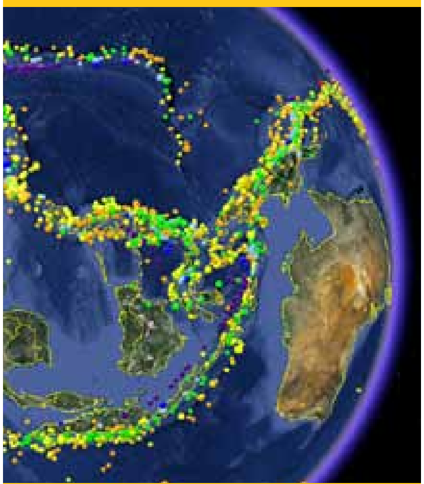
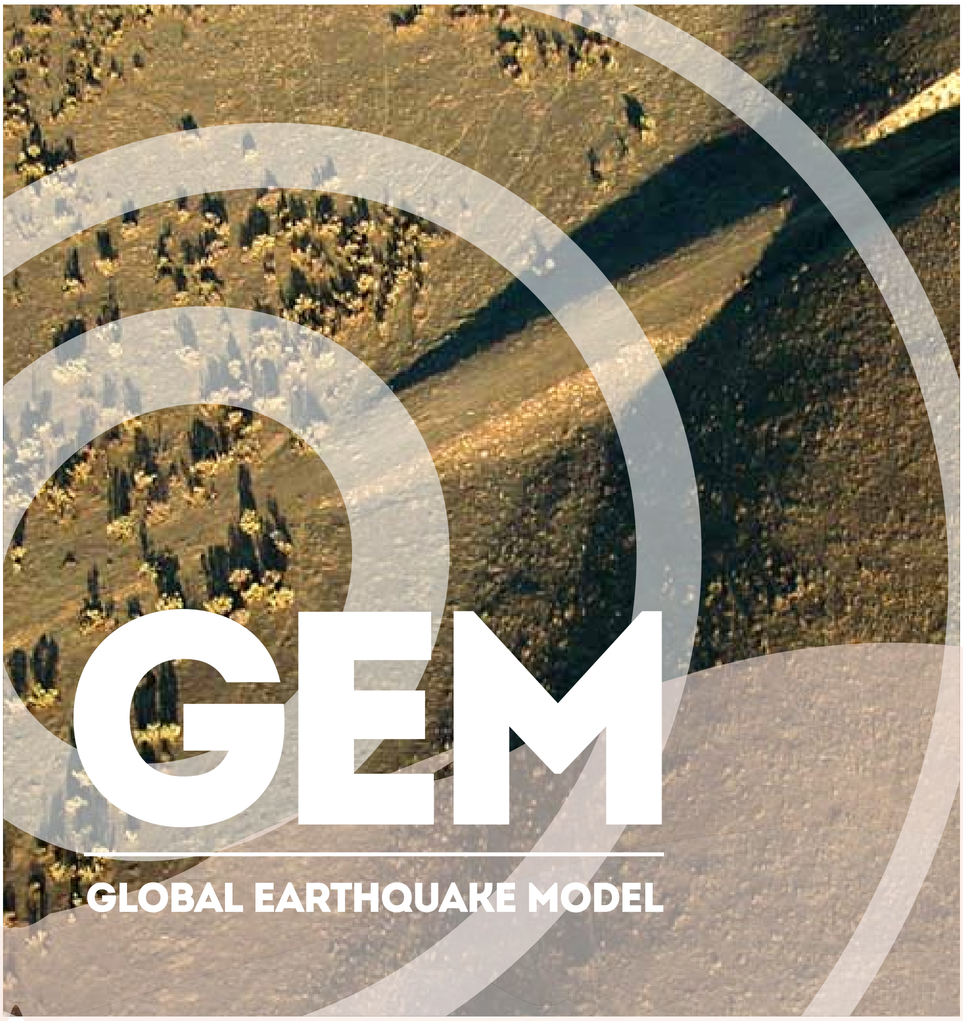
GEM TECHNICAL REPORT
2012-01 V1.0.0

ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009)



Storchak D.A., D. Di Giacomo, I. Bondár, J. Harris, E.R. Engdahl, W.H.K. Lee, A. Villaseñor, P. Bormann, and G. Ferrari

GEOLOGICAL, EARTHQUAKE AND GEOPHYSICAL DATA



ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009)

GEM Technical Report 2012-01

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Large cover image: © Scott Haefner/ USGS. Close-up shot of the southeast area along the surface trace of the San Andreas fault in the Carrizo Plain, north of Wallace Creek, where Elkhorn Rd. meets the fault.

Small cover image: © 2013 GEM Foundation and International Seismological Centre, © 2013 Google, © 2013 Geo Basis-DE/BKG, Data SIO, NOAA, U.S. Navy, NGA, GEBCO. Close-up view of the ISC-GEM Global Instrumental Earthquake Catalogue, 2013 ISC-GEM KML file overlayed on 2013 Google Earth.

www.globalquakemodel.org

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- Göran Ekström (Columbia University, *US*) who provided analysis of uncertainties of M_W values in GCMT Catalogue;
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We wish to recognize the initiative of the late Edouard Arnold and Pat Willmore, former Directors of the ISC, for their initiative, despite the financial difficulties, in organizing the first effort of transferring a large fraction of the ISS paper bulletins onto punch-cards and preparing the Shannon tape. We also wish to acknowledge the effort of Tom Boyd, Colorado School of Mines, USA, for his contribution in correcting the data on the Shannon tape.

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ABSTRACT

This report describes the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009) created on the request and with sponsorship from the GEM Foundation.

- The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009) is a major step forward on the way to improve characterization of spatial distribution of seismicity, magnitude frequency relation and maximum magnitudes within the scope of GEM.
- With a few exceptions, parameters of this catalogue are the result of computations based on the original reports of seismic stations and observatories.
- We made every effort to use uniform location and magnitude determination procedures during the entire period of the catalogue:
  - In earthquake location, we used a combination of the EHB depth determination technique and the new ISC procedures that use a multitude of primary and secondary seismic phases from the IASPEI Seismic Phase List and the ak135 velocity model and take into account the correlated error structure.
  - In determination of earthquake magnitude, where possible, we used direct M_W values from Global CMT project for the period 1976-2009. In addition, 1,127 high quality scientific papers have been processed to obtain directly measured values of M_0 and M_W for 970 large earthquakes during 1900-1979. In all other instances we computed M_W proxy values based on our own determination of instrumental surface or body wave magnitudes using updated regression models.
  - It has to be noted that a computation of M_W proxy values based on regressions from other types of magnitudes does not bring similarly reliable results as compared to a direct measurement of M_W based on the original waveform analysis. It is, nevertheless, a necessary measure since the direct measurement of M_W using historical analogue waveforms on a global scale is beyond the scope of this project.
- A number of important additional benefits have been achieved during this project:
  - The entire ISC collection of historical paper-based seismic station bulletins was reviewed, indexed and catalogued for further works. Indexes of similar collections at USGS/Berkeley were used in filling the gaps in the ISC collection.
  - A large number of seismic phase arrival times, body and surface wave amplitude measurements have been made electronically available on a global scale that have never been available on a global scale prior to this project.
  - A large number of more accurate network M_S and m_b magnitudes have been computed for large earthquakes that either had no magnitude estimate or the estimates were previously based on single or unreliable station data.
- In our work we consulted and were observed by experts from the IASPEI and, where possible, followed the IASPEI seismic standards.

- We put together an excellent team of professionals in the field and gave training to a group of technical personnel without whom the work on this project would have been impossible to complete. These personnel members are a valuable asset of this project and their experience can be used if further work was to be planned.
- Although the ISC-GEM Catalogue is a major accomplishment, we nevertheless believe that further work is necessary to enhance its qualities:
  - *Firstly*, neglecting to update the ISC-GEM Catalogue beyond 2009 would seriously hamper the GEM community efforts of testing and refining of the earthquake forecasting models.
  - *Secondly,* it is well known that in seismic hazard studies the effect of small to moderate size earthquakes is not negligible. This is especially the case in densely populated and industrialized areas. This calls for further improvement of completeness of the reference catalogue to be extensively used by GEM community for many years to come.
  - *Thirdly*, it has to be noted that we really have no magnitude estimates for many events in our main original source of historical data before 1964 – the ISS Catalog. Some of these events in the first part of the 20th century could be large enough to have caused damage. The work of including many more earthquakes recorded at teleseismic distances and bringing previously unavailable station amplitude data from historical station bulletins would greatly contribute to more accurate consequent analysis of global earthquake hazard and risk.

Keywords

instrumental catalogue; earthquake; magnitude; location; relocation; depth

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1 Introduction

In 2010, the Global Earthquake Model (GEM) Foundation issued a call for proposals to compile a reference Global Instrumental Earthquake Catalogue (1900-present) to be used for characterization of the spatial distribution of seismicity, the magnitude frequency relation and the maximum magnitude. The International Seismological Centre (ISC) made a successful bid for this proposal by bringing together an international team of most experienced professionals in the field willing to deliver the required product:

- Dmitry A. Storchak (ISC, *UK*)
- Domenico Di Giacomo (ISC, *UK*)
- István Bondár (ISC, *UK*)
- James Harris (ISC, *UK*)
- E. Robert Engdahl (Colorado University, *US*)
- William H.K. Lee (USGS, emeritus, *US*)
- Antonio Villaseñor (IES Jaume Almera, *Spain*)
- Peter Bormann (Helmholtz Centre Potsdam GFZ, emeritus, *Germany*)
- Graziano Ferrari (INGV/SISMOS, *Italy*)

The Project was managed by Dmitry Storchak, the Director of the ISC, with scientific input from William Lee. The work was overseen by observers on behalf of the International Association of Seismology and Physics of the Earth's Interior (IASPEI) to guarantee validation of the Catalogue and its acceptance as a true reference in seismic hazard studies:

- Peter Suhadolc (University of Trieste, *Italy*),
- Roger Musson (British Geological Survey, *UK*),
- Johannes Schweitzer (NORSAR, *Norway*),
- Göran Ekström (Columbia University, *US*),
- Nobuo Hamada (Japan Meteorological Agency, emeritus, *Japan*)

The ISC offered the GEM Foundation the existing efficient and internationally recognized facility, operating under non-governmental status and routinely producing one-year's worth of the most complete seismic bulletin on a global scale each calendar year (Adams et al, 1982). As many as 8 IT, Data Entry and Administration staff at the ISC worked on this project.

In this final report, we describe the procedures and results of several closely related tasks that contributed towards the reliable and uniform global catalogue of large earthquakes during the 110 year period in line with the proposed cut-off magnitudes:

- 1900-1917: *magnitude* ≥ 7.5 worldwide plus selection of smaller shallow events in stable continental areas;
- 1918-1959: *magnitude* ≥ 6¼;
- 1960-2009: *magnitude* ≥ 5.5.

2 Processing of Historical Paper-Based Sources

Here we describe the work of collecting, reviewing, digitizing and interpreting data from a multitude of historical sources: paper-based global earthquake catalogues as well as the individual observatory and network bulletins containing parameters of large earthquakes of the past.

The preliminary earthquake selection was done using available magnitude estimates from different sources.

2.1 Processing of Data from Existing Global Earthquake Catalogues

To perform the relocation of selected earthquakes that occurred prior to 1964 (the start date of the digitally available ISC bulletins) we had to collect the phase arrival time data from different sources that were available only in either printed or a hand-written form. These have been converted to a digital form using two methods. For good quality printed bulletins with standard formats we have used optical character recognition (OCR) techniques. In case of poor quality variable formats and hand-written sources we entered the data manually.

2.1.1 1904-1912: Gutenberg notepads

During the period 1904-1912, the main source of seismic phase arrival times is the Gutenberg’s collection of notepads. This collection is available on microfiche (Goodstein et al., 1980) and also as a collection of scanned images kindly provided to the project by Professor Abe. When available, we have used the scanned images because these are of slightly higher quality compared to the microfiches. However some of the notepads had not been scanned in which case we had to use the microfiches.

Gutenberg’s notepads are hand-written, and both the scanned images and microfiches are of poor quality, making it impossible to use OCR methods. Therefore we entered P and S wave arrival time data by hand. The total number of earthquakes processed from this time period was 56.

2.1.2 1913-1917: Seismological Bulletin of the British Association for the Advancement of Science (BAAS)

During the period 1913-1917, the most useful source of associated phase arrival times are the Seismological bulletins of the British Association for the Advancement of Science (BAAS). These bulletins are the predecessors of the International Seismological Summary (ISS), and are available in good quality printed form. However the format changes slightly from year to year, making it difficult to use automated methods based on OCR. Therefore, we also opted to enter the phase arrival time data of P, S and supplementary phases by hand. The number of earthquakes processed from this period was approximately 50.

2.1.3 1918-1963: International Seismological Summary (ISS)

During the period 1918-1963, the main source of phase data is the International Seismological Summary (ISS). These bulletins are available in a fairly stable printed form with some of the data already converted to digital form prior to the beginning of this project:

- A digital file containing hypocentre and phase data for most of the earthquakes during 1918-1942 was available thanks to the efforts of Pat Willmore and Edouard Arnold (the first two Directors of the ISC), who arranged for the ISS bulletins to be typed at a professional data preparation bureau based near Shannon airport in Eire (Ireland). Unfortunately, the ISC funds at the time were too short to allow this work to continue beyond data year 1942. This file (hereafter referred to as the "Shannon tape") was created by manually entering the observations from the ISS bulletins onto punch cards.

- All earthquakes in the ISS for 1960-1963 were already relocated by Villaseñor and Engdahl (2007) and the phase data were also available in digital form.
- All earthquakes in the ISS with $M_S \geq 7.0$ were part of the Centennial Catalog (Engdahl and Villaseñor, 2002), hence the corresponding phase data were also available.

We nevertheless needed to enter the phase data for some earthquakes missing from the Shannon tape (1918-1942) as well as for majority of earthquakes with $6.25 \leq M_S < 7.0$ in 1943-1959. We have used OCR to convert these data to digital form because the quality of the printed bulletins is good and the phase data are listed in homogeneous tabular form. All ISS bulletins had been previously scanned as black and white TIFF images at a resolution of 600 dpi. We used the commercial software *Textbrigde* to perform automatic OCR of all ISS bulletin pages. Then we proof read those pages that contained data for the selected earthquakes. The proof reading was done with the help of an in-house built computer program that corrected the most common misidentifications (number "1" for the letters "l" or "i", number "0" for the letter "O", etc), and checked for invalid values in different columns in the table such as the station name, distance, azimuth, P, S and supplementary phases times and residuals. The number of earthquakes processed from this period was approximately 700.

2.2 Processing of Individual Historical Seismic Station and Network Bulletins

The main disadvantage of the majority of global catalogues previously described was the absence of earthquake magnitude estimates and, most importantly, the absence of seismic wave amplitude data that in the majority of cases had to be sourced by the ISC historical data entry team from the original observatory and network bulletins.

2.2.1 Preparation of the historical bulletins

The processing of historical seismic bulletins was the core of the whole project and involved the most time consuming work of dealing with the ISC historical seismic station bulletin collection along with selected bulletins from USGS/Berkeley (courtesy of W. Lee), scanned bulletins available from Schweitzer and Lee (2003) as well as the scanned materials provided by the Institute of Seismology in Bishkek, Kyrgyzstan and by the Geophysical Survey of Russian Academy of Sciences in Obninsk.

The main target of this task was to retrieve surface wave amplitude data for M_S re-computation from individual station bulletins covering the period 1900-1970. This is because the ISC database already contained surface wave amplitudes/periods starting from 1971.

Up to five data entry officers at each time worked at the ISC on this project since August 2010 for more than 18 months.

Figure 2.1 A view of the ISC warehouse containing the original collection of historical seismic station bulletins.

The first step was to assess the original historical station bulletins that were originally stored in chronological order in the ISC warehouse in cardboard boxes, as seen on the left hand side of the Figure 2.1. The bulletins were taken out of boxes and re-organised per country and observatory in chronological order. Particulars of each booklet have been registered in the database for further reference. These included basic information such as institution and publication names, year, town, country, etc. Interactive data entry screens with underlying checks and database entry programs have been developed to increase the speed and accuracy of data entry. The final Bulletin Registry (up to year 1970) now includes 15,257 individual entries covering volumes from 293 institutions in 80 countries. While building the Bulletin Registry, the quality and the suitability of each observatory bulletin was assessed. Priority was given to observatories providing reliable and systematic surface wave amplitude measurements for earthquakes recorded at teleseismic distances. The bulletins were consequently subdivided into groups depending on the availability of reliable surface wave amplitude readings and length of time for which each observatory product is available. Therefore, the entire bulletin collection was subdivided into the following three groups (Figure 2.2):

1. Bulletins of primary importance for magnitude determination that must be used;
2. Those bulletins that could be helpful yet were to be used only if resources would permit;
3. Those bulletins that can’t be used for earthquake magnitude determination.

It is important to note that the bulletin registry time coverage did not guarantee that data for earthquakes in a given period is available in a specific bulletin, yet the Registry is still useful to indicate the data gaps for a station/institution. It must be pointed out also that some institution bulletins (e.g., the “Academy of Sciences, USSR”) provided data from a large network of stations therefore the number of individual seismic stations actually processed is larger than shown on Figure 2.2 in red.

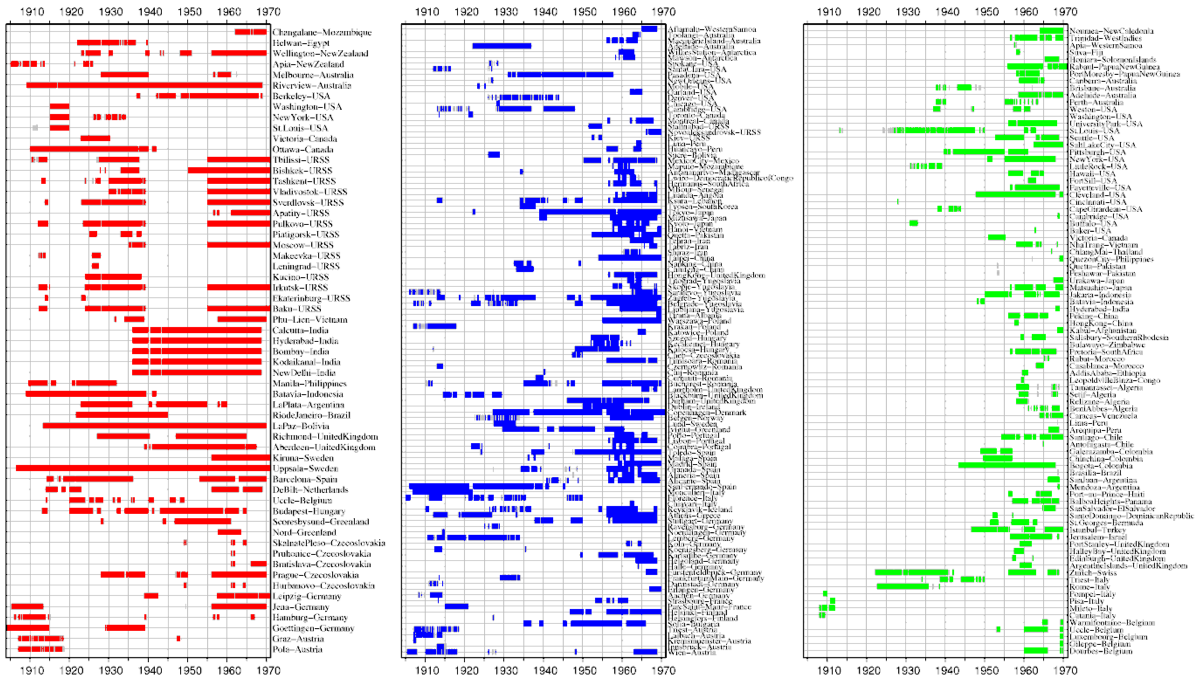


Figure 2.2 Bulletin Registry time coverage: in red are shown bulletins belonging to group 1, blue to group 2 and green to group 3; see text for details.

2.2.2 Entering parametric station records into the database

Although both the seismic phase arrival times and the seismic wave amplitude data have been entered, the most important benefit of the historical bulletin data entry work was in providing data for earthquake magnitude computation. The data entry effort benefitted from a dedicated interactive web browser interface developed at the ISC to limit the amount of manual work. Once entered, the data were automatically inserted into the database.

Specific criteria were formed to decide whether or not an individual *reading* (in the ISC jargon a *reading* groups all the parametric data from a single station associated to a specific earthquake and reported by the same agency) from a bulletin was relevant to an event of interest. For example, when a *reading* for an earthquake to be relocated is available in the station bulletin, the data entry team checked the availability of period and amplitude data for surface and body waves. An example of a *reading* selected is shown on Figure 2.3 for station Göttingen (Germany) for the well-known 1906 San Francisco earthquake. Figure 2.4 shows the same data stored in digital format.

seismische Registrierungen in Göttingen im Jahre 1906. 33

Datum	Charakter	Phasen	Zeiten (Greenwich)	Perioden Sekunden	Amplituden A_E	A_N	Bemerkungen
			h m s		μ	μ	
April 18	III u	e P	13 24 30	3, 6, 9			Kalifornien (San Francisco zerstört).
				18	3	4	
		i	43				Unregelmäßige Wellen.
		P R_1	ca. 28,2				
		P R_2	ca. 30,1				
		S	34 29	17	8		
				20			
		i	35 34	8	25		
				17		80	
		e L	50,6	60			
				35	950	1500	
		M_1	53,1	30		800	Die Ost-Westkomponente des 1200 kg Pendels hat an die Hemmung geschlagen.
		M_2	57	22		750	
		M_N	59,4	20		1600	
		F	19				

Figure 2.3 An example of the Göttingen station bulletin with the reading of the 1906 San Francisco earthquake

sta	day	onset	phase	rdid	phid	ampid	chan	per	amp	ampunits	amptype
goettingen	1906-04-18 13:24:30	e	P	675	5396	4407	??E	3;6;9;18	3	micro	0-to-p
goettingen	1906-04-18 13:24:30	e	P	675	5397	4408	??N	3;6;9;18	4	micro	0-to-p
goettingen	1906-04-18 13:24:43	i		675	5398						
goettingen	1906-04-18 13:28:12		PR1	675	5399						
goettingen	1906-04-18 13:30:06		PR2	675	5400						
goettingen	1906-04-18 13:34:29		S	675	5401	4409	??E	17	8	micro	0-to-p
goettingen	1906-04-18 13:34:29		S	675	5402	4410	???	20		micro	0-to-p
goettingen	1906-04-18 13:35:34	i		675	5403	4411	??E	8	25	micro	0-to-p
goettingen	1906-04-18 13:35:34	i		675	5404	4412	??N	17	80	micro	0-to-p
goettingen	1906-04-18 13:50:36	e	L	675	5405	4413	???	60		micro	0-to-p
goettingen	1906-04-18 13:50:36	e	L	675	5406	4414	??E	35	950	micro	0-to-p
goettingen	1906-04-18 13:50:36	e	L	675	5407	4415	??N	35	1500	micro	0-to-p
goettingen	1906-04-18 13:53:06		M1	675	5408	4416	??N	30	800	micro	0-to-p
goettingen	1906-04-18 13:57:00		M2	675	5409	4417	??N	22	750	micro	0-to-p
goettingen	1906-04-18 13:59:24		MN	675	5410	4418	??N	20	1600	micro	0-to-p
goettingen	1906-04-18 19:00:00		F	675	5411						

Figure 2.4 Göttingen data from the reading on Figure 2.3 as available in the database

Both the format and contents of each bulletin were subject to an abrupt change over a long period of time, hence care and attention to detail was essential in features such as a change of layout, language or phase names. Due to limitations in funding over many years, the concurrent ISS/ISC staff used only those parameters from the incoming bulletins that were immediately required for its operation. Thanks to the current data entry effort, amplitudes and periods of surface waves for many large events of the 20th century have now become electronically available.

Over 34,000 *readings* have been added to include over 110,000 phases with valid amplitudes and periods for magnitude re-computation. To further emphasize the importance of these data, Figure 2.5 shows the standard travel time plots that allow comparison of the volumes of parametric data from the ISS bulletins (where amplitudes are not available) and data entered from the historical station and network bulletins.

