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# COMPILATION AND ANALYSIS OF TWO DECADES WORTH OF TSUNAMI BULLETINS ISSUED BY THE PACIFIC TSUNAMI WARNING CENTER

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## *Abstract*

The PTWC has operated under the Tsunami Program of UNESCO's Intergovernmental Oceanographic Commission as an international tsunami warning center (TWC) for nations with Pacific coasts for fifty years (1965-present), and similarly as an interim center for the Indian Ocean (2005-2013) and Caribbean Sea (2005-present). It also operates as the US domestic TWC for the State of Hawaii (1949-present) and for American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands (2014-present). As part of its routine operations, the PTWC monitors seismic networks across the globe providing data in near-real time from more than 600 stations. Analysis of data from these stations allows PTWC scientists to detect and locate large earthquakes, assess their magnitude, evaluate their tsunamigenic potential, and send initial tsunami message products when necessary just a few minutes after the earthquake. The PTWC, however, not always had this rapid response. To evaluate PTWC's historical performance we compiled a database of tsunami bulletins issued by the PTWC from 1998 to April 2016. We scanned the available archives for the Federal Aviation Administration (FAA) and the Global Telecommunications System (GTS) communications' circuits to retrieve the first tsunami bulletin issued for 647 earthquakes. We then parsed these bulletins and extracted their parametric data to evaluate PTWC's performance based on essential statistics such as message delay time, epicenter offsets, and magnitude residuals. To this end, we cross-validated bulletins reporting magnitudes between 6.0 and 8.7 with more authoritative source parameters later reported by the National Earthquake Information Center (NEIC), and the Global Centroid Moment Tensor (GCMT) project. Analysis of these data gives an overall historical median value of 10 minutes for the message delay times, 19 km for the epicentral offsets, and 0.2 units for the magnitude residuals. A new magnitude dependent correction formula derived from the analysis of the $M_{wp}$ magnitudes reported in the PTWC bulletins provides better matching with the GCMT moment magnitudes. In the late 1990s it took the PTWC over an hour to send its first official message product. As of April 2016, however, the PTWC had decreased the median message delay time for teleseismic events to 6 minutes and 44 seconds, while keeping both the epicentral offsets and the magnitude residuals within the same historical margin of error. This 90% reduction of the message latencies helps to effectively warn coasts nearest a tsunamigenic earthquake, where the generated tsunami waves usually have the greatest impact, as well as to give coasts further away more time to prepare for their arrival.

*Keywords: PTWC performance, tsunami message delay, tsunami rapid response*

## 1. Introduction

Since 1965 the Pacific Tsunami Warning Center (PTWC) has operated as international tsunami warning center for countries with coasts in the Pacific Ocean under the Tsunami Program of UNESCO's Intergovernmental Oceanographic Commission. In 2005, in the aftermath of the 2004 Sumatra earthquake and tsunami, the PTWC also took on the interim responsibility of issuing tsunami message products for the Indian Ocean (until 2013), and the Caribbean Sea region. The PTWC has also operated as the US domestic tsunami warning center for the State of Hawaii since 1949, and for American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands since 2014. To quickly respond to an earthquake the PTWC relies primarily on the monitoring of a worldwide network of nearly 600 seismic stations that provide data in near-real time. Analysis of these data allows PTWC scientists to locate an earthquake, estimate its magnitude, evaluate its tsunami generating potential by applying conservative warning criteria based on pre-determined magnitude thresholds, and then send the appropriate initial tsunami message products within a few minutes of origin time. The PTWC, however, has not always had such a rapid response.

Anecdotal evidence suggests that a variety of operational factors, including the density of the seismic networks it monitored, the state of its IT and communications infrastructure, the methods and procedures it applied, as well as the operational mindset of its scientists at a given time shaped both the speed, and the accuracy of the tsunami message products issued by the PTWC. Validating this anecdotes, however, turns particularly challenging due to 1) the PTWC operating continuously for a span of over 50 years, and 2) the lack of consistent records of its operations during those years. Quantifying the recent historical performance of the PTWC, however, has practical operational value, as it should expose shortcomings whose correction could further improve the PTWC operations. Within this context, our study had a threefold motivation:

- To compile the most complete database of tsunami bulletins issued by PTWC to date, covering the last two decades,
- To characterize the accuracy of PTWC's preliminary earthquake parameters via cross-validation with more authoritative earthquake parameterizations,
- To review PTWC's operational performance in its role as international tsunami warning center relying on actual data and statistics.

