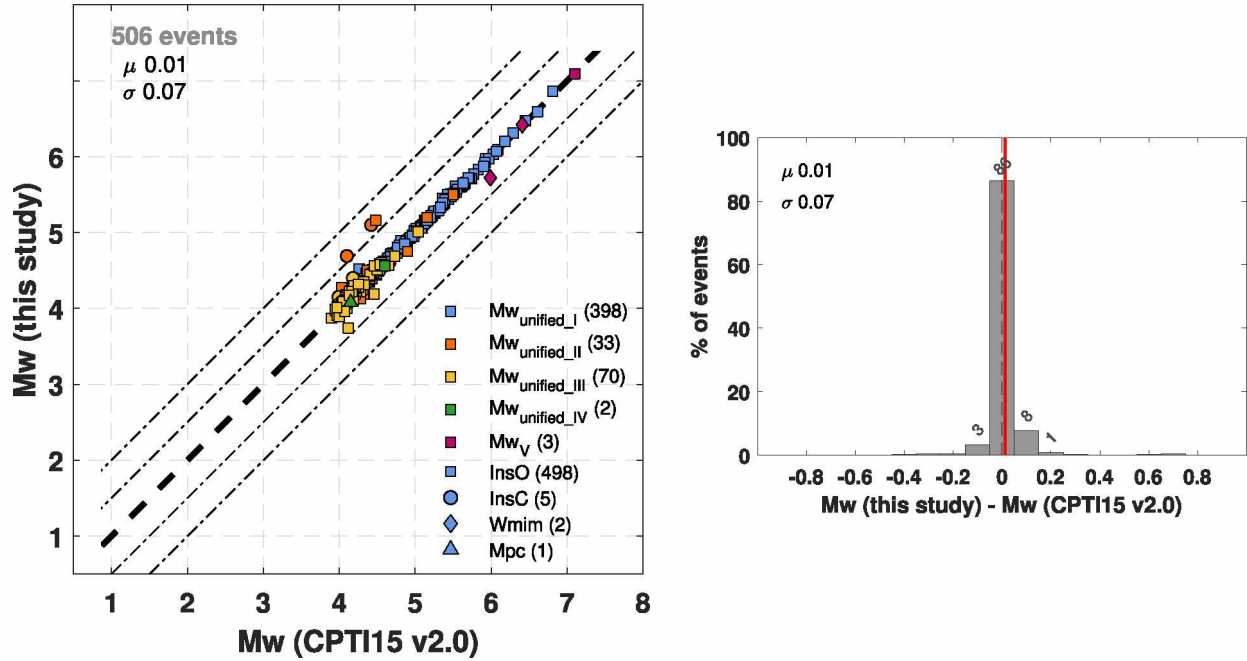
Conversely, very few  $M_w$  values were collected for the northeastern part of Europe characterized by a low-to-moderate seismic activity, such as metropolitan France.

All data sources used here were last accessed on July 2020, therefore the latest  $M_w$  IAG results, or the  $M_w$  RCMT published after 31/01/2019, are not included. Consequently, the data set that we provided for  $M_w > 5.0$  includes events up to 31/01/2019, for  $3.5 < M_w < 5.0$ , up to 19/08/2014 and only for the area on the border with Spain.

#### 4.2 Comparison with existing SHA data sets

In the following, we performed a series of  $M_w$  intercomparisons with previously existing SHA data sets to discuss the impact of the strategy used to define  $M_w$  estimates. We also aim to underline where we believe future studies are needed to further improve SHA data sets for Europe, in general, and for metropolitan France, in particular.





**Figure 9.** Intercomparison of the  $M_w$  estimates included in our data set,  $M_w$  (this study), and the Italian catalogue (CPTI15 v.2.0).  $M_w$  values (left-hand panel) and histograms of the differences between the two  $M_w$  values (right-hand panel). The average ( $\mu$ ) and the standard deviation ( $\sigma$ ) of the differences (represented by a red line at right) are given. For CPTI15, the origin of the  $M_w$  estimate method is represented by various markers (InsO— $M_w$  is from moment tensor solutions (direct); InsC— $M_w$  proxy; Wmim— $M_w$  is the mean of instrumental and macroseismic determination; Mpc— $M_w$  is from parametric catalogue of macroseismic determinations). The number of data represented by a coloured marker is indicated in parentheses. The bold dotted line represents the case for which  $M_w(X) = M_w(Y)$  and thin dotted lines deviations spaced by 0.5 unit of  $M_w$ .