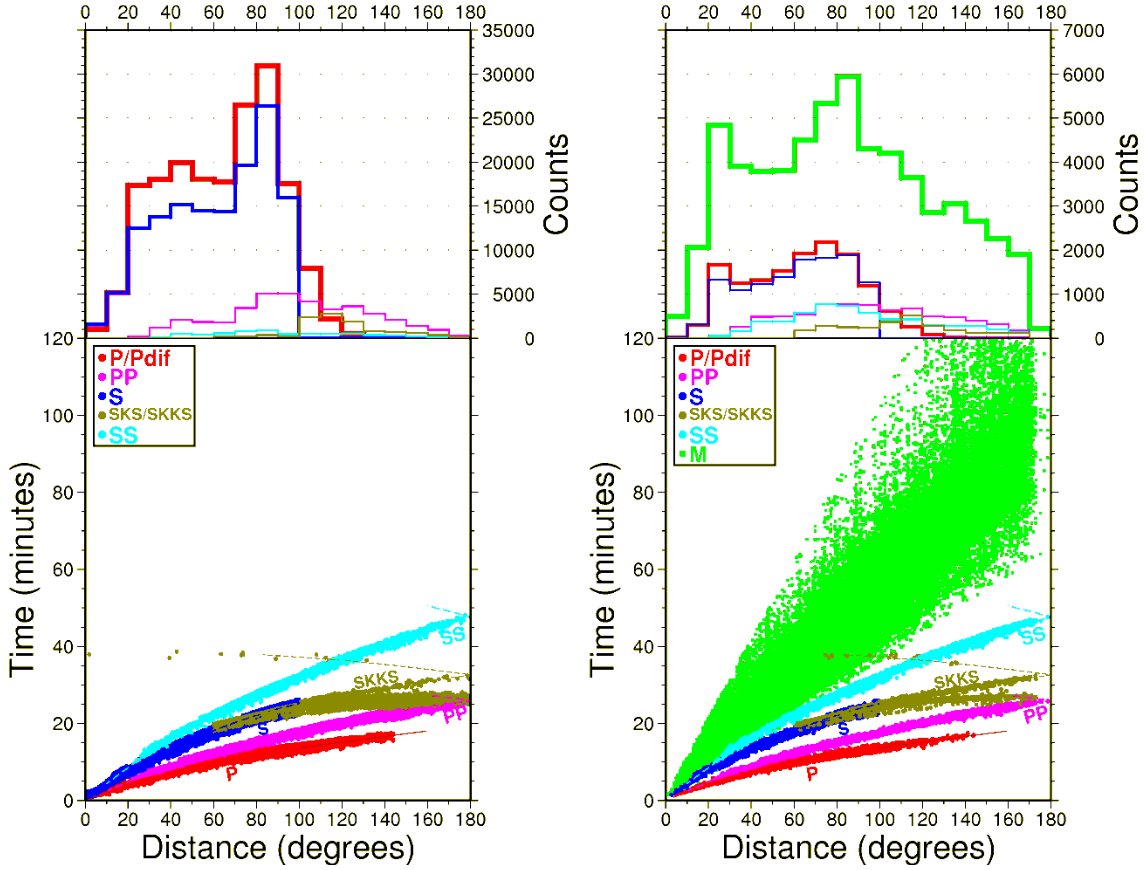


Figure 2.5 Travel time plot for ISS data for earthquakes during the period 1918-1963 is on the left; on the right is a similar graph for readings with amplitudes obtained from the individual station bulletins. Note the green symbols representing the surface wave amplitude electronically available for the first time on a global scale from several stations

Obviously, the ISS data and the new amplitude data made available during this project complement each other and are both of fundamental importance for computing homogeneous locations and magnitudes throughout the historical period.

The time coverage for individual seismic stations contributing to magnitude re-computations is shown on Figure 2.6.

The impact of both World War I and II can be seen as gaps in the reporting from many stations. There are only a few stations that worked almost continuously during the historical period. These are the Uppsala (UPP, Sweden), which is probably the best example of an excellent seismic observatory during the period 1906-1970, Riverview (RIV, Australia) and La Paz (LPZ, Observatorio San Calixto, Bolivia). Almost all good quality European stations as well as stations of the Russian Empire and the Former Soviet Union show gaps in reporting, mainly during the World War I and II. Large gaps, both in space and time, are also present in the southern hemisphere, in North America and in Africa. Despite these gaps, however, the time-space station distribution of available data usually provided a good azimuthal coverage for the determination of magnitudes of over 4,500 relocated earthquakes between 1904-1970.

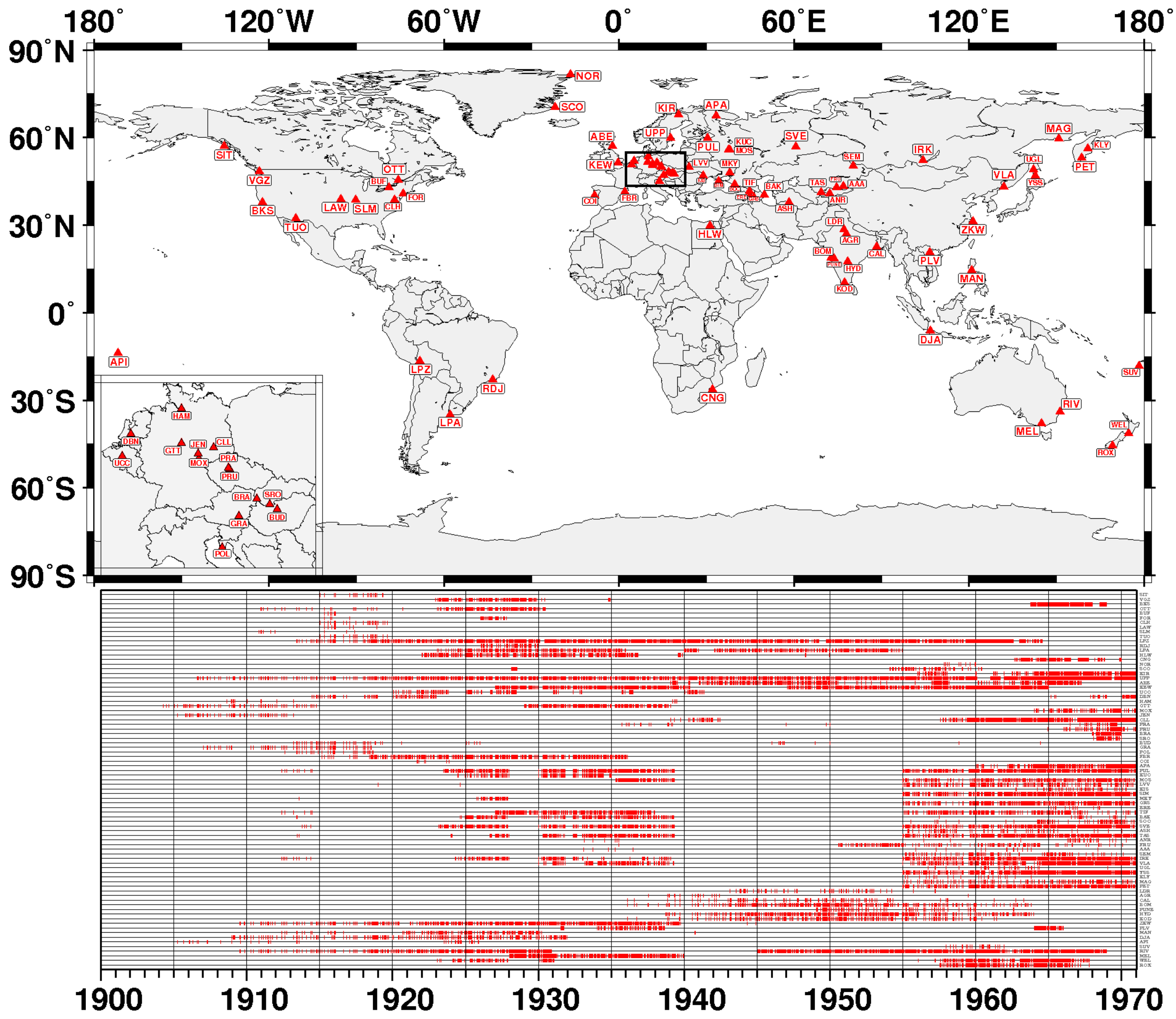


Figure 2.6 Top: locations of stations for which amplitude data has been added during this project. Bottom: time coverage for each station shown in the map; each vertical segment represents the earthquake origin time for which a reading of a station has been added. The inset shows stations in Central Europe in large scale

2.3 Remarks

As a result of the 18 months long data collection and digitising effort, we complemented digitally available data of the ISC Bulletin with bulletin data that extended it into the past until year 1900.

It has to be noted that no sufficient volume of parametric station data was found to run the standard relocation and magnitude estimation in the period 1900-1903, hence the hypocentre parameters of all earthquakes in this period were adopted from Abe and Noguchi (1983a,b).

3 Earthquake Relocation

In order to obtain improved locations for the ISC-GEM Catalogue covering the period 1904-2009, we follow a two-tier procedure using the EHB (Engdahl et al., 1998) and the ISC (Bondár and McLaughlin, 2009a; Bondár and Storchak, 2011) location algorithms. Both the EHB and ISC location algorithms use all reported phases in line with the IASPEI standard (Storchak et al., 2003 and 2011) with a valid ak135 (Kennett et al., 1995) 1D travel-time prediction in the location, together with elevation, ellipticity (Dziewonski and Gilbert, 1976; Kennett and Gudmundsson, 1996; Engdahl et al., 1998), and depth-phase bounce point corrections (Engdahl et al., 1998). The application of two of the most advanced single-event location algorithms provides the necessary quality assurance to produce highly accurate event locations for the ISC-GEM Catalogue.

For the historical period (1904-1963) where the ISC-GEM data collection effort provided data from the scanned ISS bulletins (Villaseñor and Engdahl, 2005; 2007), original station reports from the ISC archives and the Gutenberg notepads, we obtain the initial estimates of event hypocentres using the new ISC location algorithm. For the modern period (1964-2009) where no substantial volume of station readings has been added to the ISC database, we simply use the preferred solution from the ISC bulletin.

Using the initial locations described above the locations and depths of all events included in the ISC-GEM Catalogue are first determined using the EHB algorithm. In the absence of depth constraint by local station phase data, the EHB algorithm provides a comprehensive analysis of reported phases that can significantly improve event depth estimates by identifying and utilizing near-event surface reflections (depth phases). The new ISC location algorithm is used next with earthquake depths fixed to those from the EHB analysis. The ISC algorithm provides independent depth confirmation using depth phase stacking and also provides more accurate hypocentre locations by taking correlated travel-time prediction error structure into account.

3.1 Earthquake Depth Determination

Depth phases provide important constraints on event depth because their travel time derivatives with respect to depth are opposite in sign to those of the direct P phase. Depth to origin time trade-off is also avoided by the inclusion of depth phases. These phases are commonly reported as pP or sP (a P-wave or S-wave reflecting off of a hard rock interface, respectively) or as pwP (a P-wave reflected off the ocean or ice surface). However, often as not these phases are simply reported as unidentified phase arrival times. With knowledge of an event depth and distance, potential depth phase arrivals are re-identified following each iteration in the EHB procedure using a probabilistic association algorithm. Probability density functions (PDF) for depth phases, centered on their theoretical relative travel times for a given hypocenter, are compared to the observed phase arrivals. When PDFs overlap for a particular depth phase, phase identification is assigned in a probabilistic manner based on the relevant PDF values, making sure not to assign the same phase to two different arrivals. This procedure works relatively well in an automatic fashion, but the phase identifications can depend heavily on the starting depth, which in most cases is not well known. Hence, depth phase identifications for every event in the ISC-GEM Catalogue have been manually scrutinized for the possibility of an erroneous local minimum in depth because of a poor starting depth and adjusted accordingly. Normally, at least five corroborating depth phases are necessary to for an EHB depth to be accepted.

In order to determine pwP arrival times and correct all depth phases for topography or bathymetry at their reflection points on the earth's surface, it is necessary to first determine the latitude and longitude of these bounce points and then the corresponding seafloor depth or continental elevation. Bounce point coordinates are easily computed from the distance, azimuth and ray parameter of the depth phase (pP in the case of pwP). The NOAA ETOPO1 global relief file (Amante and Eakins, 2009) was averaged over 5 x 5 minute equal area cells and then projected on a 5 x 5 minute equi-angular cell model using a Gaussian spatial filter. The use of a smoothed version of ETOPO1 is justified because the reflection of a depth phase does not take place at one single point, but over a reflection zone with a size determined by the Fresnel zone of the wave. The maximum half width of a ray with a wavelength of 10 km and a ray path length of 1000 km is estimated to be 36 km (Nolet, 1987). The topographic and bathymetric information in this version of ETOPO1, referred to bedrock, is used to determine the correction for bounce point elevation/depth, which is added to the computed travel times for depth phases. Theoretical times are not computed for pwP phases in the case of bounce point water depths ≤ 1.5 km because it is nearly impossible to separate the pP and pwP arrivals on most records (about 2s separation).

Despite the general success of the EHB procedures for depth determination, there remain some issues that must be taken into account. For example, the relative frequency (or amplitude) of depth phase observations is sensitive to local structure at bounce points. Many depth phases reflect in the vicinity of plate boundaries where the slopes of surface reflectors are large (> 1 degree). Reflections at a dipping reflection zone may lead to small asymmetries in depth phase waveforms and, may influence their relative amplitudes, resulting in a greater potential for phase mis-identifications. In addition, for short-period (1s) waves, water-sediment interfaces at the sea bottom may have small impedance contrasts. Consequently, on short-period seismograms the amplitude of a pwP phase may be comparable to or larger than the pP phase reflecting at the sea bottom, and pwP may easily be mis-identified as pP.

One outstanding issue is that for large shallow-focus complex earthquakes pP often arrives in the source-time function of the P phase, which may consist of one or more sub-events. The gross features of the source-time functions of P and pP, however, remain discernible in broadband displacement records and the exact onset times of depth phases can be further refined by examination of velocity seismograms that are sensitive to small changes in displacement. For the GEM project we have relied primarily on reported phase arrival times, usually read from short-period seismograms. However, for large complex events EHB depths ordinarily have to be set to depths published by USGS/NEIC that have been determined by rigorous analysis of phase arrival times read from broadband seismograms.

Finally, there are many events in the ISC-GEM Catalogue for which there are no reported depth phases or for which those that were reported are inconsistent, especially in the earlier part of the 20th century. For these events a nominal depth is adopted, based on the depth distribution of neighbouring events that are well constrained in depth and are consistent with other event depths in that tectonic setting. For every subduction zone worldwide, all ISC-GEM events were plotted in cross section with respect to the arc center of curvature to assist in setting depths of those events that have no other available depth constraints.

3.2 Earthquake Epicentre and Origin Time Determination

In the next step of ISC-GEM location procedures we determine the earthquake epicenter and origin time parameters by fixing the depth to that obtained from the EHB analysis. The EHB location and origin time are used as the initial guess for the ISC locator. The ISC location algorithm can further refine the locations because it reduces the location bias introduced by the correlated travel-time prediction error structure due to unmodeled 3D heterogeneities in the Earth.

Figure 3.1 shows the total number of associated phases and those that are used in the location in each year. As the number of phases increases almost exponentially in time, the number of phases traveling along similar ray paths increases accordingly, contributing more and more to the potential location bias. Thus, accounting for the correlated error structure becomes imperative.

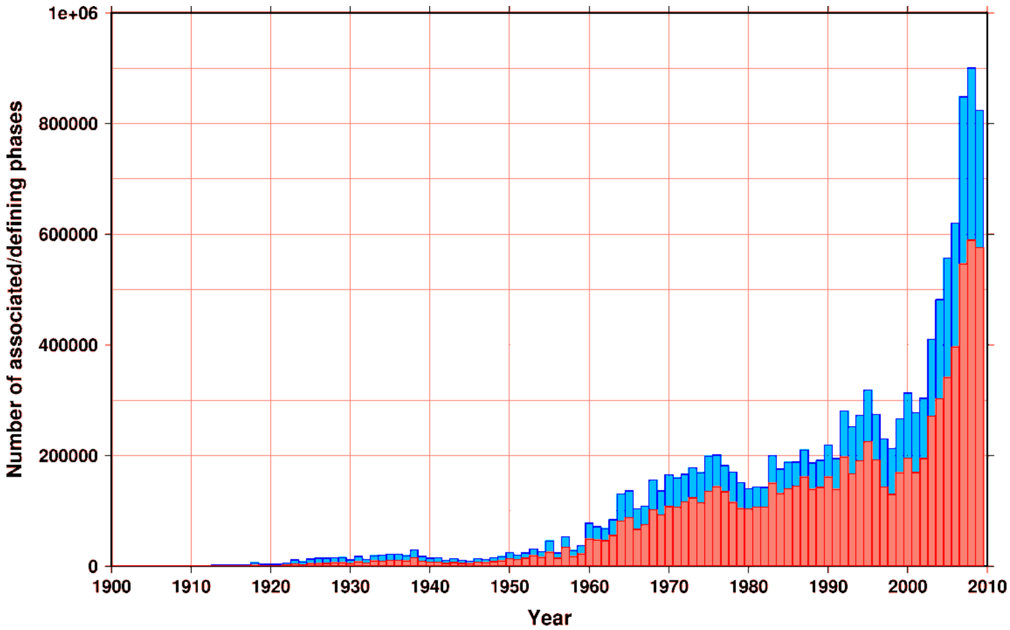


Figure 3.1 Annual number of associated (blue) and defining (red) phases in the ISC-GEM Catalogue. A defining phase is used in the location

Figure 3.2a shows the distribution of location differences between the EHB and ISC locations for events in the ISC-GEM Catalogue. 50% of the locations are within 9km of each other and 90% of the location differences are less than 20 km. Given that the ISC-GEM Catalogue locations are predominantly teleseismic, the EHB and ISC locations show remarkable consistency. Figure 3.2b shows the location deviations with respect to the EHB locations. The plot indicates that there is no bias between the EHB and ISC locations.

Even though the depth is fixed to the EHB depth, the ISC location algorithm may obtain an independent depth estimate through the depth-phase stacking (Murphy and Barker, 2006) provided that sufficient number of first-arriving P and depth-phase pairs are available. Some 65% of the events in the ISC-GEM Catalogue also have depth estimates from the depth phase stacking. Figure 3.3 shows an excellent agreement between the depths obtained through the EHB depth determination procedures and the depth-phase stacking.

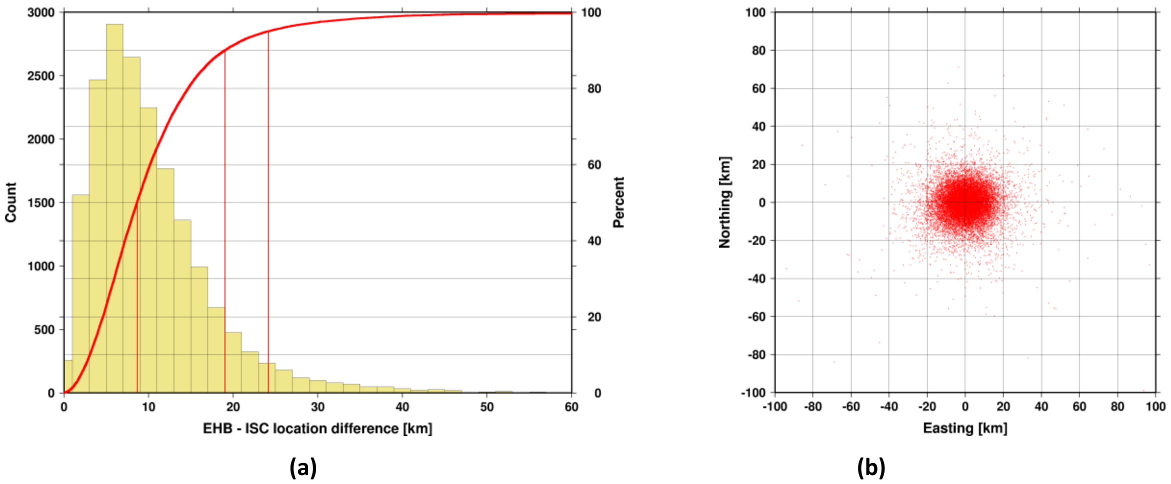


Figure 3.2 a) Histogram of distances between the EHB and ISC locations for events in the ISC-GEM Catalogue. The 50%, 90% and 95% percentile points on the cumulative distribution (red) are marked the vertical red lines. b) The deviations between the EHB and ISC locations show no bias

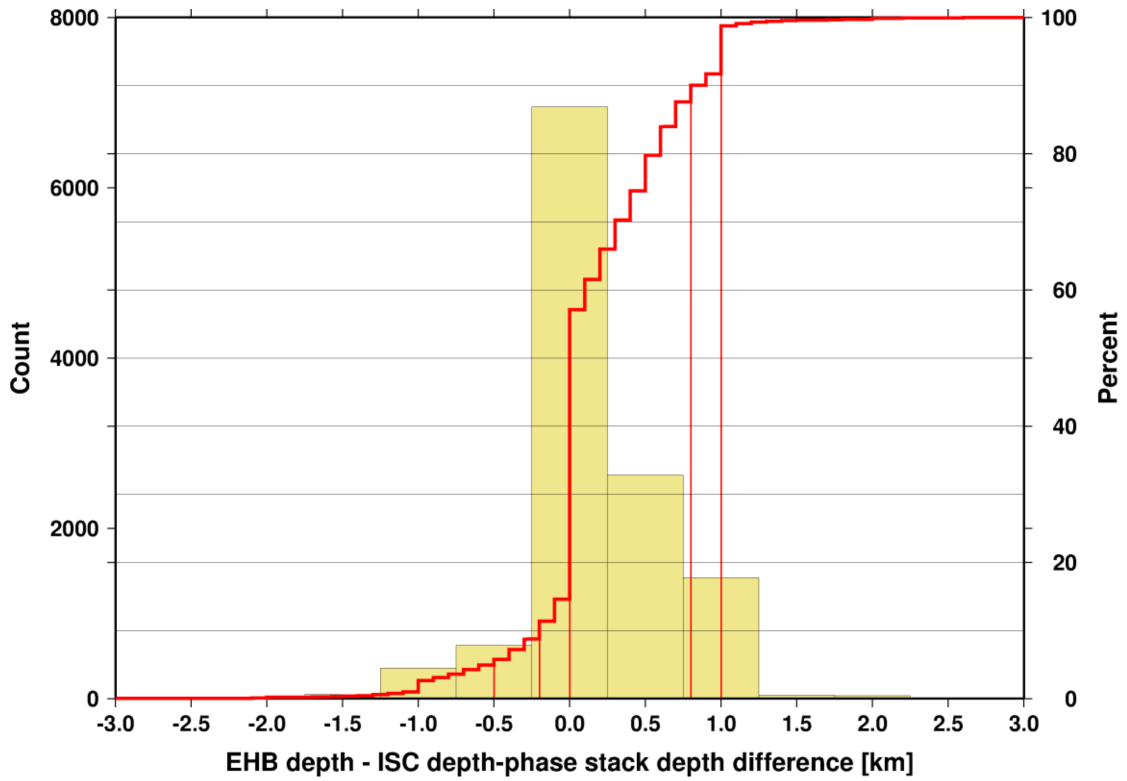
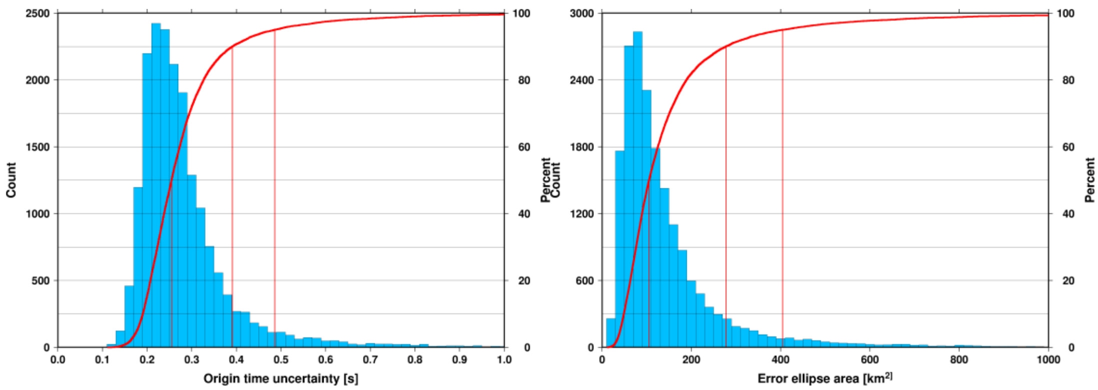


Figure 3.3 Histogram of the difference between the depth estimates from depth phase stacking and the EHB depth determination. The 5%, 10%, 50%, 90% and 95% percentile points on the cumulative distribution (red) are indicated by the red vertical lines

3.3 Uncertainty Estimates and Quality Flags

Accounting for correlated errors not only reduces location bias, but also provides more accurate uncertainty estimates. Most location algorithms assume independent, normally distributed observational errors.

Unfortunately, this assumption rarely holds. Because the 1D global average velocity model used in the location does not capture all the 3D velocity heterogeneities, travel-time predictions along similar ray paths become correlated, decreasing the effective number of degrees of freedom. Because the number of independent observations is less than the total number of observations used in the location, the assumption of independence inevitably leads to underestimated uncertainty estimates. Since the ISC location algorithm uses the effective number of degrees of freedom, the formal location uncertainties described by the *a posteriori* model covariance matrix become larger, resulting in enlarged and more circular error ellipses. Figure 3.4 shows the distribution of origin time uncertainty and the area of the error ellipse, both scaled to the 90% confidence level. The median origin time uncertainty is 0.25s and the median area of the error ellipse is 105 km^2.