## 2. PTWC Bulletins' Compilation and Cross-Reference

We compiled a database of 647 tsunami bulletins issued by the PTWC from 1998 to April 2016 by scanning the archives available for the Federal Aviation Administration (FAA), the Global Telecommunications System (GTS), and the NOAA Weather Wire (NWW) communications circuits, as well as some surviving email records. We then parsed these bulletin messages, extracted the preliminary earthquake parameters reported by the PTWC, and calculated essential statistics such as epicenter offsets, magnitude residuals, and message latencies by comparing the message parameters with the hypocenter parameters reported by the National Earthquake Information Center[1] (NEIC), and the moment magnitudes available from the Global Centroid Moment Tensor[2,3] (GCMT) Project's online catalog. Figure 1 illustrates the more authoritative location, hypocenter depth, and magnitude for the 647 earthquakes matching the PTWC bulletins.

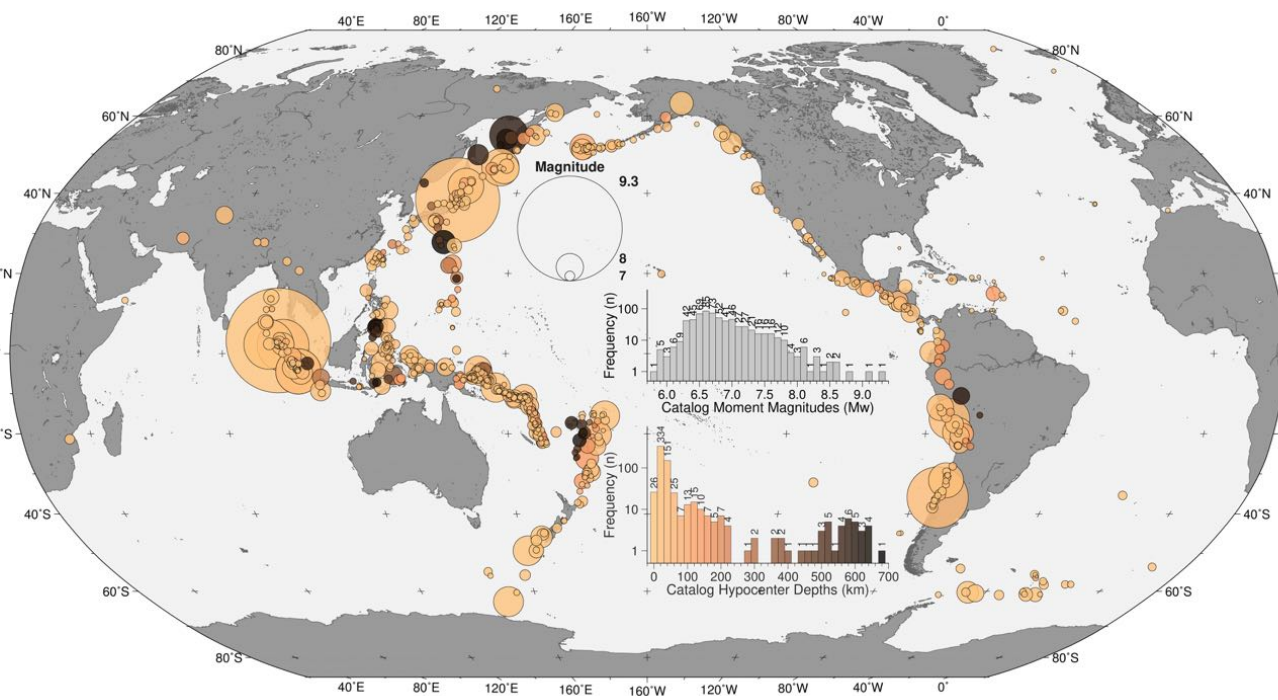



Fig. 1 – Epicenter location and depth (NEIC), and GCMT moment magnitudes ($M_w$) for the 647 earthquakes under consideration in this study. Darker colors indicate increasing hypocentral depths.