#### 4.2.1 Comparing $M_w$ estimates with the Italian earthquake catalogue

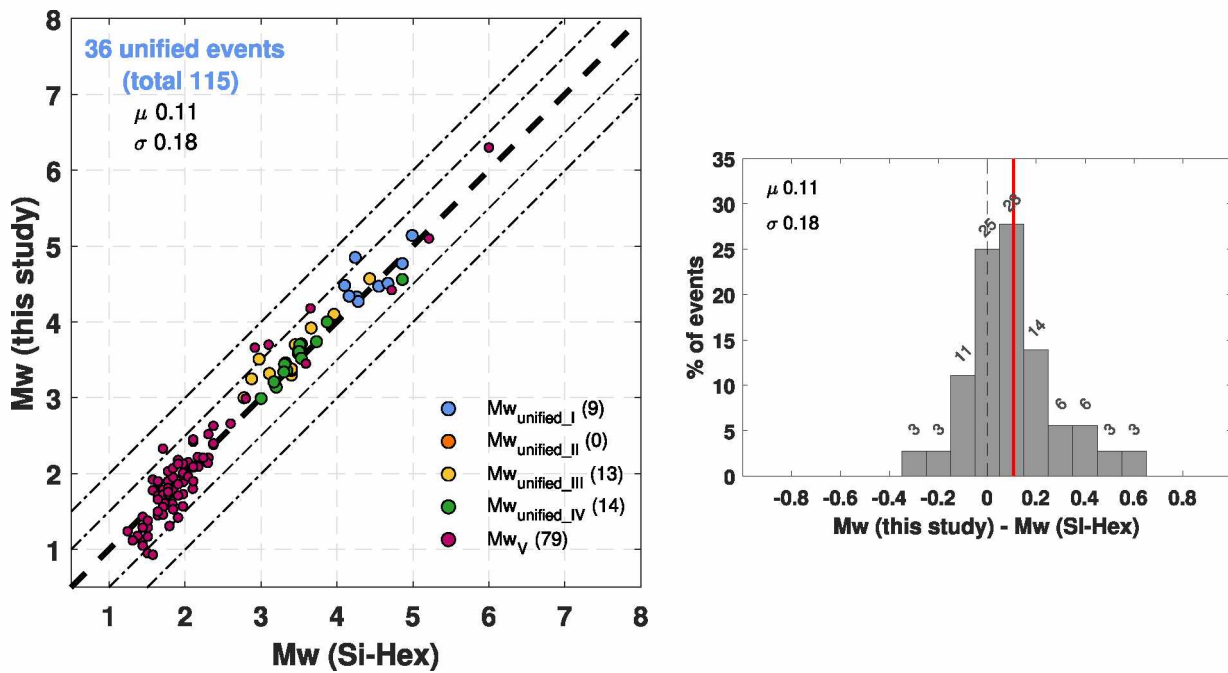
The average differences ( $\mu$ ) and the associated standard deviations ( $\sigma$ ) of the comparison between  $M_w$  estimates from this study and from the Italian CPTI15 v2.0 catalogue (Rovida *et al.* 2019) are close to zero ( $\mu = 0.01$  and  $\sigma = 0.07$ , Fig. 9) (even over the entire  $M_w$  range). We observe a slight increase in dispersion for the lowest magnitudes ( $M_w \leq 4.6$ ) which concerns mainly earthquakes with  $M_w$  estimates from category III. This confirms that applying similar procedures will improve consistency between earthquake catalogues across borders.