(a) **(b)**

Figure 3.4 Histograms of the a) origin time uncertainty, and b) area of the 90% confidence error ellipse for events in the ISC-GEM Catalogue. The 50%, 90% and 95% percentile points on the cumulative distribution (red) are marked the vertical red lines

Besides the formal location uncertainty estimates, i.e. the semi-axes and strike of the 90% confidence error ellipse, we also provide qualitative flags to indicate the quality of the location based on measures of the network geometry. Figure 3.5 shows the cross-plot of secondary azimuthal gap and the eccentricity of the error ellipse for all candidate events processed for the ISC-GEM Catalogue. The secondary azimuthal gap is defined as the largest azimuthal gap when removing a single station (Bondár et al., 2004). The eccentricity varies between 0 and 1; at zero eccentricity the error ellipse becomes a circle, indicating evenly distributed stations around the event, while the error ellipse degenerates to a line at a unit eccentricity, indicating that all stations aligned at a single azimuth from the event.

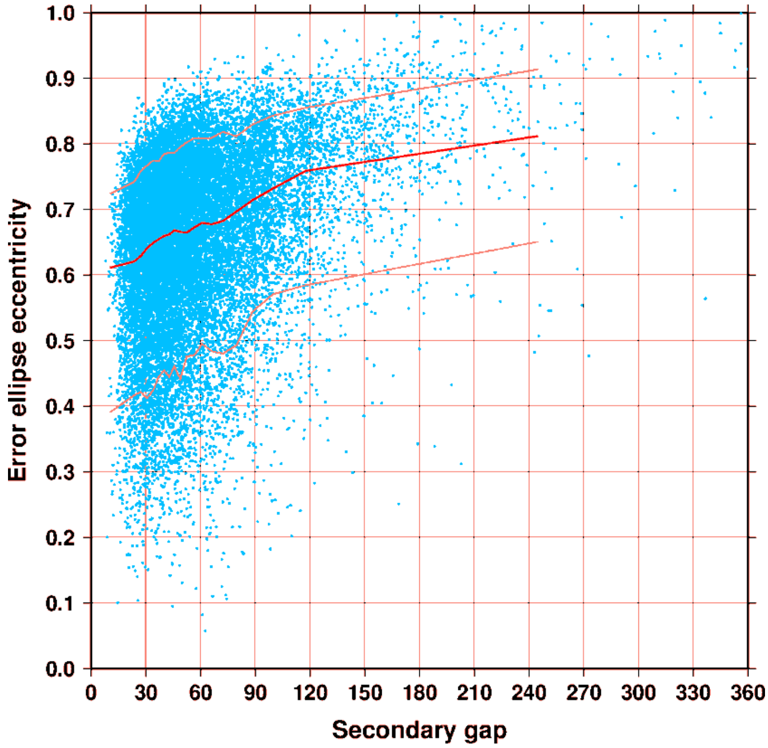


Figure 3.5 Error ellipse eccentricity as a function of secondary azimuthal gap. The thick red line indicates the median curve; the 10% and 90% percentile curves are drawn by thin red lines

The location quality flag 'A' is assigned to events that qualify for GT5 candidate (Bondár and McLaughlin, 2009b) or recorded with a secondary azimuthal less than 120° and with an error ellipse eccentricity less than 0.75. The remaining events that are recorded with a secondary azimuthal gap less than 160° get a location quality flag 'B'; the location quality flag 'C' is assigned to the rest of the locations. Note that events recorded with a huge secondary azimuthal gap (sgap ≥ 270°) or events recorded only with a small number of stations (nsta ≤ 5) are considered unreliable locations and are listed in the Appendix of the ISC-GEM Catalogue.

Because the depth is fixed to the EHB depth, no formal depth uncertainties can be calculated by the ISC locator. In order to provide a depth uncertainty, we use the depth-phase depth uncertainty from the depth phase stacking, if available. These are typically the events where the EHB depth determination procedures relied on the reported depth phases. For events with a nominal depth assigned by the EHB procedures based on the depth distribution of neighboring events we estimate the depth uncertainty as the median absolute deviation of the depths in the corresponding ISC default depth grid cell if it exists, otherwise we set the depth uncertainty to a nominal 25 km.

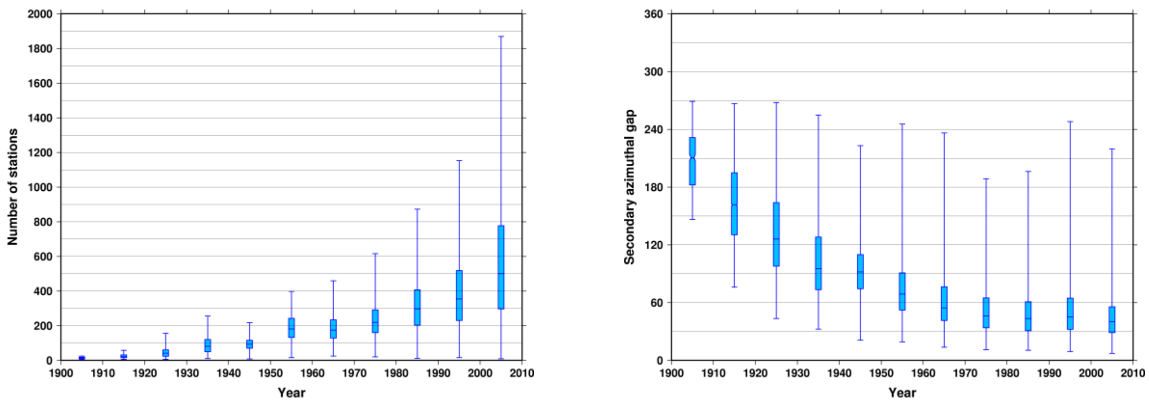
The depth quality flag 'A' is assigned to events that qualify for GT5 candidate (Bondár and McLaughlin, 2009b), or have a depth-phase stack depth estimate, or there is at least one station within 10km from the epicentre. The remaining events that are recorded with two or more stations within 150 km from the epicentre get a depth quality flag 'B'; the depth quality flag 'C' is assigned to the rest of the depth estimates.

3.4 Earthquake Relocation Results

The ISC-GEM Catalogue consists of 18,781 earthquakes between 1900 and 2009. Apart from 10 events between 1900 and 1903, for which we adopt the hypocentre parameters from the Abe Catalog (Abe, 1981, 1984; Abe and Noguchi, 1983), we relocated all earthquakes using the two-step location procedure described above.

One of the major objectives of this project was to provide improved hypocentre estimates for events in the ISC-GEM Catalogue. To achieve this goal we launched an ambitious data entry effort to add station readings that did not exist in digital form before. For events occurring between 1904 and 1963 some 1,200,000 observations were entered into the database either from the station reports in the ISC archive or by digitizing the scanned images of the ISS bulletin (Villaseñor and Engdahl, 2005; 2007). Of the total number of added phases some 600,000 are P-type phases, 300,000 are S-type phases, and the rest are amplitude readings. Some 665,000 P and S type phases contributed to the relocation of events in the historical period. Although no substantial amount of new phase data were acquired for the modern period (1964-2009), the number of phases used in the location has still dramatically increased. Recall that in the past the vast majority of locations in the ISC bulletin were obtained using only first-arriving Pg, Pn and P phases. The number of defining phases used in the location in the modern period increased from 5,369,057 to 8,323,832 owing to fact that both the EHB and ISC locators use all *ak135* phases in the location.

Figure 3.6 shows the median number of stations and the median secondary azimuthal gap together with their 25% - 75% quartile ranges and extreme values in each decade. As the number of stations used in the location increases with time, the median secondary azimuthal gap decreases and levels off around 45°.



(a) (b)

Figure 3.6 Box-and-whisker plot of a) the number of stations, and b) the secondary azimuthal gap in each decade. Blue boxes represent the 25% - 75% quartile ranges; blue lines indicate the full, minimum to maximum range

The preferred locations before the ISC-GEM project constituted a mixture of locations from the Abe (Abe, 1981, 1984; Abe and Noguchi, 1983), the Centennial (Engdahl and Villaseñor, 2002), the ISS (Villaseñor and Engdahl, 2005; 2007) and the ISC catalogues. We compare these locations (before) to the ISC-GEM locations (after). Figure 3.7 shows the locations before and after the ISC-GEM relocations for the entire period, 1900-2009. Even at the global scale it is apparent that the earthquake locations are better clustered in the ISC-GEM Catalogue. In the historical period many event depths were fixed to the surface; due to the better depth estimates, this artifact is removed from the ISC-GEM Catalogue.

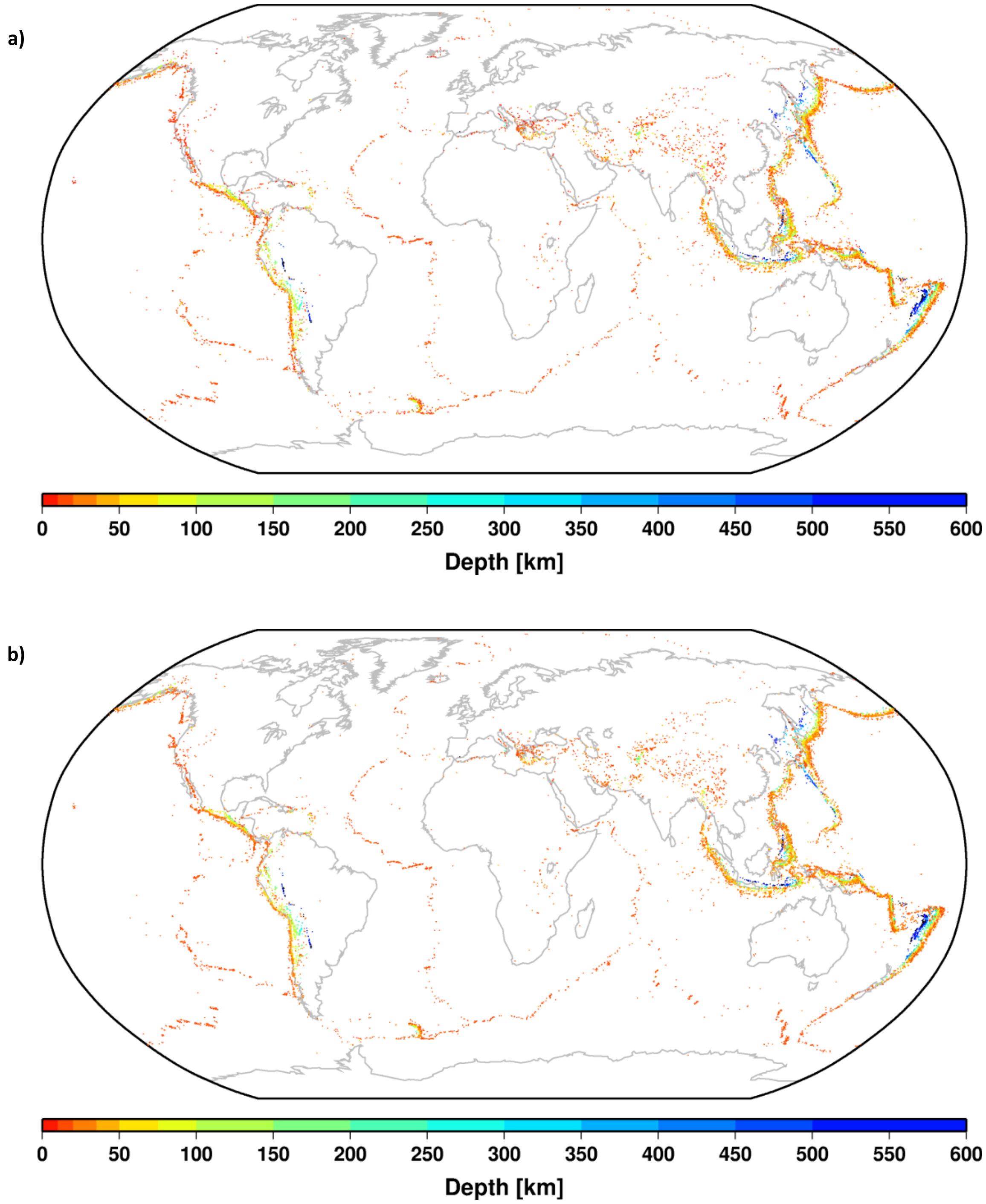
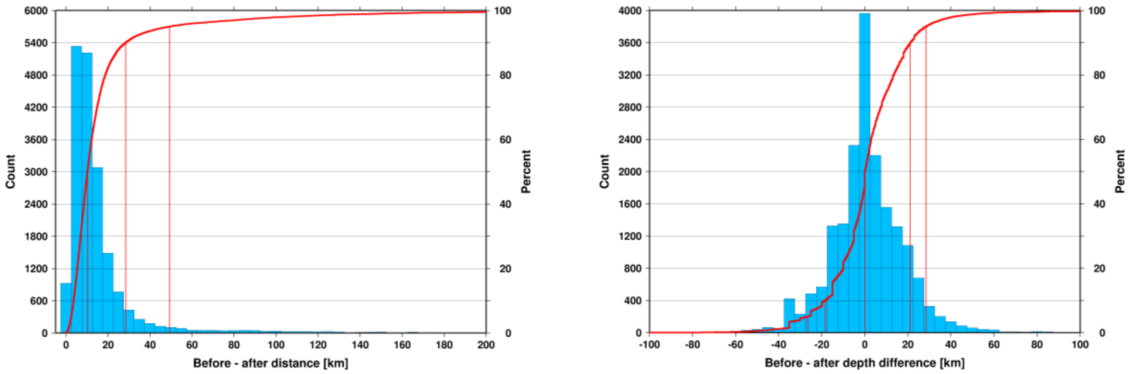


Figure 3.7 Preferred locations a) before and b) after the ISC-GEM relocations. The ISC-GEM locations show an improved view of the seismicity of the Earth

Figure 3.8 shows the distributions of location and depth differences before and after the ISC-GEM relocations. The median distance between the before and after locations is 10km. 90% of the events moved by less than 25km, and 90% of the depth changes are between ±20km.



(a) (b)

Figure 3.8 Distribution of a) location, and b) depth differences before and after the ISC-GEM relocations. The 50%, 90% and 95% percentile points on the cumulative distributions (red) are marked the vertical red lines

We expect that the largest differences between the before and after ISC-GEM relocations will come from the early years. Figures 3.9-3.10 show the minimum, maximum and the 25% - 75% quartile range of the location, depth and origin time differences in each decade. These box-and-whisker plots confirm that the large variations level off with time.

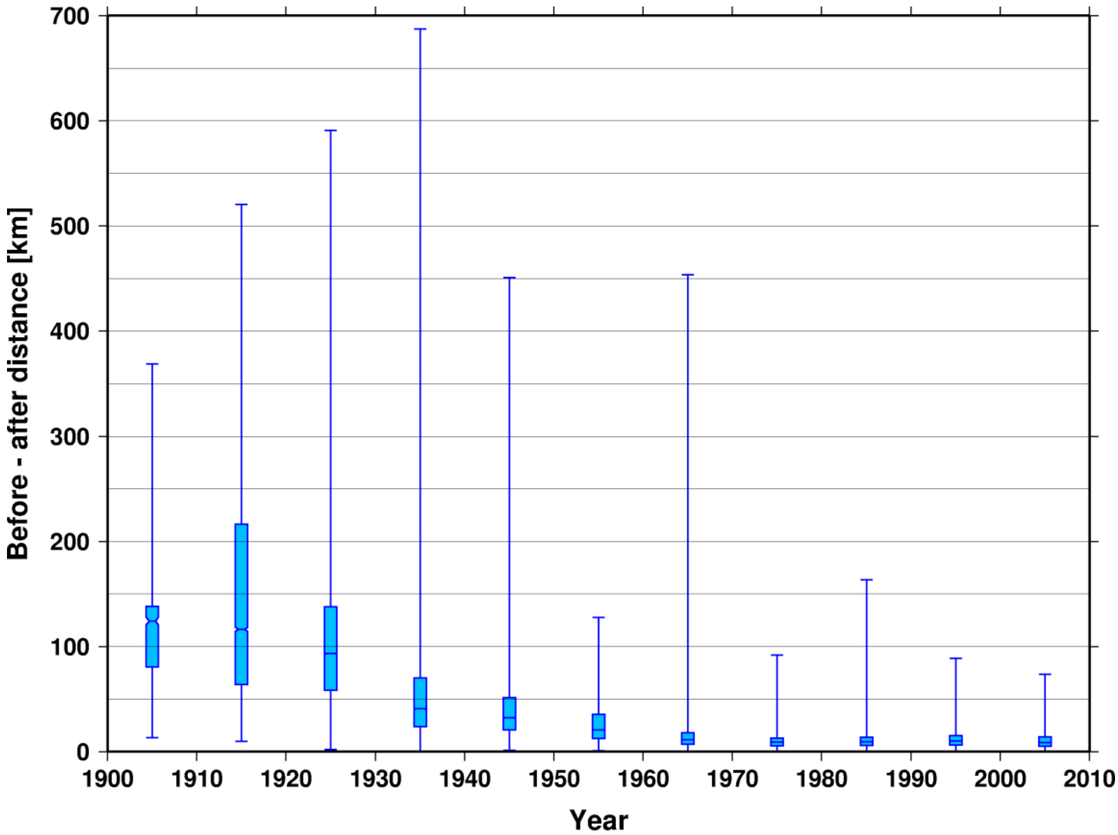
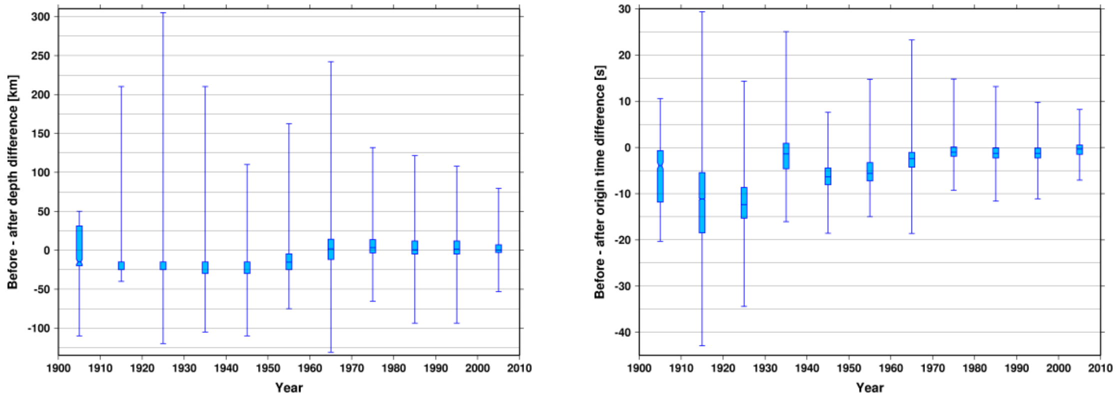


Figure 3.9 Box-and-whisker plot of the location differences before and after the ISC-GEM relocations in each decade. Blue boxes represent the 25% - 75% quartile ranges; blue lines indicate the full, minimum to maximum range. Event locations change the largest extent in the first three decades



(a) **(b)**

Figure 3.10 Box-and-whisker plot of a) the depth, and b) origin time differences before and after the ISC-GEM relocations in each decade. Blue boxes represent the 25% - 75% quartile ranges; blue lines indicate the full, minimum to maximum range. The apparent bias in the first six decades is due to the fact that previously many event depths were fixed to the surface

Figures 3.11-3.13 show the seismicity maps before and after the ISC-GEM relocations in 20-year long segments. Most of the large location changes occur in the first half of the century; the effect of improved depth estimates and better clustering can be seen through the entire period.

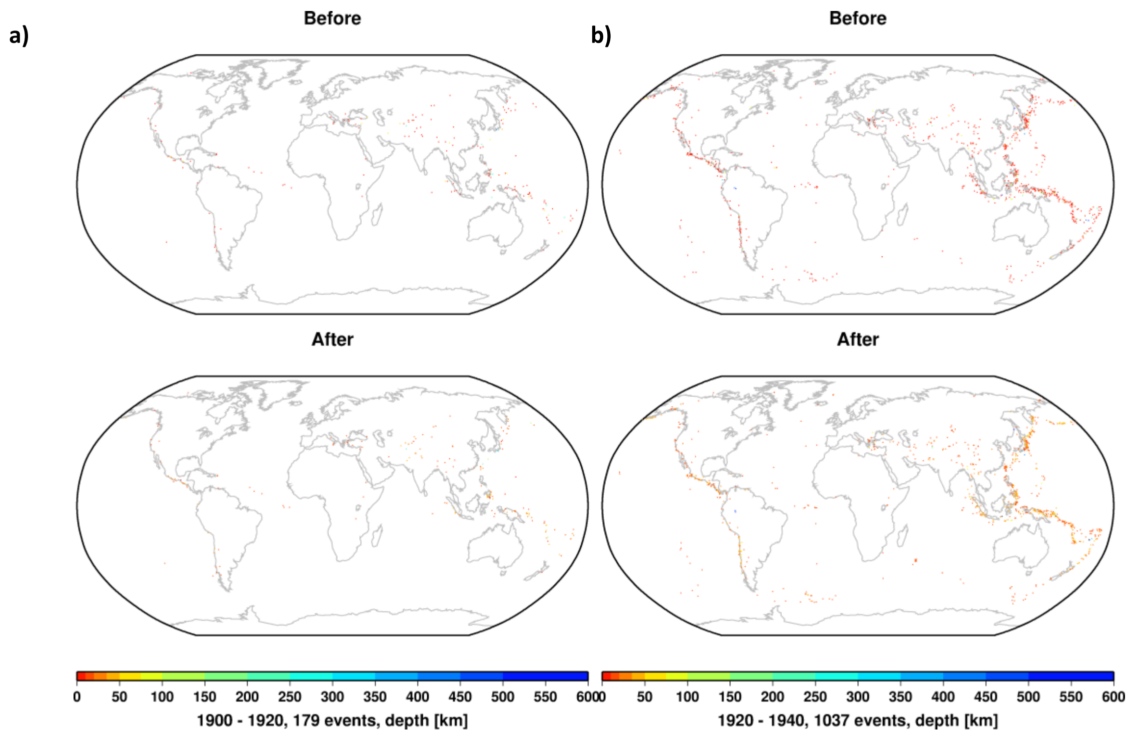


Figure 3.11 Preferred locations before and after the ISC-GEM relocations between a) 1900 and 1920, and b) 1920 and 1940

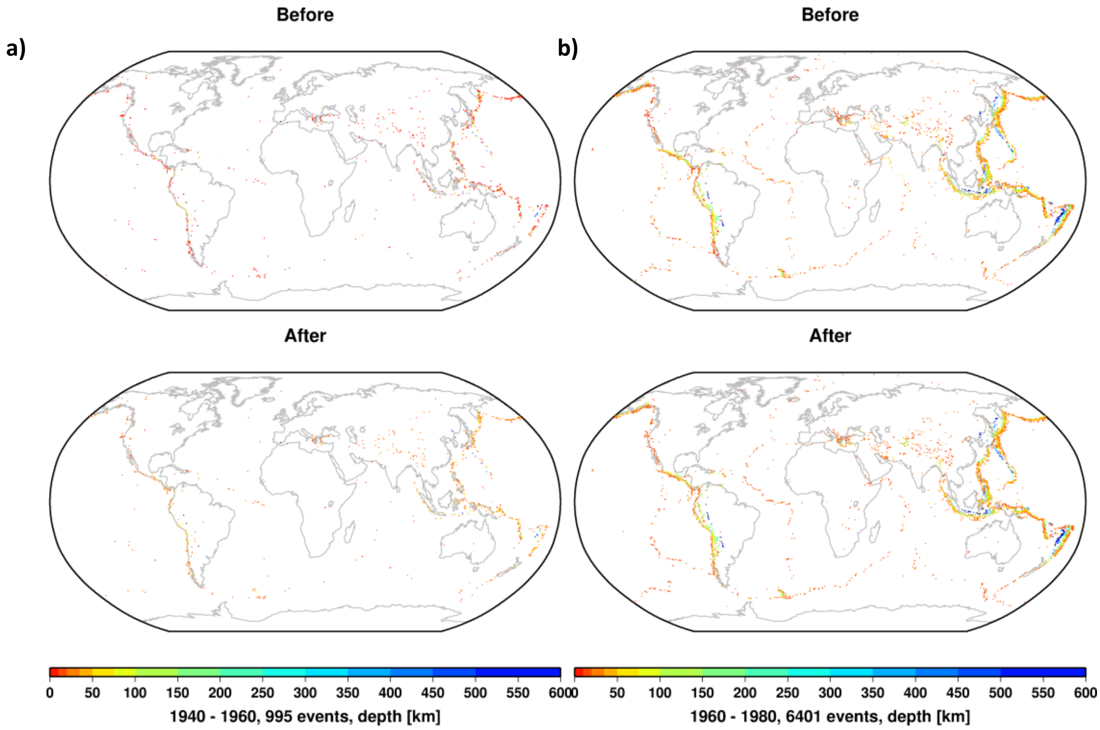


Figure 3.12 Preferred locations before and after the ISC-GEM relocations between a) 1940 and 1960, and b) 1960 and 1980

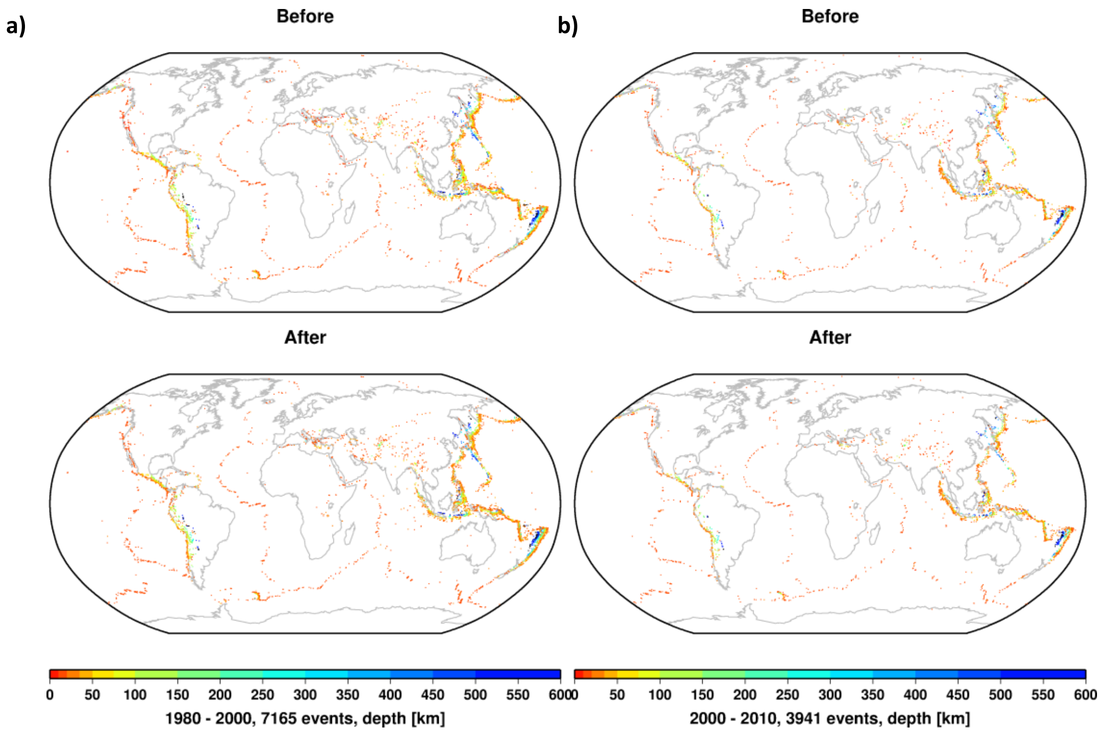


Figure 3.13 Preferred locations before and after the ISC-GEM relocations between a) 1980 and 2000, and b) 2000 and 2009

Finally, Figures 3.14-3.22 show the three-dimensional seismicity maps for some active tectonic regions before and after the ISC-GEM relocations. We conclude that owing to the ISC-GEM location procedures and to the substantial increase in the volume of observational data used in the relocations, the ISC-GEM Catalogue offers an improved view of the seismicity of the Earth with significantly better depth estimates and considerably reduced scatter in location estimates.

