Author’s Response to Anonymous Reviewer (RC2) (PAPER: https://doi.org/10.5194/essd-2021-266)

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We thank the reviewer #2 for the comments and suggestions. Below we reply in detail to each point showing the Referee Comments (RC) in bold and the Author Response (AR) in italic. Most of the RC2 suggestions have been accepted and included in the revised version of the manuscript (annotated manuscript after our answers).

RC:
With the recent advent of high-quality seismic networks, the database of observational seismology has expanded significantly, yet the availability is relatively short, about 3 to 4 decades, and it is desirable to relate the results of modern seismology to those obtained prior to the 1980s. As the authors state, the surface-wave magnitude MS is among the key parameters that would allow us to compare the modern and old events, thereby allowing us to better understand the long-term seismicity of the Earth. Unfortunately, the historical data of MS is incomplete and often confusing, and we encounter many difficulties. This paper describes the results of impressive efforts to establish a more complete historical MS database, and is a welcome contribution to seismology and merits formal publication in Earth System Science Data. As the authors state, this is not meant to be a completed product, and future developments are planned and proposed. Thus, this review consists of some questions on the procedures used, but more importantly, I would like to make some suggestions and caveats with the hope that this database can be made more useful for serious users including myself.

We thank the reviewer for this general comment.

I will make some detailed comments below, and I recommend publication of this manuscript, after the authors consider my comments at their discretion.

Comments and questions on specific points.

Line 25. Please comment on A and (A/T)max. Is the component specified? Does (A/T)max literally mean the maximum of A/T, or can (Amax/T) be used as a proxy?

We do not feel to change the text in the Introduction because there we simply report the original definition by the creators of the MS Moscow-Prague formula. However, in the Section 2 the use of the three components is detailed and we have added the following sentences to address the reviewer questions regarding Amax/T versus (A/T)max:

"Although our procedure finds the maximum of A/T within the reading, a reporter may have provided single component measurements of Amax/T".

Line 31 to 36. I thought that the basis of Abe's (1981) catalog is Gutenberg's notepad (Goodstein et al., 1980). Also, I thought that Rothé (1969) is the continuation of Gutenberg and Richter's (1954) Seismicity of the Earth. As far as I understand, most magnitudes published in Gutenberg and Richter (1954) and Rothé are MS but some are based on mB. It appears that Gutenberg's idea of "unified magnitude" had some influence on the magnitudes in these publications. Some explanations here would be helpful. Richter (1958) would be most useful on this subject.

We feel that it is not the case for our manuscript to debrief the reader on the history of past earthquake catalogues. Interested readers can look in the references of the papers already cited.

Line 44. What does "digitize" mean here? Does it mean to convert printed materials to computer- accessible format?

We have added "(i.e., converted from printed to computer accessible format)" after "digitize".

Line63. $\sqrt{\left(2*\frac{A}{T}\right)^2_{N|E}}$ **is an ambiguous notation. Please clarify.**

As pointed by other reviewers, we thank the reviewer #2 for pointing out the typeset error.

Line 70. Can you elaborate on "median absolute deviation (SMAD) of the a-trimmed station magnitude"?

From the sorted station magnitude distribution, the median is computed and the SMAD is obtained by trimming 20% the bottom and top end of the distribution. This practice has been used for several years in ISC procedures and it is well-documented, hence we did not add further explanations in the text.

Line 198. I agree with the statement "It is of paramount importance that datasets are well-documented and that users know how they are created in order to properly use them for research"

Thanks.

Line 227 to 232. Although I do not have strong objection to the statement here, I think this section reads somewhat strange. Although "Saturation" and "Under-estimation" can be used in a qualitative statement, it is important to emphasize here that MS and Mw are different parameters representing an earthquake "measure" at different periods. Both measures are equally important.

We agree with the reviewer suggestion to emphasize the importance of both magnitude types. Hence, we added in the text "We also suggest that Ms and Mw, as expressions at different periods of the earthquake size, should be used together to better characterize an earthquake the source properties of an earthquake."

Line 248. I am glad to know that development of the MS dataset will continue. Although the current database is very useful, for the events before 1970, the number of stations is often very limited with a large azimuthal gap, and it would be extremely helpful to include as many stations as possible. The plans summarized in this manuscript to "digitize" as many more station bulletins as possible are very impressive. Although I can understand the ISC's desire to go back to the original station bulletins, other amplitude data from various secondary sources (e.g., BCIS, Gutenberg notepad (Goodstein et al. 1980), Abe's note (this apparently exists at the Earthquake Research Institute), database used for Rothé (1969), and Lienkaemper (1984)) can be useful, and can be also utilized. Although there could be some small differences in the measuring method of amplitude, period etc in these secondary sources, it seems to me that the biggest uncertainties in the event Ms values come from the limited azimuthal coverage rather than the small differences in the amplitude measurements, and it would be useful to include Ms data from the secondary sources with an appropriate flag, if desired.

As outlined in Section 6, we are eager to improve the dataset by adding as much data as possible. We would be happy explore new sources and help from the community is welcome.

Line276 to 292. Conclusions

While I admire the ISC's efforts for establishing a good MS data base, many investigations have been made using some standard catalogs like Gutenberg and Richter (1953), Richter (1958), Rothé (1969), Duda (1965), Abe (1981), etc. Although there are some differences in details such as the method of amplitude measurements, the method of picking the phase (A vs A/T), attenuation relation (Gutenberg vs. IASPEI formula), the component used, station corrections, and the averaging scheme etc (some of these differences are covered in this manuscript), it would be useful if the authors make some comparisons of magnitude between the new ISC MS and that from these catalogs. It can be done by some simple figures and by some tables for important events. Again, some of the comparisons may have been already made elsewhere, but it would be useful to show them together in this paper.

We avoided to add magnitude comparisons with previous catalogues as a large literature is available to this regard. We point out in the text that Abe's catalogue is of very good quality and that magnitude comparison with our recomputed Ms are available in Di Giacomo et al. (PEPI 2015). Since Abe's catalogue is mostly for MS 6.5 and above, we feel that we would not add much by updating that figure. Nevertheless, the biggest advance of our MS dataset consists in the thousands of earthquakes for which we provide for the first time MS, and those cannot be compared to any other catalogue.

There are a few questions myself, and if the authors can provide some insight on them, it will be useful for many serious researchers to fully utilize the ISC catalog.

Questions

The most important material is the “Ms_Dataset” that accompanies this document. Many of the issues raised below are related to the content in “Ms_Dataset”.

1. **I vaguely remember that Gutenberg and Richter used some station corrections (e.g., Gutenberg, 1944), but I have not seen the list of the station corrections. It is possible that the station corrections include not only the path effects (different attenuation and focusing and defocusing of energy due to multi-pathing), but also some effects of different station practices for measuring the amplitude and applying the instrument gain corrections (static magnification vs. magnification at the period of the waves being measured.)**

To the best of our knowledge, magnitude station corrections are not implemented in any global agency that provide magnitude determination from stations worldwide. However, that does not mean that users can analyse our dataset and obtain station correction terms. These, however, are not part of our submission.

2. **Did any of the stations apply corrections for the depth? It appears that Gutenberg attempted to apply some corrections (Gutenberg, 1944), but I wonder if it is documented somewhere. I am almost certain that excitation of 20s surface waves can be significantly affected by the depth even for the relatively small depth ranges from 0 to 60 km.**

The literature covers this aspect of MS. Recently, Petrova and Gabsatarova (J. Seism. 2020, and references therein can be found for the literature on the subject) investigated depth corrections to the Moscow MS. It is true that surface wave excitation gets smaller with earthquake depth, hence standard procedures limit MS computation to 60 km (IASPEI, 2013). Depth effect up to 60 can be indeed studied and, again, we encourage users to analyse our dataset in this respect.

3. **Are any considerations given to whether the measured waves are Rayleigh type waves or Love type waves. This must have significant effects when MS from vertical and horizontal components are mixed. Geller and Kanamori (1977) discussed some of the issues.**

MSZ (Rayleigh waves) and MSH (Love and Raileigh waves) values are available in our dataset. The use of horizontal components is necessary especially in the first ~70 years of the last century due to the scarcity of vertical component instruments worldwide. In recent decades the vertical component is the most reported to the ISC. We generally find good agreement between MSZ and MSH although discrepancies are expected. As in previous replies, the dataset provides *the full information behind a MS network value, and users have the possibility to analyse in many ways our dataset.*

4. **I noticed a few cases in which 2 successive events which are very close in time are given separate MS. It will be helpful if the authors offer some explanations for these cases. Following are just 2 examples related to the 1960 Chilean earthquake.**
    - **(i) Event 879134 and 879136.**

      Event 879134 occurred about 15 min before the MS=8.58 Chilean mainshock (#879136), and is given MS=8.44. Judging from the difference in the amplitude of body waves, it would be very difficult to pull out the surface waves from Event 879134 which are buried in much larger waves of Event 879136.

We have verified the association of all reading to both events and we confirm that we associated the surface waves to each event as reported in the original bulletins. The only exception to that is the CLL reading that should be reassociated to evid 879136 (its reassociation, however, will not change significantly the MS for both earthquakes).
The Soviet Union stations are the most important contributors for both events and their original reports can be found at PDF page 134 of http://www.isc.ac.uk/printedStnBulletins/Bulletins_scans/URSS/Moscow/Seism_Bull_1960_AcademyofSciences_URSS.pdf*.*
The only station currently available for both events is Riverview (station RIV). At page 34 of its original bulletin at http://www.isc.ac.uk/printedStnBulletins/Bulletins_scans/Australia/Riverview/Seism_Bull_1960-1961_Riverview.pdf *it is possible to find the readings for both earthquakes.*
As the two earthquakes are co-located and separated by 15 minutes, it is possible to identify the surface waves at a given site for both events. However, we agree with the reviewer that it is a challenging situation to get a reliable MS in such cases as the surface wave trains can be mixed, and depending on the relative size of the pair of earthquakes it can be very difficult to properly identify and measure the surface waves belonging to each event. For RIV case, however, the surface wave phases M are separated by about 12-13 minutes between the two events, which is in line with what we would expect in such a case. Unfortunately, no time is given in the Soviet Union bulletin for the surface waves. As we explain in the text, we plan to top up the station magnitude contribution in the 1960s and the 1960 Chilean sequence will likely benefit from that activity, and it may lead us to revise and improve the MS solution for both earthquakes.

- **(ii) Event 879127 and 879128**

  These events occurred just 2 minutes apart (Ms=7.18 for #879127 and MS=7.0 or #879128), and again how the surface waves from these 2 events were separated is unclear.

The same arguments apply to this pair.

5. **For events after 1990 when the large number of modern global stations were used, a new problem emerged. This topic is closely related to the**

discussion from line 235 and Table A1. Comparison of MS and Mw is often very important for understanding the nature of earthquakes. Large differences between MS and Mw, and MS between different catalogs can be due to many causes. 1) The real physical characteristics of the event (e.g., slow earthquakes), 2) very limited Mw data (e.g., single measurement), 3) large differences in MS from different sources.

We generally agree with these comments and, although is not our aim in this manuscript, we remind the reader that difference ought to occur and are likely to give investigators cases worth studying.

Here, the issue is the difference in MS from different sources. We occasionally see a very large difference (ΔMS > 0.5) between MS from different sources. For old events (e.g., before 1970), often the difference is due to a very limited azimuthal coverage. This is to some extent inevitable because simply the number of global stations was relatively small. However, it would be important to assemble as many station Ms data as possible, even if the measurement practice is slightly different at different stations. Even if some measurements do not meet the strict ISC standard, that can be added, with appropriate flags if necessary, to the MS basic catalog. As I will show later, I think that the variation of MS with azimnuth is often much larger than that due to the difference in the measuring practice (amplitude, period, attenuation function, etc), and for many research purposes it is important to have a good azimuthal coverage.

We cannot agree more with the reviewer that it is important to gather as much data as possible and be flexible with the restriction criteria. Indeed, we detail how we adopted an expanded procedure for MS calculation before 1964. We are aware of the azimuthal limitation in the first 70 years and for the first time in a catalogue of this kind we provide the azimuthal gaps in the catalogue file for station magnitudes and discussed the matter with Figure 6.

Now going back to modern events (e.g., 1970), we have the luxury of having many and many stations, and often have an opposite problem. Occasionally, we have too many stations in a small azimuthal range with “anomalous” path effects, and this can bias the final station MS (either some sort of average or median). Since the azimuthal variation of MS due to the path effect can be as large as ΔMS=2 unit, this azimuthal bias can produce very confusing results. Of course, this is more of a research subject than catalog-related subject, but it will be helpful if some caveats are given in this paper. I have seen many problematic and questionable cases in the literature, and wish that some more careful discussions are made in this paper so that users are aware of this problem.

As mentioned in previous reply, we provide users with the full picture of the data contributing to the network MS. Hence, cases with limited azimuthal coverage are easily identified. We agree that MS could be biased to some extent in such cases. Again, tough, we have included the azimuthal gaps in the dataset and briefly discussed the implications of large azimuthal gaps. Nevertheless, we wish to satisfy the reviewer desire to stress more this issue and included in the manuscript the case *of the 1960-03-20 off east coast of Honshu (evid = 878564), see new Figure A1 in the revised manuscript and related text in Section 3.*

Following are some examples from old and modern events.

Event #878564 1960-03-20 Off east coast of Honshu

The ISC MS is 7.92, but JMA magnitude MJMA is 7.0. Although MJMA is not exactly MS, it was calibrated against Gutenberg and Richter's M, and generally believed to be close to MS. For many Japanese events, MJMA is indeed close to MS (e.g., Utsu, 2001, Relationships between magnitude scales). Thus, this large difference caught my attention. Figure 1 compares the azimuthal variation of MS taken from "Ms_Dataset" and that computed for a nearby Mw=7.3 event (3/9/2011) using the global data. The azimuthal variation patterns of MS for the 2 events are very similar, and large. The range is almost 2 magnitude unit (6.5 to 8.5) for the 1960 Sanriku event, and 1.5 unit for the 2011 event. Since the number of stations for the 2011 event is very large (what are shown on the figure represent only a subset), and the azimuthal coverage is uniform, the median appears to be well defined. On the other hand, for the 1960 event, the data set is dominated by the stations in the azimuthal range from 300 to 360 deg. Although there is some evidence that the 1960 event was a slow earthquake, it should not affect MS, and the users should be aware of this strong azimuthal variation of MS.