The observed  $M_w$  value differences may be related to the strategy applied to assign a unique  $M_w$  value to an event. Indeed, in the Italian catalogue, a weighted average is computed with the available  $M_w$  estimates (maximum of five sources) while these same sources can be ranked into different categories in our procedure. Secondly, the  $M_w$  intercomparisons between sources, such as in Table 6, were carried out on slightly different data sets (in terms of input data selection criteria, such as the quality, the depth and the period covered) and slight differences are observed in the offset corrections ( $Mwb$  NEIC: +0.05 for Gasperini *et al.* (2012)/+0.09 for this study;  $Mwr$  INGV-TDMT: +0.213/+0.24;  $Mwr$  of SED specific studies: -0.05/-0.04).

It should also be pointed out that for few earthquakes, discrepancies between the  $M_w$  values can be larger than 0.5. Further inspection showed that: (i) for two earthquakes (13/03/2014 and 30/10/2016),  $M_w$  were estimated from another magnitude scale (flag InsC) in the case of the Italian catalogue and (ii) for the 30/10/2016 event ( $n^\circ 3885$ ), CPTI15 v2.0 uses  $Mwr$  INGV-TDMT corrected at 4.48 and we use  $Mwx$  GEOFON corrected at 5.16, which gives a large discrepancy around 0.68 unit of  $M_w$ . In the new Homogenized Instrumental Seismic Catalogue (HORUS) of Italy (Lolli *et al.* 2020), this event is now associated to an  $M_w$  value of 4.79, corresponding to the weighted average of the corrected  $Mwx$  GEOFON and  $Mwr$  INGV-TDMT, reducing the discrepancy to 0.37 compared to our  $M_w$  estimate. This example illustrates well the importance of the choice of ranking of  $M_w$  sources.

#### 4.2.2 Comparing $M_w$ estimates with the French earthquake catalogue

Only 36 unified  $M_w$  estimates with  $M_w > 3.0$  could be compared with the  $M_w$  of the SI-Hex catalogue (Cara *et al.* 2015, 2017) (Fig. 10). SI-Hex  $M_w$  estimates are on average lower ( $\mu = +0.11$ ) and relatively dispersed ( $\sigma = 0.18$ ) compared to our unified  $M_w$ . This average difference is also observed for the nine  $M_w$  estimates from the category I ( $\mu = +0.12$ ) and is stronger for the  $Mw_{unified\_III}$  ( $\mu = +0.18$ ). In the SI-Hex catalogue, most earthquakes with  $M_w > 3.0$  are described by an  $M_w$  value estimated from Mcoda, a magnitude defined from the inversion of the amplitude of the coda wave envelope (Denieul *et al.* 2015), then calibrated to  $M_w$  using as a reference ‘direct’  $M_w$  values from different sources. In addition, when the extended version of the SI-Hex catalogue (obtained on request from authors) is used (see Supporting Information S6), the  $M_w$  values are even lower on average and very dispersed ( $\mu = +0.36$  and  $\sigma = 0.34$ ). This extended version of the SI-Hex catalogue is used in the recent French PSHA study of Drouet *et al.* (2020).



**Figure 10.** Intercomparisons of the  $M_w$  values for earthquakes included in our data set,  $M_w$  (this study), and the SI-Hex catalogue.  $M_w$  values (left-hand panel) and histograms show the differences between the two  $M_w$  values (right-hand panel). The average ( $\mu$ ) and the standard deviation ( $\sigma$ ) of the differences (represented by a red line at right) are given only for the 36 earthquakes with a unified  $M_w$  estimate. The number of data represented by a coloured circle is indicated in parentheses. The bold dotted line represents the case for which  $M_w(X) = M_w(Y)$  and the other thin dotted lines deviations spaced by 0.5 unit of  $M_w$ .

For  $M_w$  SI-Hex < 3.0, our data set is only composed of  $M_w$  values from category V, that is to say not unified  $M_w$  values. These  $M_w$  values are mainly estimated from the local network around the Durance Fault (Nechtschein 2003). We observe differences, and probably a scaling bias, between these  $M_w$  values and the ones from SI-Hex, which have been estimated for a majority after applying a double magnitude scale correction law (Cara *et al.* 2017), from a regional network ML to  $ML_{LDG}$  and then to  $M_w$ , using a magnitude scale conversion law based on Godano *et al.* (2013)'s  $M_w$  data set. This observed scaling bias could be also due to the application of the OLS regression technique used to define the magnitude scale conversion law, as pointed out by Laurendeau *et al.* (2019).