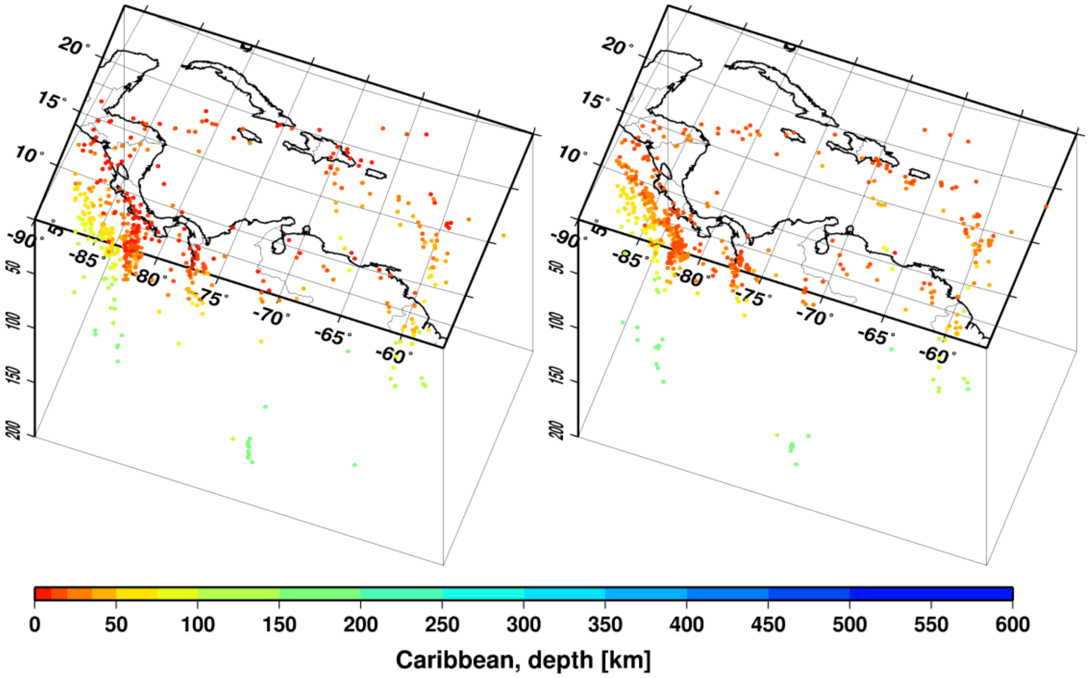


Figure 3.14 Preferred locations before (left) and after (right) the ISC-GEM relocations in the Caribbean region

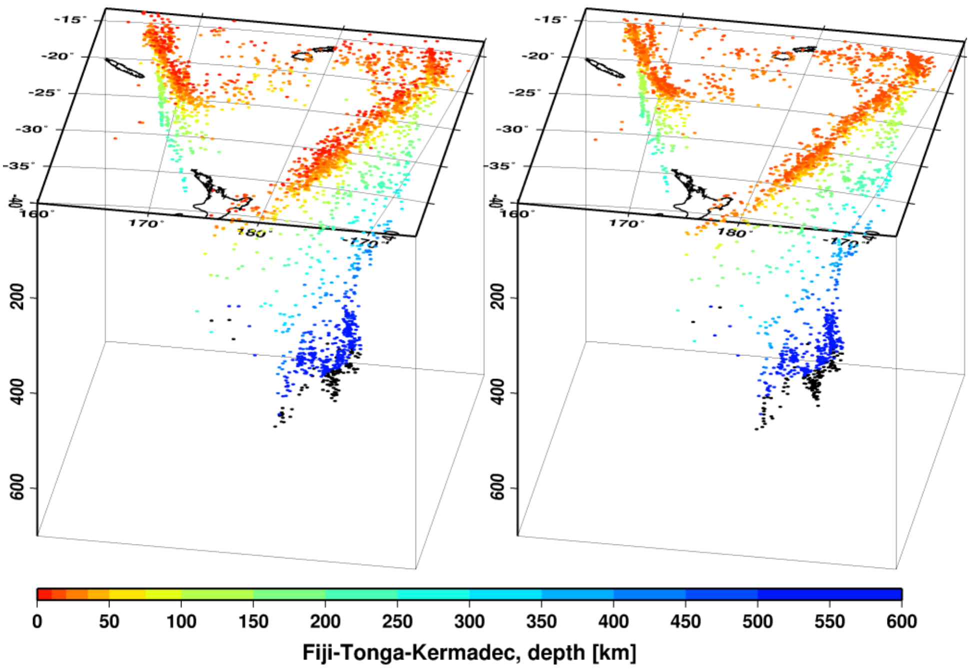


Figure 3.15 Preferred locations before (left) and after (right) the ISC-GEM relocations in the Fiji – Tonga – Kermadec Islands region

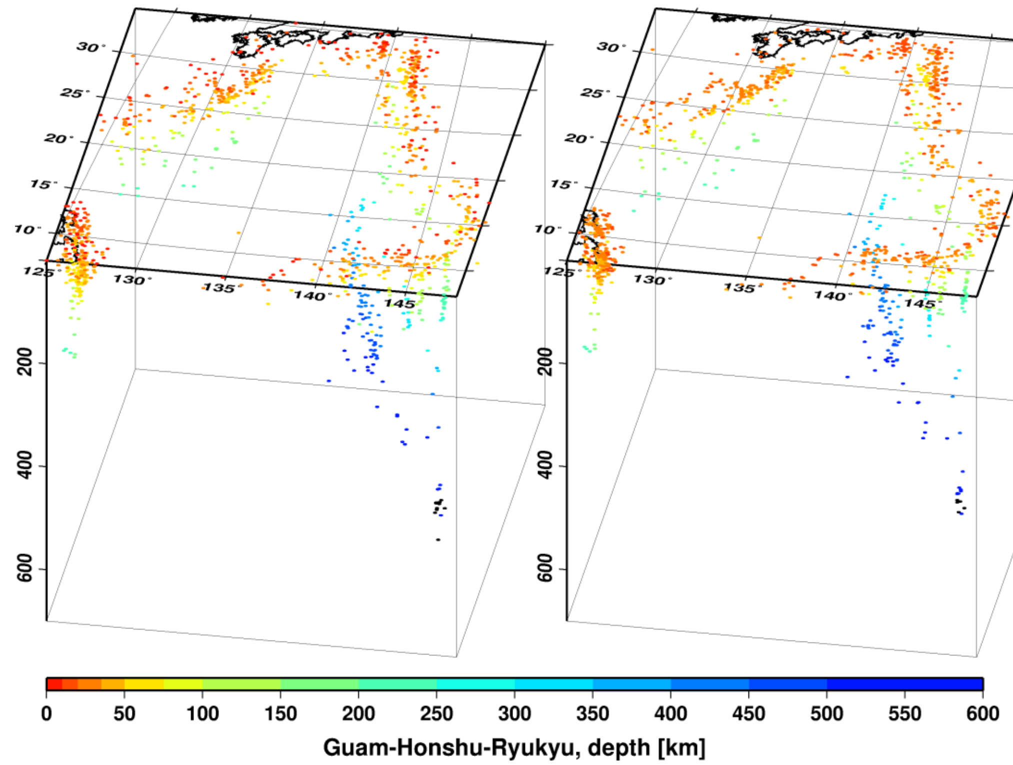


Figure 3.16 Preferred locations before (left) and after (right) the ISC-GEM relocations in the Guam – Honshu – Ryukyu Islands region

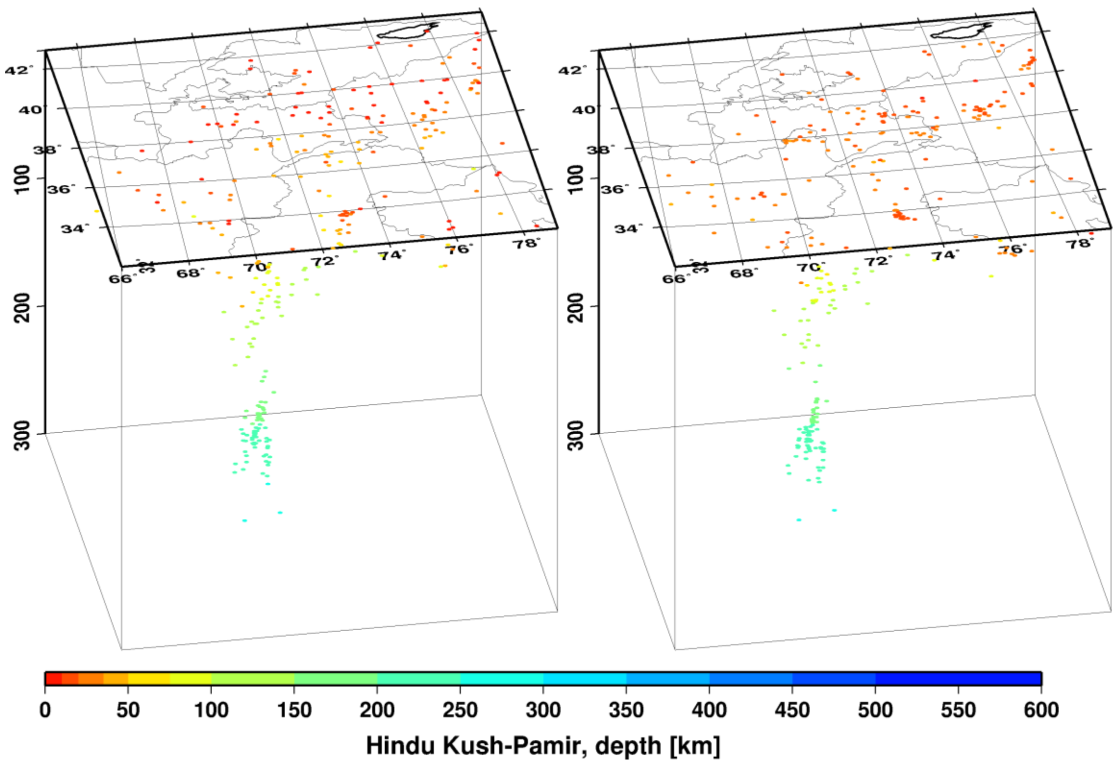


Figure 3.17Preferred locations before (left) and after (right) the ISC-GEM relocations in the Hindu Kush – Pamir region

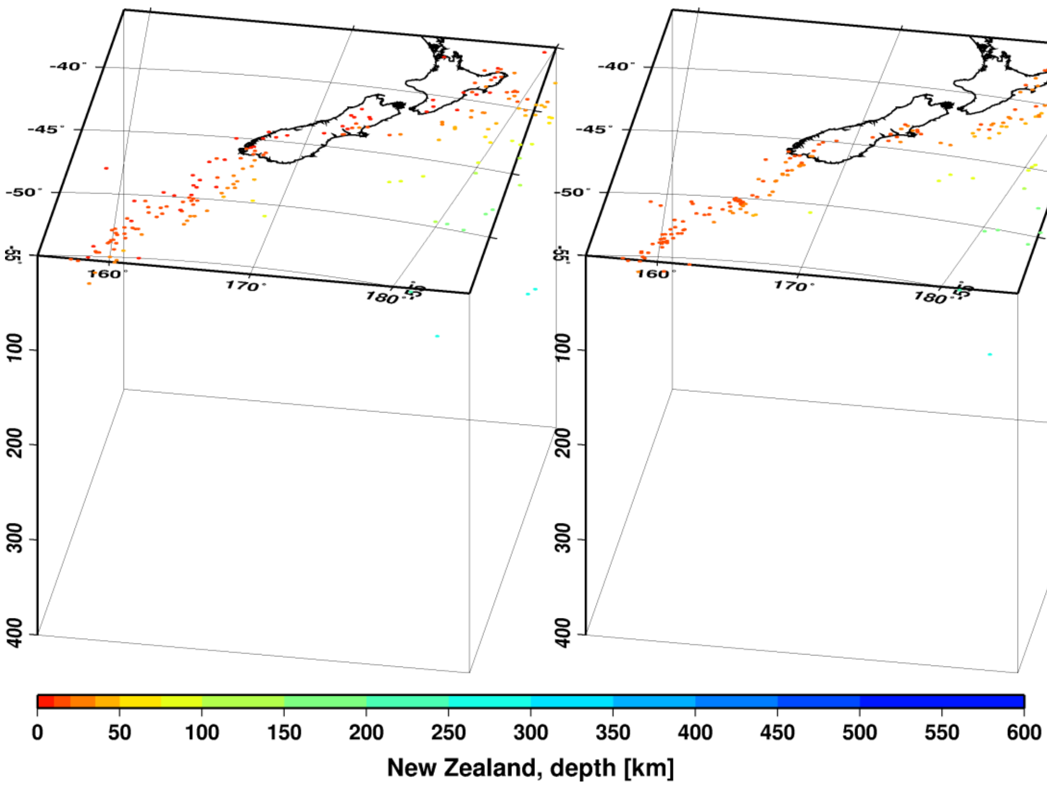


Figure 3.18 Preferred locations before (left) and after (right) the ISC-GEM relocations in New Zealand

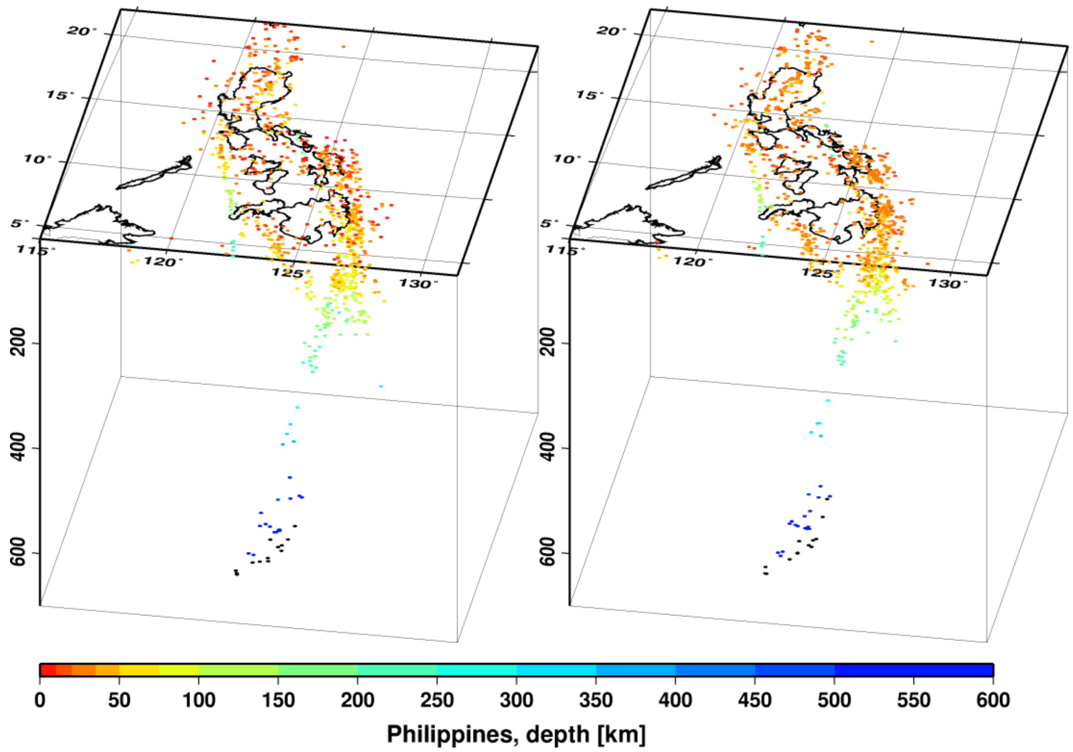


Figure 3.19 Preferred locations before (left) and after (right) the ISC-GEM relocations in the Philippines

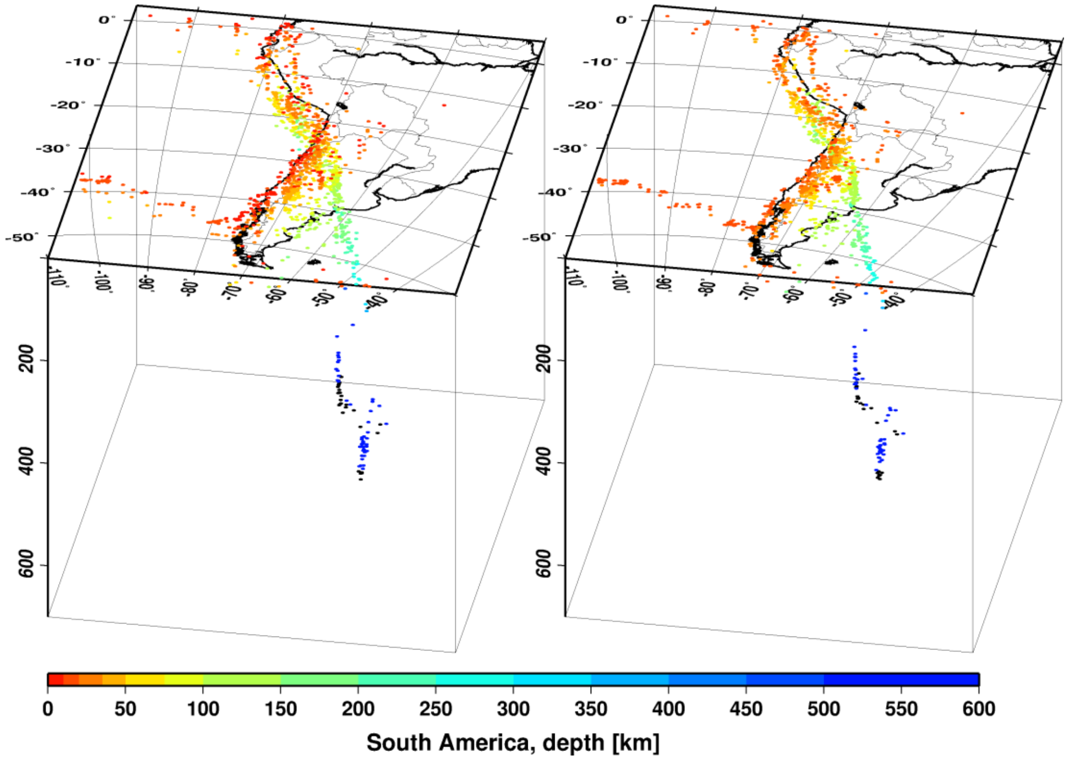


Figure 3.20 Preferred locations before (left) and after (right) the ISC-GEM relocations in South America

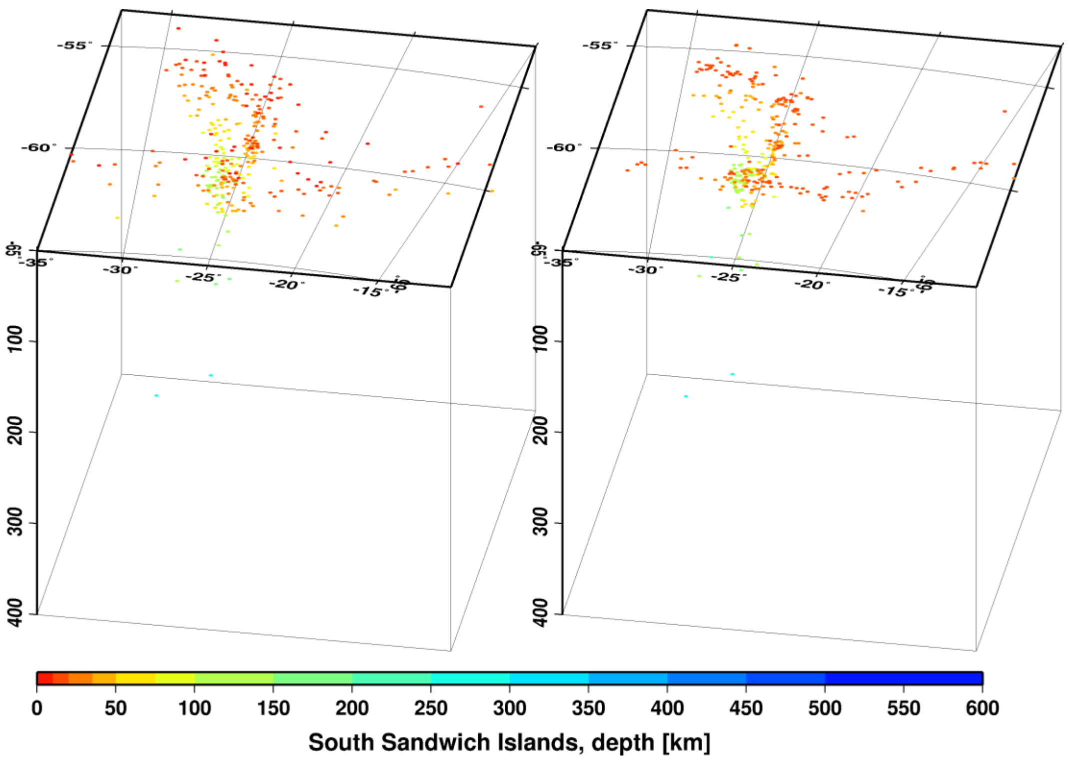


Figure 3.21 Preferred locations before (left) and after (right) the ISC-GEM relocations in the South Sandwich Islands region

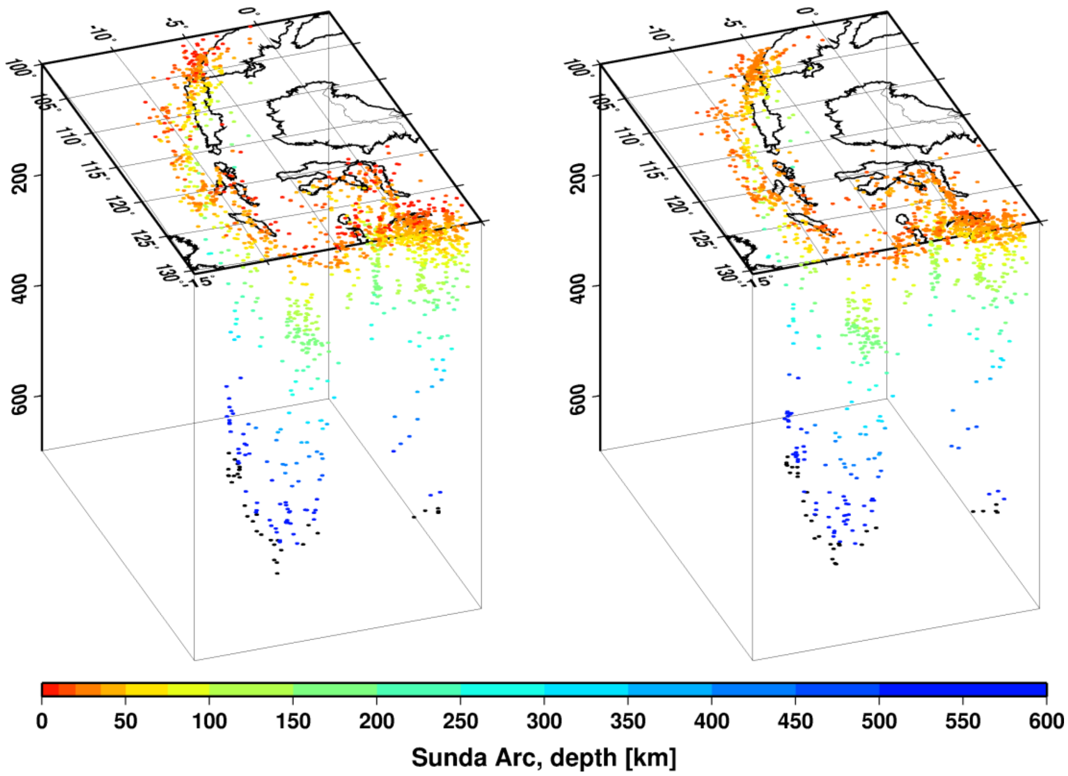


Figure 3.22 Preferred locations before (left) and after (right) the ISC-GEM relocations in Indonesia

4 Determination of Earthquake Magnitudes

In order to obtain the most homogeneous record of earthquakes for consequent seismic risk and hazard assessment, the GEM Foundation requested to express the magnitudes of all earthquakes in the catalogue in terms of M_W.