The earthquakes illustrated in Fig.1 have GCMT moment magnitudes ($M_w$) between 5.8 and 9.1, and NEIC hypocenter depths between 3 and 677 km. For the 2004 Sumatra earthquake, however, we adopted the 9.3 magnitude reported in 2007 by Stein and Okal[3]. The parametric data shown in Fig. 1 serves as a reference to 1) cross-validate the earthquake hypocenter parameters reported in the PTWC bulletins, and 2) quantify the message latencies, measured as the time in seconds between the origin date and time listed by the NEIC for a given earthquake and the time when PTWC issued the corresponding initial bulletin.

## 3. Results and Discussion

The dataset presented in Fig. 1 may not include all earthquakes for which the PTWC issued a tsunami bulletin during the last two decades. For the period before 2003 we had access only to an incomplete set of archives. Consequently, we limited the parametric data in this database to those events for which we could find a copy of the original tsunami bulletin issued by the PTWC.

### 3.1 Distribution of PTWC Epicentral Offsets

Figure 2 below illustrates the spatial distribution of epicentral offsets for the preliminary earthquake locations included in PTWC tsunami bulletins. As a rule, preliminary locations for teleseismic earthquakes might differ from the final epicenter determinations by up to 50 km. As we can observe in the lower histogram shown in Fig. 2, 73% of the PTWC preliminary earthquake locations fall within less than 30 km of the catalog locations shown in Fig.1. Likewise, only 10% of the PTWC preliminary earthquake determinations included in its tsunami bulletins have epicentral offsets exceeding 50 km. The distribution of epicentral offsets shown in Fig. 2 has a mean value of 25.7 km, a standard deviation of 22.8 km, and a median value of 19.1 km.

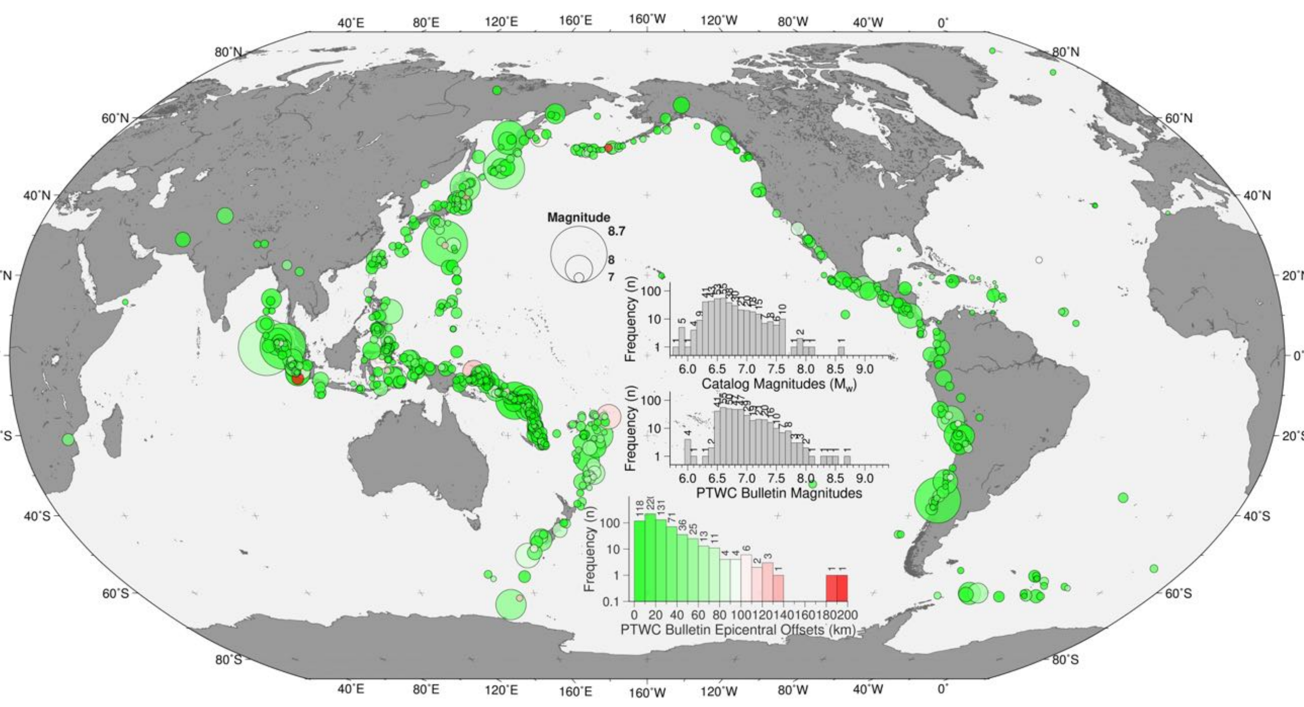



Fig. 2 – Spatial distribution of PTWC epicentral offsets calculated as the distance in km between the tsunami bulletins preliminary epicenter locations and the catalog parameters shown in Fig. 1.

