REVIEW OF MWP MAGNITUDE CORRECTIONS BASED ON THE ANALYSIS OF PTWC OPERATIONAL DATA

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Abstract

We compiled a database of operational Mwp magnitudes by scanning the PTWC communications log files for messages issued between 2003 and June 2020. Matching of the earthquake hypocenter parameters reported in these messages with their official catalog counterparts resulted in 5222 pairs of operational Mwp vs. Mw magnitudes. Analysis of the magnitude residuals for increasing hypocentral depths reveals a distinct depth-dependency. Regression analysis for different hypocentral depth intervals exposes an average of ~0.2 magnitude unit difference between the regression lines for shallow and deep earthquakes regardless of magnitude. Application of regression analysis to 675 intermediate-depth earthquakes with hypocenters located between 75 and 300 km results in a near replica of the 2002 correction formula. These results corroborate that automatic application at the tsunami warning centers of the 2002 correction coefficients to all earthquakes regardless of hypocentral depth or seismic source region turns both inadequate and insufficient. Analysis of the operational Mwp data shows that the 2002 formula neither corrects enough for the overestimation of 64% of shallow earthquakes nor the underestimation of 19% of shallow and 67% of deep hypocenter earthquakes. For shallow earthquakes, the results indicate both, a stronger magnitude and regional dependency, manifested as a pervasive tendency to increasingly larger overestimations toward smaller magnitudes, and increasingly larger underestimations toward larger magnitudes. These findings can have a straightforward practical impact by operationalizing a new set of Mwp correction formulae that account not only for global magnitude dependency but also for the Mwp residuals' hypocentral depth and seismic source regional dependencies. The current operational procedures require the issuance of a tsunami threat message for teleseismic earthquakes with a 7.1 or larger magnitude. The application of global magnitude and depth-dependent correction formula alone, for instance, can potentially eliminate the issuance of a significant number of otherwise inessential tsunami threat messages routinely issued for earthquakes in the Pacific. The application of a new magnitude correction scheme that takes into consideration not only magnitude but also depth and seismic source regional dependencies can significantly improve the trustworthiness of the Mwp method within the context of tsunami warning operations.

Keywords: Mwp corrections; depth dependency; regional dependency; tsunami warning operational environment;

1. Introduction

Since at least 2003 the US Tsunami Warning Centers (TWCs) have relied on the P-wave moment magnitude method (Mwp) to evaluate the tsunamigenic potential of earthquakes occurring around the world. First published by Tsuboi et al. in 1995 [1], formulation of the Mwp method relied on the analysis of 57 shallow earthquakes with epicenters located at distances of 250~1620 km from two broadband seismic stations in Japan. In 1999 Tsuboi et al. [2] modified the Mwp method to extend its applicability to deep and teleseismic earthquakes using a database of 178 worldwide earthquakes recorded at up to 14 broadband seismic stations. Although the Mwp magnitudes do not seem to saturate, the method has a documented tendency to incur larger magnitude underestimations for large, complex rupture earthquakes, as presented by Kanjo et al. in 2006 [3], and Hara and Nishimura in 2011 [4]. The post-event study of the M9.3 December 24th, 2004 Sumatra – Andaman, and the M8.7 May 28th, 2005 Northern Sumatra earthquakes conducted by Kanjo et al. [3], for instance, found that an Mwp average of 15 stations underestimated the magnitude of both earthquakes by as much as 0.6 magnitude units even after adjusting the coefficient to compensate for the radiation pattern in the Mwp original formula. To overcome some of its shortcomings, both US TWCs apply a magnitude-dependent correction formula derived from the study of 416 worldwide earthquakes by Whitmore et al. in 2002 [5]. The analysis of the operational PTWC Mwp magnitudes listed in 647 tsunami bulletins conducted by Sardina et al. in 2017 [6], however, confirmed that a) the Mwp method has a tendency to incur larger underestimations for large earthquakes, and b) the application of the 2002 correction formula at the US TWCs neither resolves the overestimation of smaller magnitude earthquakes nor the underestimation of the largest ones.

Similarly, and as a follow up to the analysis of the tsunami bulletins' operational data [6], in this study we do not apply the Mwp method post-event to elucidate how or why Mwp estimates do not match the final, official Mw magnitudes. We instead review the operational performance of the Mwp method relying on operational data extracted not only from official tsunami bulletins, but also from thousands of observatory messages reporting preliminary magnitudes computed via the application of the Mwp method during round the clock real-time tsunami warning operations at the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawai'i.

2. Motivational Ruminations and Operational Purpose

To better understand both, the motivation and purpose of our study, we find worth noting some practical differences between post-event magnitude estimation studies and operational Mwp estimations within the context of 24/7 tsunami warning operations:

a) Implicit bias: Once an authoritative institution releases an earthquake's final hypocenter parameters, including its moment magnitude (Mw), it turns quite difficult to make unbiased manual Mwp picks, for instance, even if we consciously intended to do so. In practice, when picking individual station Mwp values, a priori knowledge of the official magnitude will affect the final estimate, as we will subconsciously tend to pick values closer to the already known final Mw. A way to minimize the effects of implicit bias consists in conducting blind studies. As a rule, however, researchers conducting post-event magnitude estimation studies know the official hypocenter parameters of all events included in their analysis dataset from the very beginning. In contrast, within the operational environment characteristic of the TWCs implicit bias has no room to exist. This stems from the fact that the TWCs usually provide the fastest magnitude estimate for most events with Mw~5.5 or larger magnitude occurring around the world, way in advance of more robust magnitude estimations released later on.

b) Operational time constraints: Mwp estimation studies conducted post-event do not have operational real-time constraints. When compared to the TWC duty scientists, the research scientist has the rather rare luxury of picking Mwp values at will, all the way to the farthest stations that recorded the event, while also having the ability to repeat the process many times before reporting the results. Given the TWCs mission, however, duty scientists at the TWCs must issue a message product within an operational environment where speed takes precedence over achieving the highest possible hypocenter parameters' accuracy. The PTWC, for instance, issues most observatory messages for teleseismic earthquakes within 4 to 6 minutes from origin time. These operational time constraints limit the number of stations available to the TWC duty scientists for Mwp magnitude estimations, a factor not reflected in post-event studies. This translates into the TWC duty scientists having to base operational Mwp estimations on the analysis of near-real time data provided by a rather limited number of seismic stations usually located no more than 10~15 degrees away from the epicenter.