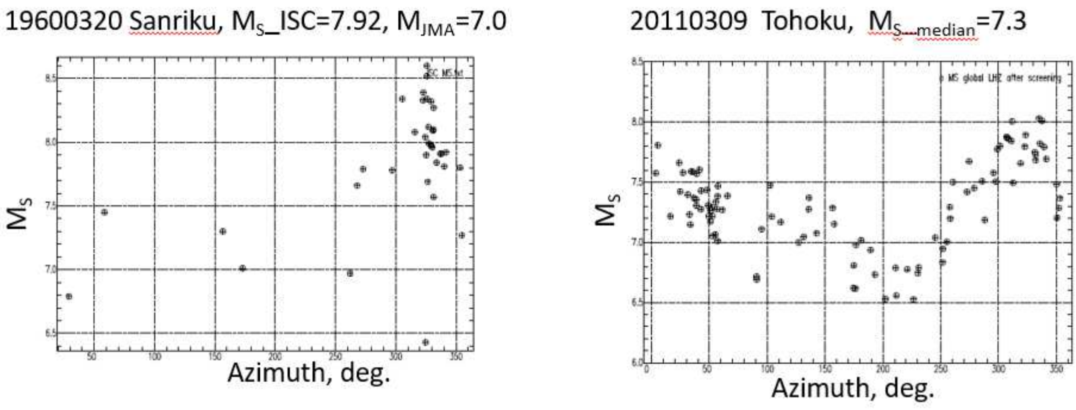

Fig. 1

We are aware of the large MS of this event compared to other magnitudes, including MJMA. As mentioned above, we have included this example in the text (Section 3) to stress even more the limitation due to the azimuthal distribution of the stations contributing to the network MS. We consider this the best example in this respect among the ones highlighted by the reviewer. As the event is in 1960, we hope to be able to add station magnitudes in different azimuths and update accordingly the MS for this event in future versions of the dataset.

Figure 2 is an example given in Table A1 of this manuscript: the 3/7/1927 event with an ISC MS of 7.82. To compare this event with a recent event in the same area, the MS data of the 2016 Tottori earthquake (MS=6.2) are shown. Again the 1927 case is strongly influenced by the stations in the azimuth range

of 300° to 360°. A somewhat similar pattern is seen for the 2016 Tottori earthquake, but since the azimuthal coverage is uniform, the median (MS=6.2) seems to be fairly stable, and in fact this value agrees well with the value quoted in GCMT catalog .

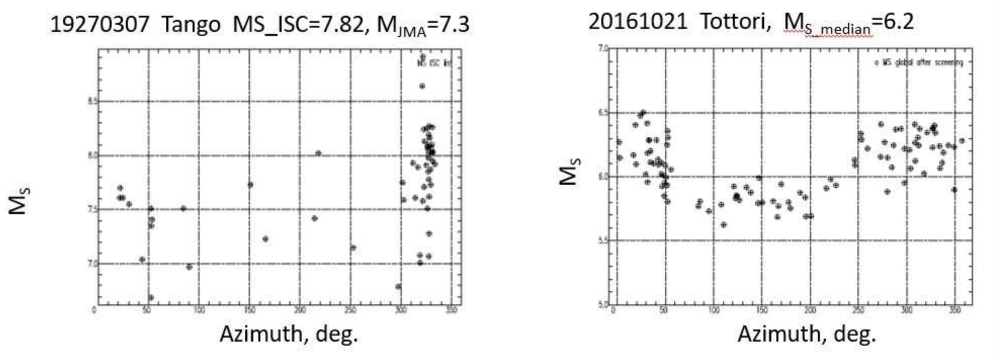

Fig. 2

As the event is included in Table A1, we do not think it is necessary to discussed it any further. Points regarding the azimuthal issue are remarked in the revised manuscript.

Figure 3 shows an example of the 2002 Denali earthquake (Mw=7.8). The MS value given by NEIC and listed in the GCMT catalog is 8.5, presumably an average of more station data than those shown in Figure 3. The existing global stations are far more than those shown in Figure 3, especially in the azimuth of about 100°, and an average can become very large. I do not know exactly what an averaging scheme is used. In this particular case, if we take a bin- average, we get the following:

Azimuth range	number of stations	bin average
0-45	20	7.536
45-90.	4	8.468
90-135	14	8.539
135-180	8	8.273

The average of the bin average is 7.85, very close to the ISC value of 7.82. This is a new problem with recent events with so many stations, and the averaging scheme is very important.

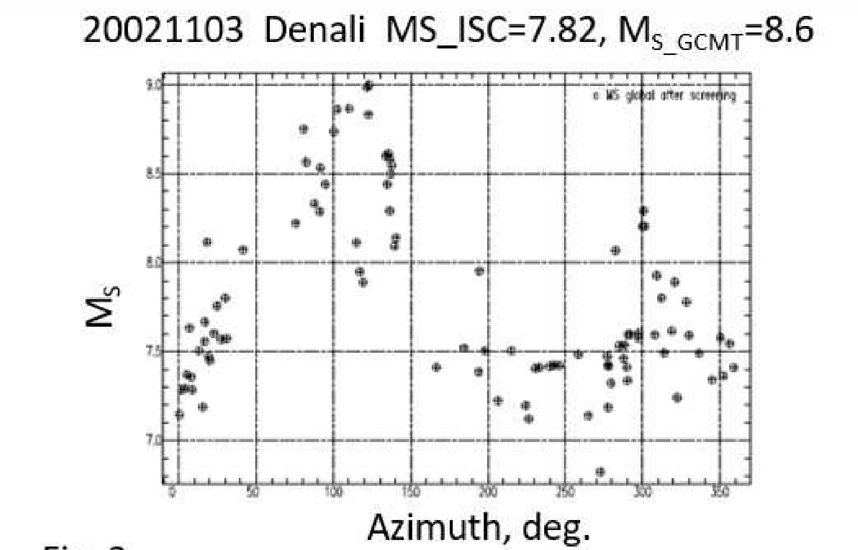

Fig. 3

Ditto.

This bring us to a problem with old events again. As discussed on line 238 and illustrated in Table A1 of this manuscript, the famous 1906 San Francisco is given MS_ISC=8.61. However, as shown in Figure 4, only 6 stations are used, with 4 stations essentially in the same azimuth, and it is hard to assess the uncertainty of the assigned MS value. Since the Gutenberg notepad lists station MS values from some 16 stations, and Gutenberg and Richter (1954) gave MS= 8 1⁄4. I like this notation which probably implies an uncertainty of 1⁄4 magnitude unit. Unfortunately, many journals demand that it should be written as 8.25 which has a very different implication for the uncertainty. Also, I suspect that Gutenberg and Richter's assignment of "quality, A, B, and C, or a, b, and c is somewhat subjective on the basis of their experience, but in case of this kind of data to which rigorous statistical method is hard to apply, I believe that it is a very reasonable practice. Actually, Lienkaemper (1984) examined Gutenberg's notepad data, and came up with M=8.3. Although I did not follow exactly what he did, he did use the 16 stations. I suspect that the data listed in the Gutenberg's note pad did not meet the strict criterion of ISC, and were not adopted in "MS_Dataset" (I may be wrong.). However, as shown in the examples presented in Figures 1 to 4 in this review, the azimuthal station coverage is so important for obtaining a reasonable average that I would like to see as many station data as possible in the ISC catalog, even if the measurement procedure was slightly different. Overall, my experience is that the difference caused by the limited azimuthal coverage is far greater than that caused by the difference in the station practice.

190604 San Francisco M_{S_ISC}=8.61, $M_{\_GR}$=8 ¼, M_{LK}=8.3

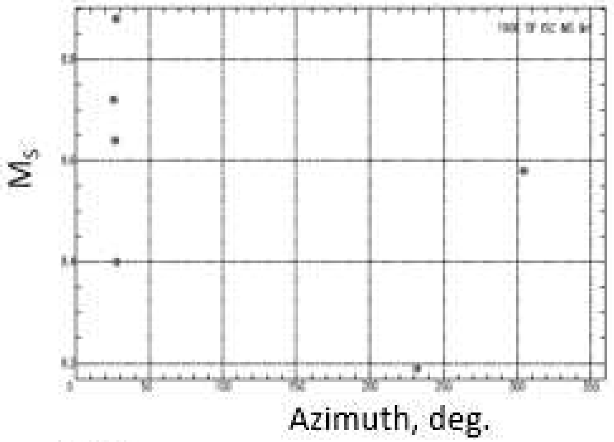

Fig. 4

We provide the MS uncertainty for every earthquake in the dataset. We have Abe's adaptation of Gutenberg's notepads but, unfortunately, we cannot find the Gutenberg's solution for the 1906 San Francisco earthquake. In Lienkaemper (1984) the list of stations contributing to MS (first earthquake in Table 3 of https://doi.org/10.1785/bssa0740062357) includes also amplitudes from publications and not only from the original station bulletins, Hence, many of those stations are not included in our MS solution for the 1906 San Francisco earthquake. As far as we know, station bulletins are not available for many of those stations, and we believe that Gutenberg and the other quoted authors sourced those amplitudes in different ways. This is the reason for our solution to list less station magnitudes in this case. The result, however, does not change much as most station magnitudes are well above 8, and this would still lead to a large discrepancy between MS and Mw from the literature. Hence, azimuthal effects alone cannot explain the large MS of this earthquake. We indeed suggest that the large MS may be due to instrumental issues.

My comments above are in no way the criticism of the ISC practice and catalog, but they represent my hope that the ISC catalogs will be used most effectively and properly by serious users. The historical data are important but they can have all kinds of problems and uncertainties, and very often rigorous handling is not possible. Nevertheless, these data do contain historical information which we cannot get otherwise. After all, how to use the data base and interpret it is ultimately the responsibility of the users, rather than the catalog producers, but it is most important that the catalog producers provide adequate caveats to the users so that the catalogs can be carefully used for understanding the Earth's seismicity.

We agree with this final remark.

100+ years of recomputed surface wave magnitude of shallow global earthquakes

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Abstract. Among the multitude of magnitude scales developed to measure the size of an earthquake, the surface wave magnitude *MS* is the only magnitude type that can be computed since the dawn of modern observational seismology (beginning of the 20th century) for most shallow earthquakes worldwide. This is possible thanks to the work of station operators, analysts and researchers that performed measurements of surface wave amplitudes and periods on analogue instruments well before the development of recent digital seismological practice. As a result of a monumental undertaking to digitize such pre-1971 measurements from printed bulletins and integrate them in parametric data form into the database of the International Seismological Centre (ISC, www.isc.ac.uk, last access: August 2021), we are able to recompute *MS* using a large set of stations and obtain it for the first time for several hundred earthquakes. We summarize the work started at the ISC in 2010 which aims to provide the seismological and broader geoscience community with a revised *MS* dataset (i.e., catalogue as well as the underlying station data) starting from December 1904 up to the last complete year reviewed by the ISC (currently 2018). This *MS* dataset is available at the ISC Dataset Repository at https://doi.org/10.31905/0N4HOS2D.

1 Introduction

Since its introduction, the surface wave magnitude *MS* has been very popular and for a long period of time, before the moment magnitude *Mw* was introduced by Kanamori (1977) and Hanks and Kanamori (1979), it was considered the most reliable magnitude to estimate an earthquake size. Its popularity originated due to: 1) as opposed to the magnitude concept introduced at a local scale by Richter (1935), *MS* allows seismologists to compute magnitudes for earthquakes worldwide, including those recorded at teleseismic distances (i.e., from 20° onward), without relying on local recordings that were not available in most seismic zones; 2) thanks to the work of station operators, analysts and researchers at various observatories around the world that produced readings of surface wave data for shallow earthquakes since the beginning of the last century, *MS* can be computed (systematically) since the dawn of instrumental seismology (Fig. 1). In addition, *MS* is probably the only type of earthquake magnitude that can be computed systematically for all damaging earthquakes for the last 100+ years. However, as any magnitude type *MS* has also shortcomings, as the possible underestimation for some large earthquake (as discussed later), the inability of processing surface waves from short-period instruments (hence for many small local earthquakes) and the limitation, at least in standard procedures (IASPEI, 2013), of being defined for shallow earthquakes.

Gutenberg (1945), using measurements of amplitudes and periods of surface waves accumulated during the first 40 years of the last century, introduced *MS* as: $MS = logA + 1.656log\Delta + 1.8$. Since then a team of researchers from Moscow and Prague further developed Gutenberg's work and proposed the formula (Kárník et al., 1962; Vaněk et al., 1962): $MS = log(\frac{A}{T})_{\max} + \sigma_{\mathrm{S}}(\Delta) = log(\frac{A}{T})_{\max} + 1.66log\Delta + 3.3$, where *A* and *T* are the amplitude (in μm) and period (in *seconds*) of the surface wave train, respectively, and Δ is the distance in degrees of the seismic station from the earthquake epicentre (distance and period limits will be discussed in the next section). This is the so-called Moscow-Prague formula and it was accepted as the standard for *MS* computation by the International Association of Seismology and Physics of the Earth's Interior (IASPEI, http://www.iaspei.org/, last access: August 2021) at the 1967 Zürich meeting (Bormann et al., 2012; IASPEI, 2013). The calibration function $\sigma_{\mathrm{S}}(\Delta)$ and its best fit up to 160° ($1.66log\Delta + 3.3$) are shown in Fig. 2.

Several earthquake catalogues that listed *MS* have served the seismological community for various purposes in the past decades. One that has been instrumental for many studies is Abe's catalogue (Abe, 1981; Abe and Noguchi, 1983a, b; Abe, 1984). This catalogue lists *MS* values for large earthquakes (mostly *MS* > 6.5) up to 1980 and its reliability was recently confirmed by Di Giacomo et al. (2015a). Since then researchers have extend Abe's catalogue beyond 1980 with *MS* solutions from the International Seismological Centre (ISC, www.isc.ac.uk, last access: August 2021) and/or the National Earthquake Information Center of the USGS (https://earthquake.usgs.gov/earthquakes/search/, last access: August 2021). Such a composite *MS* catalogue was then used as the magnitude basis for recent compilations such as the Centennial Catalogue (Engdahl and Villaseñor, 2002) and PAGER-CAT (Allen et al., 2009) as well as various types of research, from calibration purposes (Herak and Herak, 1993; Rezapour and Pearce, 1998) to patterns of the Earth's seismicity (e.g., Pérez and Scholz, 1984; Ogata and Abe, 1991; Pacheco and Sykes, 1992; Pérez, 1999).

Considering the important legacy of *MS* in the seismological community, here we present a revised *MS* catalogue ~~of~~ (cut-off magnitude of 4.5) listing over 46,000 earthquakes ~~with *MS* ≥ 4.5 and~~ as well as the underlying station data (files described in Section 8) used to derive *MS* for each earthquake. Hereafter we refer to the catalogue and underlying station data as ISC *MS* dataset (International Seismological Centre, 2021d). To create this product we benefit from the work done by Di Giacomo et al. (2015b, 2018) to digitize (i.e., converted from printed to computer accessible format) a large volume of surface wave parametric data prior to 1971 and by Storchak et al. (2017, 2020) to rebuild the ISC Bulletin from 1964 onwards.