To fulfil this requirement we used the following strategy. Existing direct measurements of M_W were given a priority. Hence, in the period 1976-2009, where possible, we obtained the M_W determinations from Global CMT project (Section 4.1, Figure 4.1). For earthquakes in the period 1900-1979, we also performed a comprehensive search of quality scientific articles to obtain M_0 (and consequently M_W) determined by individual researchers (see Section 4.2).

In parallel, where possible, we computed conventional M_S and m_b magnitudes, using the original amplitudes and periods of surface and body waves reported by station operators in the multitude of bulletins and catalogues described in Section 4.3. Based on the large volume of data in the ISC database, we devised an improved regression scheme (Section 4.4) that allowed us to compute M_W proxy values (magnitudes values to be used in lieu of the direct measurements of M_W) based on conventional surface and body wave magnitudes. The description of how these conventional magnitudes have been obtained can be found in Section 4.3.

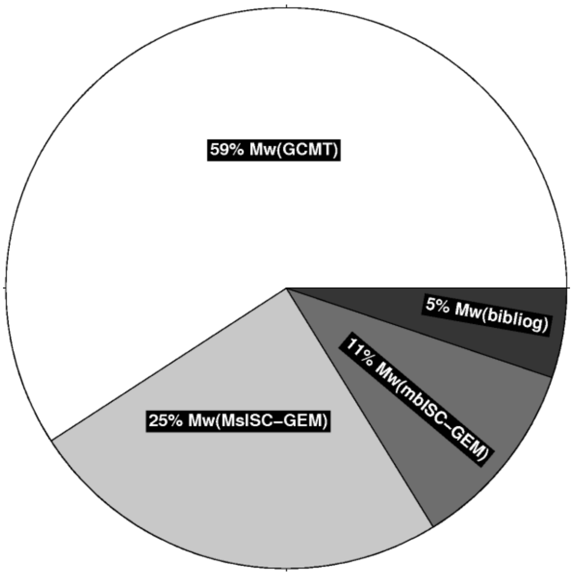


Figure 4.1 Distribution of M_W in the ISC-GEM Catalogue per source of information: GCMT, bibliographical search or re-computation from M_S or m_b

In order to provide the most reliable magnitude value for every earthquake in the catalogue, in case of several magnitude estimates available for a single earthquake, we gave priority to M_W values in the following order:

1. M_W GCMT;
2. M_W from bibliographical search;
3. M_W proxy based on M_S;

4. M_W proxy based on m_b.

Those earthquakes with no M_W proxy values were removed from the main catalogue and placed into the appendix. Earthquakes occurred during the 1900-1903 period have been assigned with proxy M_W recomputed from M_S of Abe and Noguchi (1983a,b) according to regression model described in Section 4.4.

It has to be noted that a computation of M_W proxy values based on regressions from other types of magnitudes does not bring similarly reliable results as compared to a direct measurement of M_W based on the original waveform analysis. It is, nevertheless, a necessary measure since the direct measurement of M_W using historical analogue waveforms on a global scale is beyond the scope of this project. To address this issue we introduced a scheme of M_W quality flags (A, B or C) (see Section 4.5); users are strongly encouraged to take a note of these flags in order to take into account reliability of each magnitude determination.

Finally, Figure 4.2 shows a magnitude timeline that exhibits a distribution of direct versus proxy (regression from M_S/m_b) determinations of M_W in the final ISC-GEM Catalogue. It is clear that prior to 1976, the ISC-GEM Catalogue would have been several units of magnitude less complete without M_W proxies.

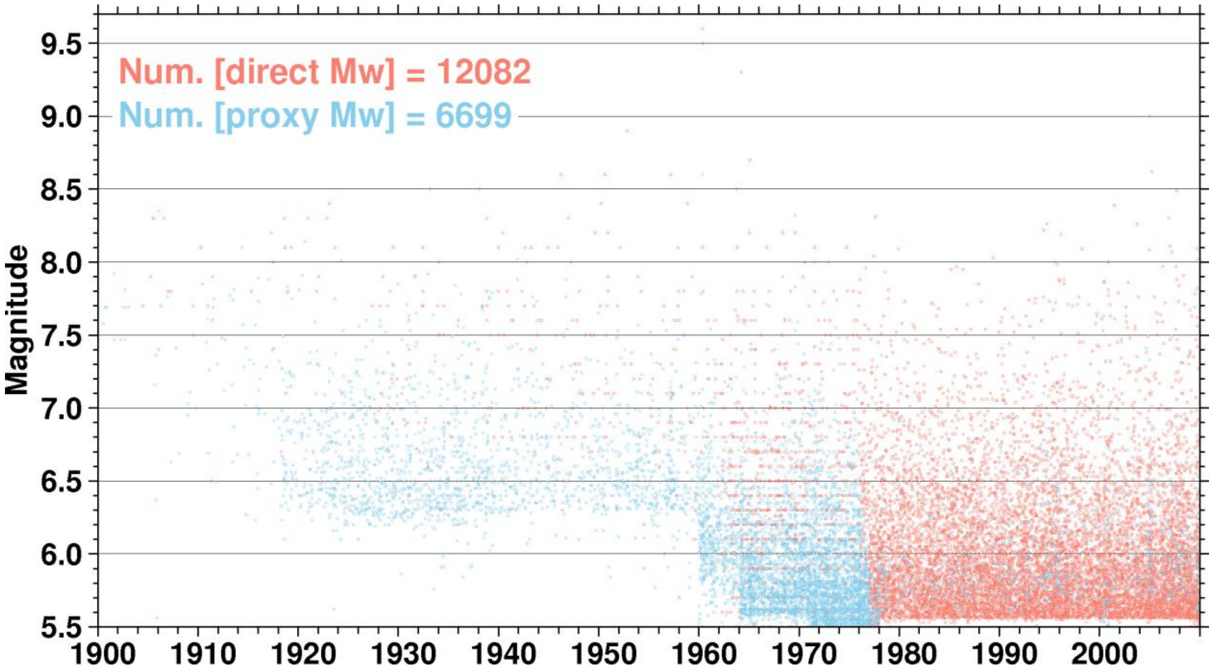


Figure 4.2 Magnitude timeline of the ISC-GEM Catalogue showing earthquakes with direct determination of M_W (red) and those M_W proxies (blue) determined by means of regression from M_S/m_b

The following sections provide the detailed description of the process of magnitude determinations in the final ISC-GEM Catalogue.

4.1 M_W from the Global CMT Catalog

The Global Centroid Moment Tensor (GCMT) Catalog is acknowledged as the authoritative agency for computing the moment tensor solutions for earthquakes worldwide. The catalogue is available at http://www.globalcmt.org/ and is the continuation of the Harvard CMT project (Dziewonski et al., 1981). Today the GCMT project is leaded by G. Ekström at the Lamont-Doherty Earth Observatory of Columbia University (Ekström et al., 2012).

Figure 4.3 shows the annual distribution of earthquakes in the ISC-GEM Catalogue with M_W from both GCMT and those originated from the bibliographical search (See Section 4.2). The GCMT M_W values before 1976 relate exclusively to deep earthquakes. Out of 12,182 in the ISC-GEM Catalogue between 1976 and 2009, only 1,216 have no GCMT magnitude available.

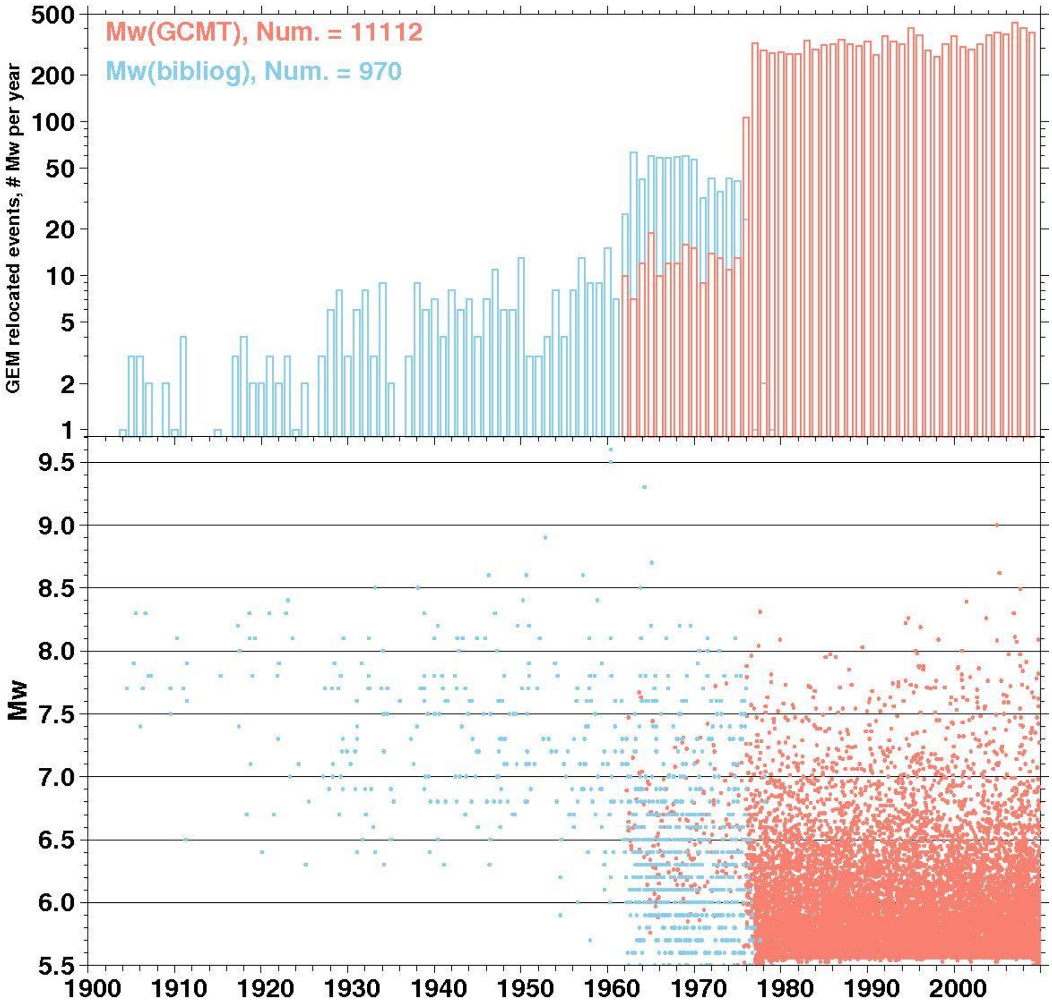


Figure 4.3 Annual number (top) and magnitude distribution (bottom) of earthquakes in ISC-GEM Catalogue with M_W magnitudes from GCMT (red) and bibliographical search (blue)

4.2 M_W from Bibliographical Search

Here we describe the task of compiling seismic moments and related information from the published literature for earthquakes before 1980 and selecting preferred seismic moment values M_0 with a quality assessment. Selected values of M_0 were then used to compute the moment magnitudes, $M_W[M_0]$ with error assignments based on our quality assessment. The period from 1977 to 1979 provides some comparisons between the M_0 values in the GCMT Catalog and those calculated by other authors.

The following sub-sections describe the moment compilation procedure, selection of preferred seismic moment values and comments. Appendix B describes a list of references for the 1,127 papers that have been examined.

4.2.1 Procedure for Compiling Seismic Moment Values

We used the IASPEI formula for computing M_W based on M_0:

$$M_W = (2/3)\ (\log M_0 - 9.1) \qquad (4.1)$$

This way of writing Eq. (4.1) was first proposed by Bormann et al. (2002). It avoids frequent inconsistencies of M_W values reported by different agencies with a precision of 0.1 magnitude units, depending on whether or not M_W has been calculated according to formulas equivalent with Eq. (4.1) or formulas obtained by first expanding Eq. (4.1) and then rounding-off constant terms (as in the original relationship: (2/3) log M_0 – 10.7 published by Hanks and Kanamori (1977). The NEIC and the Harvard (now GCMT) groups have agreed to calculate and correct backward the M_W values given in their catalogues according to the IASPEI recommended standard (i.e., Eq. (4.1)).

The first compilation of seismic moments appeared in Kanamori and Anderson (1975) when these authors presented the theoretical basis of some empirical relations in seismology. A more extensive compilation appeared in Kanamori (1977) when the M_W scale was first introduced in a landmark paper on the energy release in great earthquakes. The moment magnitude scale was introduced by Hanks and Kanamori (1979), and they proposed the symbol, **M**, for moment magnitude. However, it has few followers. As explained above, M_W as originally introduced by Kanamori (1977) is now generally known as the moment magnitude.

Since 1977, many compilations of seismic moments and/or moment magnitudes were published. Two popular compilations are: Pacheco and Sykes (1992), and Wells and Coppersmith (1994). Since we only need seismic moments from 1900 to 1979, one would assume that it will be an easy task to update these two catalogues with recent papers and add data for the intermediate and deep earthquakes (which accounts about 10% of the total seismicity of the Earth). Unfortunately, this is not the case, because Pacheco and Sykes (1992) omitted many published papers (they listed 168 papers up to 1990), and seismic moments in Wells and Coppersmith (1994) are 10 times larger than they should due to a typographic error in the exponent of seismic moments.

We conducted an extensive search of literature using the following procedure. Starting from several published compilations (e.g., Kanamori (1977), and Pacheco and Sykes (1992), their cited references were entered in an Excel file. Computer-readable files of these cited papers were obtained in PDF format (either from online sources or by scanning the papers) and printed. We then examined each paper and extracted seismic moments values and related information (such as the earthquake origin time, location, magnitudes, etc.) to an Excel file for moment compilation. In the compilation, we made a note on whether the seismic moment values were obtained by the author(s) of the paper, or they were values from previously published paper(s). We then added the cited papers as well as any new references in the paper that were judged to be useful to the Excel file of references. We also made an effort to track down the original papers that published seismic moment value(s) for a given earthquake.

After examining 1,127 papers, we found one or more seismic moment values for 970 events that are in ISC-GEM Catalogue. There are also several hundred earthquakes with seismic moment values that are *not* in the ISC-GEM Catalogue.

4.2.2 Selecting seismic moments values and uncertainties

The moments presented in this catalogue have been obtained according to the methodology used in their computation:

- mainstream Harvard or Global CMT type M_0, obtained using *digitally* recorded seismograms; corresponding M_W uncertainty is set to 0.1;
- M_0, obtained by an inversion procedure using *analog* seismograms that were digitized by the authors; corresponding M_W uncertainty is set to 0.2;
- M_0 solutions involving forward modeling of seismic waveforms, in the context of a constrained focal mechanism; corresponding M_W uncertainty is set to 0.3;
- M_0 estimates obtained using *bona fide* measurements of physical parameters, but under the philosophy of a *magnitude* scale, *i.e.,* without resolving the exact geometry or depth of the earthquake. For example, Okal and Talandier (1989) measured spectral amplitudes of long-period (> 40 sec) Rayleigh waves and interpreted them within the context of a fully justifiable theory (Okal and Talandier*,* 1987) to derive mantle magnitude (M_m) values, which could then be used to assess their seismic moments (Okal, 1992a; Okal, 1992b). Because the effects of focal mechanism and depth are not considered, it is expectedly of a lesser quality than a measurement involving complete waveform modeling for a (hopefully) exact focal mechanism; corresponding M_W uncertainty is set to 0.4;
- M_0 estimates derived from direct field surveys (e.g., geodetic and/or geologic); corresponding M_W uncertainty is set to 0.4;

We rejected seismic moment (or moment magnitude) values that was obtained by applying purely empirical relationships between seismic moments and other observables.

4.2.3 Comments on the preferred seismic moments values

Starting in the early l980s, computing seismic moments became routine because sufficient digital seismograms were available. The CMT, and now the GCMT projects have been performing a very useful task in providing seismic moment tensor solutions, and thus a uniform set of seismic moment values and moment magnitudes. Although the establishment of WWSSN in the early 1960s provided a uniform set of analog seismograms worldwide, digitizing analog seismograms is tedious. Nevertheless, thanks to a few hundred authors, seismic moments were determined for about 1,000 individual earthquakes. Before 1963, collecting, digitizing, and interpreting old seismograms is extremely difficult, and only about 200 earthquakes have been studied for seismic moments. Table 4.1 shows the number of earthquakes by decade for which we were able to find M_0 values. This table indicates that there is a scope for further improvement of this collection.

4.2.4 Remarks

We would like to emphasize the following points:

1. The seismic moment/moment magnitude catalogue presented here should be used with caution. Users are urged to consult the original papers, because in any compilation, some important information is lost due to condensation into a simple table. This catalogue is intended to be just a guide.
2. Although we adopted the GCMT double-couple solutions as the “standard”, they may be fine for just about 90% of all earthquakes, as some earthquakes have large *non* double-couple components. Users are urged to examine the detailed moment tensor solutions provided by the Global CMT online (http://www.globalcmt.org/) for the earthquakes they wish to investigate.

3. In general, we selected seismic moment values based on the more recent papers. In the case of giant earthquakes (such as the 1960 great Chilean earthquake), the seismic moments and thus the moment magnitudes often have larger values than those commonly in use. Users should be aware that all earthquake parameters may be subjected to revisions in the future as seismology advances in time.

Table 4.1 Number of earthquakes with M_0 available in each 10-year period included in the ISC-GEM Catalogue

Period	# earthquakes
1900-1909	11
1910-1919	15
1920-1929	30
1930-1939	49
1940-1949	66
1950-1959	74
1960-1969	447
1970-1979	278
Total	970

4.3 M_W proxy based on the ISC-GEM M_S and m_b determinations

In order to obtain M_W proxy values for earthquakes in the ISC-GEM Catalogue we computed the classical magnitude scales such as M_S and m_b. These computations were based on the ISC-GEM hypocentre solutions using the amplitude-period data available from:

- the ISC-GEM data entry effort (1904-1970);
- the ISC database (1971-2009);
- additional ISC-GEM data entry effort (1971-1977) to introduce missing from the ISC database amplitudes and periods of surface and body wave recordings at the backbone stations of the Former Soviet Union as well as two high quality seismic stations of Sweden (Uppsala and Kiruna).

These magnitudes served as a basis for computing proxy M_W of a large majority of earthquakes before 1976 (the start of GCMT Catalog) where direct computations of seismic moment M_0 were not available.

4.3.1 Determination of M_S

After the local magnitude (M_L) scale introduced by Richter (1935), Gutenberg (1945a) suggested the surface wave magnitude so that, differently from M_L, the earthquake magnitude could be computed for (shallow) earthquakes worldwide by measuring the amplitude of surface wave trains:

$$M_S = \log(AH_{max}) + 1.656\log\Delta + 1.818 \qquad (4.2)$$

where AH_{max} is the maximum horizontal ground motion in microns of surface waves with period T = 20 ($\pm$2) seconds and Δ the distance. After Gutenberg (1945a), the formulation of M_S has been object of changes. The modern formulation reads as:

$$M_S = \log(A/T)_{max} + \sigma_s(\Delta) \quad (4.3)$$

where $\sigma_s(\Delta)$ identifies the calibration function of Vaněk et al. (1962), which reads $\sigma_s(\Delta) \approx 1.66\log\Delta + 0.3$ for distances between 20° and 160°, if amplitudes are measured in nanometers. For what concerns the period and distance range where the surface wave amplitude is measured, there are basically two standards:

1. T = 20 ($\pm$2) or ($\pm$3) s, and measured at distances between 20° and 160°, close to the original formulation of Gutenberg, providing what in the modern IASPEI (2005) standard is $M_S(20)$;

2. according to IASPEI (2005), the maximum of A/T is measured in a much wider range of periods and distances, namely between 3-60 s and 2° and 160° for the broad-band $M_S(BB)$.

Bormann et al. (2009) showed that differences between $M_S(20)$ and $M_S(BB)$ are more pronounced below magnitude 5.5 (that is below the cut-off magnitude for the ISC-GEM Catalogue), whereas for larger values the two agree very well. Over the years, the ISC accepted and used for M_S calculation amplitudes in the period range 10-60 s, which is very close to the current formulation of $M_S(BB)$. This fits well with the practice in the early instrumental period. The maximum of A/T, indeed, was measured in a wide period range. This is shown on Figure 4.4, where the period here is the maximum of A/T for a *reading* for data up to 1970 (recall that a *reading* groups all the parametric data from a single station associated to a specific earthquake and reported by the same agency).

Before computing M_S for a *reading*, the vertical M_{SZ} and horizontal M_{SH} are calculated. First the maximum of A/T on the vertical component is searched among the surface wave maxima belonging to a *reading* and, if available, M_{SZ} obtained; secondly, for periods ($\pm$10s) of Tz, M_{SH} is obtained from the maximum of A/T for horizontal components as $\sqrt{\left(\frac{A}{T}\right)_N^2 + \left(\frac{A}{T}\right)_E^2}$.

If one of the two horizontal components is not available, $\left(\frac{A}{T}\right)_{H\max} = \sqrt{2 * \left(\frac{A}{T}\right)_{E|N}^2}$.

Finally, the *reading* $M_S = (M_{SZ} + M_{SH})/2$ if both exists, or $M_S = M_{SZ}$ or M_{SH} when one of them is not available. Since several agencies may report data from the same station (and this is the especially the case for recent years), the M_S station magnitude is defined as the median of the *reading* magnitudes for the same station. Once all station M_S values are determined, the station magnitudes are sorted and the lower and upper α percentiles are made non-defining (α = 20%). The network M_S and its uncertainty are then calculated as the median and the standard median absolute deviation (SMAD) of the alpha-trimmed station magnitudes, respectively. At least 3 station magnitudes are required to compute a network magnitude, with the exception of 87 earthquakes in the early instrumental period where only 2 reliable stations have been used to compute a M_S network magnitude.

Figure 4.5 shows the number of stations contributing to M_S over the two periods. Obviously, in the modern period (1971-2009) network M_S are obtained from a much larger number of single stations.