Let us consider whether or not Mwp magnitude estimates using seismic stations at teleseismic distances beyond 20 degrees, as opposed to regional distances, can consistently provide more accurate magnitude estimations. The PTWC operational data, however, does not support that hypothesis, as 77.7% of Mwp magnitudes computed as an average of the closest 6 seismic stations listed in the observatory messages had an accuracy matching (60.4%) or exceeding (17.3%) the accuracy of those reported in the official bulletins that followed them [7]. Anecdotal evidence attests to the fact that within the PTWC operational environment the Mwp method can fail to provide more useful magnitude estimates for large magnitude, complex rupture earthquakes unless the duty scientists wait 7 to 9 minutes after origin time before issuing an official tsunami message. In such cases the physics of the fault rupture make it impractical to expect a more accurate Mwp magnitude estimate unless the reporting seismic stations have recorded a P-wave window capturing a large enough portion of the source process in progress.

To clarify this point, however, let us assume that the Mwp method required the use of stations located at teleseismic distances beyond 20 degrees, say at least 50 degrees. At those distances it would take the P-waves ~9 minutes or more to reach the recording stations. If we also consider a source duration of ~200 seconds or more for a 9.0 magnitude earthquake, then it would take in excess of 13 minutes for the stations to record a P-wave window that captures the rupture process. After adding processing time and manual review of the results it would take in excess of 18 minutes to obtain an Mwp magnitude estimate and issue a tsunami message.

The TWCs, however, rely on the Mwp method primarily for its operational speed and good-enough accuracy to identify large magnitude earthquakes just a few minutes after origin time. A time requirement of more than 15 minutes, for instance, would certainly make it impractical to apply the Mwp method within the context of local (in the near field) tsunami warning operations. Moreover, the development of faster CMT analytical methods such as the Wphase method by Kanamori and Rivera in 2008 [8], combined with the worldwide availability of an increasing number of seismic stations at regional scale, has made it possible to obtain a robust, accurate magnitude and focal mechanism at regional distances. At present, for instance, the PTWC has a regional, albeit still experimental, implementation of the Wphase method that allows its duty scientists to obtain an accurate, robust CMT solution within ~15 minutes from origin time.

What practical, operational reason would the TWCs have to justify the use of the Mwp method if it provided good results only when using data recorded at such teleseismic distances? What would justify to even consider the operational use of Mwp at the TWCs if it took a similar amount of time to that needed to obtain a more robust and accurate CMT-based solution? Under those assumptions, we cannot find any operational reason neither to justify the resources needed to implement, maintain and improve the method nor the operational processing time needed to systematically apply it in real-time case scenarios. Under the time constraints inherent to tsunami warning operations, as stated by the TWCs mission requirements, a wait requirement of more than 15 minutes from origin time would make the Mwp method operationally irrelevant.

Fortunately, the hypothetical case scenario discussed above have never materialized, and actual comparison of faster against slower operational Mwp estimations corroborate that the Mwp method does not depend on the farthest away stations to provide useful results for tsunami warning operations [7]. In spite of its shortcomings, the Mwp method has survived the test of time due to the fact that its speed and simplicity when compared to other more robust analytical methods make it almost ideal for tsunami warning operations. Since its adoption by the TWCs more than eighteen years ago, the Mwp method has remained as their most reliable tool for the fastest possible evaluation of the tsunamigenic potential of earthquakes worldwide on a regular basis. It will remain in that rather prominent role until more robust and accurate methods such as the Wphase CMT method, GNSS data processing, or perhaps a novel data processing technique, can match the Mwp method's speed, currently characterized by a median of less than 6 minutes from origin time.

The discussion so far highlights the fact that post-event research studies, although necessary, valuable and useful in their own right, seldom reflect the rather astringent operational environment familiar to duty scientists at the TWCs. Despite its shortcomings, owing to its relative simplicity, and its ability to provide the fastest possible actionable data to assess the tsunamigenic potential of large earthquakes, the Mwp method will certainly retain its place as the fastest seismic analysis tool in the TWCs' arsenal. Owing to its past, present, and projected prominent role into the future of tsunami warning operations, we review the PTWC Mwp magnitude corrections via cross-validation and analysis of operational data. We focus primarily on the hypocenter depths and the seismic source region of the earthquakes under consideration, and the effect of both factors on the operational Mwp magnitude residuals.

We aim to derive Mwp correction formulae better suited for use within the TWCs operational environment, as obtained from actual operational data that reflects the astringent operational conditions typical of round the clock tsunami warning operations. We hope that the results will not only contribute to improve the accuracy of the Mwp method implementation at the TWCs, but also improve the accuracy and trustworthiness of their tsunami message products.

3. Data Sources and Hypocenter Parameters Database Compilation

We compiled a database of both observatory and tsunami messages issued by the PTWC between 2003 and June 2020. We scanned the communication circuits' log files using a C++ software package [9] written to detect, extract, and parse the messages issued by the TWCs. These communication circuits include the Global Telecommunications System, the Federal Aviation Administration, and the now-defunct NOAA Weather Wire. To compile a catalog of final, authoritative earthquake solutions we relied on a set of classes that extend the capabilities of the C++ software package [9] to parse, sort, and merge the hypocenter solutions listed in the International Seismological Centre (ISCGEM) [10], the Global Centroid Moment Tensor (GCMT) project [11], and the National Earthquake Information Center (NEIC) [12] catalogs. Owing to the thoroughness and quality

of the review process, we gave priority to the location parameters listed in the ISCGEM catalog and the Mw magnitudes listed in the GCMT catalog, while resorting to the NEIC solutions for the most recent or relatively small magnitude earthquakes. Then we matched the hypocenters listed in the PTWC messages' database against the merged catalog entries. After selecting only entries listing Mwp vs Mw magnitudes the final analysis database contains 5222 pairs of PTWC versus the catalog hypocenter parameters. This database enables us to not only analyze the relationship between the Mwp and Mw magnitudes, but also the distribution of the magnitude residuals depending on the hypocentral depth and the Flinn-Engdahl seismic source regions (FES).