We first recall the basic steps in our procedure to compute *MS* and outline the major features of the station data behind the calculation of the network *MS*. Then we discuss some properties of the ISC *MS* dataset in terms of completeness and rates in different time periods. Finally, we briefly discuss the largest earthquakes ever recorded and outline further activities that could improve this dataset in different time periods.

2 ~~Recomputing~~ Reporters and *MS* recomputation

A big part of the ISC mission consists of collecting and reprocessing reports from seismological agencies all over the world to produce the ISC Bulletin (International Seismological Centre, 2021c). Details about agencies contributing data to the ISC can be found at http://www.isc.ac.uk/iscbulletin//agencies/, last access: August 2021. The summary of the agencies (hereafter also referred to as reporters or data contributors) that contributed surface wave parametric data to create the ISC *MS* dataset is shown in Fig. 3. A few aspects are worth mentioning regarding the surface wave data reporters.

Originally, the ISC had no surface wave data available in digital form for pre-1971 earthquakes. Hence, to fill this data gap, an onerous undertaking of digitizing surface wave data from station/network printed bulletins began in 2010 (Di Giacomo et al., 2015b, 2018). As shown in Fig. 3, this effort resulted in the ISC having digitized surface wave data from a total of 282 stations for over 12,000 earthquakes (it is our intention to continue this effort, see Section 6).

Between 1971 and 1998 the ISC Bulletin contains surface wave data from 457 stations worldwide. However, in this time period we cannot associate such data to specific reporters (hence reporter = UNK, unknown, in Fig. 3). The only exceptions to that are data reports (e.g., agency MOS, JEN, CLL) parsed in the ISC Bulletin during the Rebuild project (Storchak et al., 2017, 2020). Since 1999, coinciding with a major update in ISC data collection procedures and the setup of the ISC database, we are able to routinely associate station data with their agency. Only 30 reporters out of about 150 contributed surface wave data in the last 20 years, with the largest contributors being IDC, NEIC, MOS and BJI (Fig. 3).

Our approach to computing *MS* closely follows the standard ISC procedure (Bondár and Storchak, 2011) and is already detailed in Di Giacomo et al. (2015a). However, it is beneficial here to 1) recall some aspects of the procedure in light of the content of station data files (Section 8), and 2) explain some necessary deviations from it.

First, we consider the surface wave data belonging to a reading (in ISC jargon a reading groups all parametric data from a single station associated to a specific seismic event and reported by the same agency). A reading can have any number of surface wave data entries and different reporters may provide a reading for the same station. An example of a reading is shown in Table 1 for station CLL (Collm, Germany) for an earthquake which occurred in the Northern Mid-Atlantic Ridge, 24 September 1969. We have chosen this example as the reading lists multiple surface wave data entries on all three components. Within the surface wave phases of the reading (L in our example), we first search for the maximum of $\frac{A}{T}$ on the vertical component, and, if available, the component magnitude MS_Z is obtained via the Moscow-Prague formula. Then, for periods within ± 10 seconds of T on the vertical component, the maximum of $\frac{A}{T}$ for the horizontal vector component $\sqrt{(\frac{A}{T})^2_N + (\frac{A}{T})^2_E}$ is searched to calculate the component MS_H magnitude. If one of the two horizontal components is not available then ~~$(\frac{A}{T})_H = \sqrt{(2 * \frac{A}{T})^2_{N|E}}$.~~ $(\frac{A}{T})_H = \sqrt{2 * (\frac{A}{T})^2_{N|E}}$. Although our procedure finds the maximum of $\frac{A}{T}$ within the reading, a reporter may have provided single component measurements of $\frac{Amax}{T}$. In our CLL reading example the maximum $\frac{A}{T}$ on the vertical component is defined by *ampid* = 601627636, whereas *ampid* = 601627639 and 601627638 on the North-South and East-West component, respectively, define the maximum horizontal vector component. Such defining entries are included in the station data files (more details in International Seismological Centre, 2021d). Then the *MS* for the reading is computed as $(M_{SZ} + M_{SH})/2$ if both exists, or $M_S = M_{SZ|H}$ if one of them is not available. If more than one reading *MS* exists for a station, the median of the readings *MS* is used as station *MS*. Finally, the network *MS* is computed as the median of the stations *MS* if at least three or five station magnitudes are available prior or since 1971, respectively. The uncertainty of the network *MS* is expressed as standard median absolute deviation (SMAD) of the α-trimmed station magnitudes (α = 20%).

In line with IASPEI recommendations (IASPEI, 2013), we only allow *MS* for earthquakes with depth $\leq$ 60 km. The locations adopted in this work come from the ISC-GEM Catalogue (Bondár et al., 2015; Di Giacomo et al., 2018) between 1904 and 1963 and the rebuilt ISC Bulletin (Storchak et al., 2017, 2020) from 1964 onward.

Standard procedures at the ISC consider surface wave periods between 10 and 60 seconds and distances between 20° and 160°. Such delta-period ranges are also adopted here for earthquakes which occurred after 1963 (hereafter also referred to as standard delta-period ranges). Prior to 1964 we expand the period and distance ranges to 5-60 seconds and 2°-180°, respectively, as discussed in Di Giacomo et al. (2015b). The augmentation of the delta-period limits prior to 1964 is mainly due to the relative scarcity of surface wave data in the first part of the last century compared to its second half (hence the need for not discarding station *MS*), and to changes in seismological practice in many institutes coinciding with the introduction of the World-Wide Standardized Seismograph Network (WWSSN, Oliver and Murphy, 1971; Peterson and Hutt, 2014). When stations beyond 160° are used we use the tabulated values of $\sigma_S(\Delta)$ instead of its best-fit (Fig. 2), as recommended by Bormann et al. (2012). In the next section we show that the amplitude/period measurements prior to the WWSSN introduction justifies our delta-period expansion for pre-1964 earthquakes.

3 Station data

~~A big part of the ISC mission consists of collecting and reprocessing reports from seismological agencies all over the world to produce the ISC Bulletin (International Seismological Centre, 2021c). Details about agencies contributing data to the ISC can be found at , last access: August 2021. The summary of the agencies (hereafter also referred to as reporters or data contributors) that contributed surface wave parametric data to create the ISC *MS* dataset is shown in Fig. 3. A few aspects are worth mentioning regarding the surface wave data reporters.~~

~~Originally, the ISC had no surface wave data available in digital form for pre-1971 earthquakes. Hence, to fill this data gap, an onerous undertaking of digitizing surface wave data from station/network printed bulletins began in 2010 (Di Giacomo et al., 2015b, 2018). As shown in Fig. 3, this effort resulted in the ISC having digitized surface wave data from a total of 282 stations for over 12,000 earthquakes (it is our intention to continue this effort, see Section 6).~~

~~Between 1971 and 1998 the ISC Bulletin contains surface wave data from 457 stations worldwide. However, in this time period we cannot associate such data to specific reporters (hence reporter = UNK, unknown, in Fig. 3). The only exceptions to that are data reports (e.g., agency MOS, JEN, CLL) parsed in the ISC Bulletin during the rebuild project (Storchak et al., 2017, 2020). Since 1999, coinciding with a major update in ISC data collection procedures and the setup of the ISC database, we are able to routinely associate station data with their agency. Only 30 reporters out of about 150 contributed with surface wave data in the last 20 years, with the largest contributors being IDC, NEIC, MOS and BJI (Fig. 3).~~

The decadal spatial distribution of the stations contributing to the ISC *MS* dataset is summarized in Figs. 4-5. At times we mention seismic stations that, for sake of brevity, we may only identify by their code (station's full details can be accessed at International Seismological Centre, 2021b).

Not surprisingly, the *MS* network geometry is unbalanced as the Northern hemisphere features many more stations than the Southern one (a known issue in every aspect of instrumental seismology). In more detail, these figures highlight how the *MS* network became more dense and widespread over time after most of the stations were located in Europe at the beginning of the last century. Indeed, most of the *MS* in the first two decades of the last century heavily rely on stations in Germany (e.g., GTT, JEN), UPP in Sweden, and a few others (e.g., DBN in Netherlands and PUL in Russia). From the 1920s to the 1960s the station density increased in Europe and in former Soviet Union territory. North American stations also contributed but for a small number of earthquakes.

The Southern hemisphere had only a handful of *MS* reporting stations up to the 1970s-1980s. However, thanks to the extraordinary efficiency in observatory practice at the Observatorio San Calixto (LPZ, Bolivia, opened in 1913, Coenraads, 1993) and Riverview (RIV, Australia, opened in 1909, Drake, 1993), both from the Jesuit network (Udias and Stauder, 1996), our capabilities of obtaining *MS* improved significantly in the first half of last century both for Southern hemisphere and worldwide earthquakes, as was noted by Gutenberg and Richter (1954).

From the 1970s, when surface wave data started to be digitally available in the ISC Bulletin, we witness a significant increase in the *MS* network coverage, particularly in the last two decades, where many more stations in the Southern hemisphere have contributed to *MS*. However, their spatial distribution is not yet as dense as in North America or the Euro-Mediterranean area.

To summarize the evolution of the *MS* network over the decades, Fig. 6 shows the network *MS* decadal box-and-whisker plot of the number of stations (*Nsta*) and secondary gap (i.e., the largest azimuthal gap ~~filled by a single station~~ in which only one station exists, and the quality of the data at that station may bias the solution). The latter parameter is normally used as a network geometry parameter in earthquake location (Bondár et al., 2004), but here it is used as a measure of the azimuthal coverage of the station contributing to *MS* computation (both gap and secondary gap are included in the *MS* catalogue file). Ideally, the station distribution should sample the focal sphere from different azimuth to reduce the effects of ~~the~~ propagation path heterogeneities and radiation pattern (von Seggern, 1970) on the network *MS*, although the latter is symmetric for surface waves (either two-lobed or four-lobed). In light of the station distributions shown in Figs. 4-5, it is not surprising that for most of the last century the secondary gap is usually 180°-270° or above, meaning that the stations contributing to the network *MS* are often located in a narrow azimuth. ~~However, significant improvements~~ To showcase the possible effects of this aspect, in Fig. A1 we show the azimuthal distribution of the station *MS* for the 1960-03-20 off east coast of Honshu earthquake (event 878564). Most of the *MS* stations are located in Europe and it appears that those are responsible for making the network *MS* = 7.9, as most of the station magnitudes at different azimuth are well below the final network *MS*. Nevertheless, significant improvements in the station azimuthal coverage occur from the 1970s, and with the increase in *Nsta* we observe an overall decrease in secondary gap.

The final aspect of the station data we discuss here regards the period at which the amplitudes of the surface waves are measured. We do that by showing, similarly to Bormann et al. (2009, 2012), the distance-period distributions of $(\frac{A}{T})_{max}$ for earthquakes prior to and since 1964 (Fig. 7 and Fig. 8, respectively). The separation in these two time periods is linked both to the start of the original ISC Bulletin (Adams et al., 1982) in 1964 and a change in observatory practice by many institutions due to the WWSSN introduction in the early 1960s. The standard WWSSN practice produces amplitudes of surface waves as measured for T around 20 seconds (usually ± 2 or ± 3 seconds) for distances $\geq 20°$ (in addition, measurements on the vertical component were preferred to horizontal ones since the 1970s). Before WWSSN, however, the standard practice was to measure the surface wave amplitudes in broader period ranges (such differences led IASPEI, 2013, to recommend the computation of two types of *MS*, MS_{20} and MS_{BB}). Therefore, before 1964 we observe in Fig. 7 that T falls reasonably well within the expected period ranges of Vaněk et al. (1962) (i.e., amplitudes measured over a broad T range and using data below 20°), whereas from 1964 onward we see surface amplitudes predominantly measured around T of 20 seconds throughout the entire distance range, as shown by the vertical component of Fig. 8. The surface wave amplitude-period measurements pre-WWSSN, therefore, allow us to expand the delta-period limits for pre-1964 earthquakes as outlined in Section 2.

However, not all reporters fully adopted WWSSN standards. Indeed, among the largest ones (Fig. 3), agency BJI, MOS and PRU report surface wave amplitudes in broad period ranges. The delta-period plots of those agencies are shown in Appendix A (Figs. A2, A3, A4). Other agencies, instead, strictly adhere to amplitude-period measurements around 20 seconds (Figs. A5, A6, A7, for agencies IDC, LDG and NEIC from 2009, respectively).

As a final remark in this section, we reiterate, as already done in Di Giacomo et al. (2015a), that the differences in distance and period ranges do not introduce a discontinuity in the *MS* estimates before-after 1964. The expansion of the delta-period limits pre-1964 is allowed by the data and it often gives us the opportunity to increase *Nsta* for our network *MS* computation in a time period where surface wave data was scant (compared to current times) and not digitally available (hence the need of not discarding precious and hard to get data). As a result of our approach, about 40% of the pre-1964 earthquakes we list in the ISC *MS* dataset gained from 1 to 28 station magnitudes, and 1,000 of those earthquakes would not have network *MS* without delta-period augmentation. This is synthesized in Fig. 9. An area encompassing the North Atlantic mid-oceanic ridges, the Euro-Mediterranean and the Middle-East benefitted the most thanks to European and central Asian stations that measured surface waves in broad period ranges at distances below 20°.

4 Catalogue properties

The ISC *MS* dataset has a minimum cut-off magnitude of 4.5. Earthquakes with lower *MS* values are available in the ISC Bulletin but mostly in recent decades. The major improvements regard earthquakes prior to 1964, where, according to our records, out of 10,057 earthquakes the ISC is the first to compute *MS* for 4,940 of them (their distribution and timeline is shown in Fig. A8).

Considering the whole ISC *MS* dataset, major features can be discussed using Fig. 10, where we show the magnitude timeline, number of earthquakes per year for various magnitude thresholds and annual magnitude of completeness (*Mc*) computed with the maximum curvature method of Wiemer and Wyss (2000). Overall, we include *MS* < 5.5 earthquakes mostly from the 1980s, and *Mc* approaches approximately 4.5 in the last 20 years. We note that we were able to obtain more solutions at the low magnitude end particularly in the late-1920s-1930s. This has been possible thanks to the establishment of the backbone network in former Soviet Union territory and a general increase of *MS* stations in other areas (see annual station maps in International Seismological Centre, 2021d). An overall dip is observed in the 1940s, most likely caused by the disruption of

World War II on the seismic network (Di Giacomo et al., 2018). The period 1960-1977 also features less earthquakes below 5.5 than previous and following decades. This is due both to the limited number of stations available and the fact that we digitized surface wave data from the 1960s printed station bulletins only for earthquakes selected in the first version of the ISC-GEM Catalogue (magnitude 5.5 and above, Storchak et al., 2013). In Section 6 we propose activities that are likely to mitigate significantly the deficiencies of the ISC *MS* dataset in most of the 1960s-1970s. Another fluctuation at low magnitudes is observed in the early-1980s. Indeed both the annual counts and *Mc* show a significant variation from 1978-1979 (*Mc* close to 5.0) to 1980-1983 (higher *Mc* ranging between 5.2-5.5). We believe this is due to the temporary absence of MOS surface wave data in 1980-1983 (see Section 6), which was included into the rebuilt ISC Bulletin (Storchak et al., 2020) from 1984 onward (*Mc* dropping again to about 5 and below).