## 3.2 Distribution of PTWC Magnitude Residuals

We calculated the magnitude residuals reported herein as the difference between the earthquake magnitudes reported in the PTWC bulletins and the corresponding GCMT moment magnitudes ($M_w$). Figure 3 below illustrates the worldwide spatial distribution of the magnitude residuals thus calculated. The sizes of the circles indicate the magnitudes reported in the PTWC bulletins. The color of each circle represents the magnitude residual, with blue indicating an underestimation, and red an overestimation. The absolute values of these magnitude residuals have a mean of 0.19, a standard deviation of 0.16, and a median value of 0.2 magnitude units. These general statistics, however, fall short of revealing some significant trends in the data. Closer inspection of Fig. 3 suggests, for instance, that tsunami bulletins issued by the PTWC for 48 earthquakes located along the Andean South America source region underestimated the earthquake magnitudes. Looking closer, we found that 22 bulletins (46%), issued for earthquakes with moment magnitudes between 6.6 and 8.8, underestimated their magnitudes by as much as 0.8 magnitude units. In contrast, for this same region, the PTWC bulletins overestimated the magnitudes of only 15 earthquakes (31%) with smaller GCMT magnitudes between 6.5 and 7.2.

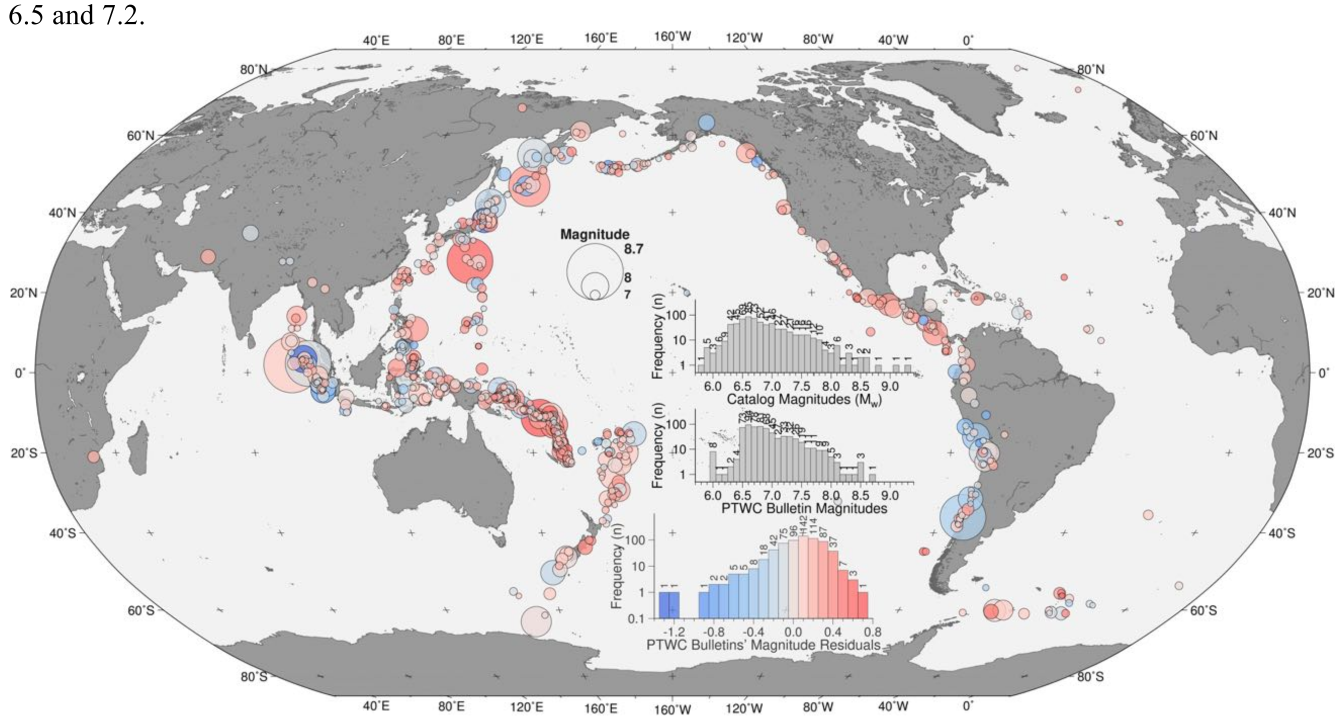



Fig. 3 – Spatial distribution of PTWC magnitude residuals calculated by subtracting the catalog moment magnitudes ($M_w$) shown in Fig. 1 from the magnitudes reported in the PTWC bulletins.