4. Analysis Methodology

We first reverse the effect of the 2002 correction coefficients from all the corrected Mwp^* magnitudes listed in the messages via application of the formula $Mwp = (Mwp^* * 0.843) + 1.03$ to obtain their uncorrected (raw) Mwp equivalent. Then we apply regression analysis to different subsets of Mwp vs Mw magnitude pairs using the hypocentral depths and the FES regions as grouping criteria. Owing to a variety of operational reasons, over the years duty scientists at the TWCs have had to make real-time operational decisions in a very short time (3~5 min) while relying on information provided by a limited number of seismic stations. The analysis of operational Mwp magnitude estimates then presents the additional challenge that real-time operations can sometimes lead to Mwp estimates with larger residuals that statistically would classify as outliers. To mitigate this problem, since 2011 the PTWC incorporated real-time, automatic detection and exclusion of single station outliers while computing an Mwp average. Our analysis database, however, contains messages issued as far back as 2003. To further minimize the influence of potential outliers we apply a reweighted least squares scheme consisting of three steps: 1) we perform an initial regression using the least median of the squared residuals as the norm for the misfit calculation, 2) use the initial regression to identify and remove outliers, and 3) perform the final regression using the mean of the squared residuals as the norm for the misfit calculation. In addition, we make extensive use of the GMT software package [13] to plot all scatterplots, as well as the geographic distribution of hypocentral depths and the magnitude residuals, as shown in Figs. 1 and 2.
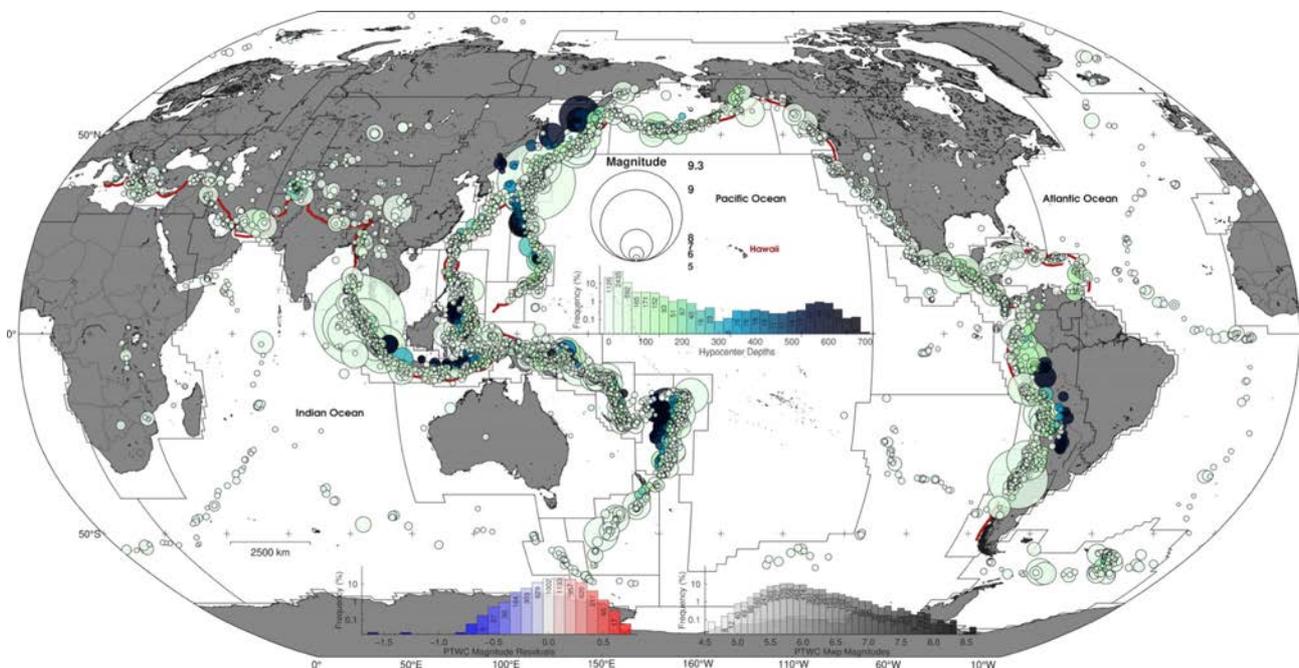

Figure 1 – Global distribution of hypocentral depths for the 5222 earthquakes under analysis. Magnitude symbols scaled by a factor of 5 between magnitude unit increments. Lighter to darkest hues of green indicate increasingly deeper hypocenters, as listed in the histogram located at the center of the map. Thin black lines delineate the 50 Flinn-Engdahl Seismic Source (FES) regions.

4

5. Results and Discussion

Figure 1 illustrates the worldwide spatial distribution of hypocenters for the 5222 earthquakes with magnitudes between 4.4 and 9.3 under scrutiny. Lighter to darker hues of green indicate increasingly deeper hypocenters. Inspection of the hypocenter depths (h) histogram shown at the center of Fig.1 shows that 4259 earthquakes (81.5%) fall in the shallow (h 0~75 km), 675 (13%) in the intermediate-depth (h 75~300), and 288 (5.5%) in the deep (h 300~700) hypocentral depth categories. As observed, the location of the epicenters delineates the subduction zones and plate margins, a feature particularly discernible around the well-known subduction zones surrounding the Pacific basin.

Likewise, Fig. 2 shows the global distribution of the magnitude residuals, with lighter to darker hues of red and blue indicating increasingly larger Mwp overestimations and underestimations, respectively. The predominance of hues of red clearly indicates that Mwp overestimates the magnitude of most earthquakes in the database. Moreover, inspection of the global distribution of magnitude residuals in the histogram located at the center of Fig. 2 allows us to discern the following features regarding the performance of the PTWC operational Mwp implementation: a) it overestimates the size of 58% of all earthquakes, b) it underestimates 23% of the time, including most of the largest magnitude and deep hypocenter earthquakes, and c) it matches the official moment magnitudes with zero magnitude residual the remaining 19% of the time.

Statistically, the PTWC duty scientists computed the average Mwp magnitudes shown in Fig. 2 relying on a median of 6 seismic stations. At least 88% of the Mwp estimates resulted from averaging 4 or more individual station estimates, while only 8% resulted from averaging more than 15 stations. Only 4% of all Mwp values resulted from averaging 20 or more stations, with a maximum of 101.