Less strong variations are seen for moderate size earthquakes (i.e., *MS* between 5.0 and 6.0). The early part of last century (up to the mid-1920s) is clearly complete above magnitude 6.0, whereas since the 1950s the frequency of *MS* 5.5 and 6.0 appears rather stable. Pronounced variations are observed from the mid-1920 to the 1940s for reasons mentioned above.

Variations over time of the frequency of large (i.e., $MS \geq 6.0$) earthquakes based on past catalogues have been the subject of debate in past literature. In particular, Pérez and Scholz (1984) suggested that, under the assumption of constant rate earthquake occurrence, temporal variations of large shallow earthquakes were driven by instrumental changes. Ogata and Abe (1991) and more recently Ogata (2021), however, suggest that variations in the frequency of global large earthquakes are a real effect of the Earth's seismic activity (long-range dependence nature of earthquake occurrence). Therefore, to further discuss the rate of the Earth's large shallow seismicity, we show in Fig. 11 the cumulative number of strong to major earthquakes in the ISC *MS* dataset similarly to the figures in Pérez and Scholz (1984) and Pérez (1999). Compared to these works, our rates for *MS* $\geq$ 7.0 and 6.0 in different time intervals (Table 2) show some significant differences and lack large jumps from one period to another. This is strikingly evident for the $MS \geq 6.0$ distribution, where Pérez (1999) rate goes down to $38y^{-1}$ during 1964-1978 compared to a rate of about $78y^{-1}$ in the ISC *MS* dataset. We note that this period in the original ISC Bulletin lacked the ISC's own computations of *MS*. Therefore, Pérez (1999) rates may have been biased by using largely incomplete inputs.

In general, we see that shallow seismicity rates are characterized by a global low occurring between the great earthquakes of the early 1960s and the beginning of the current century (Ammon et al., 2010). Although rates for $MS \geq 7.0$ in the first part of the last century are comparable to the rate we have observed since 2005, it seems that rates for $MS \geq 6.0$ from the WWSSN introduction appear to be lower than rates in the first part of the last century. We also assessed if by declustering (Reasenberg, 1985) the *MS* catalogue the rates would be different but only small variations occur, and, more importantly, relative differences between time periods remain. This is not surprising as the ISC *MS* dataset does not contain a large number of aftershocks for $MS \geq 6.0$ (by the very nature of *MS* it is more difficult to obtain it for aftershocks of large earthquakes due to association challenges in overlapping signals, particularly in routine operations).

It is not the aim of this work to investigate whether fluctuations in seismic activity rates are partially due to instrumental changes or purely due to natural variations of the Earth's seismicity. However, we believe that the ISC *MS* dataset is one of the best inputs to date to do such studies. In this context it is important to point out that the quality of instrumental earthquake catalogues depends on the quality of the data available at the time of processing. In our experience, for long-term datasets it is almost unavoidable that different types of shortcomings may occur in different time periods, for example due to external factors (e.g., network deficiencies during World Wars) and that faulty individual entries may be present. It is of paramount importance, therefore, that datasets are well-documented and that users know how they are created in order to properly use them for research.

5 On the *MS* saturation and large differences with *Mw*

By the time *MS* was introduced by Gutenberg (1945) no magnitude 9 or 9+ earthquake had been recorded instrumentally. The occurrence of the 4 November 1952, Kamchatka earthquake and the well-know great earthquakes of the early 1960s (22 May 1960, Chile and 28 March 1964, Alaska earthquakes), drew attention to a shortcoming of *MS*, that is commonly referred to as magnitude saturation. This was one of the factors that led Kanamori (1977) and Hanks and Kanamori (1979) to introduce the moment magnitude *Mw*, which is based on a physical parameter of the seismic source (i.e., seismic moment) rather than amplitude-period measurements.

In Fig. 12 we compare the ISC *MS* dataset with *Mw* from GCMT and the bibliographic search for pre-1976 earthquakes of Lee and Engdahl (2015) and follow-up updates as listed at www.isc.ac.uk/iscgem/mw_bibliography.php, last access: August 2021 (hereafter referred to as *Mw* from literature). Such magnitude comparison has been discussed in several papers, particularly to derive magnitude conversion relationships. For this work, however, we show this comparison to focus on the *MS* saturation issue and briefly touch upon earthquakes with large (*Mw*-*MS*) differences.

The ten largest earthquakes (in *Mw* terms) ever recorded are easily identified in Fig. 12 by the event code in the ISC Event Bibliography (Di Giacomo et al., 2014; International Seismological Centre, 2021a). As already summarized by Kanamori (1983), the saturation of *MS* is generally expected to start between 8.2 and 8.5. For recent (26 December 2004, Sumatra and 11 March 2011, Tohoku) and pre-GCMT earthquakes (the above mentioned Chile 1960 and Alaska 1964) with *Mw* 9 and above, the effects of saturation are quite severe and vary between 0.6 and 1 magnitude unit (m.u.). However, for earthquakes with *Mw* between 8 and 9 the variation of the saturation appears to vary much more (from near to 0 up to 1 m.u.). For example, the 27 February ~~2018~~2010, Maule, *Mw* 8.8 earthquake has an *MS* of only 0.25 m.u. smaller, close to common *Mw*-*MS* differences observed across a wide magnitude range before the saturation of *MS* is expected. Fig. 12 shows other examples where *Mw* and *MS* are close to the 1:1 line between 8 and 8.7 (including the 15 August 1950 Assam earthquake). ~~On the other hand, large differences are observed for other earthquakes (e.g., 4 February 1965, Rat Islands and the 28 March 2005, Nias earthquakes). This often occurs~~ With regard to great earthquakes with large *Mw*-*MS* differences, some of those belong to a peculiar category~~of events~~, the so-called tsunami earthquakes (Kanamori, 1972). ~~As already well-documented in the literature, these are earthquakes characterized by~~ These have a relatively small *MS* compared to their *Mw* and are well-documented in the literature. The most striking example is probably the 1 April 1946, Aleutian earthquake, where our *MS* of 7.4 is much smaller than the *Mw* 8.6 by López and Okal (2006). On the other hand, large differences are observed for other earthquakes (e.g., 4 February 1965, Rat Islands and the 28 March 2005, Nias earthquakes) not strictly considered as tsunami earthquakes.

~~Considering~~ In light of the *MS* values for the largest earthquakes ever recorded, we support the remarks by Bormann (2011) that it would be more correct to speak of *MS* underestimation rather than saturation, as the latter would require to be systematically observable for great earthquakes with *Mw* between 8.2-8.5 and above. However, we have shown that underestimation ("saturation") depends on the type of earthquake, and it is severe only for a handful of the largest earthquakes ever recorded ($Mw \geq 9$). Therefore, the underestimation ("saturation") of *MS* should not discourage researches to use it as a reliable measure of the size of shallow earthquakes. We also suggest that *MS* and *Mw*, as expressions at different periods of the earthquake size, should be used together to better characterize the source properties of an earthquake.

Overall, the magnitude comparison of Fig. 12 shows that *MS* is typically close to *Mw* over the magnitude range 6.2 to 8, whereas for smaller earthquakes *MS* is usually smaller than *Mw*. However, some earthquakes show large differences (examples listed in Table A1, for $MS \gg Mw$ and vice-versa). For the sake of brevity we do not discuss every earthquake with such large differences but touch only on the case of the 18 April 1906, San Francisco earthquake (SANFRANCISCO1906, first event in Table A1) to clarify our reasons for keeping such entries in the ISC *MS* dataset.

The *MS* of the SANFRANCISCO1906 earthquake is dominated by stations located in Germany (GTT, POT, LEI and JEN), plus Apia (API, Samoa Islands) and OSA (Osaka, Japan) at different azimuths. All station *MS* are consistently above 8, resulting in a network *MS* of 8.6 ± 0.1 (full station details listed under event = 16957905 in International Seismological Centre, 2021d). This is a much higher value than the $Mw = 7.7$ obtained by Wald et al. (1993). Such outliers occur in most earthquake catalogues for various reasons. As mentioned earlier, parameters of individual earthquakes are the result of the processing of the data available at a given time. For the SANFRANCISCO1906 earthquake, instrumental issues could have played a major role in the high *MS* value. However, we believe that listing such results in the dataset (rather than deprecating) is important for legacy reasons, and that users may still use such information for further studies and, ideally, motivate the community to attempt additional data collection. The latter is an activity that we will continue and discuss in the next section.

6 Future developments

The maintenance and development of the ISC *MS* dataset will not cease with this work. First, we intend to routinely add the last calendar year reviewed by the ISC. This means that once the ISC review is over for 2019 earthquakes, the ISC *MS* dataset will be updated and end in 2019, and so on in following years. Secondly, we aim at refining and adding *MS* solutions for past years. Indeed, we are aware that the *MS* station contribution can be improved in certain years. One example was already pointed out for 1980-1983, where MOS surface wave data was not included in time for ISC rebuild project (Storchak et al., 2020). By adding such data we expect to fill (or, at least, partially fill) the gap shown in those years for low *MS* earthquakes, as shown in Fig. 10.

Before the early 1980s, the following time periods may benefit from additional station contributions:

- During the 1970s, one source that, to our knowledge, has never been digitized, is the printed bulletins of the Chinese network. Tens of stations with plenty of surface wave data are available in those bulletins, which can potentially increase *Nsta* for earthquakes already listed in the dataset and allow us to compute *MS* for several new ones;

- Due to time and funding limitations, the digitazion of 1964-1970 surface wave data from printed station/network bulletins (Di Giacomo et al., 2015b) was not done for all bulletins available at the ISC, and, if done, it focused on earthquakes with magnitude 5.5 and above. Hence, a more comprehensive approach for surface wave data digitazion is desirable for these years;
- For the period 1936-1963 we are finalizing the digitazion of station arrival times for earthquakes in the bulletins of the Bureau Central International de Séismologie (BCIS, 1933-1968) that were not listed in the International Seismological Summary (ISS, 1918-1963) (earthquakes in this time period that are not listed in the ISS currently have no station data digitally available in the ISC database). Once this undertaking is finished, we will add surface wave data for earthquakes recorded teleseismically and attempt to obtain *MS* for as many earthquakes as possible;
- Improvements in the first part of the last century are more challenging as we have nearly exhausted the digitazion of printed bulletins available to us. It is hard to verify if our surface wave data collection from printed bulletins is as complete as possible. Assistance in this respect from observatories and archives around the world would be highly appreciated (the presence or absence of a set of station data can be easily checked in the ISC *MS* dataset).

Hence, if conditions permit, we wish to continue the digitazion of printed bulletins and add surface wave data in order to improve the *MS* solutions for a significant fraction of pre-1980 earthquakes. However, we stress that additional contributions for earthquakes in recent decades are welcome as well and we will strive to include them in the ISC Bulletin, and in turn, in the ISC *MS* dataset.

7 Conclusions

An aspect that differentiates *MS* from other magnitude scales is that it can be computed from original measurements of surface wave amplitudes and periods throughout the instrumental period. The ISC *MS* dataset we presented here includes 100+ years of earthquakes with $MS \geq 4.5$ starting from the dawn of modern instrumental seismology (1904) up to the last complete reviewed year by the ISC (2018). This achievement is possible as a result of a monumental undertaking thanks to which pre-1971 measurements of surface waves were digitized from a multitude of printed station/network bulletins.

We have summarized the evolution of the station network contributing to *MS* and highlighted its shortcomings (e.g., significant lack of stations in the Southern hemisphere for a large part of the last century) and strengths (e.g., high density in Europe that allowed us to obtain *MS* for earthquakes in a wide area in low magnitude ranges before the introduction of modern digital stations). The expansion of the delta-period ranges, as allowed by the data, resulted in more and better constrained *MS* estimations for about 40% of the pre-1964 earthquakes.

We have discussed the *MS* underestimation for the largest earthquakes ever recorded and pointed out the presence of occasional large differences with *Mw*. Those entries are listed for legacy and other purposes and may require further work.

Inevitably, the dataset has fluctuations in terms of completeness and earthquake rates over different time periods. We discussed the most relevant ones and outlined plans for continuing and improving this dataset.

In the years to come we envisage the ISC *MS* dataset as one of the best input researchers can use for various seismological studies, including the Earth's seismicity patterns.

8 Data availability

The ISC *MS* dataset (International Seismological Centre, 2021d) is available in the ISC Dataset Repository at http://doi.org/10.31905/0N4HOS2D. The dataset is released without licence. It is composed of a catalogue file (CSV format) and annual files containing the underlying station data used to obtain *MS* for each earthquake. All parameters in the catalogue and annual files are detailed in the README file in International Seismological Centre (2021d). The annual files include, below the earthquake parameters, two data blocks: first the station magnitude block (sorted by distance) and then the phase data block, which includes the original amplitude and period measurements as well as the intermediate magnitude results (amplitude and reading magnitude, MS_Z, MS_H) that lead to the station magnitude computation (see Section 2). Annual station plots and annual station lists are also included as well as the file with the data points to generate Fig. 12.

Author contributions. DDG is the lead author, prepared the dataset and figures, supervised the digitazion of the surface wave data and vetted the *MS* results up to 1963. DAS obtained the funding for the work and established and maintained operational connections with many data providers, especially in obtaining additional datasets previously unavailable. Both authors contributed to the manuscript and approved the final version.