#### 4.2.3 Comparing unified $M_w$ estimates with those used in strong ground motion data sets

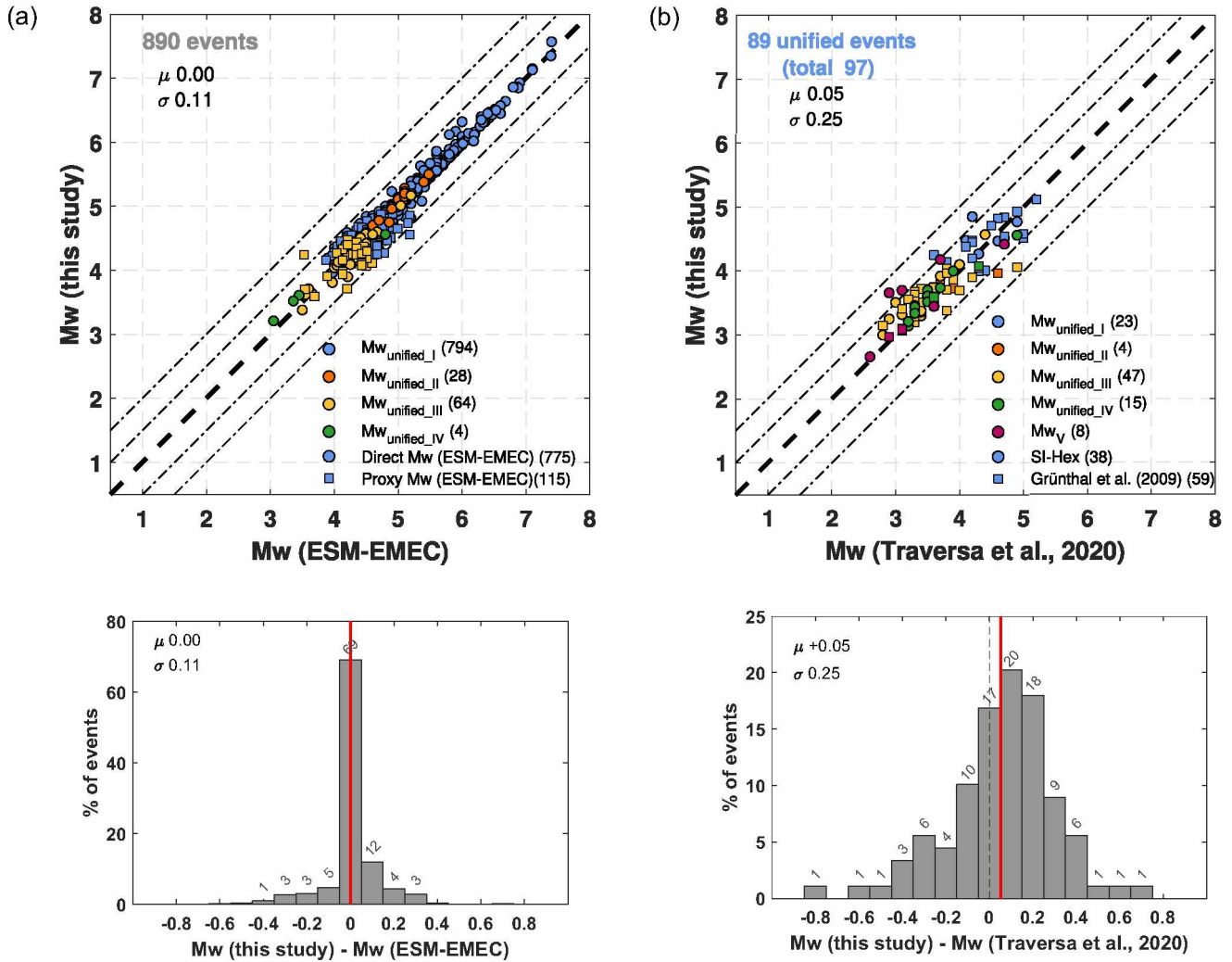
We compared our unified  $M_w$  estimates with the ones currently available in the strong ground motion databases both for Europe and France (Fig. 11).