Table 1 lists some statistics for magnitude overestimations (+), underestimations (-), an exact match (=) once we split the 5222 earthquakes into three intervals of increasing hypocentral depths. It turns apparent that as we increase the hypocentral depth the Mwp magnitude residuals seem to migrate from overestimating the magnitude of 64% of all shallow earthquakes, to overwhelmingly underestimate the magnitude of deep earthquakes 67% of the time.
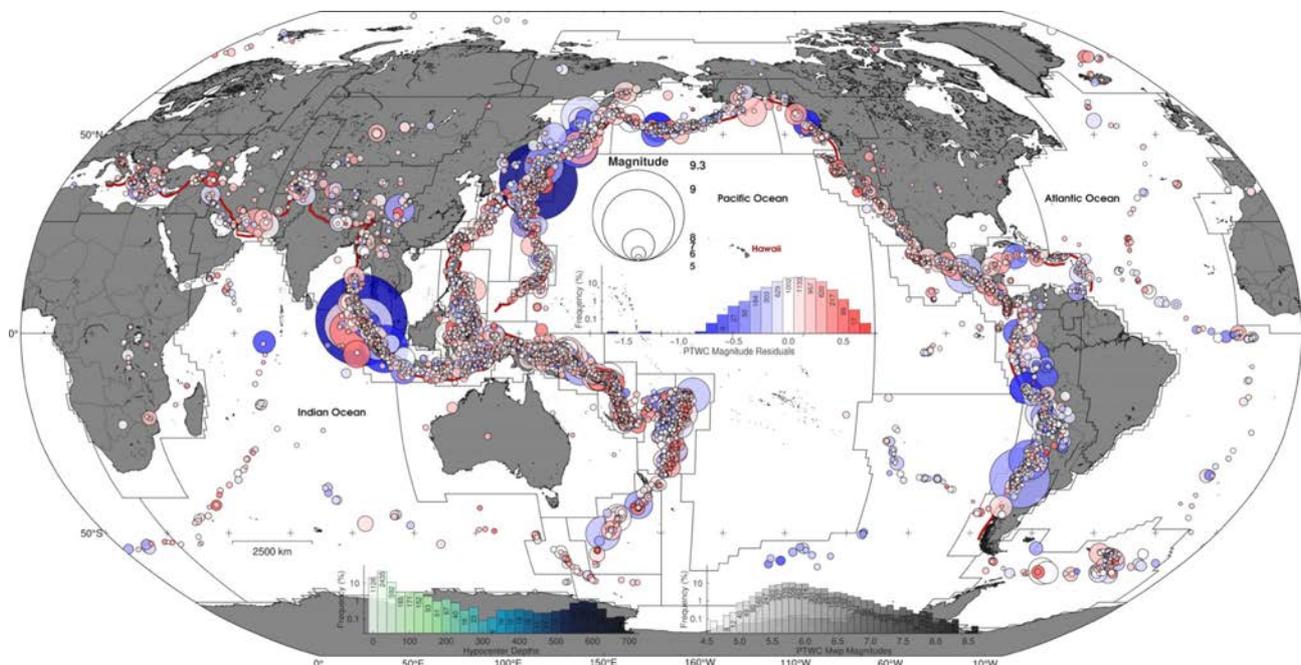

Figure 2 – Global distribution of the Mwp magnitude residuals for the 5222 PTWC operational Mwp magnitudes reported in messages issued between 2003 and June, 2020. Magnitude symbols scaled by a factor of 5 between magnitude unit increments. Lighter to darkest hues of red and blue indicate increasing Mwp overestimations and underestimations, as indicated by the magnitude residuals histogram located at the center of the map. Thin black lines delineate the 50 Flinn-Engdahl Seismic Source (FES) regions.

5

These findings reveal that the operational Mwp magnitudes have a distinct depth, and therefore also a distance dependency. We also find worth noting that for intermediate-depth earthquakes the Mwp magnitude residuals strike an almost even proportion of overestimations (39%) and underestimations (37%), while exact matches increase to 24%, the highest percentage among the three depth intervals.

Table 1 – Distribution of Mwp magnitude residuals after sorting the 5222 earthquakes in the database into four different hypocentral depth (h) intervals: All: h 0~700 km, Shallow: h 0~75 km, Intermediate-depth: h 75~300 km, and Deep: h 300~700 km. Overestimations (+) account for 64% of shallow earthquakes, underestimations increase to 67% for deep earthquakes, and exact match (=) account for 19% of all 5222 operational Mwp magnitude residuals.

Depth Category	+ Residuals		- Residuals		= No Residual	
	N	%	N	%	N	%
All (5222)	3012	58	1208	23	1002	19
Shallow (4259)	2704	64	187	18	788	18
Intermediate (675)	264	39	247	37	164	24
Deep (288)	44	15	194	67	50	17

5.1 Hypocentral Depth Dependency of Mwp Magnitudes at Global Scale

The scatterplots in Fig. 3 illustrate the results of regressing Mwp on Mw using all 5222 data pairs regardless of hypocentral depth or source region. We plot the resulting regression lines given by the formulae shown at the top center of each scatterplot with a solid black line, and show the 2002 correction formula with a thinner grey line as reference in Fig. 3a and c. The regression (black) line in Fig. 3a confirms the tendency of the Mwp method to underestimate the magnitude of larger earthquakes.
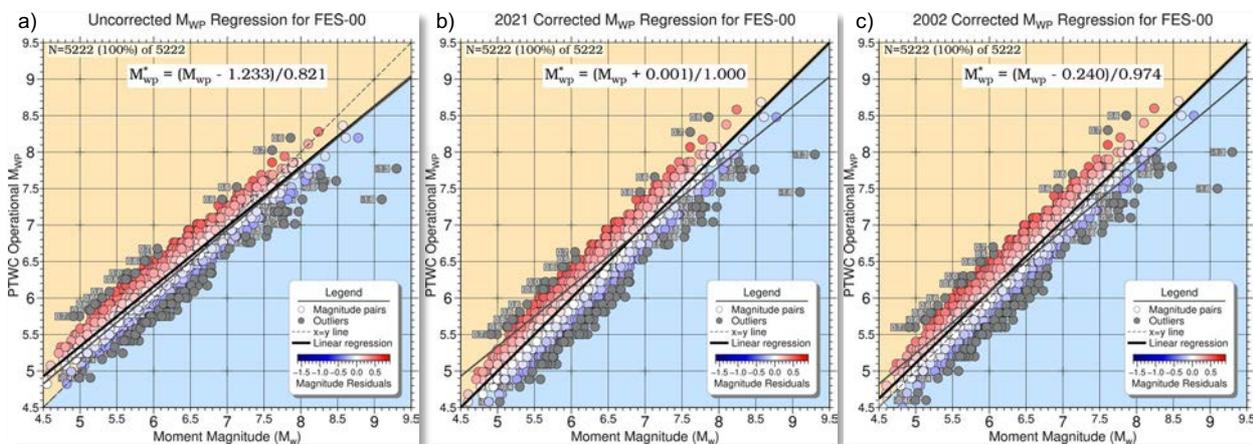

Figure 3 – Scatterplots showing the PTWC operational Mwp vs Mw at global scale for a) Uncorrected Mwp, b) after applying the new correction formula shown in a), and c) after applying the 2002 correction formula. The thick black line shows the regression lines given by the formulae at the top-center of each scatterplot. The thin grey line shows: a, c) the 2002 correction formula, b) the new regression formula at the top-center of a).