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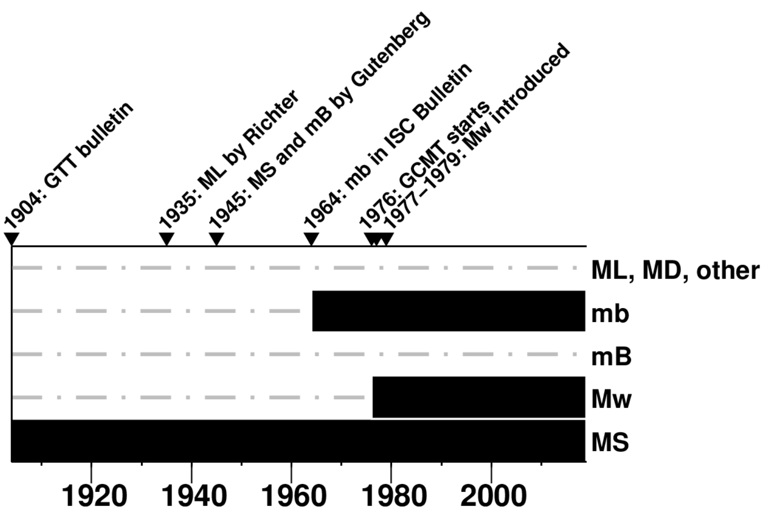

Figure 1. Availability over time of common magnitude scales for worldwide (*MS*, *Mw*, broad-band and short-period body-wave magnitude *mB* and *mb*, respectively) and local/regional (e.g., Richter and duration magnitude *ML* and *MD*, respectively) earthquakes. Solid thick black lines represent time periods over which a magnitude scale is available or can be recomputed systematically, dashed-dotted thin grey lines otherwise. For local/regional magnitudes the availability only regards limited continental areas (Di Giacomo and Storchak, 2016). On top are listed some significant developments in terms of earthquake magnitude. Among those GTT refers one of the first printed station bulletin produced at the Göettingen observatory in Germany (Schering, 1905), which pioneered modern observational seismological practice, and GCMT is the Global Centroid Moment Tensor project (www.globalcmt.org, last access: August 2021, Dziewonski et al., 1981; Ekström et al., 2012).

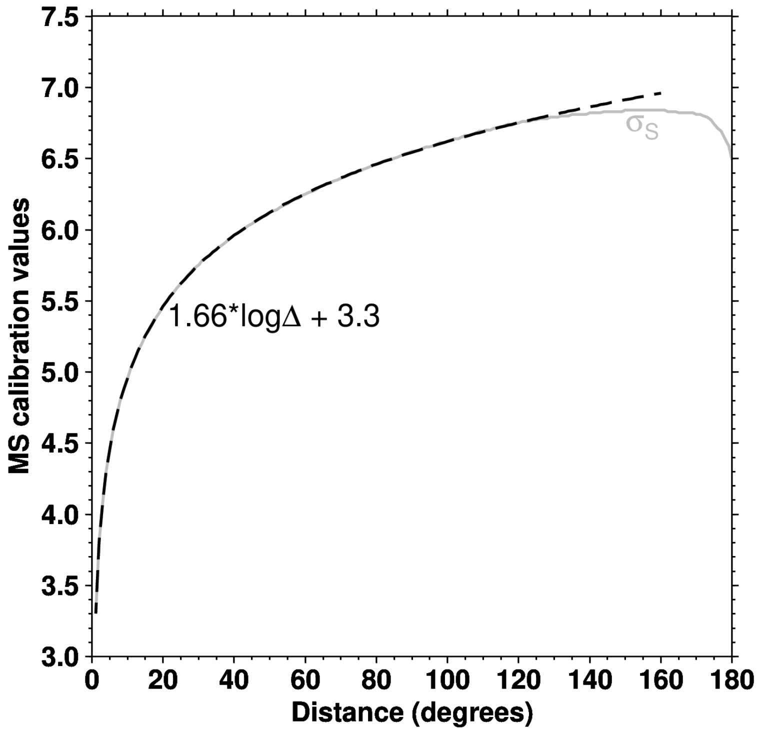

Figure 2. *MS* calibration function (tabulated values, σ_S) from the Moscow-Prague (grey solid curve) group and its best-fit for distances between 2° and 160° ($1.66 log\Delta + 3.3$, black dashed curve). See Bormann (2012) for details.

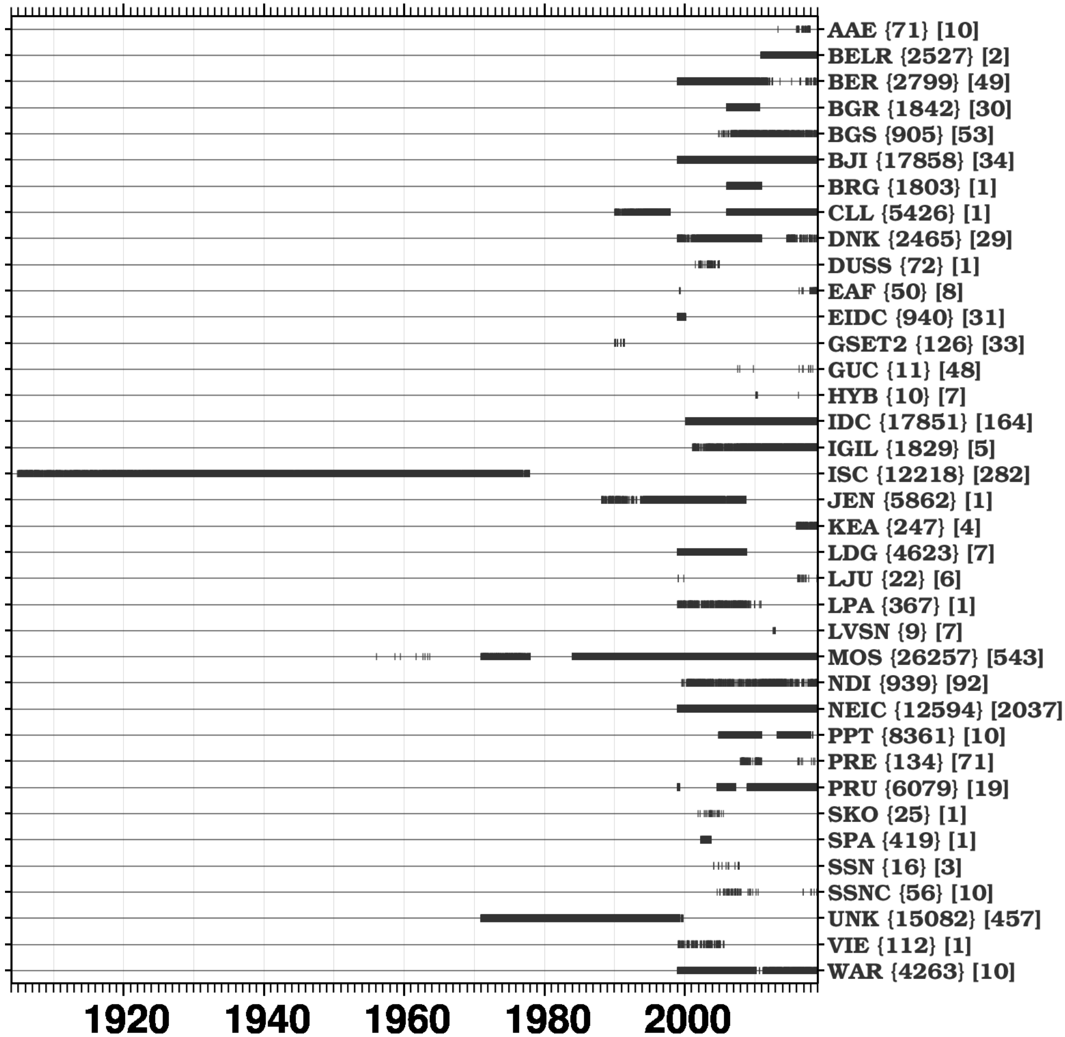

Figure 3. Timelines of the agencies contributing with surface wave data (amplitude and period measurements). Each symbol represents the origin time of an earthquake. Details about each agency code can be found by typing the agency code at www.isc.ac.uk/iscbulletin//agencies/, last access: August 2021. The total number of earthquakes and stations for each agency are listed in curly and square brackets, respectively. Note that reporter = UNK (unknown) is not a genuine reporter code but it simply represents data collected before the ISC database was set up, i.e., when the association between data and reporter was not maintained.

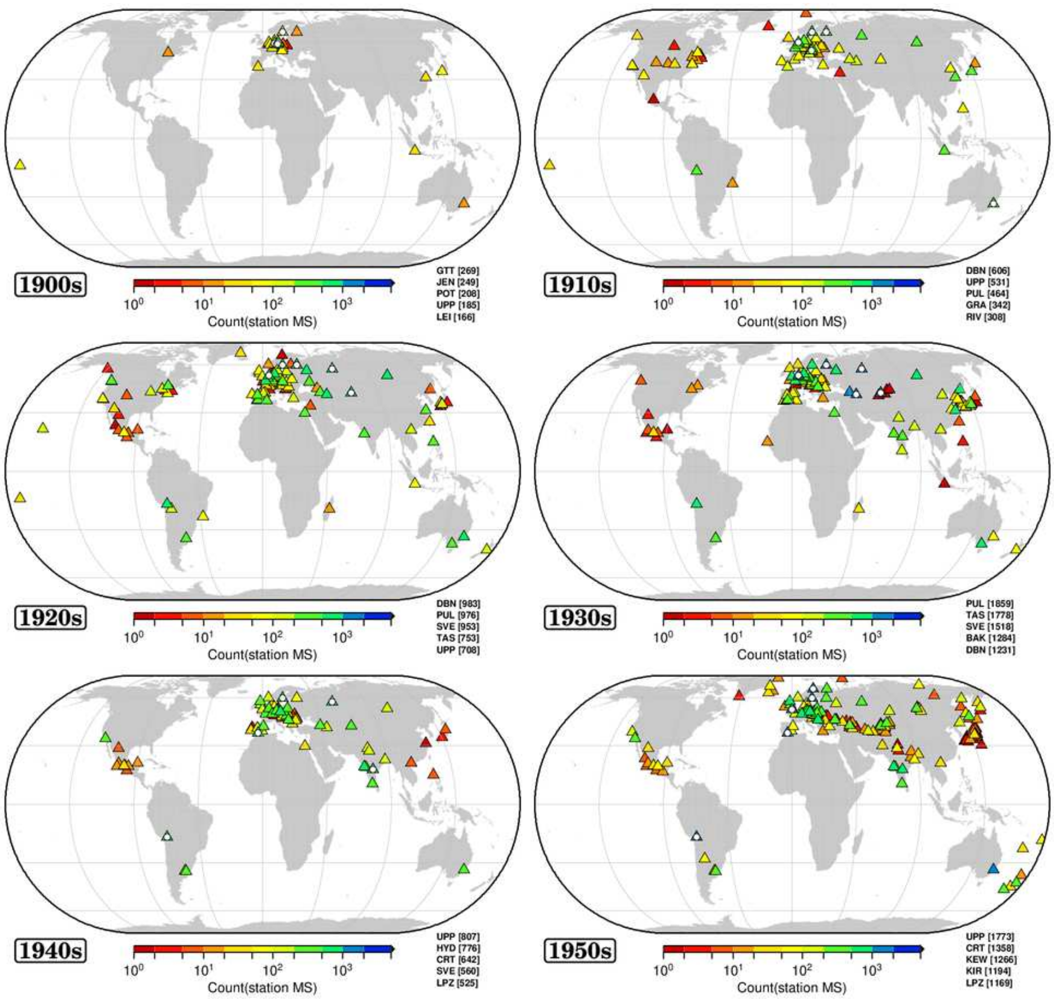

Figure 4. Decadal (up to the 1950s) distribution of the stations (triangles) that contributed with surface wave data. Symbols are colour-coded by number of station *MS*. For each decade, the top five stations in terms of *Count(station MS)* are identified by a white circle and listed in the bottom-right corner outside each map. Maps drawn using the Generic Mapping Tools (GMT) (Wessel et al., 2013) software. Plots of the annual station *MS* distributions are included in International Seismological Centre (2021d).

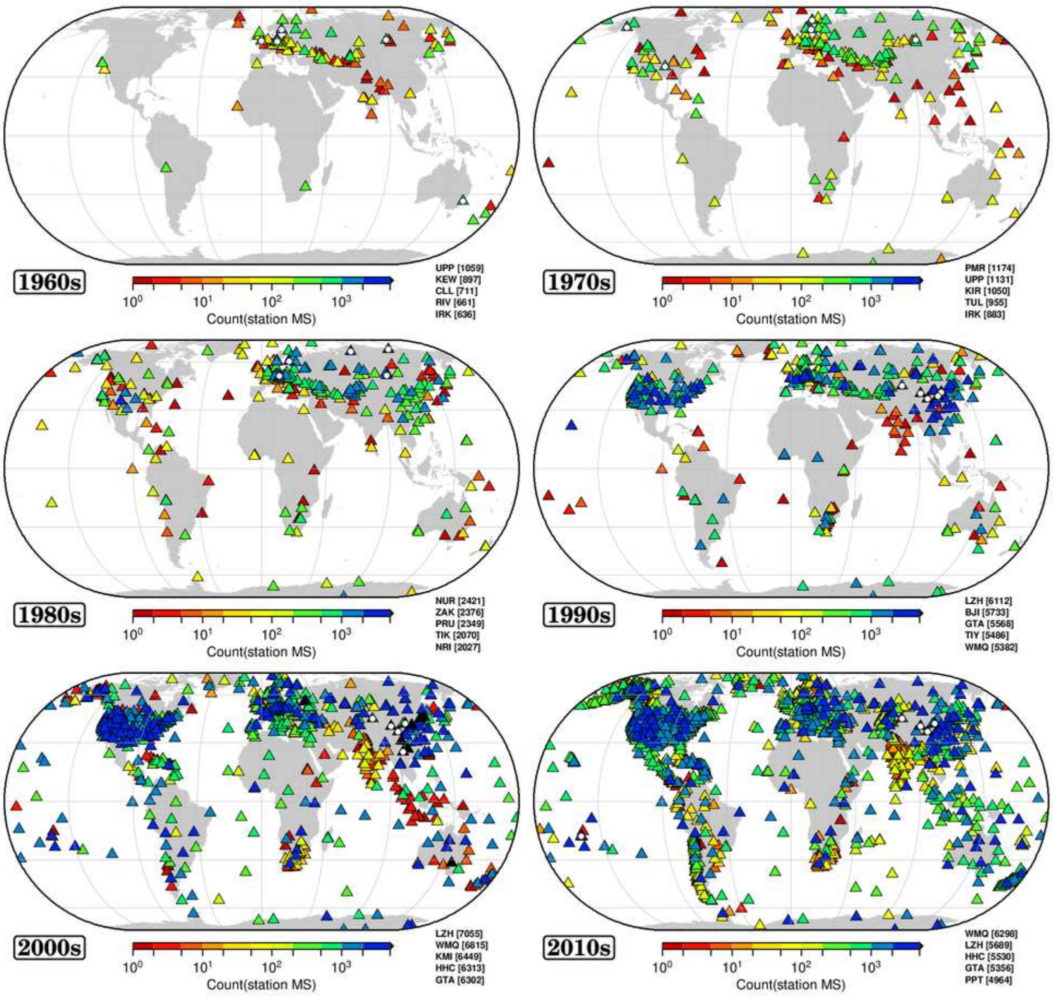

Figure 5. As for Fig. 4 but since the 1960s. Maps drawn using the Generic Mapping Tools (GMT) (Wessel et al., 2013) software.