For Europe, we analysed the recently published ESM data set (Bindi *et al.* 2018; Lanzano *et al.* 2019) which contains 2179 events located in a larger region than ours ( $26^\circ\text{W}$ – $68.5^\circ\text{E}$ ;  $23.5^\circ\text{N}$ – $72^\circ\text{N}$ ). In the ESM data set 61 per cent of the earthquakes are associated to an  $M_w$  estimate (defined following a similar strategy to EMEC, hereafter ESM-EMEC data set). We found a subset of 890 events in common with our data set (Fig. 11a). For metropolitan France, we analysed the recently published Résif-Epos ground motion data set (Traversa *et al.* 2020). In this data set, different strategies were used to define  $M_w$  estimates but all are proxy  $M_w$ . We found 89 out of 468 events have a unified  $M_w$  value (Fig. 11b).

For  $M_w > 5.0$ , only covered by ESM-EMEC, ESM-EMEC and our unified  $M_w$  estimates are similar for most events. Indeed, a majority of these  $M_w$  estimates are defined by sources similar to the ones used in this study, such as RCMT. For  $M_w < 5.0$ ,  $M_w$  estimates can differ from our data set by up to  $\pm 0.4$  and  $\pm 0.8$  for ESM-EMEC and the French data sets, respectively. For ESM-EMEC, it seems that the largest discrepancies are when EMEC  $M_w$  are estimated from proxies. These direct  $M_w$  values were probably not available when estimating these EMEC  $M_w$ . Differences between direct and proxy  $M_w$  may also explain the larger differences observed in the case of the French data set. In addition, the  $M_w$  values of Traversa *et al.* (2020) data set have a slight tendency to be lower compared to the  $M_w$  estimates from our study ( $\mu = +0.05$ ), as already observed for the SI-Hex catalogue (Fig. 10).

#### 4.2.4 Discussion about the strategies to build $M_w$ data sets

These intercomparisons highlight that the strategy for defining  $M_w$  has a strong impact on  $M_w$  estimates provided in SHA data sets. Indeed, there is a good agreement of the  $M_w$  values when the strategies are similar (case of CPTI15 v2.0) and a significant dispersion when different



**Figure 11.** Intercomparisons of the  $M_w$  values for earthquakes included in our data set,  $M_w$  (this study), and common events found (a) in the ESM-EMEC data set (Bindi *et al.* 2018; Lanzano *et al.* 2019) and (b) in the Résif-Epos ground motion data set (Traversa *et al.* 2020) for which a marker specifies the original procedure used to define proxy  $M_w$ .  $M_w$  values (top panels) and histograms of the differences between the two  $M_w$  values with the red line representing the mean of the difference between the  $M_w$  values of the two data sets (bottom panels).

strategies are used (ESM-EMEC, SI-Hex, Traversa *et al.* 2020, data sets). This dispersion is particularly important when the comparison is between direct and proxy  $M_w$  estimates, and also for  $M_w < 5.0$  events, for which  $M_w$  from different sources can be used.

In this study, we have chosen to apply  $M_w$  correction laws to the direct  $M_w$  estimates in order to unify them considering the same source chosen as a reference. However, the differences observed between data sets seem to be more related to the choice of the  $M_w$  source: the average difference between two data sets is small compared to the offset/scaling corrections defined in Table 6. For example, in the case of the ESM-EMEC data set, there is no observed difference on average, the  $M_w$  corrections that were applied are not reflected in the average difference (for categories II + III + IV).

In our strategy, the ranking of sources (Fig. 5) can therefore be the factor that has the most impact on the final  $M_w$  estimate. We have favoured the  $M_w$  of the CMT services, whereas for example in the case of ESM-EMEC, the specific studies have priority. Our choice was guided by the need to have homogeneous  $M_w$  at the largest spatio-temporal scales possible and compatible with the majority of the metadata in the GMMs. However,  $M_w$  estimates from the regional methods are more sensitive to the density and spatial distribution of stations, to the velocity model used (e.g. Scognamiglio *et al.* 2016) which can lead to larger differences in the  $M_w$  estimates as observed for some specific earthquakes, such as the 2005 September 8 Vallorcine earthquake (Table 4), and to the systematic offsets as observed by various  $M_w$  correction laws (Table 6) for these regional methods. Metropolitan France may be particularly concerned by these limitations: indeed, the heterogeneous spatial distribution of stations is imposed by the presence of numerous coastlines and a lower amount of stations in the less seismically areas. Furthermore, the small quantity of  $M_w$  values estimated from specific studies would not allow the implementation of an  $M_w$  unification strategy with a unique source as reference.