The gap between the black regression lines in Fig. 3a and c with respect to the 2002 regression (gray) or x=y line indicates, however, a strong tendency to increasingly overestimate towards smaller magnitudes by an amount not accounted for by the 2002 formula. As seen in Fig. 3b application of the regression formula shown at the top-center of Fig. 3a centers the cloud of Mwp values around the x=y line, as expected from the application of a regression formula. Application of the 2002 correction formula, however, does not center the cloud of Mwp values around the x=y line, particularly toward smaller magnitudes, as shown in Fig. 3c. We find worth noting, however, that the spread of the Mwp values around the x=y line spans 1.4 magnitude unit (-0.7~07) in all cases. Despite the newly derived global single correction formula shown in Fig. 3a performing better than the 2002 formula, as seen in Fig. 3b, the pervasive scatter of the Mwp magnitude residuals hints at the need for a different approach.
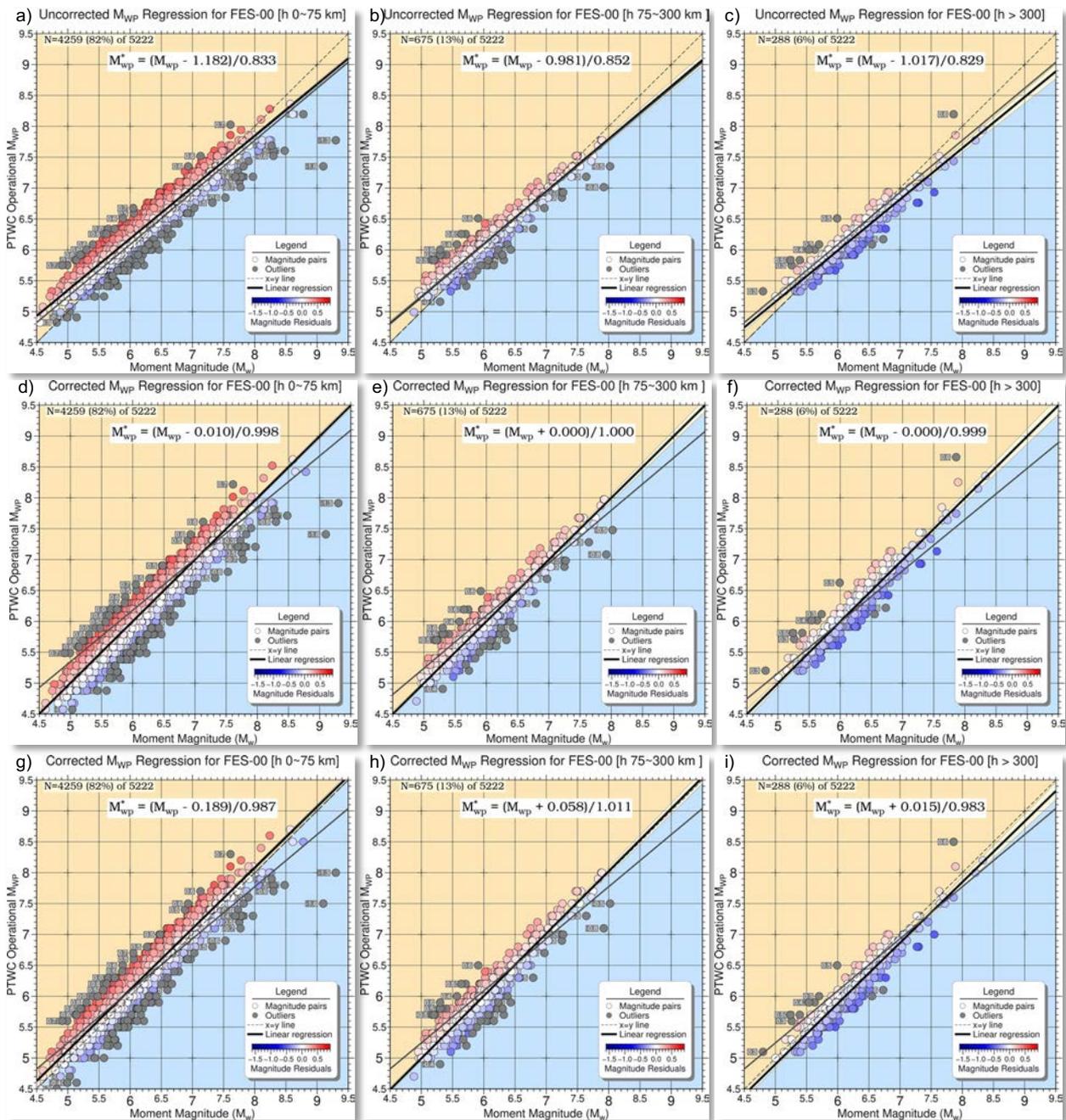
6

Figure 4 – Scatterplots illustrating the result of regressing the PTWC operational Mwp on Mw after sorting the earthquakes into three hypocentral depth (h) intervals: a, d, g) Shallow (h 0~75 km), b, e, h) Intermediate-depth (h 75~300 km), and c, f, i) Deep (h 300~700 km). Likewise, the rows show: a, b, c) results of regression analysis for uncorrected Mwp values; d, e, f) effect of applying the new depth-dependent correction formulae shown in a), b), and c); and g, h, i) effect of applying the single 2002 correction formula. The thick black lines show the resulting regression lines given by the formula at the top center of each scatterplot. The thin grey lines show the newly derived depth-dependent regression lines in a), b), c), d), e), and f); or the 2002 regression line in g), h), and i).

Figure 4 illustrates the results of regression analyses after sorting the 5222 magnitude pairs into the three incremental hypocentral depth intervals listed in Table 1. As observed in Fig. 4a, the Mwp method overestimates the magnitude of most shallow earthquakes (64%) and incurs larger magnitude residuals than

those resolved by the 2002 formula shown by the grey thinner line. The results shown in Fig. 4c on the other hand reveal that the Mwp method underestimates the magnitude of most earthquakes (67%) with hypocentral depths below 300 km. Regression analysis of magnitude pairs for earthquakes with intermediate-depth hypocenters between 75~300 km, however, results in a near replica of the 2002 formula. The regression coefficients describing the regression line shown in Fig. 4b come so close to those for the 2002 formula that when plotted both regression lines overlap. The results shown in Fig. 4a, b, and c strongly suggest that the 2002 correction formula describes the Mwp magnitude dependency for intermediate-depth earthquakes, and also that it neither applies to shallow nor deep hypocenter earthquakes.

The scatterplots in Fig. 4d, e, and f, illustrate the effect of applying the newly derived depth-dependent correction formulae for Mwp shown at the top-center of Fig. 4a, b, and c. As observed, their application centers the cloud of Mwp values around the x=y line. After applying the new formulae the regression lines now have a zero intercept, meaning that a zero Mwp estimate corresponds to a zero Mw magnitude, as expected. In addition, the ~0.2 magnitude unit gap between the regression lines obtained for shallow and deep hypocenter earthquakes shown in Fig. 4a and c disappears.