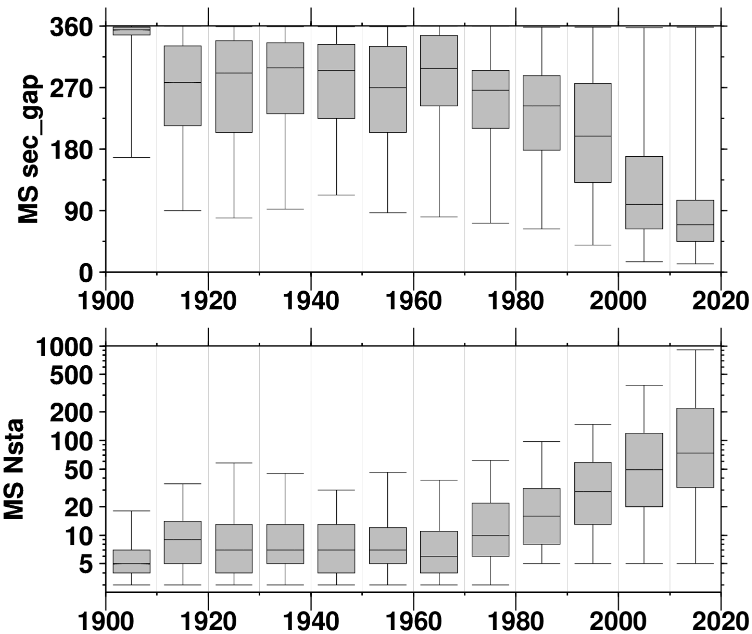

Figure 6. Decadal box-and-whisker plot of the secondary gap for *MS* (top) and number of *MS* stations (bottom).

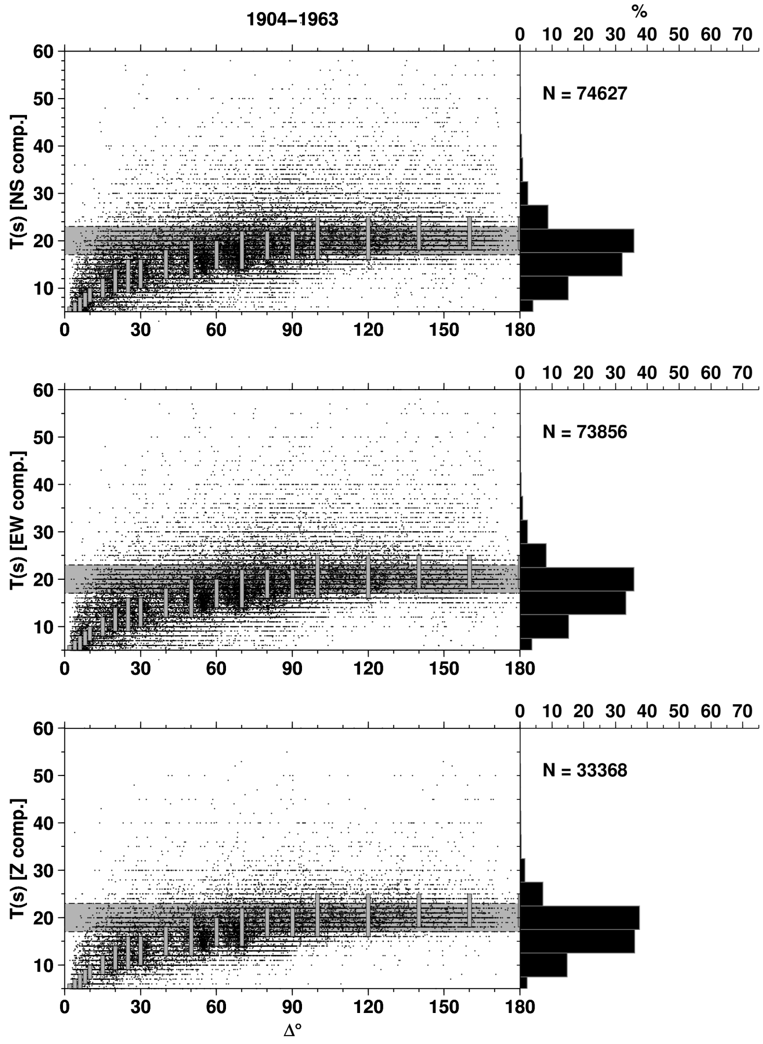

Figure 7. 3-component distance-period plots of $(\frac{A}{T})_{max}$ for surface wave readings digitized from printed bulletins for earthquakes that occurred before 1964. The horizontal grey shaded area depicts measurements around 20 seconds, whereas the vertical grey bars represent the expected period ranges at various distances (Vaněk et al., 1962) as published in Table 3.2.2.1 of Willmore (1979). The histograms on the right-hand side show the period distribution in bins of 5 seconds. See text for details.

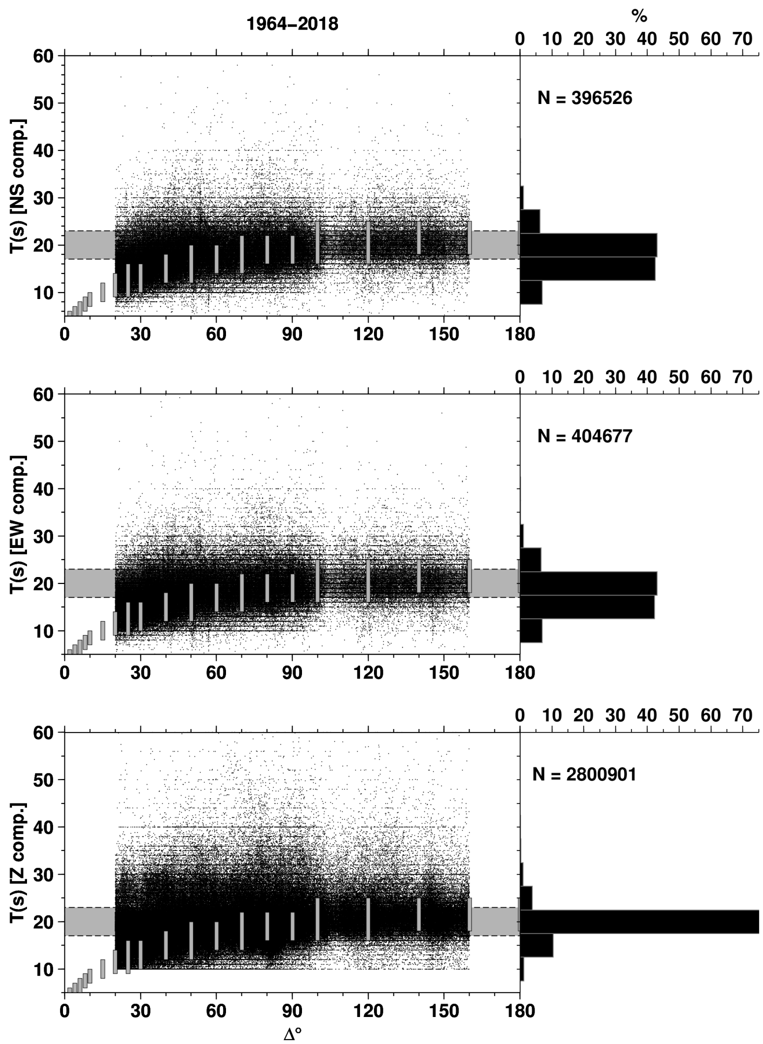

Figure 8. As for Fig. 7 but for 1964-2018.

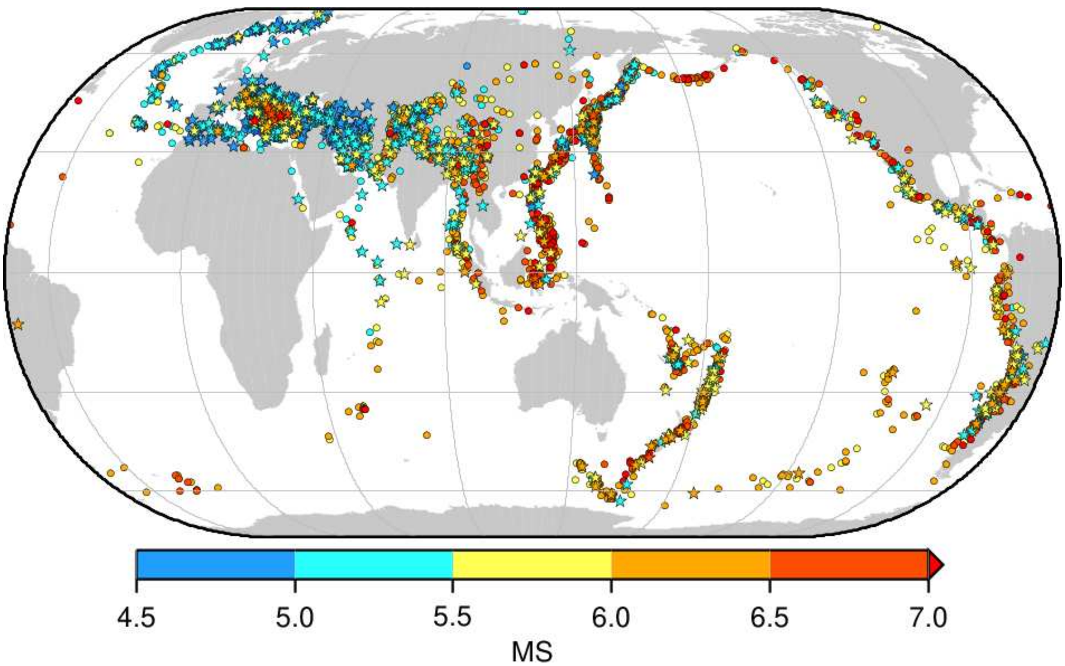

Figure 9. Map of the pre-1964 earthquakes where the expansion of the delta-period ranges compared to the current ISC practice allowed us to better constrain *MS*. Stars are for the 1,000 earthquakes that otherwise would not have network *MS*. All symbols colour-coded by *MS*. Map drawn using the Generic Mapping Tools (GMT) (Wessel et al., 2013) software.

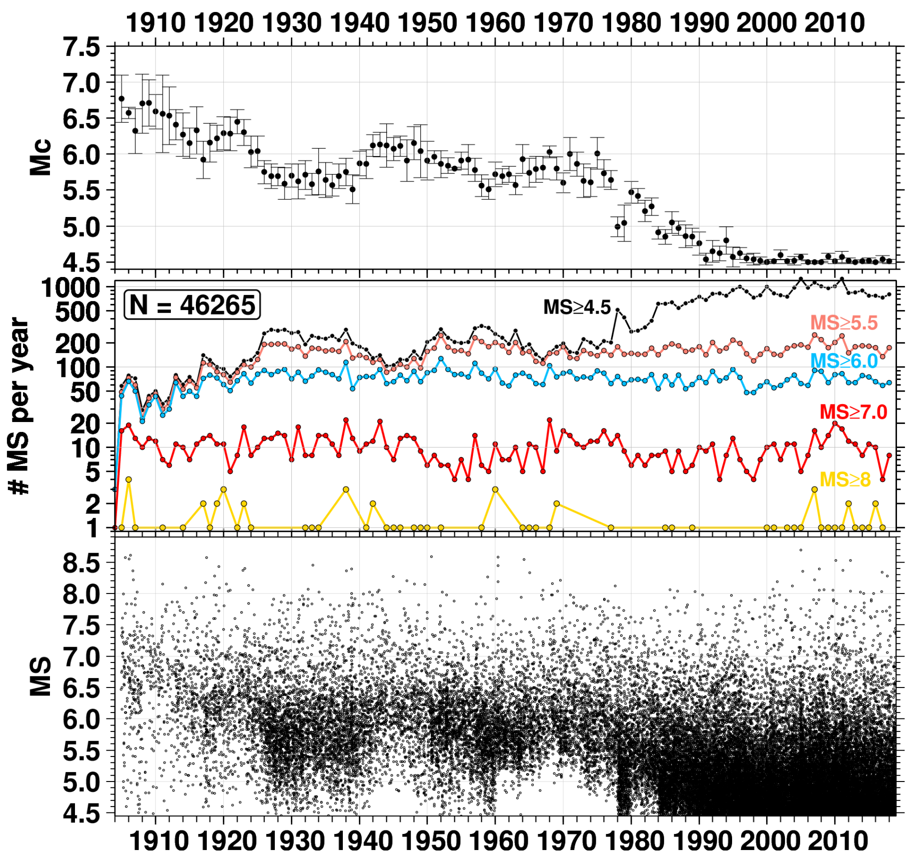

Figure 10. Bottom panel: magnitude timeline of the ISC *MS* dataset. Middle panel: number of *MS* per year for different *MS* thresholds (4.5, 5.5, 6.0, 7.0 and 8.0 in black, light red, blue, red and yellow, respectively). Top panel: annual magnitude of completeness *Mc* (Wiemer and Wyss, 2000) in the dataset, shown as average ± 1 standard deviation.

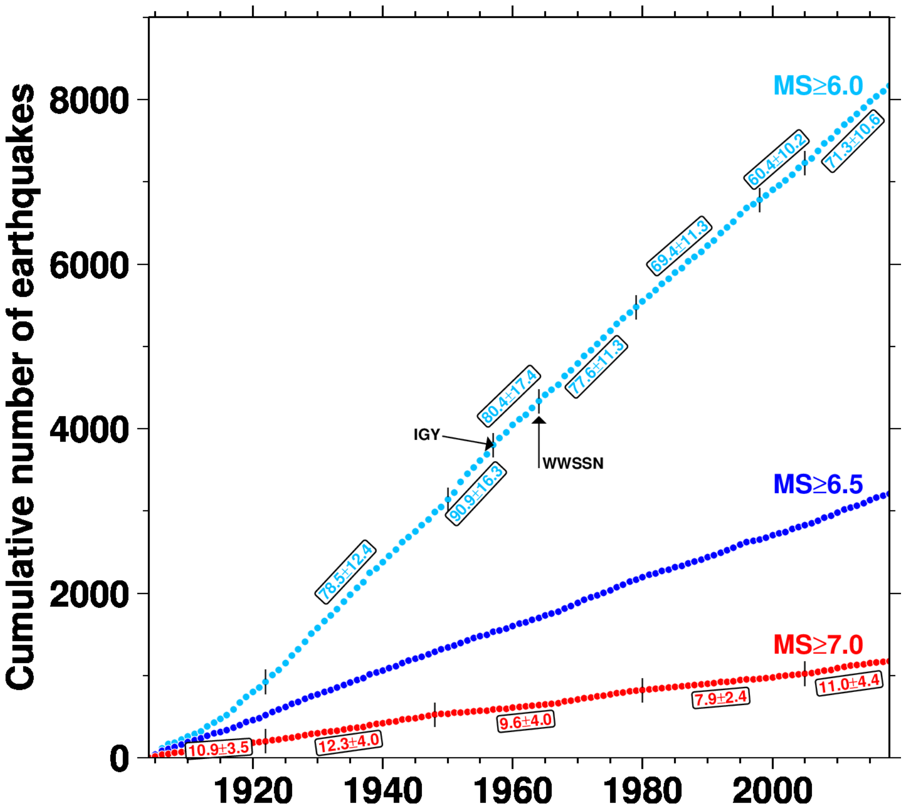

Figure 11. Cumulative number of earthquakes with *MS* ≥7.0 (red), ≥6.5 (blue) and ≥6.0 (cyan). The vertical black segments on the red and cyan symbols locate the time periods considered by Pérez and Scholz (1984) for *MS* ≥7.0 (up to 1980) and Pérez (1999) *MS* ≥6.0 (from 1950 to 1997), respectively. IGY stands for International Geophysical Year started in 1957. See text for details.