The table called ‘ $M_w$ \_sources\_used’ of the Supporting Information S4 provides the  $M_w$  values from the different sources, and end-users are free to make their own choices. It is important to encourage the community to pursue the effort of homogenizing  $M_w$  estimates at large scales in order to better understand the origin of the inconsistencies and to try to avoid them.

### 4.3 Traceability, reproducibility and quality of the $M_w$ collections

The establishment of this unified  $M_w$  data set from various and heterogeneous  $M_w$  collections highlights some difficulties related to its traceability, reproducibility and quality. We intend to stress these points here, as it would also help in the selection or not of an  $M_w$  estimate by a source in an automatic way.

#### 4.3.1 Traceability of $M_w$ results over time

(i) A first difficulty is that the original results used in a study are no longer accessible online. This is already the case for the SismoAzur collection used in this study but also for  $M_w$  collections used in the CPTI15 (Gasperini *et al.* 2012) and the HORUS (Lolli *et al.* 2020) catalogues for ETHZ and NEIC data sets.

(ii) A second difficulty arises from the evolution over time of the approaches used to compute or select  $M_w$  which are not always easily traceable for end-users. For example, in the case of ETHZ a series of authors computed  $M_w$  using different approaches. For SismoAzur, previously published results were withdrawn from online publication following different choices of focal mechanism quality criteria.

(iii) A third difficulty arises from updates of the  $M_w$  values after performing a new analysis without tracing the date of the last modification or of the previously published  $M_w$  values. For example, the 2010/08/31 event (n° 2120) for which our  $M_w$  value is different from the one in CPTI15 while the same source  $M_w$  INGV-TDMT was used. Therefore, it seems important to update the original collections each time a new data set is compiled.

(iv) It should also be pointed out that evolutions in data formats, such as the entries of the quakeml files in the case of NEIC, require routinely checking and adapting the data extraction codes to the new formats.

#### 4.3.2 Reproducibility of results to define a 'standard' $M_w$ estimate

As discussed in Section 2.3, for many sources (mainly the oldest ones), the level of information associated to an  $M_w$  estimate does not allow the  $M_0$  and  $M_w$  values to be reproduced either because they are not provided by their authors or they are not provided with sufficient accuracy (see Supporting Information S2). When  $M_w$  are mixed together in the same data set, it seems important to define them with the same standards. The different authors do not necessarily use the GCMT standards and thus it is necessary to recompute homogeneously the  $M_w$  values, which is not always possible. This lack of information can induce discrepancies (smaller than those between sources) but which remain notable (larger than 0.1 for some cases).

#### 4.3.3 Quality of the $M_w$ solutions

In this study, we focused on the mean  $M_w$  values to characterize the seismic events. However, the question of the uncertainty values associated to the  $M_w$  estimates is a paramount question for the development of magnitude scale conversion laws (Castellaro & Bormann 2007; Gutdeutsch *et al.* 2011), or to take into account uncertainties in a PSHA study (e.g. Drouet *et al.* 2020). In this part, we discuss only the difficulties for end-users to appreciate the quality of an  $M_w$  estimate.