We illustrate the effect of indiscriminately applying the 2002 correction formula to all Mwp estimates regardless of hypocentral depth in Fig. 4g, h, and i, but this time after splitting the dataset into the same three depth intervals. Both Fig. 4g and i corroborate that application of the 2002 correction does not have the expected effect of centering the cloud of operational Mwp values around the x=y line, except when applied to intermediate-depth earthquakes, as seen in Fig. 4h. Moreover, the application of the 2002 corrections neither compensates enough for the marked tendency to overestimate for shallow earthquakes, as seen in Fig. 4a; nor the tendency to underestimate for both deep and large shallow earthquakes, as observed in Fig. 4c and a, respectively. We find worth noting that the separation between the regression lines for shallow and deep earthquakes shown in Fig. 4a and c, as well as on Fig. 4g and i, averages ~0.2 magnitude unit regardless of magnitude, a value that matches the 0.2 coefficient applied to correct for the average effect of the radiation pattern in the original Mwp formulation [1, 2].

5.2 Hypocentral Depth Dependency of Mwp Magnitudes at Regional Scale

The spread of the magnitude residuals for some seismic source regions, even after accounting for depth and magnitude dependence via the new depth-dependent correction formulae, however, suggests that regional factors also affect the Mwp accuracy. After performing independent regression analysis on data subsets for all the 50 Flinn-Engdahl source regions we have corroborated that the global depth-dependent correction formulae introduced in Fig. 4 center the Mwp values around the x=y line reasonably well for most source regions. For several regions, however, the application of the global correction formula for shallow earthquakes shown in Fig. 4a does not suffice. We discuss the Mwp method's seismic source regional dependency by presenting the results for one of the most glaring examples: the Kermadec - Tonga - Samoa Basing Area shown in Fig. 5. The hypocentral depth of the 416 earthquakes included in the data subset for this source region cover the whole depth range under consideration, while their Mw magnitudes vary between 5.1 and 8.1, as seen on Fig. 5a and b, respectively. The scatterplots in Fig. 6 illustrate the results of applying regression analysis to the 416 data subset shown in Fig. 5 without discriminating by hypocentral depth. Examination of Figs. 6a and b corroborate that although the newly derived global correction formulae for shallow earthquakes shown in Fig. 4a would do a better job than the 2002 correction formula, neither one would truly center the cloud of Mwp values around the x=y line, particularly for magnitudes smaller than Mw~7, as shown in Fig. 6b and c.

Figure 7 illustrates the result of regressing Mwp on Mw after sorting the 416 earthquakes into the three depth intervals discussed so far. The gray line in Fig. 7a, b, and c shows the regression lines for shallow, intermediate, and deep hypocenter earthquakes shown in Fig. 4a, b, and c, respectively. It turns apparent that within this region the newly derived global correction formula for shallow earthquakes shown in Fig. 4a would not correct enough towards smaller magnitudes. We can discern these features only after sorting the 416 earthquakes included in the regional data subset into shallow, intermediate-depth, and deep hypocenter earthquakes. Had we relied on the analysis of Fig. 6a alone, for instance, we would have overlooked the fact that shallow earthquakes account for most of the extra spread of the Mwp magnitude residuals seen in Fig. 7 also at regional scale.
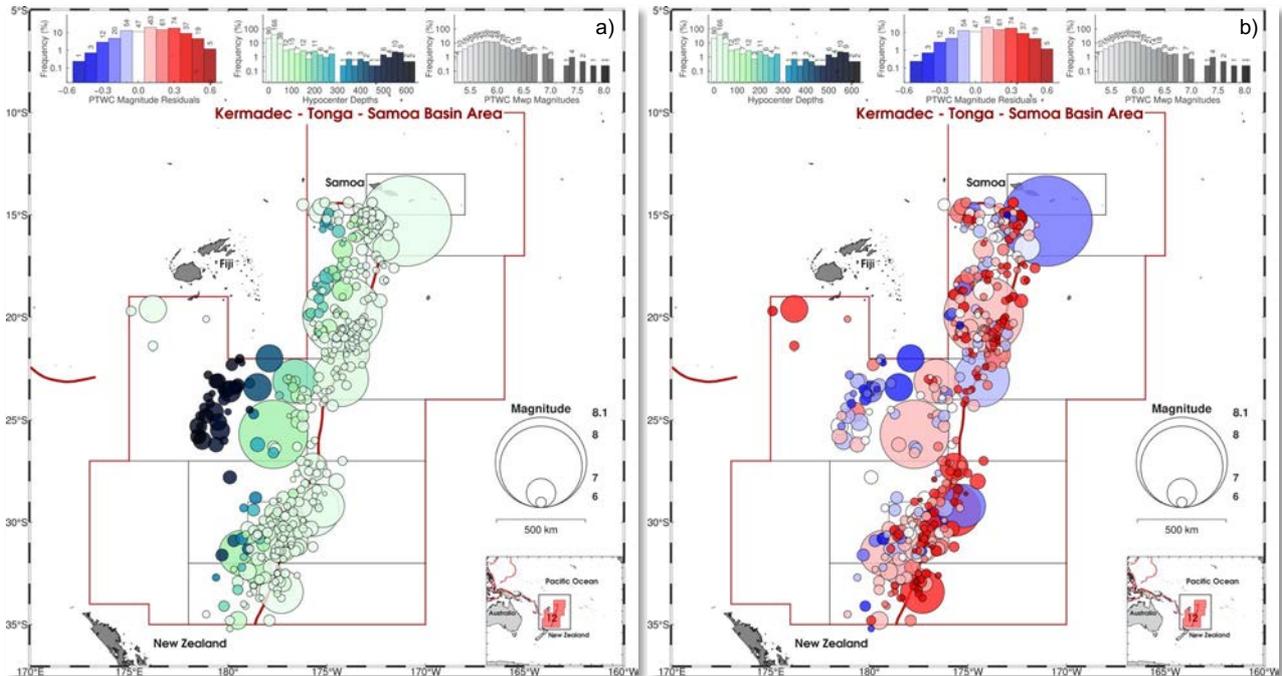
Figure 5 – Spatial distribution of a) hypocentral depths, and b) operational Mwp magnitude residuals within the Kermadec – Tonga – Samoa Basin Area Flinn-Engahl seismic source region (FES-12), delineated with a red solid line in a), and b).
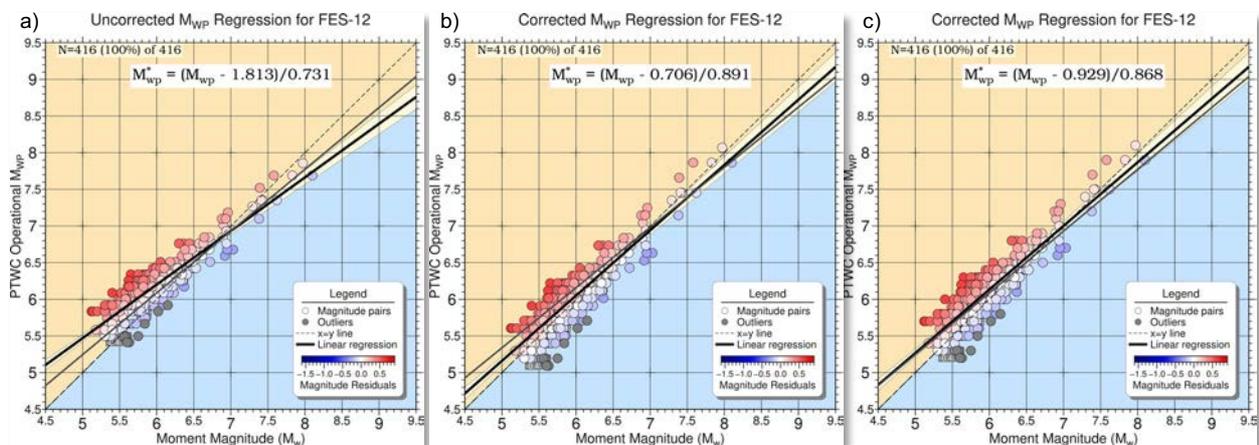