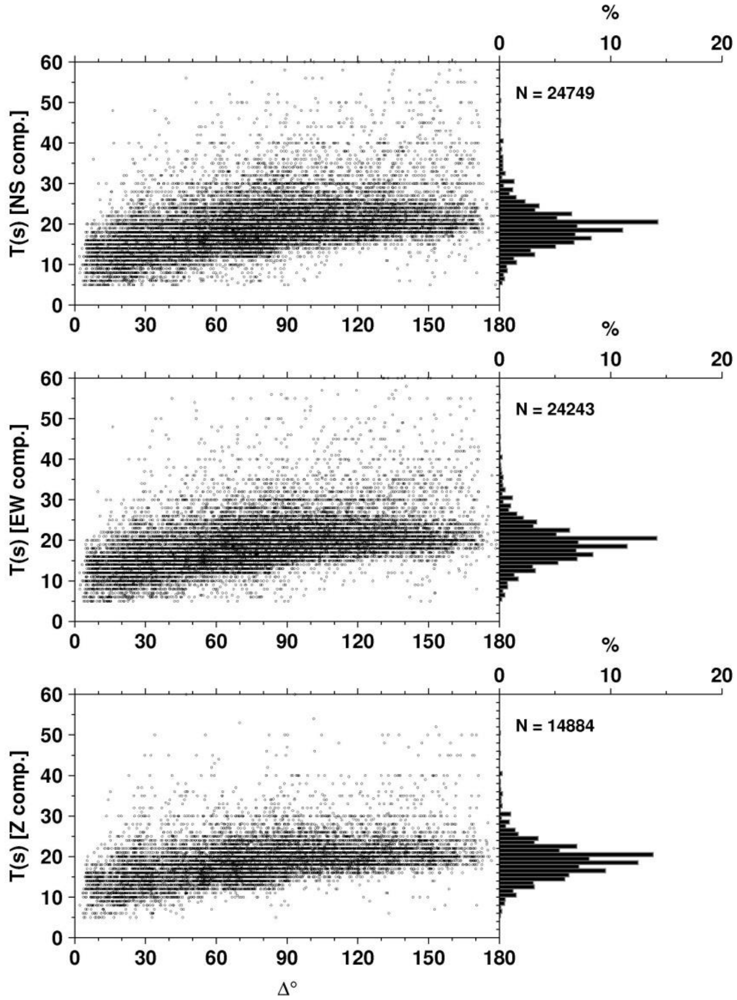


Figure 4.4 Period distribution over the entire distance range for data up to 1970 (i.e., before surface wave magnitude are available in the ISC database). The period is from the maximum of the A/T of a reading. From top to bottom: data for N-S, E-W and vertical components

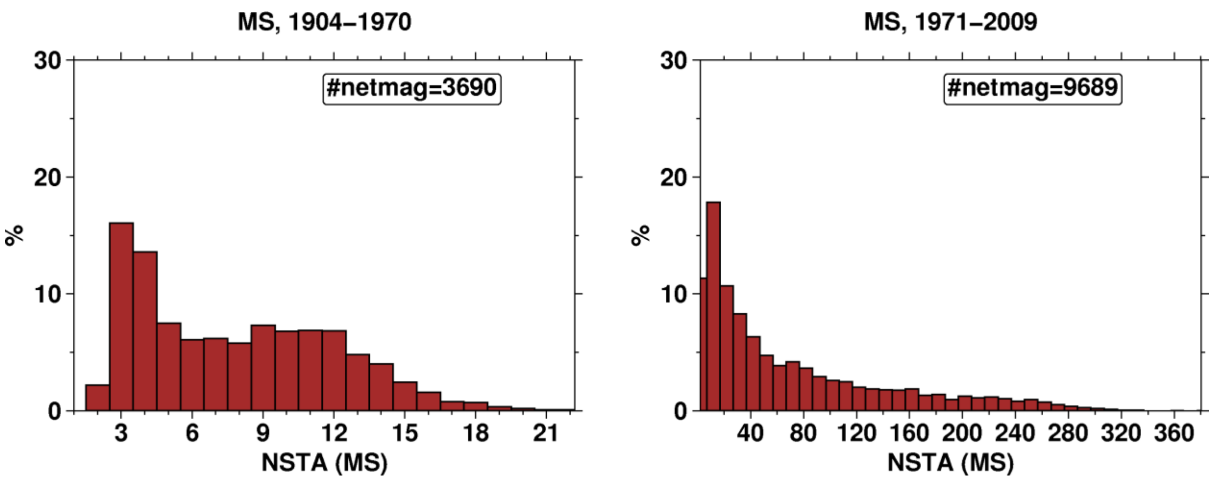


Figure 4.5 Distribution of the number of stations (NSTA) contributing to network MS during 1904-1970 (left) and during 1971-2009 (right)

In order to use the largest amount of available *readings* manually entered between 1904-1970 for M_S computation, surface wave amplitudes in the distance range 2° < Δ < 180° and in the period range 5 ≤ T ≤ 60 s have been considered. For the modern period (1971-2009), instead, where the ISC database was plenty of single station magnitudes digitally available, amplitude data with Δ < 20° and T < 10 s has been excluded. These small differences in distance and period ranges do not imply significant differences between M_S obtained up to and after 1970, but allowed us to compute more network M_S up to 1970 and also from more stations.

For ISC-GEM Catalogue, M_S has been recomputed for earthquakes where the depth minus depth uncertainty (Section 3.3) is ≤ 60 km. Figure 4.6 shows the M_S recomputed for ISC-GEM Catalogue as function of time as well as the number of M_S per year.

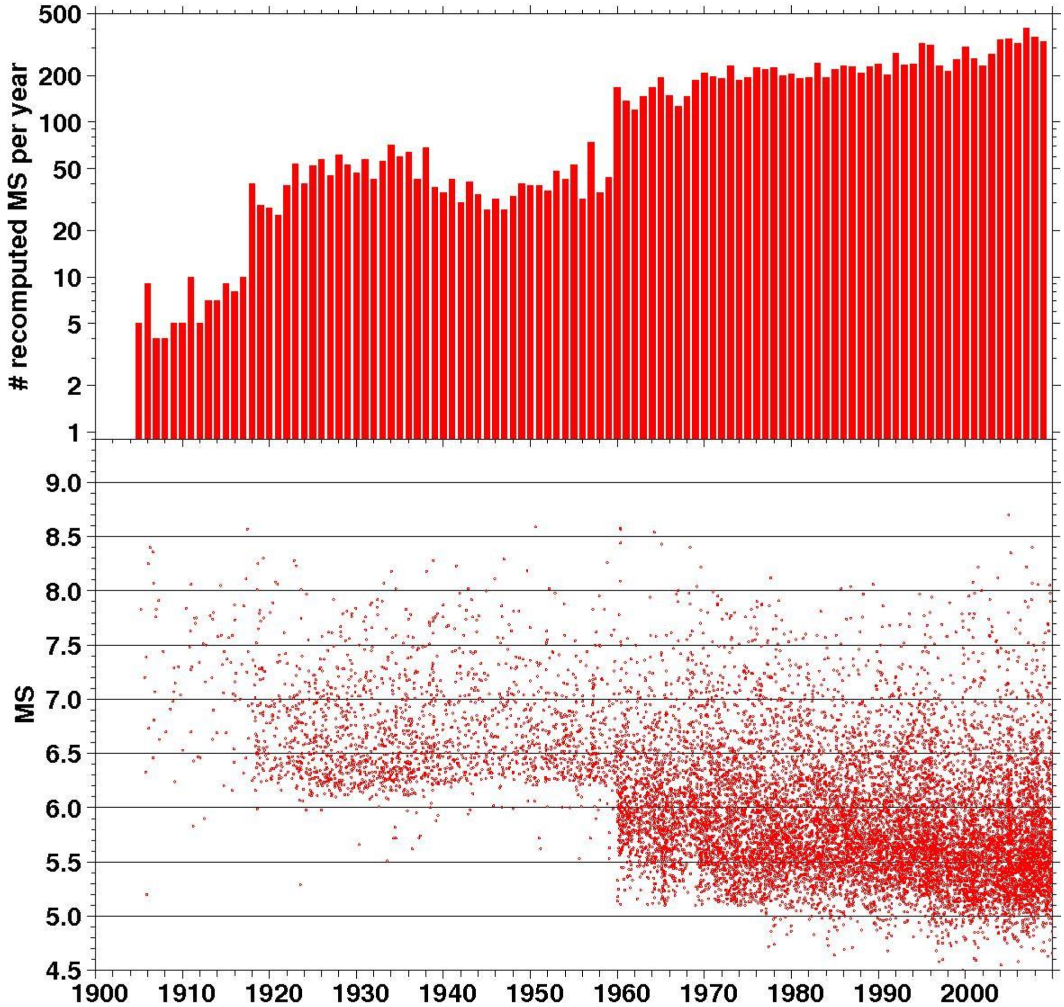


Figure 4.6 Top: number of recomputed M_S per year; bottom: recomputed M_S versus earthquake origin time

4.3.2 Determination of m_b

Gutenberg (1945b, c) introduced teleseismic magnitude scales for body-waves which are applicable also to deep earthquakes down to source depths of 700 km. The calibration functions were obtained in the medium to long periods (2 < T < 30 s) range and for PZ, PH, PPH, PPZ and SH waves. However, only the vertical component of P-waves is systematically used (i.e., PZ calibration function) in the last ~50 years. Furthermore, with the introduction of the WWSSN in the 1960s, it became routine practice to measure the P-wave amplitude in a narrow band, mostly around 1 s. This practice is different from the original body-wave magnitude definition of Gutenberg and is referred to as short-period body-wave magnitude m_b. The main advantage of measuring the amplitude on P-wave trains filtered around 1 s consists in a better signal-to-noise ratio for small earthquakes, allowing teleseismic magnitude to be determined down to $m_b \approx 4$. This made m_b the most popular and measured teleseismic magnitude for the last ~50 years. However, being the amplitude measured in a very narrow short-period range, m_b suffers of saturation for major earthquakes and generally underestimates the magnitude for strong earthquakes. This has been showed in several papers (e.g., Gelller, 1976; Kanamori, 1983; Bormann et al., 2009).

IASPEI (2005) established the standards for m_b computation as:

$$m_b = \log(A/T) + Q\,(\Delta,h) - 3.0 \qquad (4.4)$$

where A = P-wave ground amplitude in nm, calculated from the maximum trace-amplitude in the entire P-phase train (time spanned by P, pP, sP, possibly PcP and ending preferably before PP), period T < 3 s, and *Q(Δ,h)* are the calibration functions for distances 20° < Δ < 100° and depths *h* between 0 and 700 km. As previously described for M_S, first the *reading* m_b, then the station magnitudes m_b are obtained, and then the network m_b as the median of the α-trimmed station magnitudes m_b if at least 3 stations are available.

Similarly to Figure 4.5, Figure 4.7 shows the number of stations contributing to m_b over the two periods and Figure 4.8 shows the m_b recomputed for ISC-GEM. Due to lack of lack of stations equipped with vertical component short-period instruments before the WWSSN deployment in the 1960s, only a few m_b are obtained before 1964.

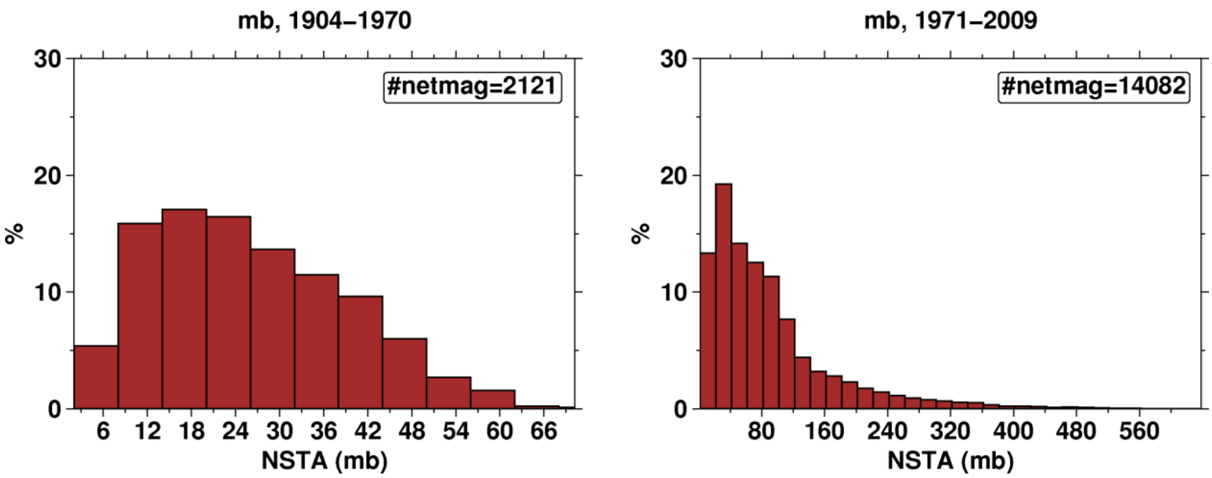


Figure 4.7 Distribution of the number of stations (NSTA) contributing to network m_b during 1904-1970 (left) and during 1971-2009 (right)

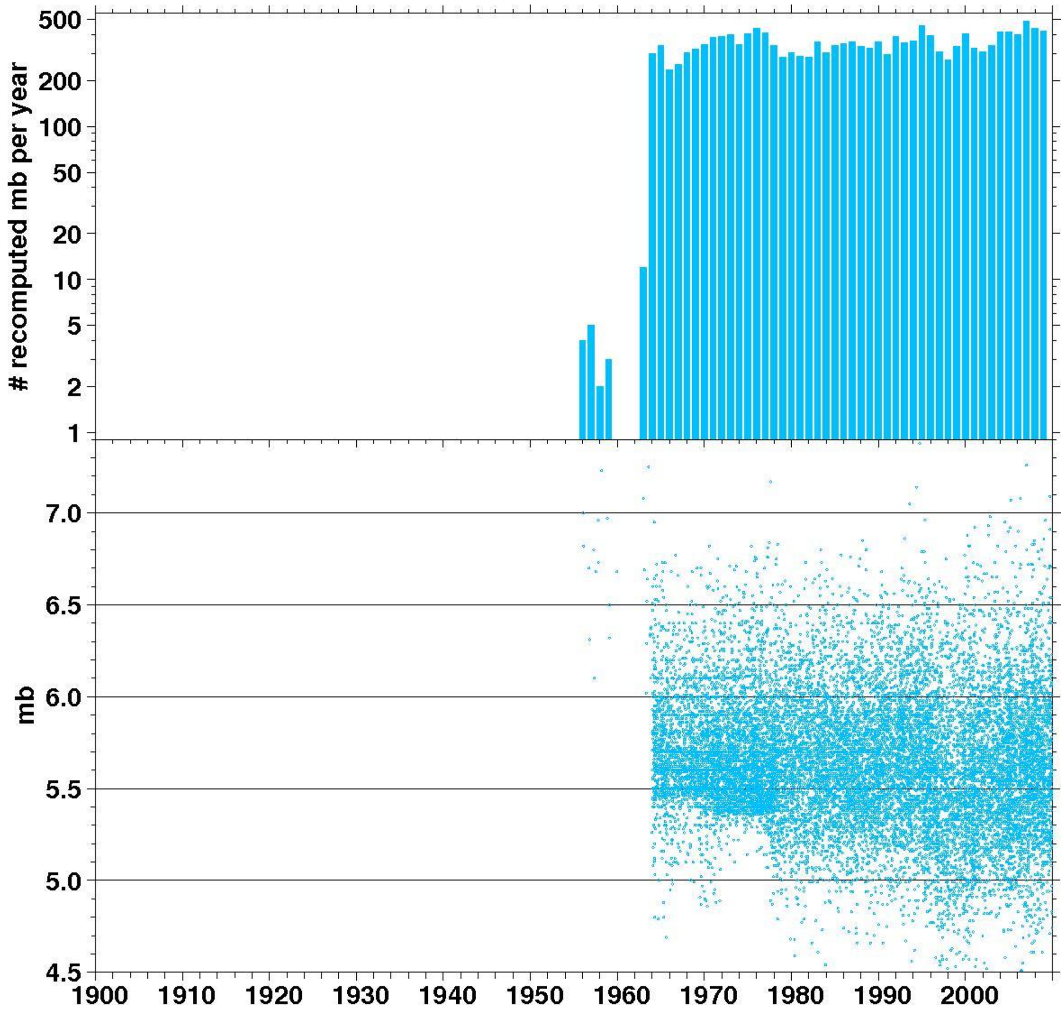


Figure 4.8 The number of recomputed m_b per year (top); the number of recomputed m_b values versus earthquake origin time (bottom)

4.4 Determination of M_W Proxy

To fulfill the GEM request of producing the instrumental catalogue with the most possible homogeneous moment magnitude values, it was necessary to obtain empirical relationships between the classical magnitude scales and M_W, so that proxy values of M_W can be obtained. This is especially important for several hundreds of earthquakes in the early instrumental period (and before the beginning of the GCMT Catalog in 1976), where no direct measurements of seismic moments are available, especially for strong-major earthquakes. The ISC-GEM Catalogue consists of 18,781 earthquakes; of these 11,112 has a GCMT M_W value, 970 an M_W value from the literature search. For the remaining earthquakes in the catalogue we provide M_W proxy values obtained from regression relations between M_W and M_S, or if there is no M_S measurement available, between M_W and m_b.

Several articles in the recent years dealt with the magnitude conversion problem, mostly applying linear regression techniques (e.g., Scordilis, 2006; Castellaro and Bormann, 2007; Bormann et al., 2007, 2009; Das et al., 2011). Regardless of the different datasets and event selection criteria, as well as the small differences in the parameters of the models obtained from different authors, one of the main outcomes of the recent literature is that the Generalized Orthogonal Regression (GOR) performs better than standard linear regressions and, therefore, its use is advisable to derive magnitude conversion relationships.

However, the linear regression models are subject to certain limitations when applied to highly heterogeneous datasets such as M_S-M_W and m_b-M_W, as we will discuss further. Therefore, instead of applying any of the published regression relations, we take advantage of the ISC-GEM Catalogue that represents the most comprehensive data set to date with uniformly computed M_S and m_b values and derive new empirical relationships using exponential as well as GOR linear regressions to obtain M_W proxies from M_S and m_b. The new models are tested against true values of M_W.

4.4.1 5.4.1 Determination of M_W proxy based on M_S

The surface wave magnitude M_S is proven to be a good estimator of M_W since it scales rather well in a wide range of magnitudes. This makes M_S our preferred magnitude to obtain proxy M_W. Figure 4.9 shows a standard scatter plot the comparison between the M_S and $M_{W(GCMT)}$. In order to avoid censoring effects around the lower cut-off magnitude (i.e., between 5.5 and 5.7) in the ISC-GEM magnitude catalogue, data pairs for smaller earthquakes have been added. These additional data includes earthquakes occurred between 1996 and 2009.

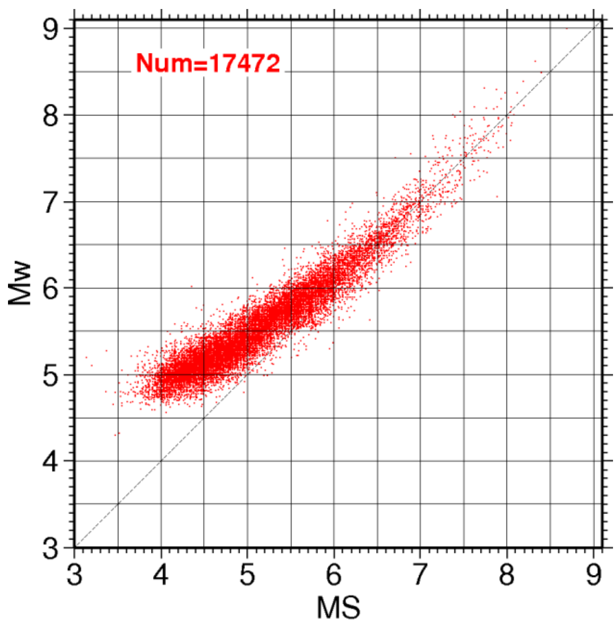


Figure 4.9 Comparison between $M_{S(ISC-GEM)}$ and $M_{W(GCMT)}$. Data includes the 1976-2009 relocated earthquakes in the ISC-GEM Catalogue and smaller earthquakes during 1996-2009. These additional values have been added with the only purpose of avoiding censoring effects around 5.5-5.7

The comparison on Figure 4.9 confirms the good correlation between M_S and M_W, even if large differences for a few earthquakes can occur, at times possibly due to the presence of outliers stemming from errors in the measurements. However, to better describe the heterogeneities of such a population, Figure 4.10 shows the same plot as Figure 4.9, but color-coded by the number of observations in cells of 0.05x0.05 magnitude units.

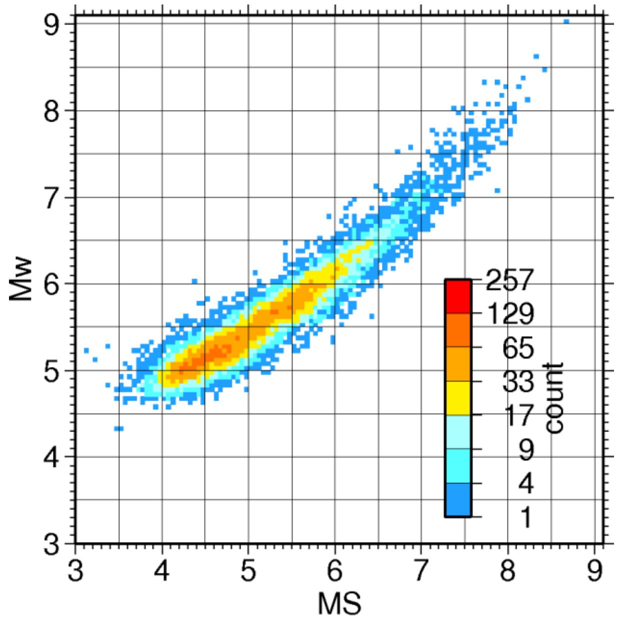


Figure 4.10 Data frequency plot from the M_S-M_W population of Figure 5.9

An important feature is that earthquakes below magnitude 6 dominate the data population, and the proportion of large earthquakes (>7) is rather small compared to the overall size of the distribution. It should also be noted that the M_S does not appear linearly correlated with M_W across the entire magnitude range.

To derive and validate the regression relationships, we divide the data set into two subsets: one that is the training set used to derive the model (90% of the whole population), and the second (remaining 10%) to be used as a validation set. Owing to the large amount of earthquakes with M_S – M_W pairs, selecting 10% of the whole data set means that the validation data set consists of over 1,700 data pairs. Rather than randomly selecting data points on the whole magnitude range, the validation data set is selected using an histogram equalization scheme, as shown on Figure 4.11. The histogram equalization defines magnitudes bins with varying width so that each bin contains equal number of data points. For each bin, a randomly chosen 10% of the data is assigned to the validation set, while the remaining 90% of the data is added to the training set. Thus both the training and validations sets retain the shape of the distribution of the entire data. Moreover, since we need to obtain a proxy M_W for a few major and great earthquakes and also considering the lack of data points for very large earthquakes, we did not exclude M_S-M_W pairs where M_S is probably saturated (possibly around 8.3 and above).

As we mentioned before, another important aspect of the M_S-M_W distribution is that the trend on the whole magnitude range is not linear, as illustrated by the median value in each bin on Figure 4.11. This aspect affected regression approaches between M_S and M_W in the recent literature, and especially after Scordilis (2006). Indeed, it became common practice to split the M_S-M_W population in two different domains: one truncated at M_S = 6.1 or 6.2, where the slope of the linear trend is ~0.7, and the other for larger values of M_S, where the linear trend has a slope of ~1. This is normally referred to as bi-linear trend between M_S and M_W. Although the *"bi-linear regression"* proved to work well enough in obtaining reliable M_W proxies, such an approach introduces some arbitrariness in the data set separation and also a discontinuity point in the relationships derived. Indeed, the separation between slope ~0.7 and ~1 is not sharp at all and the separation normally adopted at M_S = 6.1 could be moved anywhere between M_S 6 and ~6.5. Thus, data pairs in this M_S range may belong to a domain or another depending on the subjective choice of an author of how the data set was divided into the two domains. This also means that the crossing point of the two linear models will vary with different separation criteria. In addition, it must be considered that a bi-linear model raises the question on how to consistently map the uncertainty in M_S to M_W proxies around the separation of the two linear trends. To avoid the problems raised with the bi-linear regression, we fit a single, continuous regression curve to the training dataset using an exponential model of the form *My = exp(a+b*Mx)+c*. The regression is performed using the non-linear least square algorithm (Bates and Watts, 1988; Bates and Chambers, 1992) freely available with the R-language.