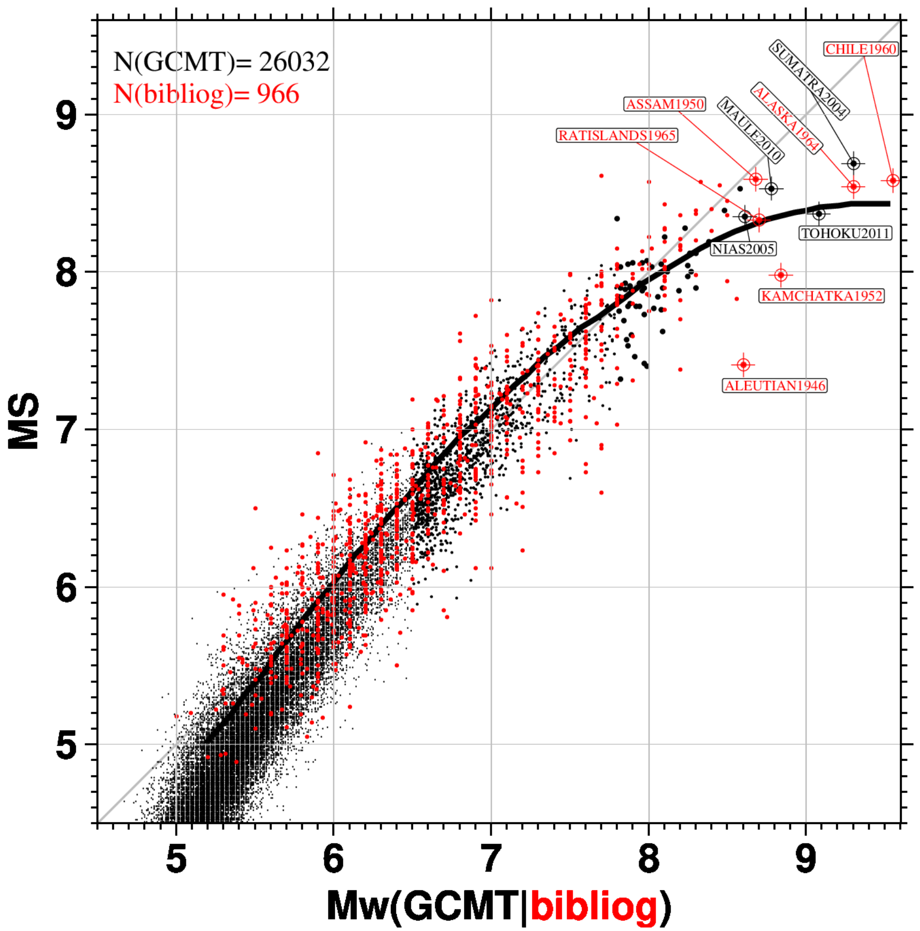

Figure 12. Comparison of *MS* with *Mw* from GCMT (black dots) and from the literature (red, Lee and Engdahl, 2015, and further updates listed at www.isc.ac.uk/iscgem/mw_bibliography.php, last access: August 2021). The black solid curve is a digitized version of the mid-point *Mw-MS* curve shown in Figure 4b of Kanamori (1983). The largest 10 earthquakes in terms of *Mw* (bulls eye symbols) are also identified by the event code in the ISC Event Bibliography (www.isc.ac.uk/event_bibliography/index.php, last access: August 2021).

Table 1. Reading example from station CLL (Collm, Germany) associated to an event in the Northern Mid-Atlantic Ridge occurred the 24 of September 1969 ($\Delta = 58.8°$). The surface wave measurements (L phases) are used by our procedure to obtain the reading *MS*. *Rdid* and *ampid* are database identifiers for the reading and single amplitude-period entries, respectively. See text for details.

Phase	Comp.	Arrival Time (UTC)	rdid	ampid	A (nm)	T (s)
S	N	1969-09-24 18:21:14	38936	601627645	16500	20.0
S	E	1969-09-24 18:21:14	38936	601627644	25500	20.0
L	N	1969-09-24 18:32:00	38936	601627642	23000	24.0
L	E	1969-09-24 18:32:00	38936	601627641	44500	24.0
L	Z	1969-09-24 18:32:00	38936	601627640	43500	24.0
L	N	1969-09-24 18:39:00	38936	601627639	24000	17.0
L	E	1969-09-24 18:39:00	38936	601627638	30000	17.0
L	Z	1969-09-24 18:39:00	38936	601627637	25000	17.0
L	Z	1969-09-24 18:43:00	38936	601627636	32000	16.0

Table 2. Rates of seismicity in the ISC *MS* dataset and in Pérez and Scholz (1984); Pérez (1999). See text for details.

$MS \geq 7.0$	Period	Rate (ISC *MS*)	Rate (Pérez and Scholz, 1984)
	1905-1922	10.9 ± 3.5	7.3 ± 1.8
	1922-1948	12.3 ± 4.0	12.6 ± 4.0
	1948-1980	9.6 ± 4.0	7.1 ± 2.8
$MS \geq 6.0$	Period	Rate (ISC *MS*)	Rate (Pérez, 1999)
	1950-1956	90.9 ± 16.3	109 ± 17
	1957-1963	80.4 ± 17.4	137 ± 14
	1964-1978	77.6 ± 11.3	38 ± 6
	1979-1997	69.4 ± 11.3	55 ± 7

Appendix A: Additional plots

Here we show figures in support of the main text. Most of them regard additional delta-period plots similar to Fig. 7 for major *MS* reporters.

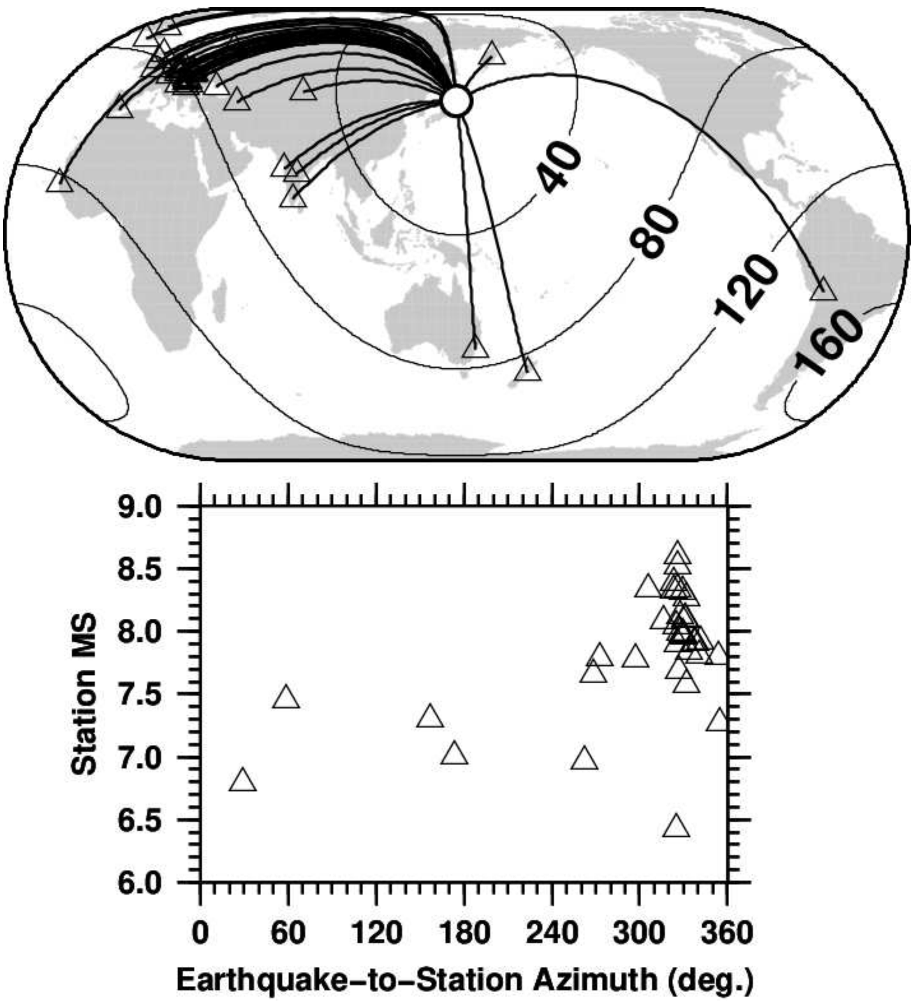

Figure A1. Top: map showing the location of the 1960-03-20 off east coast of Honshu earthquake (event id = 878564, white circle) and the stations (triangles) contributing to the network *MS* = 7.9. Contours every 40 degrees distance shown for guidance. Map drawn using the Generic Mapping Tools (GMT) (Wessel et al., 2013) software; Bottom: azimuthal distribution of the single station *MS* for this event.

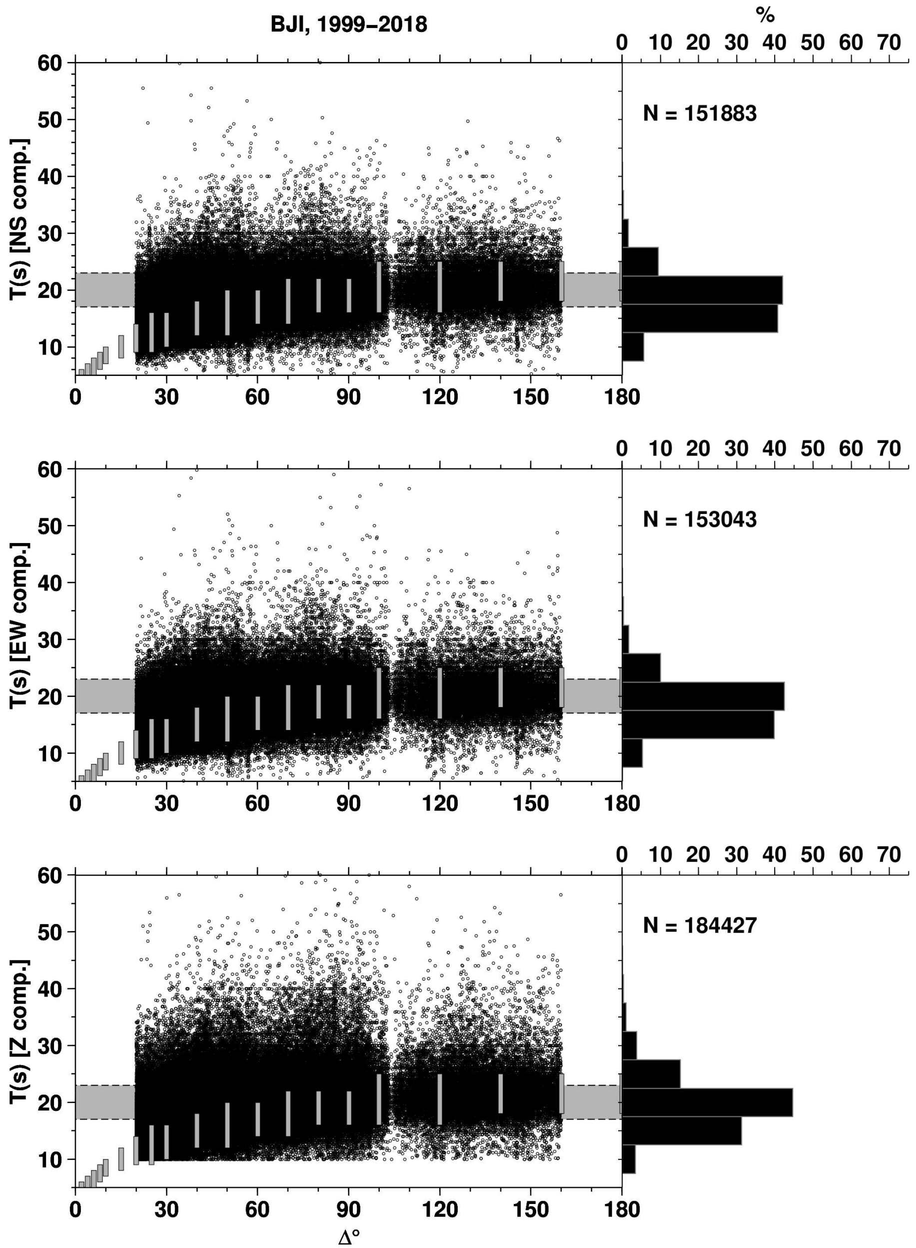

Figure A2. As for Fig. 7 but for reporter BJI.