We further illustrate the pattern of magnitude residuals by isolating their negative and positive values in Figs. 4 and 5, respectively. In both Figs. 4 and 5 the sizes of the circles now represent the catalog locations and magnitudes, while darker hues of either blue or red indicate larger PTWC bulletin magnitude underestimations or overestimations, respectively. Figure 4 makes it apparent that, historically, the PTWC has tended to underestimate the magnitude of the largest earthquakes. The 160 earthquakes plotted in Fig. 4 represent just 24% of the 647 bulletins in our dataset, yet this 24% contains 39 (68%) of the 57 events with a moment magnitude equal to or larger than 7.6. In the case of magnitude overestimations, however, inspection of Fig. 5 suggests that for earthquakes along Central America, the West Coast of the United States, Vanuatu and the Solomon Islands, as well as along the Tonga trench in the Southern Pacific, the magnitudes reported in the PTWC bulletins tend to overestimate their magnitudes. Figure 5 also suggests that, as a rule, the PTWC overestimates the magnitude of mostly smaller earthquakes. The 391 earthquakes plotted in Fig. 5 represent 60% of the 647 bulletins, and yet this 60% contains 379 (64%) of the 590 events with a moment magnitude smaller than 7.6. Notable overestimations involving large earthquakes include the $M_w$=8.6 April 2012 Sumatra earthquake, and a cluster of medium size earthquakes along the Tonga trench seen clearly overestimated in Fig. 5. Overestimations of the magnitude of large and moderate earthquakes with moment magnitudes $M_w$ between 7.6 and 8.6 accounts for only 1.8% (12) of the events. Among these twelve events, however, only three have magnitude residuals larger than 0.3 magnitude units.