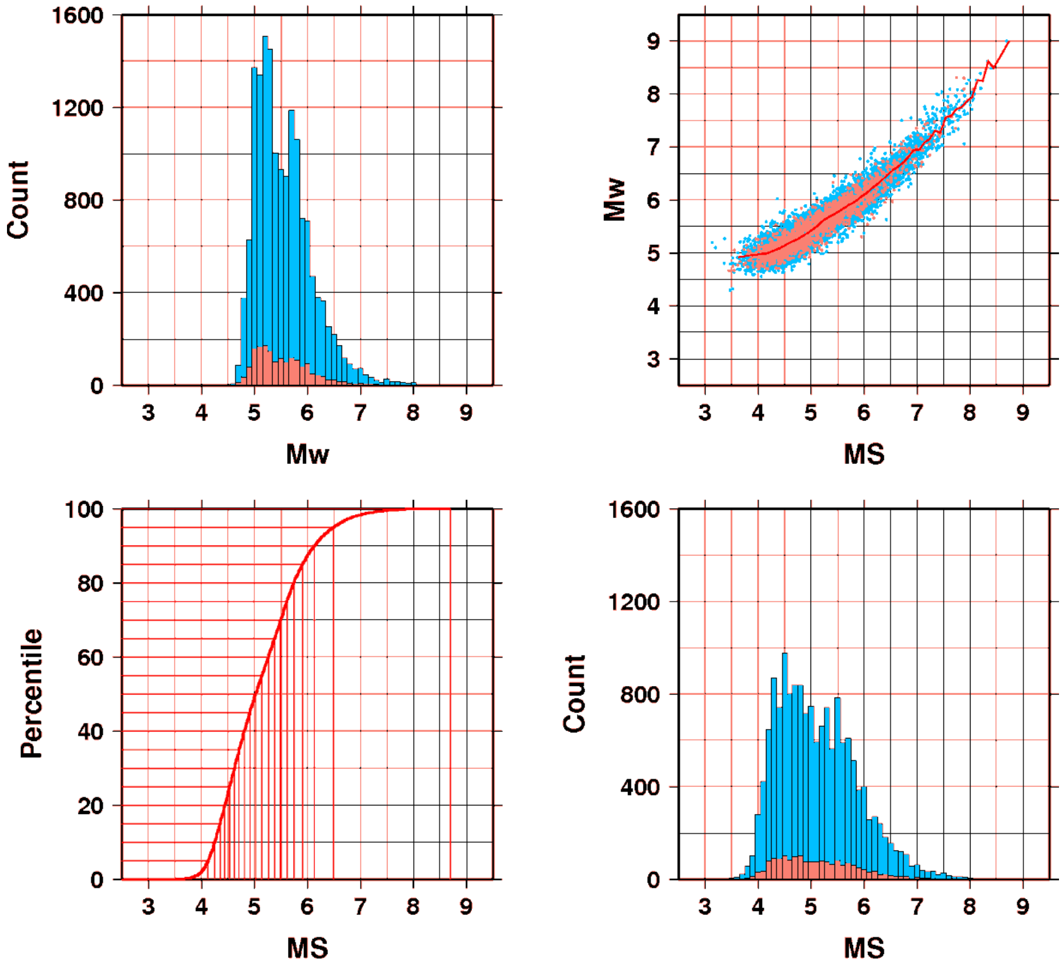


Figure 4.11 Top left and bottom right: histograms distribution of MW and MS, respectively; Bottom left: cumulative percentile. Top right: scatter plot showing in blue the 90% of the whole population falling in the training set, and in red - the remaining 10% to be used as validation set; overlaid is also shown the median value in each bin

Figure 4.12 shows the exponential regression curve, as well as the “classical” GOR bilinear regression lines. The exponential regression not only helps us to avoid the pitfalls of bilinear regression, but also fits the observations better. The exponential model to convert M_S to proxy M_W follows more closely the empirical median values and reads as

$$M_W = \exp^{(-0.22x0.23xMs)} + 2.86 \tag{4.5}$$

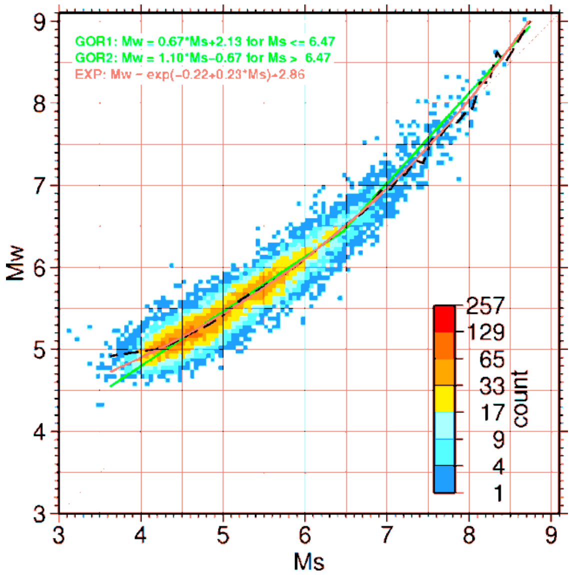


Figure 4.12 Training dataset set M_S-M_W with regression models: the exponential fit is drawn in red; the bi-linear GOR model is shown in green. The dashed black curve is the median value in each bin from Figure 4.11

The GOR models read as

$$M_W = 0.67M_S + 2.13 \text{ for } M_S \leq 6.47 \tag{4.6}$$

and

$$M_W = 1.10M_S - 0.67 \text{ for } M_S > 6.47 \tag{4.7}$$

and are comparable with the GOR models obtained from globally distributed earthquakes by Bormann et al. (2009)

$$M_W = 0.67M_{S(20)} + 2.18 \text{ for } M_{S(20)} < 6.55 \tag{4.8}$$

and

$$M_W = 0.99M_{S(20)} + 0.08 \text{ for } M_{S(20)} \geq 6.55 \tag{4.9}$$

respectively

$$M_W = 0.75M_{S(BB)} + 1.63 \text{ for } M_{S(BB)} < 6.73 \tag{4.10}$$

and

$$M_W = 0.96M_{S(BB)} + 0.38 \text{ for } M_{S(BB)} \geq 6.73 \qquad (4.10)$$

or the GOR models of Das et al. (2011)

$$M_W = 0.67M_S + 2.12 \text{ for } 3.0 \leq M_S \leq 6.1 \tag{4.11}$$

and

$$M_W = 1.06M_S - 0.38 \text{ for } 6.2 \leq M_S \leq 8.4 \tag{4.12}$$

as well as with the respective linear standard models obtained by Scordilis (2006)

$$M_W = 0.67M_S + 2.07 \text{ for } 3.0 \leq M_S \leq 6.1 \tag{4.13}$$

and

$$M_W = 0.99M_S + 0.08 \text{ for } 6.2 \leq M_S \leq 8.2 \quad (4.14)$$

Figure 4.13 shows the derived models against the validation dataset and the comparison of true M_W values versus corresponding proxies.

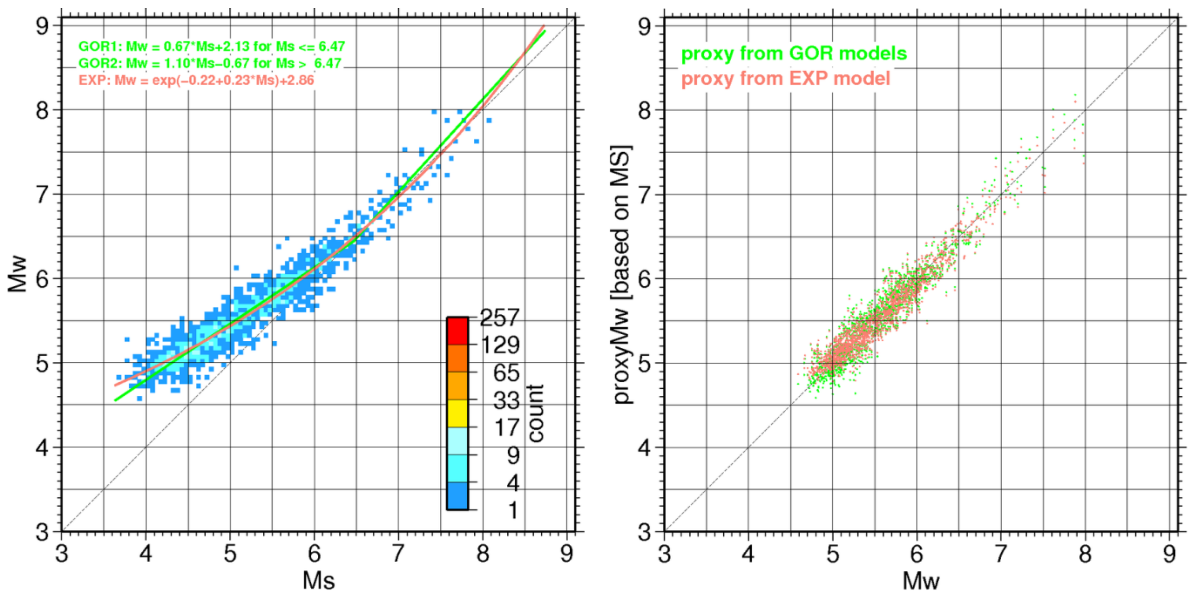


Figure 4.13 Left: validation dataset with regression models as on Figure 4.12: in red is shown the exponential fit, in green the two GOR models. Right: comparison of true MW values and proxies for the validation dataset (green: from the GOR models, red: from the exponential model)

Generally, both models produce proxies reliable enough, but for earthquakes with $M_W < 7$ the exponential fit appears to work better than the GOR model. Hence, we used the exponential fit for converting M_S values in the ISC-GEM Catalogue to obtain M_W proxies. The uncertainty of the proxy is mapped by projecting the uncertainty of the recomputed M_S to the Y-axis.

The conversion relationship constrained with GCMT data (i.e., starting from 1976) is applied whenever necessary to derive a proxy for the entire time span of the ISC-GEM Catalogue. For M_S, however, we can compare M_W values compiled from the literature with proxy M_W values based on recomputed M_S for earthquakes occurred between 1904 and 1975. This comparison is shown on Figure 4.14.

Although the data scatter on Figure 4.14 is larger than on Figure 4.13, the general trend is satisfactory. Besides, it must be considered that M_W from the bibliography is generally less reliable than M_W from GCMT. Figure 4.14 shows also how the proxy for the well-know 1960 $M_W = 9.6$ Valdivia earthquake is significantly underestimated. In the ISC-GEM Catalogue, however, only 5 earthquakes with M_S between 8 and 8.5 have been used to obtain a proxy.

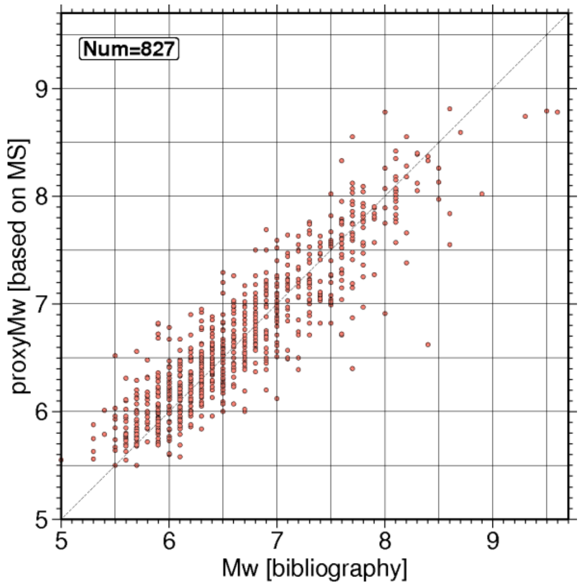


Figure 4.14 Comparison of MW values compiled from the bibliography search and proxy MW values based on MS for earthquakes occurred between 1905 and 1975

4.4.2 Determination of M_W proxy based on m_b

Differently from M_S, the short-period body-wave magnitude m_b has a larger scatter with M_W, especially for earthquakes with magnitude above 6. Therefore m_b is used only when M_S is not available to obtain a proxy (this is especially the case of deep earthquakes). Similarly to the M_S-M_W distribution, the m_b-M_W population is not uniform and is best described in a frequency plot (Figure 4.15).

Again, the dataset is strongly dominated by earthquakes below magnitude 6 and also with a much larger scatter compared to the M_S-M_W distribution. Moreover, m_b strongly underestimates M_W above 6, and saturates already for major earthquakes (more details in Kanamori, 1983; Bormann et al., 2009). For the same reasons mentioned for M_S, however, we did not exclude data pairs close to or above the saturation level of m_b.

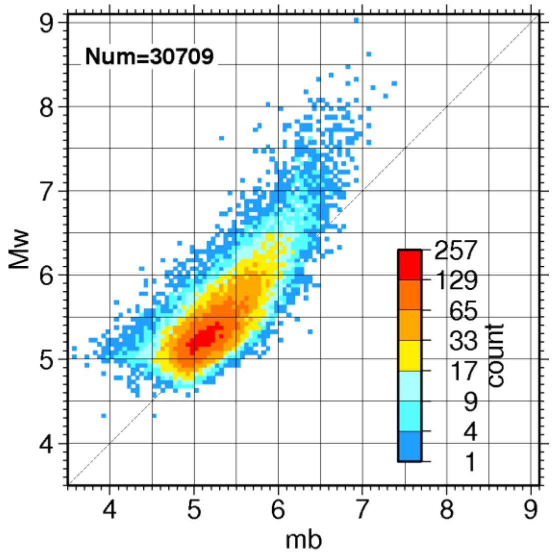


Figure 4.15 Data frequency plot from the mb-MW population

The selection criteria to select the training and the validation datasets are the same as for M_S and shown on Figure 4.16.

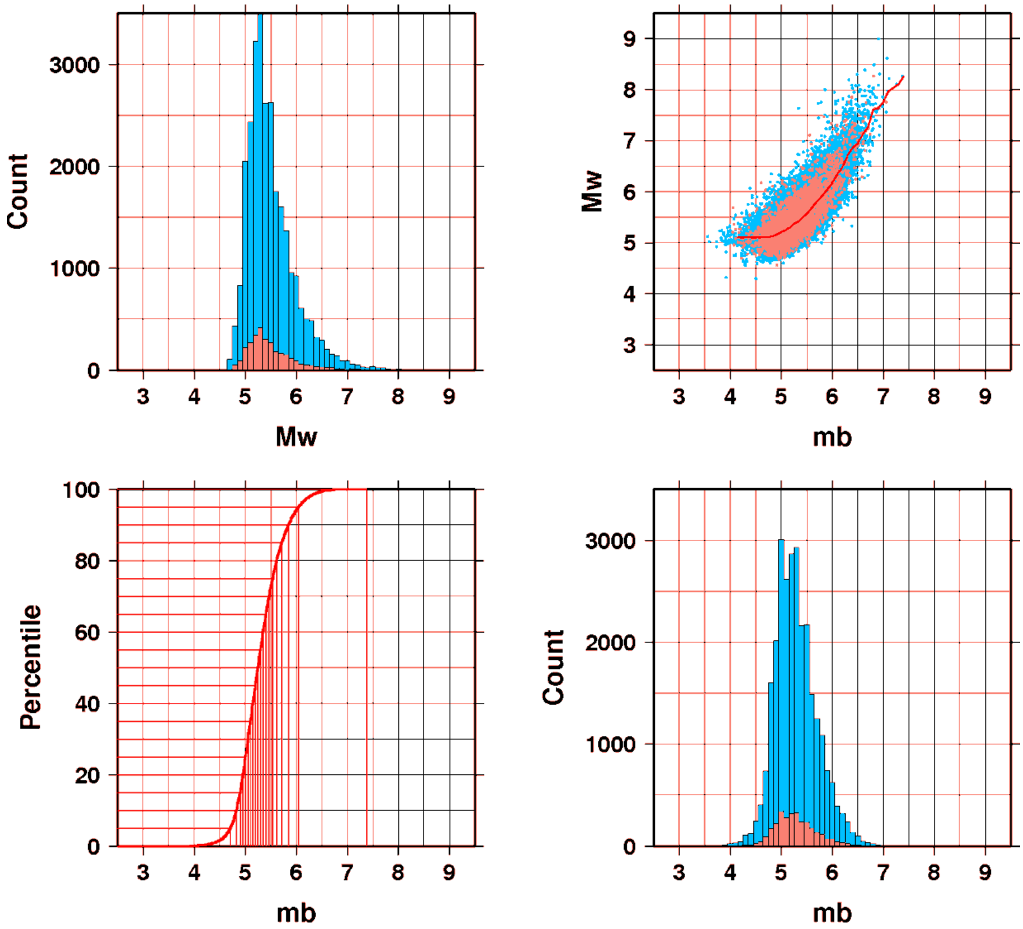


Figure 4.16 The same as for Figure 4.11 but for the m_b-M_W population

Figure 4.17 shows the derived GOR and exponential models. Here the GOR model is obtained without splitting the distribution. The exponential model to convert m_b to proxy M_W reads as

$$M_W = \exp^{(-4.66+0.86mb)} + 4.56 \quad (4.15)$$

and GOR model as

$$M_W = 1.38m_b - 1.79 \quad (4.16)$$

The GOR model differs more with respect to linear standard model of Scordilis (2006)

$$M_W = 0.85m_b + 1.03 \text{ for } 3.5 \leq m_b \leq 6.2 \quad (4.17)$$

and the inverted standard regression of Das et al. (2011)

$$m_b = 0.61M_w + 1.94 \text{ for } 3.8 \leq m_b \leq 6.5 \quad (4.18)$$

These differences are probably due to the dataset truncation at m_b = 6.2 and 6.5 adopted by Scordilis (2006) and Das et al. (2001), respectively. Indeed, the Das et al. (2011) relationship is closer to our GOR model, as they used an upper m_b truncation.

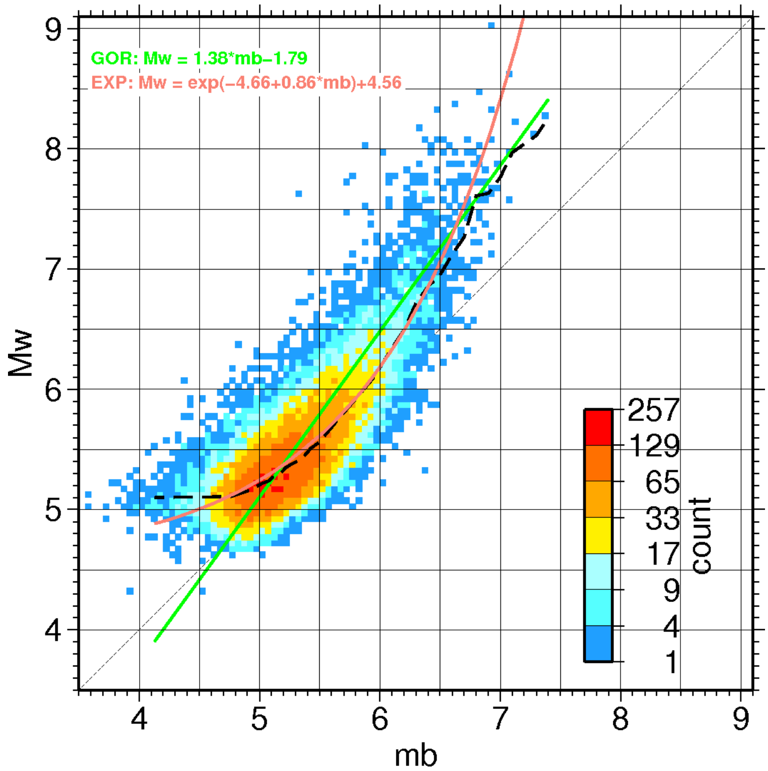


Figure 4.17 Training dataset m_b-M_W with regression models: in red is shown the exponential fit, in green the GOR model. The dashed black curve is the median value in each bin as from Figure 4.16

The exponential model follows even more closely the median values than the GOR model. Both models, however, suffer from the saturation of *mb* for larger earthquakes, and tend to underestimate the M_W value. Thus, M_W proxies derived from the m_b–M_W relation should be used with caution for m_b values above 6.8. For the ISC-GEM Catalogue, only 13 earthquakes require M_W proxy based on m_b with m_b > 6.5, but all of them have m_b < 6.8.

Figure 4.18 shows the regression models against the validation dataset with the regression models and the comparison between *true* M_W values against proxies.

For m_b values above 6.5, neither the GOR nor the exponential model produce excellent proxies, but for smaller M_W values, in a range approximately between 4.5 and 6, the results from the exponential model are generally preferred to the linear one. Thus, as with M_S, our choice for deriving M_W proxy from for m_b is the exponential model. As for M_S, the uncertainty of the proxy is obtained by projecting the uncertainty of the recomputed m_b to the Y-axis. Note that if we used the linear regression model, the m_b uncertainties would also linearly project to the M_W proxy uncertainties, that is, the uncertainty in the M_W proxy would be the same for an m_b =5.6 ± 0.1 earthquake as for an m_b =6.6 ± 0.1 earthquake. The exponential model on the other hand, would provide increasingly larger M_W proxy uncertainties with increasing m_b values, thus providing more reliable uncertainty estimates when m_b starts saturating.

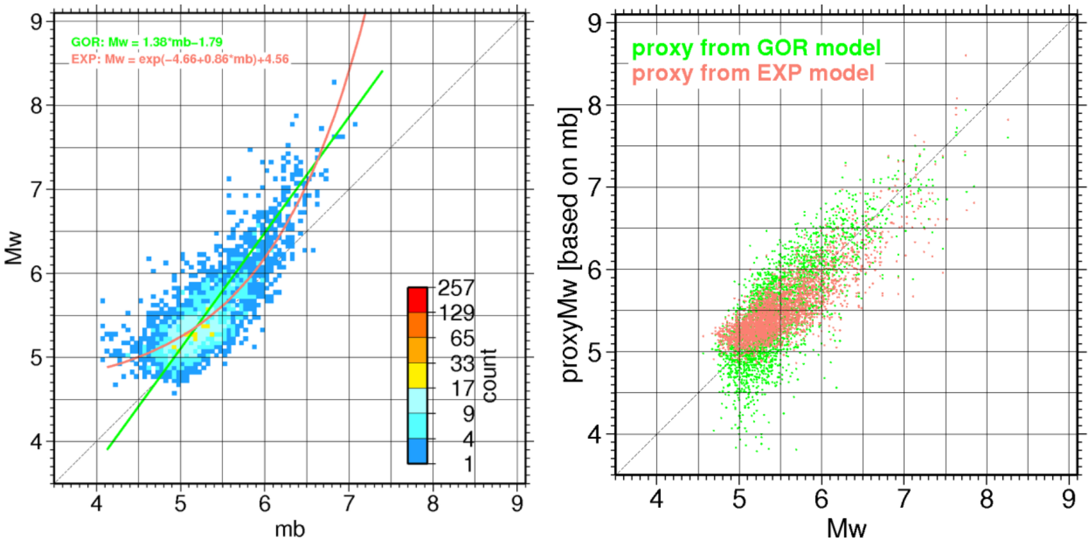


Figure 4.18 Left: validation dataset with regression models as on Figure 4.17: in red is shown the exponential fit, in green the two GOR model. Right: comparison of true MW values and proxies for the validation dataset (green from the GOR model, red from the exponential model)

4.5 Description of the Magnitude Source and Quality Flags

In the ISC-GEM Catalogue (See Appendix A) the field describing the source of the magnitude can be set equal to "p" (stands for proxy) when the moment magnitude is obtained from a conversion relationship, or "d" when the moment magnitude is obtained from a direct measurement of the seismic moment M_0.

The magnitude quality field, instead, can have 4 different flags (as for the location and depth) varying from highly reliable (**A**) to not reliable (**D**). In the following are listed the conditions to assign the magnitude quality flag in the ISC-GEM Catalogue.

Flag A (most reliable) is reserved for magnitudes of those events where a direct measurement of M_0 is available. This is, in practice, the case of M_W from the GCMT Catalog.

Flag B is assigned in two different situations. One case is when M_0 estimations are available from the bibliographical search (Section 4.2) and the estimated uncertainty spans from 0.2 to 0.3. The other case is when M_W proxies are based on M_S, but only for highly reliable M_S determinations (that is, number of station magnitudes contributing to network $M_S > 4$, uncertainty of network $M_S \leq 0.2$, uncertainty of proxy $M_W \leq 0.3$, and only for $5.5 \leq M_S \leq 7.5$).

Flag C is assigned in different situations. One case is when M_0 estimations are available from the bibliographical search (Section 4.2) and the estimated uncertainty is 0.4. The second case is when M_W proxies are based on M_S, but only for M_S determinations not satisfying the criteria for assigning flag **B**. Here it is worth to recall that a network M_S magnitude from two high quality single stations has been obtained for 87 earthquakes. The flag is set to **C** for these events. Finally, flag **C** is assigned to those earthquakes where M_W proxies are based on m_b, which has been shown to be the poorest predictor for M_W.

Flag D is assigned for those earthquakes where there is no network magnitude. This is the case for the earthquakes in the early instrumental period listed in the Appendix. This situation is encountered especially before the deployment of the WWSSN in the 1960s. For those earthquakes, therefore, no single station magnitude is available or only 1 to 2 single stations are available (with the exception of the 87 earthquakes mentioned above).

5 Completeness analysis of the ISC-GEM Catalogue

5.1 Assessment of Completeness on a Global Scale

As already mentioned, the ISC-GEM Catalogue has three different cut-off magnitudes applying in the following time periods:

- Magnitude ≥ 7.5 up to 1917; in addition, selected earthquakes in stable continental region and/or away from major plate boundaries with magnitude between 6.5 and 7.5 have been considered;
- Magnitude ≥ 6.25 between 1918 and 1959;
- Magnitude ≥ 5.5 between 1960 and 2009.

For all figures in this chapter, the word magnitude designates direct M_W, where available, or proxy M_W otherwise.

Figure 5.1 shows the time-magnitude distribution of the ISC-GEM Catalogue.