In fact, the sources which estimate  $M_w$  do not necessarily report an associated error and it is not easy to define *a posteriori* a quality with the information provided by their authors. To give an indication about the quality of one moment tensor solution, some authors have added letters depending on different criteria (e.g. Pondrelli *et al.* 2006; Scognamiglio *et al.* 2009): the number of data analysed, the azimuthal coverage of the recordings, the quality of the fit between the synthesized and the observed data (VR, the centroid location, . . .), the moment tensor double-couple (DC) percentage. From one study to another, the criteria for defining the reliability of one solution are not necessarily the same. That is why in this study, we relied on the opinions of the authors to consider or not a moment tensor solution. However, for a large number of  $M_w$  collected in this study (~40 per cent), information on the reliability of the solution was not provided, and thus in this case all solutions were considered reliable. Depending on the parametric studies and the methodologies used, uncertainty errors can range from 0.07 (e.g. Gasperini *et al.* 2012) to 0.8 (Stork *et al.* 2014). It would be interesting in the future to define international standards for quality criteria associated to each  $M_w$  estimate to be able to work more easily with different  $M_w$  estimates from different sources. This would allow assigning an error value to the  $M_w$  estimates consistent between the different sources.

## 5 CONCLUSIONS AND PERSPECTIVES

We propose a novel strategy to build unique and unified  $M_w$  reference data sets based on (i) intercomparisons of  $M_w$  estimates at the European–Mediterranean scale, (ii) ranking sources of  $M_w$  in five levels from global to specific studies and (iii) using a  $M_w$  value threshold that are useful for low-to-moderate seismicity regions such as metropolitan France, the target region in our study.

We collected 6752 direct  $M_w$  estimates from 34 sources (from webservices to specific published studies) for 4454 shallow seismic events (depth < 40 km) that occurred in the European–Mediterranean area (20°W–50°E; 25°N–60°N) between 1963 and 2019. We recomputed an  $M_w$  value following the GCMT standards when it was possible and attributed quality flags depending on the level of the information provided by the sources.

The proposed unification strategy allowed assigning to 185 events ( $2.36 \leq M_w \leq 5.35$ ) direct, unique and unified  $M_w$  value using the CMT services as reference for the FRANCE region (including neighbouring countries). For the European–Mediterranean region, 3351 events ( $3.06 \leq M_w \leq 7.57$ ) have a unified  $M_w$  value. This strategy could also be extended by collecting regional and specific  $M_w$  studies in other European countries in order to have a more complete unified  $M_w$  data set for Europe.

We observed comparable  $M_w$  values on average with the European SHA data sets (the CPTI15 v2.0 and ESM-EMEC data sets) and slightly larger  $M_w$  values compared to the French SHA data sets (the SI-Hex and Traversa *et al.* 2020, data sets). For all these data sets with which we compared our unified  $M_w$  values, we noted an increase of the discrepancies for  $M_w < 5.0$ , especially when different strategies were used. We attributed this variability to differences in the choice of  $M_w$  source, reflecting the wide variability of  $M_w$  estimates between sources for  $M_w < 5.0$ .

Despite all our efforts, the unified  $M_w$  estimates remains limited in number of events characterized, in their spatio-temporal distribution and in the magnitude range. To reduce the dependence on the need for  $M_w$  proxies in SHA data sets, future efforts will need to focus on estimating ‘direct’  $M_w$  for a larger number of earthquakes and reducing differences between sources for  $M_w < 5.0$  earthquakes, an  $M_w$  range that concerns metropolitan France in particular.

Our data set aims to be upgradeable over time, by integrating new  $M_w$  estimates and then applying again the hybrid strategy. For example, the recordings used to estimate the  $M_w$  of category V (not unified today), could be used again to estimate  $M_w$  from a unique method in order to unify them.

Our unified  $M_w$  data set will certainly already improve the  $M_w$  estimates of the SHA data sets (instrumental catalogues and ground motion data sets) not only in France but also in Europe: we have unified  $M_w$  estimates for 1/5 of the Traversa *et al.* (2020) data set and 2/5 of the ESM-EMEC data set. This unified  $M_w$  data set could be also used directly as metadata to describe the events included in the recently published database of earthquake focal mechanisms in metropolitan France and conterminous Western Europe, FMHEX20 (Mazzotti *et al.* 2021). Furthermore, the impact of such unification strategy on the interevent variability of GMMs will have to be assessed.

Finally, in this work, we shared our feedback on the traceability, reproducibility and quality of the  $M_w$  collections in the requested databases. Efforts should be pursued in this direction in order to define international standards, to facilitate the choice of the best  $M_w$  estimate for the end-users.

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## DATA AVAILABILITY

The data used in this paper are available in its online supplementary material.

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