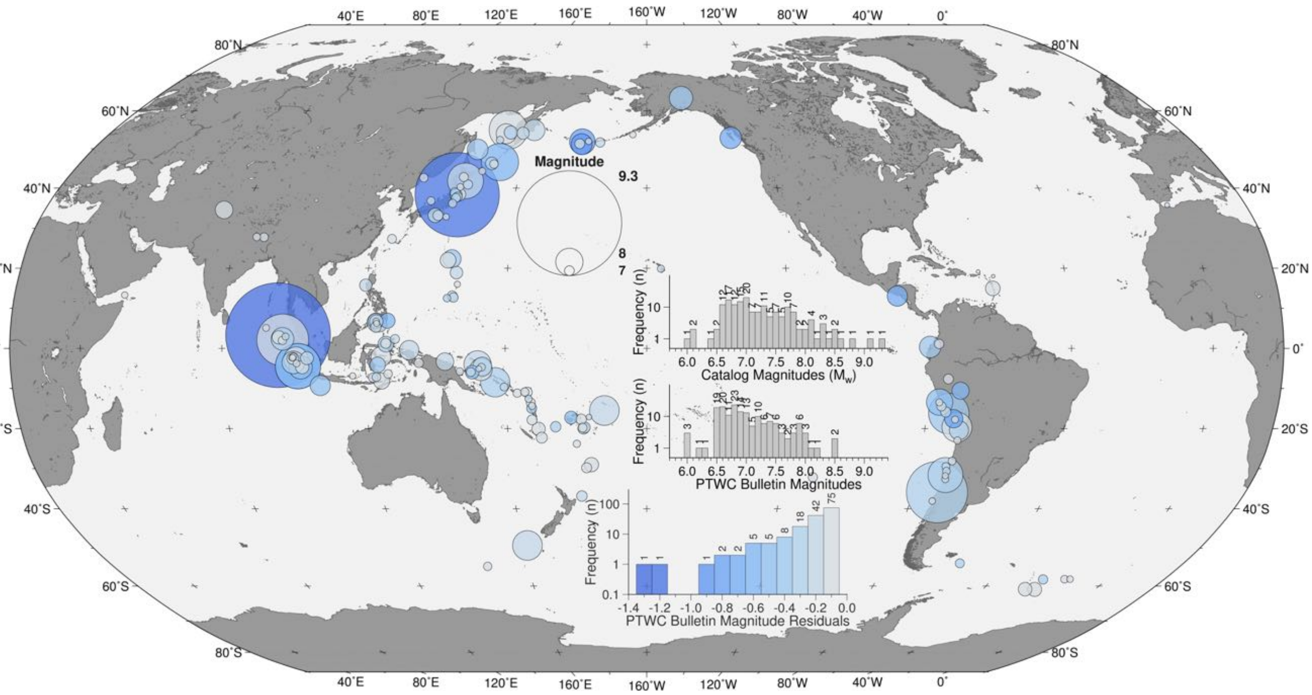



Fig. 4 – Spatial distribution of PTWC negative magnitude residuals (underestimations). Notice the absence of the largest magnitudes in the middle (PTWC) histogram when compared to the one on top (catalog).

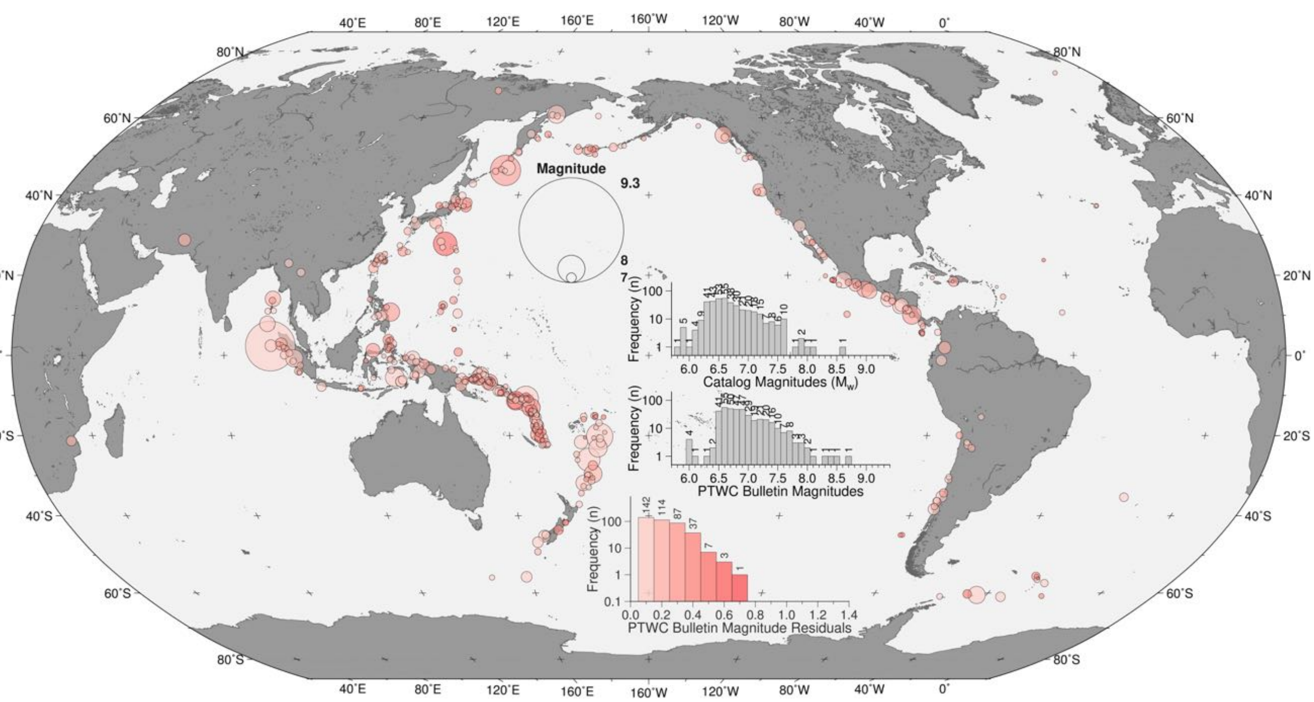



Fig. 5 – Spatial distribution of PTWC positive magnitude residuals (overestimations). Notice the scarcity of smaller magnitudes in the middle histogram (PTWC) when compared to the one on top (catalog).