Figure 6 – Scatterplots illustrating the results of regressing the PTWC operational Mwp on Mw using the data subset for the Kermadec – Tonga – Samoa Basin Area source region shown in Fig. 5 for a) Uncorrected Mwp, b) after applying the global correction formula shown in Fig. 4a, and c) after applying the 2002 correction formula. The thick black line shows the resulting regression lines given by the formulae at the top-center of each scatterplot. The thin grey line shows a) the single global correction formula shown in Fig. 3a; b) the newly derived global correction formula for shallow earthquakes shown in Fig. 4a; and c) the 2002 correction formula. Although all global single correction formulae fail to center the cloud of Mwp values around the x=y line, the global formula for shallow earthquakes shown in Fig. 4a would performs the best, as seen in b).

The new global single correction formula derived in Fig. 4a performs better, as seen in Fig. 6b, simply because it specifically targets the increasing underestimation of smaller shallow earthquakes more aggressively. Indiscriminate application of any single global regression formula to all 416 earthquakes, even the newly derived formulae shown in Figs. 3a and 4a, however, would apparently exacerbate the underestimation of most intermediate-depth and deep hypocenter earthquakes occurring within this region, while still not correcting enough for the overestimation of shallow earthquakes, as shown in Fig. 7a.
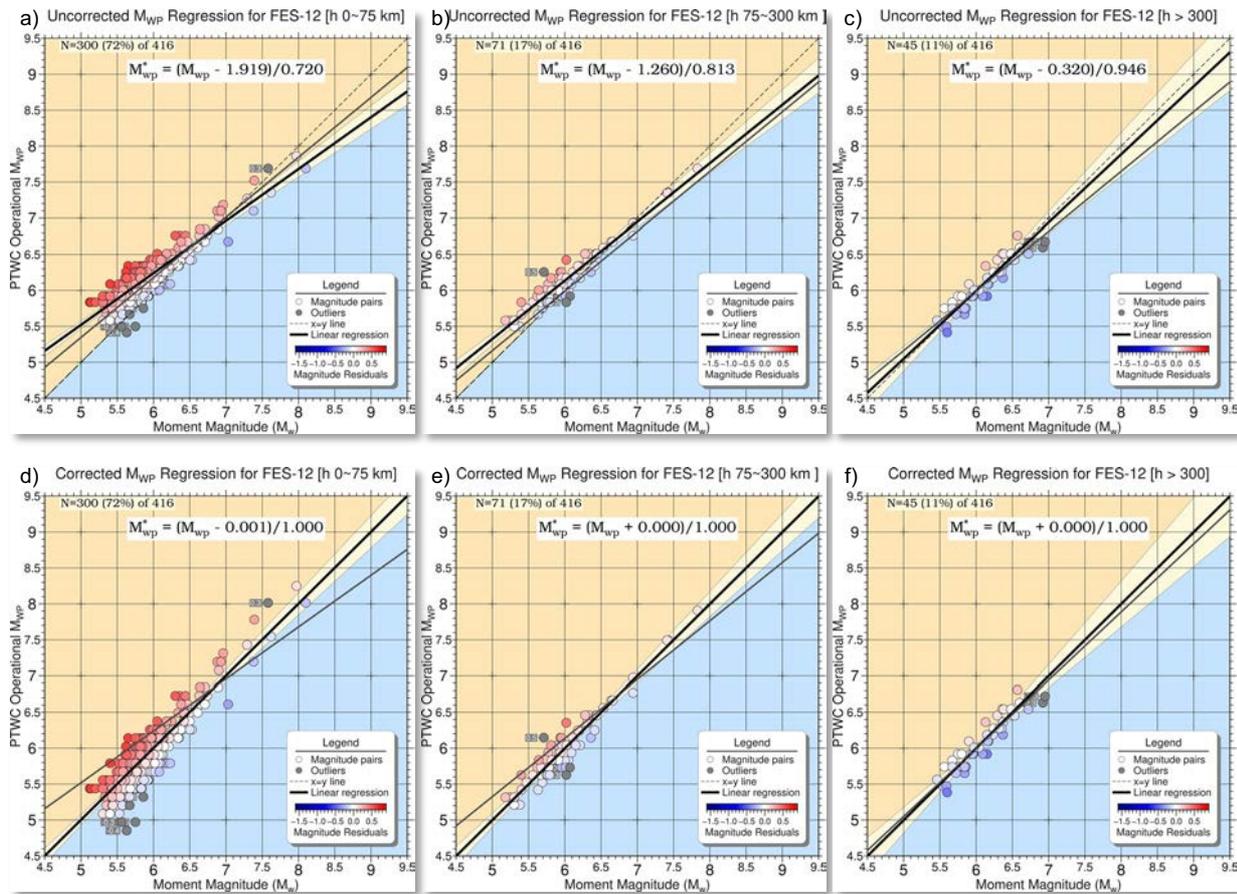
Figure 7 – Scatterplots illustrating the results of regressing the PTWC operational Mwp on Mw for the Kermadec – Tonga – Samoa Area source region after sorting the 416 earthquakes shown in Fig. 5 into three hypocenter depth (h) intervals: a, d) Shallow (h 0~75 km); c, e) Intermediate-depth (h 75~300 km); and c, f) Deep (h 300~700 km). The black lines in a), b), and c) show the regression lines for the regional depth-dependent correction formulae specifically derived for the Kermadec-Tonga-Samoa Basin Area seismic source region (FES12) shown at the top-center of each plot. The gray lines show: a, b, and c) the regression lines for the global depth-dependent correction formula shown in Fig. 4a, b, and c; and d, e, f) The regression lines derived in a, b, and c for this specific region. Application of the regional depth-dependent formulae centers all Mwp values around the x=y line, while also resulting in a zero valued intercept in all cases, as shown in d), e), and f).