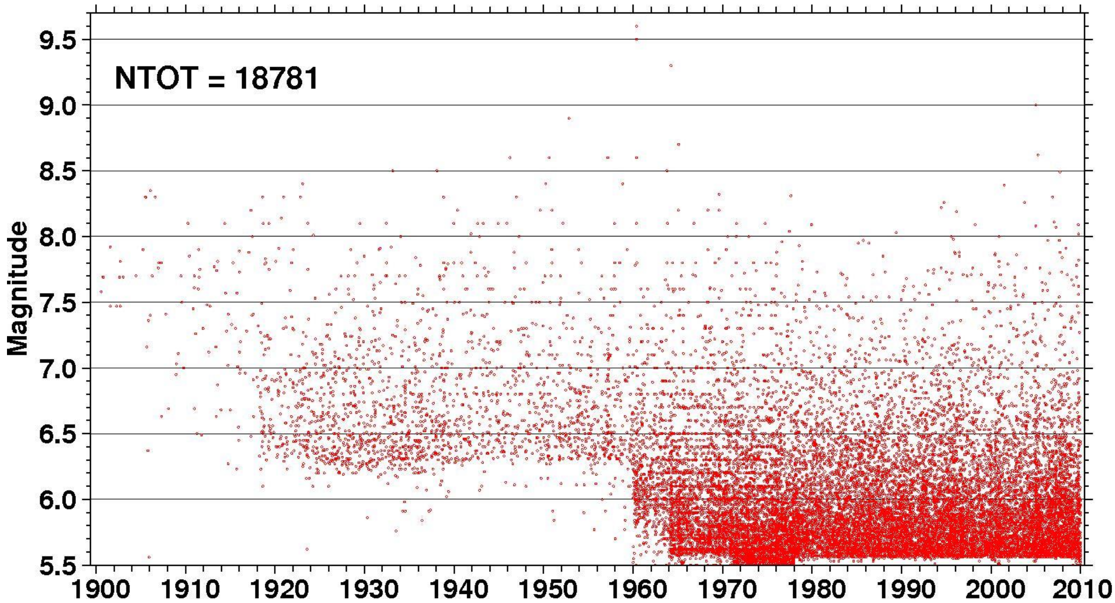


Figure 5.1 Time-magnitude distribution of the ISC-GEM Catalogue

The effect of these three cut-off magnitudes is clearly depicted. However, to visualize the actual time variation of the frequency-magnitude distribution better, it is preferable to consider Figure 5.2.

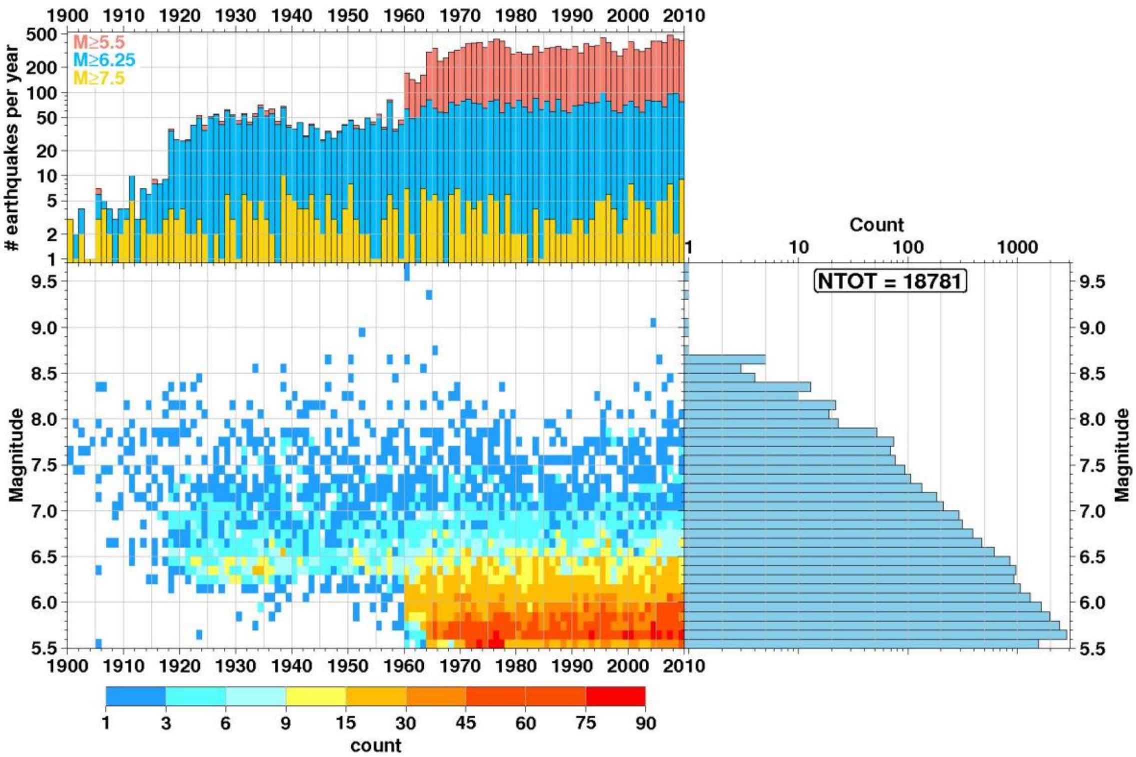


Figure 5.2 Bottom panel: same as Figure 6.1 but color-coded in bins of 0.1 magnitude units for each year. Top panel: cumulative number of earthquakes per year for the three cut-off magnitudes. Right panel: magnitude distribution for the entire ISC-GEM Catalogue

One important feature shown on Figure 5.2 is the significant increase in the number of earthquakes starting from 1964. Secondly, even if fluctuations are present, the number of events per year between 6.5 and 7.5 seems to be quite stable for most of the catalogue from 1918 to 2009, with the apparent decrease observed in the 1940s most probably due to inoperative good quality stations as result of WWII. Another characteristic is that the occurrence of earthquakes above 7.5 can significantly vary from decade to decade. For example, between 1980 and 1994 the occurrence of earthquakes above 7.5 seems much smaller than in other time periods. Thus, the time window for assessing the seismicity rate of large earthquakes should be selected as large as possible.

Evidently, the frequency-magnitude distribution is strongly time dependent for the 110 years covered by the ISC-GEM Catalogue. In order to assess the effect of such variability over the years, Figure 5.3 shows the frequency-magnitude distributions for cumulative time periods (in steps of 22 years) starting from 1900, where the next period adds data from the previous one. In addition, curves for the early instrumental period (up to 1963) and the modern one (1964-2009) are also shown along with estimated magnitude of completeness *Mc* estimated with the maximum curvature method of Wiemer and Wyss (2000).

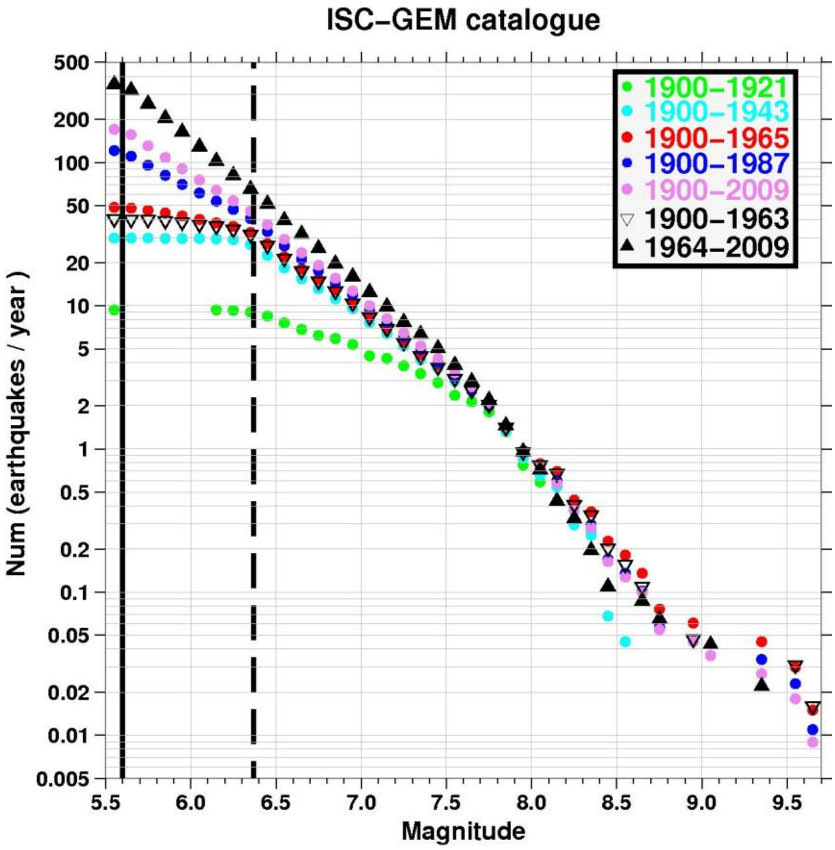


Figure 5.3 Classical cumulative frequency-magnitude distributions for different time periods. In color are plotted the curve for cumulative time periods in steps of 22 years starting from 1900, whereas the black triangles refer to data between 1964 and 2009 only and the inverted triangles refer to data between 1900 and 1963. The completeness magnitude Mc for the 1964-2009 and for the 1900-1963 periods are shown as solid black line and dashed black lines, respectively. Mc is computed via the maximum curvature method of Wiemer and Wyss (2000)

Figure 5.3 is only one of the many possibilities of showing the frequency-magnitude distributions for different time periods. The main intent is to emphasize the effects on the seismicity rates that can be derived without a proper time window selection. In more detail, it is interesting to note how the frequency-magnitude distribution for the period 1964-2009 is above all the others up to magnitude 7.5-7.6. For higher magnitudes, instead, frequency-magnitude distributions are comparable if the time range covered is larger than 60 years. In the light of these considerations, we computed the completeness magnitude only for the period up to 1963 (*Mc* = 6.37) and from 1964 to 2009 (*Mc* = 5.6). This way, when considering the frequency-magnitude distribution between 1964 and 2009, a better representation of the seismicity rate is given for moderate earthquakes up to magnitude ~7.5, whereas for the period up to 1963 the *Mc* of 6.37 seems to be slightly underestimated if compared to the number of earthquake above 6.3-6.4 observed in the modern period (as also deducible from the color-coded plot of Figure 5.2). On the other hand, when considering the seismicity rate of earthquakes above 7.5, it is advisable to extend the time window and consider the frequency-magnitude distribution for the entire catalogue (see pink symbols that relate to the 1900-2009 period on Figure 5.3).

5.2 Assessment of Completeness on a Regional Scale

In order to estimate the spatial completeness for different areas, we selected 12 macro-regions, as shown on Figure 5.4.

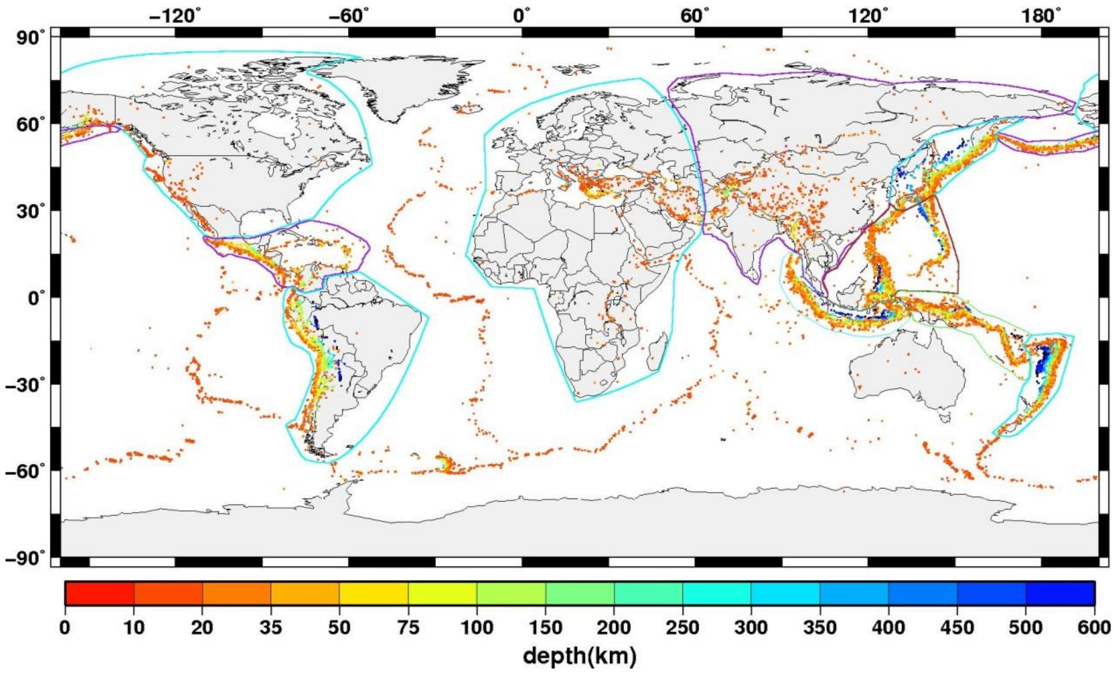


Figure 5.4 The map shows the ISC-GEM locations and the area selection for the regional magnitude completeness assessment. From top left, these regions encompass roughly North America, Central America and the Caribbean, South America, Europe-Africa-Middle East, continental Asia, and then six regions for the East Pacific ocean (Aleutian, Kuril-Japan, Taiwan-Philippines-Marianna Is., Indonesia, New Guinea-Vanuatu, Fiji-Tonga-New Zealand). The names given to each geographical region are indicated on the top of each subplot in the following figures. Earthquakes not included in any polygon are considered in a single group called Oceans

The area selection has been made as a reasonable compromise between number of earthquakes in a polygon, vicinity to land, and geodynamic setting. For example, due to the small number of earthquakes in Africa, we grouped these earthquakes with the ones occurred in a large area covering Europe and the Middle East.

Figure 5.5 shows the frequency-magnitude distributions for the five polygons covering mostly the continents and the group considering the earthquakes in the oceans. On Figure 5.6, instead, are reported the distributions for the six polygons covering the East Pacific ocean (mostly subduction zones). In both figures, each subplot shows the frequency-magnitude distributions for three periods only: 1) from the beginning of the past century up to 1963; 2) from the beginning of the past century up to 2009; 3) from 1964 up to 2009.

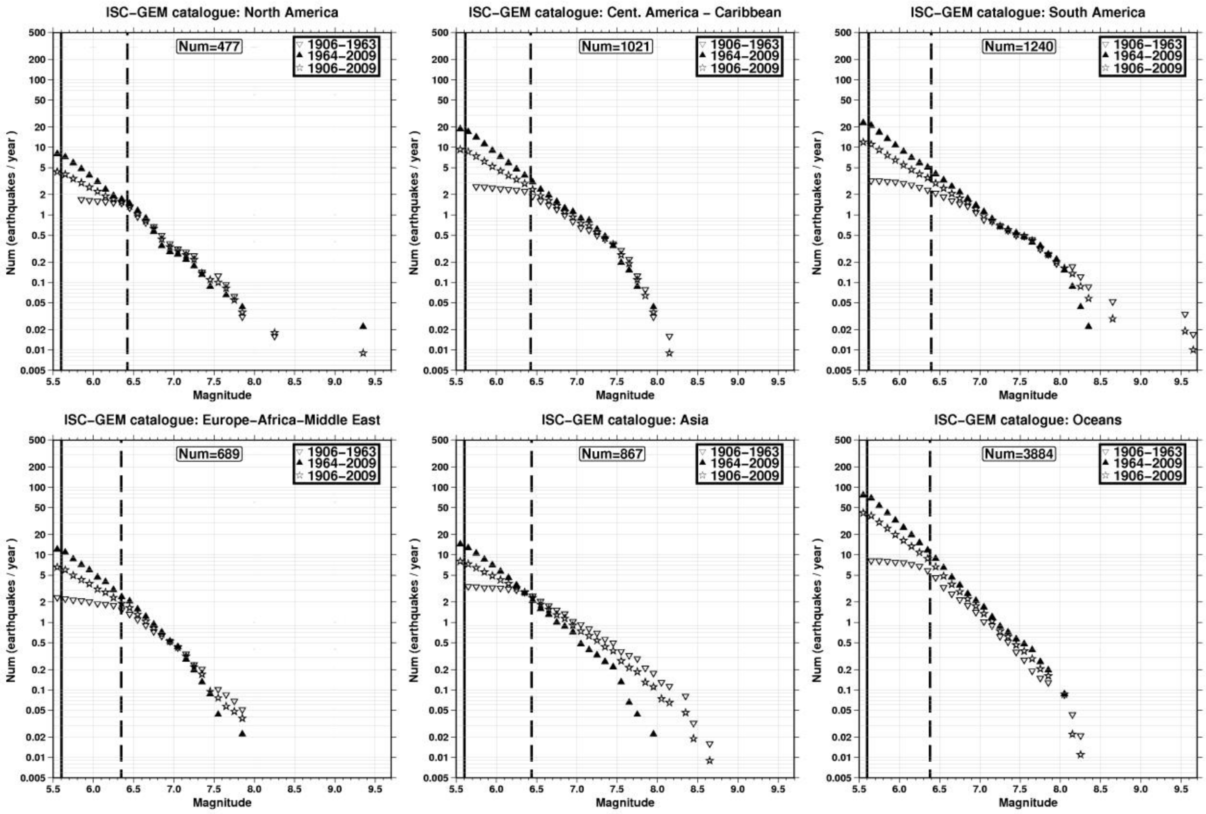


Figure 5.5 Cumulative frequency-magnitude distributions for the regions named in each subplot are shown. Filled black triangles indicate frequency-magnitude distribution for the period 1964-2009, inverted triangle - up to 1963 only, and stars - for entire time range of the catalogue. The completeness magnitude Mc for the period 1964-2009 and up to 1963 are shown as solid black and dashed black lines, respectively

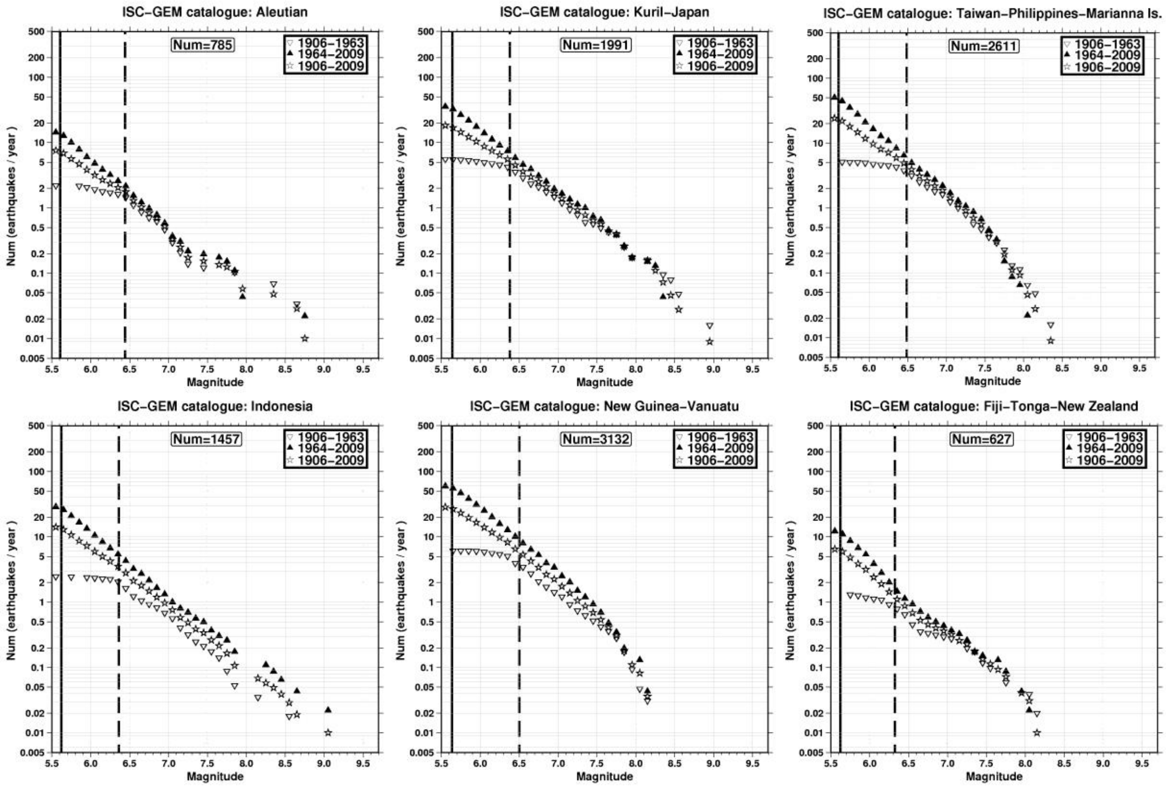


Figure 5.6 As for Figure 5.5 but for the six polygons covering the East Pacific ocean

The estimated *Mc* is rather stable at about 5.6 for all the polygons in the modern period, whereas for the early instrumental period *Mc* spans from 6.3 to 6.5. Especially the areas regarding the East Pacific ocean tend to have a slightly larger *Mc* between 6.4 and 6.5 compared to the polygons covering the continents. This is not surprising as many good quality stations up to 1963 are rather distant from these areas.

6 Conclusions

On request and with sponsorship from the GEM Foundation we compiled and delivered the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009).

- The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009) is a major step forward on the way to improve characterization of spatial distribution of seismicity, magnitude frequency relation and maximum magnitudes within the scope of GEM.
- With a few exceptions, parameters of this catalogue are the result of computations based on the original reports of seismic stations and observatories.
- We made every effort to use uniform location and magnitude determination procedures during the entire period of the catalogue:
    - In earthquake location, we used a combination of the EHB depth determination technique and the new ISC procedures that use a multitude of primary and secondary seismic phases from the IASPEI Seismic Phase List and the ak135 velocity model and take into account the correlated error structure.
    - In determination of earthquake magnitude, where possible, we used direct M_W values from Global CMT project for the period 1976-2009. In addition, 1,127 high quality scientific papers have been processed to obtain directly measured values of M_0 and M_W for 970 large earthquakes during 1900-1979. In all other instances we computed M_W proxy values based on our own determination of instrumental surface or body wave magnitudes using updated regression models.
    - It has to be noted that a computation of M_W proxy values based on regressions from other types of magnitudes does not bring similarly reliable results as compared to a direct measurement of M_W based on the original waveform analysis. It is, nevertheless, a necessary measure since the direct measurement of M_W using historical analogue waveforms on a global scale is beyond the scope of this project.
- A number of important additional benefits have been achieved during this project:
    - The entire ISC collection of historical paper-based seismic station bulletins was reviewed, indexed and catalogued for further works. Indexes of similar collections at USGS/Berkeley were used in filling the gaps in the ISC collection.
    - A large number of seismic phase arrival times, body and surface wave amplitude measurements have been made electronically available on a global scale that have never been available on a global scale prior to this project.
    - A large number of more accurate network M_S and m_b magnitudes have been computed for large earthquakes that either had no magnitude estimate or the estimates were previously based on single or unreliable station data.
- In our work we consulted and were observed by experts from the IASPEI and, where possible, followed the IASPEI seismic standards.
- We put together an excellent team of professionals in the field and gave training to a group of technical personnel without whom the work on this project would have been impossible to complete. These personnel members are a valuable asset of this project and their experience can be used if further work was to be planned.

- Although the ISC-GEM Catalogue is a major accomplishment, we nevertheless believe that further work is necessary to enhance its qualities:
    - *Firstly*, neglecting to update the ISC-GEM Catalogue beyond 2009 would seriously hamper the GEM community efforts of testing and refining of the earthquake forecasting models.
    - *Secondly,* it is well known that in seismic hazard studies the effect of small to moderate size earthquakes is not negligible. This is especially the case in densely populated and industrialized areas. This calls for further improvement of completeness of the reference catalogue to be extensively used by GEM community for many years to come.

Thirdly, it has to be noted that we really have no magnitude estimates for many events in our main original source of historical data before 1964 – the ISS Catalog. Some of these events in the first part of the 20th century could be large enough to have caused damage. The work of including many more earthquakes recorded at teleseismic distances and bringing previously unavailable station amplitude data from historical station bulletins would greatly contribute to more accurate consequent analysis of global earthquake hazard and risk.

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APPENDIX A ISC-GEM Catalogue Format

The ISC-GEM Catalogue is delivered in the CSV (comma separated values) format that contains:

- earthquake origin date and time;
- epicentre (lat,lon);
- error ellipse parameters (smajax, sminax, strike), epicentre quality (q:A(highest)/B/C);
- depth, depth uncertainty (unc), depth quality (q:A(highest)/B/C);
- Mw, Mw uncertainty (unc), quality (q:A(highest)/B/C), source(s:p-proxy, d-direct computation);
- *where available*: scalar moment (mo), factor (fac) , mo author (mo_auth);
- *where available*: six moment tensor components (mpp, mpr, mrr, mrt, mtp, mtt);
- ISC numerical event identificator.

The Appendix to the catalogue is provided in the same format as a separate file. It contains a list of those earthquakes for which poor data availability prevented the authors from performing a reliable determination of either the epicentre or the magnitude parameters or both. Quality flag D indicates which parameter is unavailable or poorly estimated.

We also provided the kmz-formatted file for those willing to examine the catalogue properties using the Google Earth package.

APPENDIX B Articles with Direct M_0 Determination Collected During the Bibliographical Search

The list of references below includes 1,127 scientific articles that contained direct determination of Mo of earthquakes included in the ISC-GEM Catalogue.

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THE GLOBAL EARTHQUAKE MODEL

The mission of the Global Earthquake Model (GEM) collaborative effort is to increase earthquake resilience worldwide.

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working together to assess risk