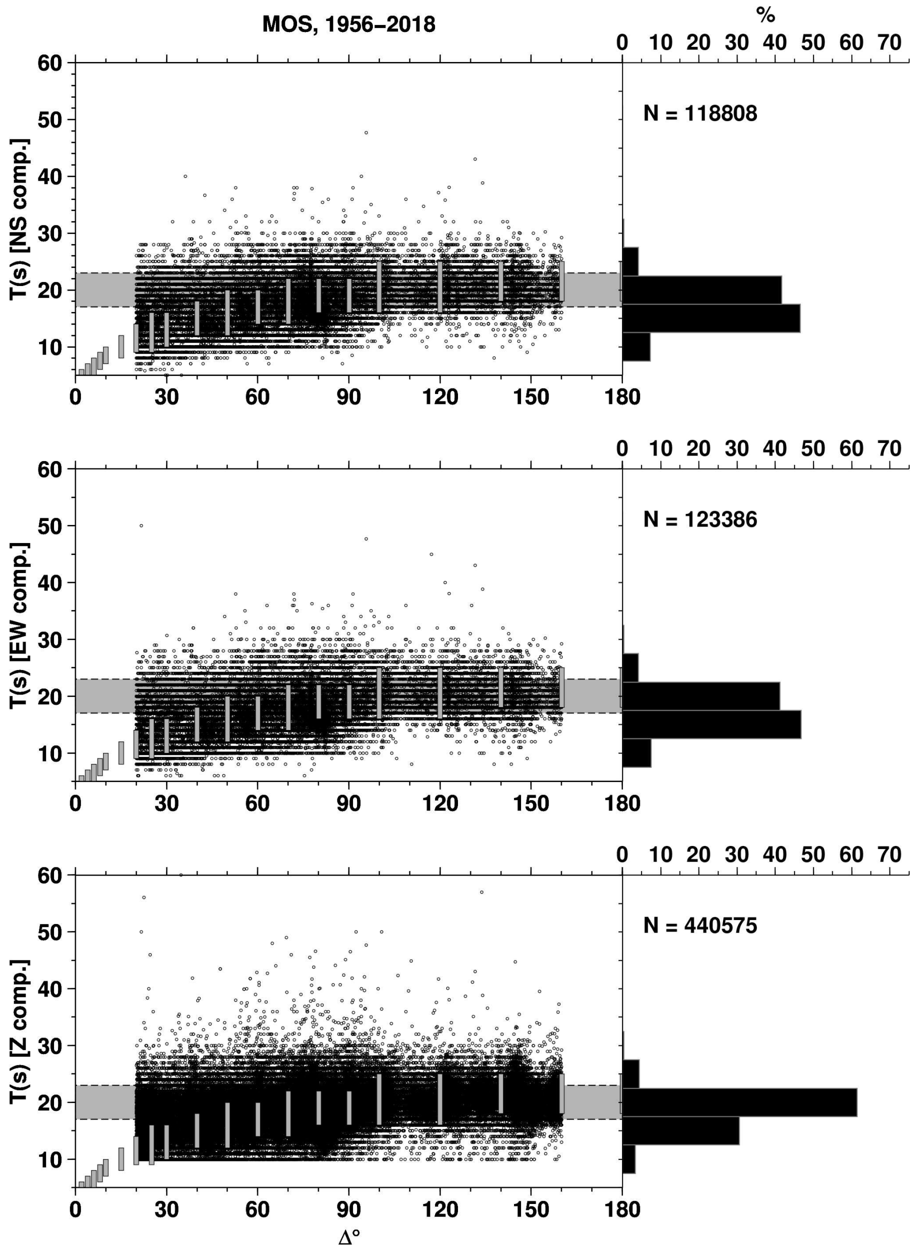

Figure A3. As for Fig. 7 but for reporter MOS.

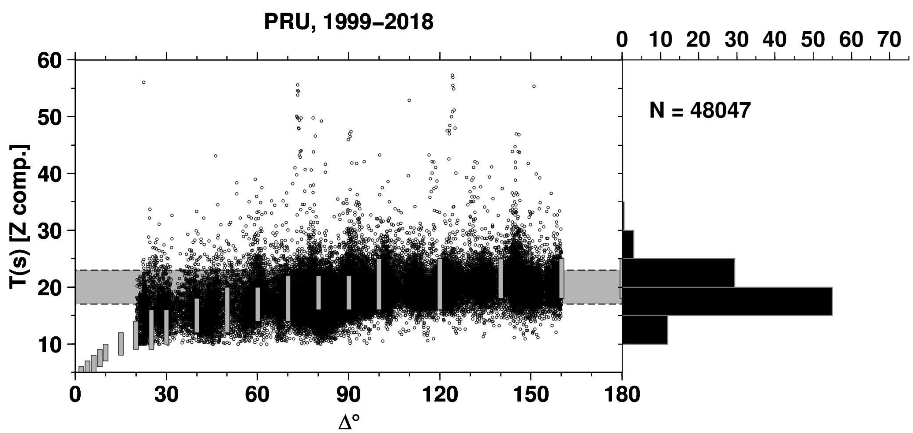

Figure A4. As for Fig. 7 but for reporter PRU, vertical component only.

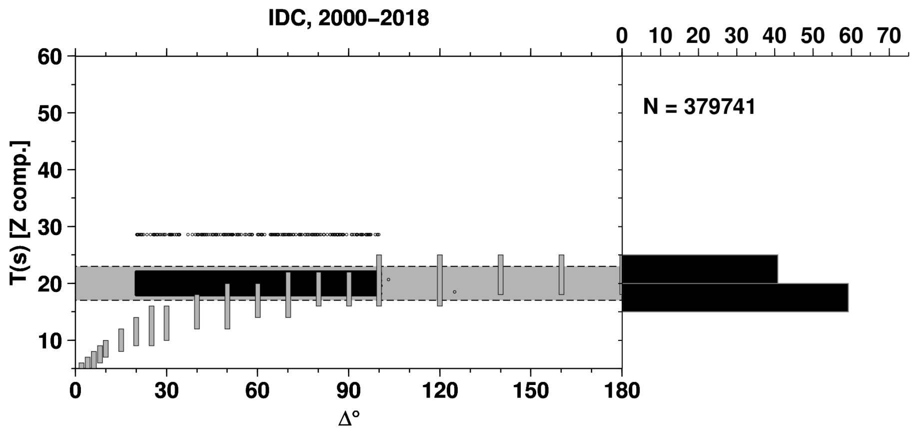

Figure A5. As for Fig. 7 but for reporter IDC, vertical component only.

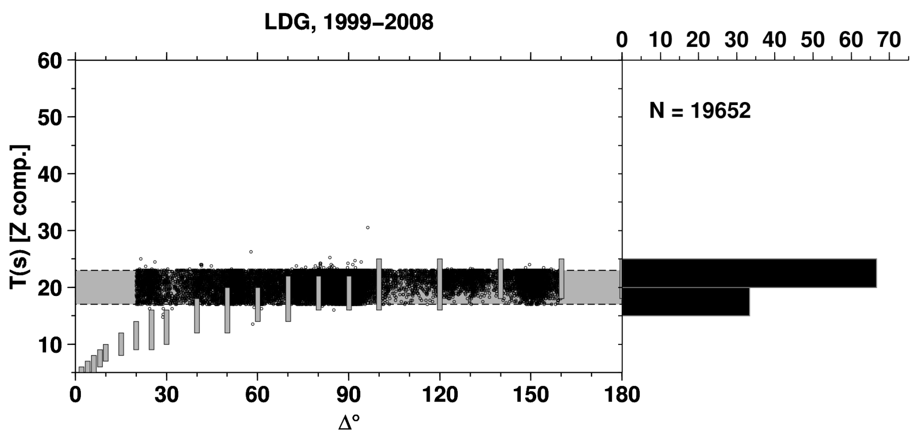

Figure A6. As for Fig. 7 but for reporter LDG, vertical component only.

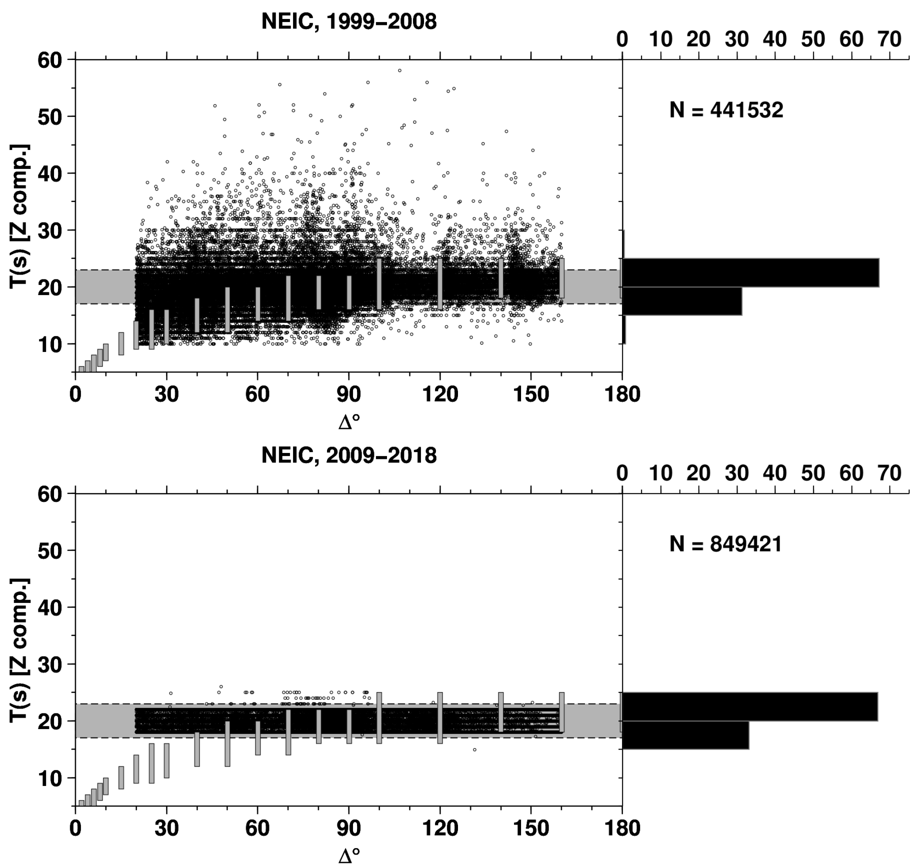

Figure A7. As for Fig. 7 but for reporter NEIC, vertical component only. Here we split the plot in two time periods to emphasize the change in 2009 by NEIC in reporting surface wave amplitudes strictly around 20 seconds

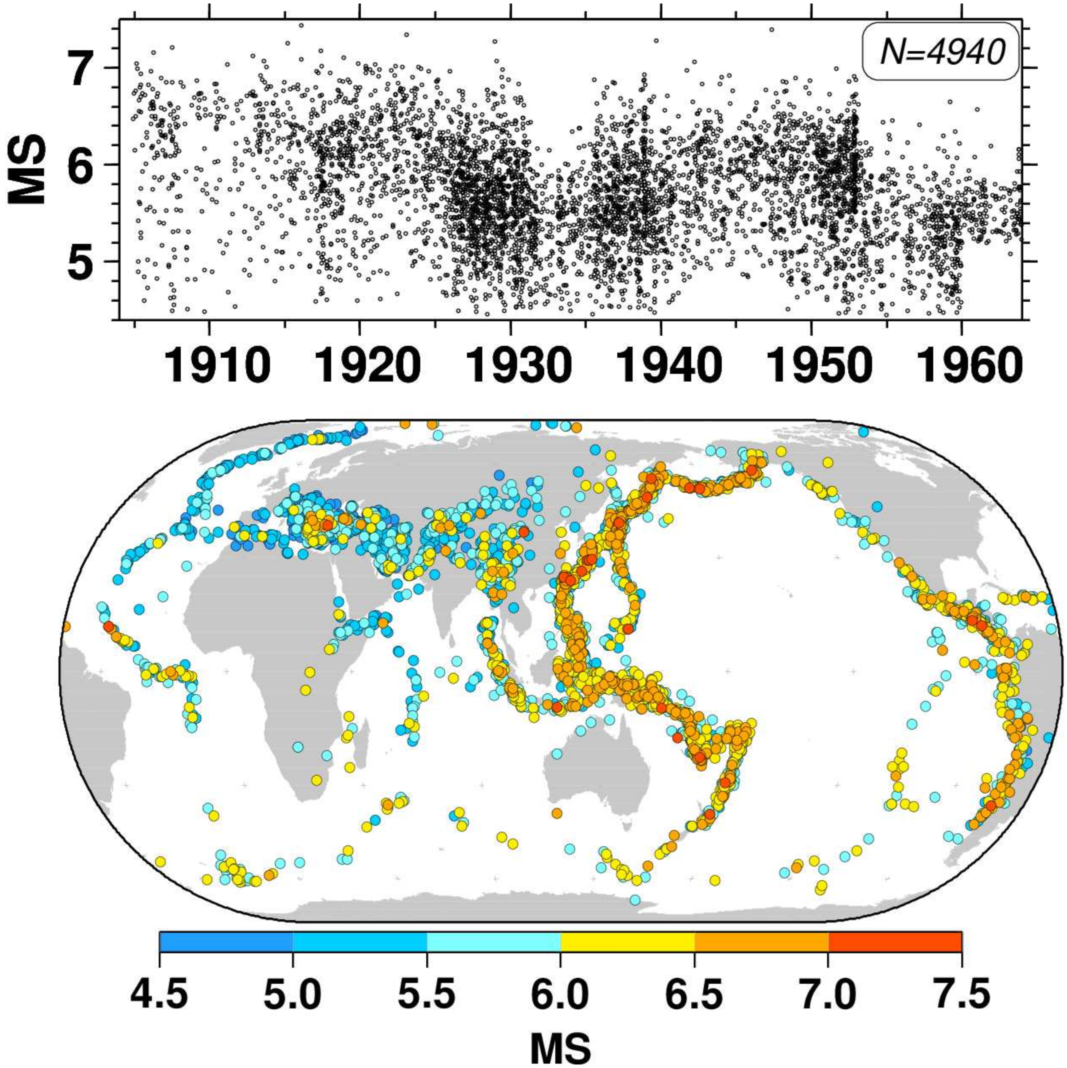

Figure A8. Map colour-coded by *MS* and timeline of the pre-1964 earthquakes where, according to our records, *MS* has been computed for the first time. Map drawn using the Generic Mapping Tools (GMT) (Wessel et al., 2013) software.

Table A1. Examples of $Mw < 8.2$ earthquakes characterized by large differences between Mw and MS. Mw is from literature for pre-1976 earthquakes, GCMT otherwise. The last column is the ISC event identifier.

$Mw \ll MS$	Origin Time (UTC)	Lat.	Long.	Mw	MS	ISC_evid
	1906-04-18 13:12:26	38.04	-122.40	7.70	8.61	16957905
	1915-10-03 06:53:21	40.27	-117.58	6.80	7.61	913944
	1927-03-07 09:27:41	35.56	134.99	7.00	7.82	909128
	1969-07-18 05:24:45	38.35	119.51	6.90	7.72	807162
	1970-05-27 19:05:37	40.27	143.03	5.90	6.85	796053
$Mw \gg MS$	Origin Time (UTC)	Lat.	Long.	Mw	MS	ISC_evid
	1940-12-28 16:37:44	18.20	147.46	7.70	6.60	901750
	1954-08-27 10:54:55	23.99	143.02	7.20	6.23	891003
	1983-01-13 09:23:49	-35.83	-102.88	6.12	5.10	584568
	1995-05-26 03:11:15	11.89	58.02	6.46	5.42	106101