In the case of intermediate-depth and deep hypocenter earthquakes, however, the new global correction formula shown in Figs. 4b and c would center the cloud of Mwp values around the x=y line reasonably well, as suggested by the gray lines in Fig. 7b and c. The Mwp magnitude estimates for shallow earthquakes within this source region, however, require an extra correction on top of the new global correction for shallow earthquakes, as suggested by the gap between the black and grey lines in Fig. 7a. The results shown in Figs. 4 and 7 corroborate that the accuracy of the PTWC operational Mwp would benefit from the application of correction formula that account not just for magnitude dependency, but also for depth-dependency at both global and regional scale.

6. Depth, Seismic Source Region, and Magnitude Dependent Mwp Correction Scheme

As an alternative to the current application of a single formula, we propose the application of a combination of the newly derived global and regional depth dependent correction formula. As an example, we will focus on earthquakes located along the Kermadec–Tonga subduction zone shown in Fig. 5. Once alerted about the occurrence of an earthquake the scientists on duty at the TWCs make a quick estimation of the preliminary hypocenter parameters. This process provides three essential pieces of information: a) the location of the

10

epicenter, b) the hypocenter depth, and c) the preliminary Mwp magnitude. Depending on the hypocenter depth, once we obtained a preliminary Mwp average we have three possible case-scenarios:

1) Shallow earthquake with its hypocenter located between 0 and 75 km:
   - If the preliminary Mwp magnitude falls in the interval $5.3 \leq Mwp \leq 6.9$ then apply the regional magnitude-dependent correction formula for shallow earthquakes specifically derived for the FES-12 seismic source region shown in Fig. 7a: $Mwp^* = (Mwp - 1.919)/0.720$.
   - Otherwise, for $Mwp > 6.9$ apply the global magnitude-dependent correction formula for shallow earthquakes shown in Fig. 4a, namely: $Mwp^* = (Mwp - 1.181)/0.833$

2) Intermediate-depth earthquake with its hypocenter located between 75 and 300 km: Apply the global magnitude-dependent Mwp correction formula for intermediate-depth earthquakes shown in Fig. 4b, namely: $Mwp^* = (Mwp - 0.919)/0.852$, or alternatively the regional formula shown in Fig. 7b, namely $Mwp^* = (Mwp - 1.260)/0.813$.

3) Deep earthquake with its hypocenter located below 300 km: Apply the global magnitude-dependent correction formula for deep earthquakes shown in Fig. 3c, namely: $Mwp^* = (Mwp - 1.017)/0.829$, or alternatively the regional formula shown in Fig. 7c, namely: $Mwp^* = (Mwp - 0.320)/0.946$.

In the absence of depth-dependent regional correction formulae similar to the ones presented in Fig. 7a, b, and c, the application of the global depth-dependent correction formulae presented in Fig. 4a, b, and c will result in a significant reduction of the spread of the Mwp magnitude residuals when compared to the application of a single formula that disregards the distinct hypocentral depth-dependency of the Mwp method.

7. Conclusions

In this study we compiled a database of 5222 messages issued by the Pacific Tsunami Warning Center between 2003 and June 2020. Then we matched the earthquake hypocenter parameters reported in these messages with their official catalog solutions. Statistical analysis and the results obtained from the application of regression analysis to different data subsets using the hypocentral depths and the seismic source region as grouping criteria allows us to draw the following conclusions:

1) Operational Mwp estimates have a distinct hypocentral depth, and therefore a distance dependency, evidenced by larger overestimations and underestimations for shallow and deep earthquakes, respectively. At global scale we derived the following hypocentral depth- and magnitude-dependent correction formulae:
   - Shallow earthquakes with hypocenters between 0~75 km: $Mwp^* = (Mwp - 1.181)/0.833$
   - Intermediate-depth earthquakes with hypocenters between 75~300 km: $Mwp^* = (Mwp - 0.919)/0.852$
   - Deep earthquakes with hypocenters between 300~700 km: $Mwp^* = (Mwp - 1.017)/0.829$

2) Regression analysis of Mwp on Mw for increasing hypocentral depths reveals an average of ~0.2 magnitude unit difference between the regression lines obtained for shallow and deep earthquakes regardless of magnitude.

3) The results corroborate that the application of hypocentral depth- and magnitude-dependent regression formulae centers the cloud of Mwp estimates around the x=y line both at the global (Fig. 4), and regional scale (Fig. 7), something not achievable via application of any single global correction formula.

4) Operational Mwp estimates have a seismic source regional dependency characterized by increasingly larger than average magnitude residuals for shallow earthquakes, particularly for but not limited to magnitudes smaller than Mw~7 depending on the specific seismic source region (Figs. 6 and 7)

5) Application of regression analysis to 675 intermediate earthquakes with hypocenters located between 75 and 300 km results in a near replica of the 2002 correction formula (Fig. 3c). This strongly suggests that the 2002 correction formula describes the Mwp magnitude-dependent characteristics for intermediate-depth earthquakes, but it neither applies to shallow nor deep hypocenter earthquakes (Figs. 4, 7).

6) Automatic application at the tsunami warning centers of the same 2002 Mwp correction formula to all earthquakes regardless of hypocentral depth or seismic source region turns both inadequate and insufficient. The results show that the 2002 formula neither corrects enough for the overestimation of the magnitude of 64% of shallow earthquakes (Fig. 4a), nor the underestimation of 19% of shallow and 67% of deep earthquakes (Fig. 4b and c).

11

7) The results of this study can have an immediate, straightforward practical impact by operationalizing a new set of Mwp correction formulae that account not only for the Mwp method's magnitude dependency, but also for their hypocentral depth and seismic source regional dependencies.

8) The operational use of global, hypocentral depth- and magnitude-dependent correction formula alone can potentially eliminate the issuance of a significant number of otherwise inessential tsunami threat messages routinely issued for earthquakes in the Pacific with uncorrected Mwp magnitudes ~7 (Fig. 4).

9) Integration of both, global and regional, magnitude- and depth-dependent correction formula under the coherent correction scheme proposed in this study can further reduce the scatter of the Mwp magnitude residuals.

10) Application of a new magnitude correction scheme that takes into consideration not only magnitude, but also the Mwp method's distinct hypocentral depth and seismic source regional dependencies can significantly improve the reliability of the Mwp method for tsunami warning purposes, and the trustworthiness of the initial tsunami message products issued by the TWCs.

8. Acknowledgements

9. Copyrights

10. References

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