Figure 6 illustrates the relationship between the PTWC's bulletin magnitudes ($M_{wp}$) and the GCMT moment magnitudes ($M_w$). The black regression line in Fig. 6a intersects the Y=X line around $M_w$=7.45, where the data trend clearly shifts from mostly overestimations to underestimations. This seems to agree well with our previous discussion of Figs. 4 and 5. We clearly see how from around 7.5 onwards the PTWC bulletins tend mostly to underestimate the magnitudes.

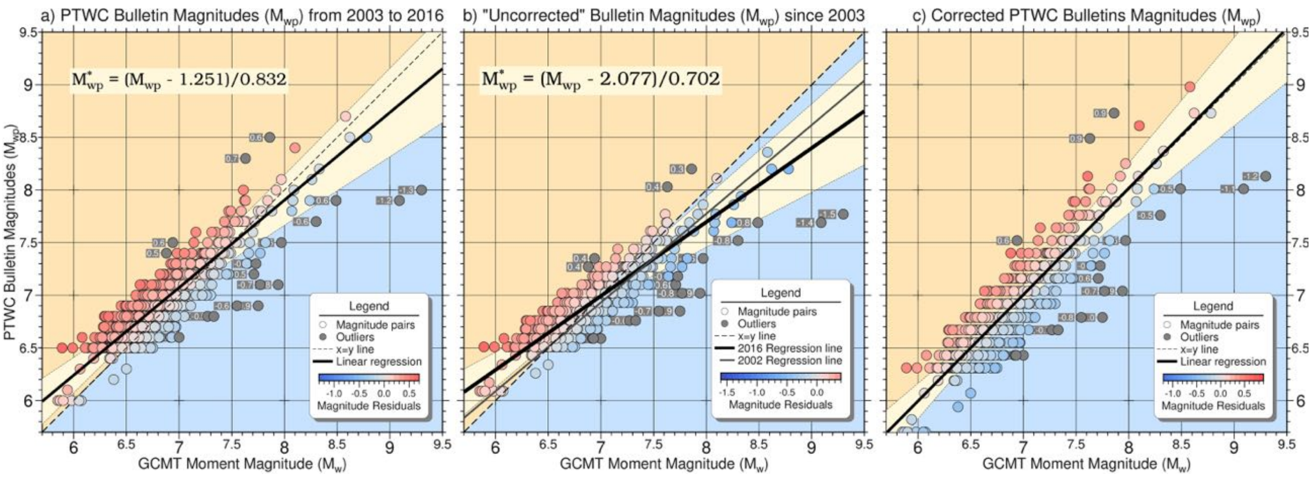



Fig. 6 – Mwp Magnitudes vs. GCMT Moment Magnitudes (Mw). a) Mwp as reported in PTWC Bulletins, b) After removing 2002 Correction, c) After applying the new Correction Formula shown in b).

Both US TWCs automatically apply a magnitude dependent $M_{wp}$ correction proposed by Whitmore et al. in 2002[10]. Figure 6a clearly shows that automatic application of this formula at the PTWC does not result in the expected alignment of the corrected values around the Y=X line. This indicates the presence of a bias in the operational data not captured by the 2002 regression formula[10], plotted as a gray line in Fig. 6b. Furthermore, application of this automatic correction has a twofold effect: 1) insufficient correction of the magnitude underestimations for the largest earthquakes (Figs. 4 and 6a), and 2) contributions to the overestimation of the magnitude of over 52% of moderate earthquakes (Figs. 5 and 6a). This also confirms the known tendency of the $M_{wp}$ method[8] to incur increasingly larger magnitude underestimations the greater the earthquake, as presented by Hara and Nishimura, 2011[9], and seen also in Figs. 3 and 4. To further illustrate why the 2002 magnitude correction formula[10] does not satisfactorily resolve these issues we subtracted the 2002 correction coefficients from the bulletin magnitudes and plotted the "uncorrected" values in Fig. 6b. The thick, solid black line in Fig. 6b shows the regression line used to derive the new magnitude dependent correction formula shown on top. Figure 6c illustrates the effect of applying this new correction formula to the "uncorrected" $M_{wp}$ magnitudes shown in Fig. 6b. The application of the new formula results in the expected centering of the magnitudes around the Y=X line. Despite the magnitude correction formula shown in Fig. 6b providing better overall $M_{wp}$ magnitude estimates, however, we do not consider it a throw in replacement for the 2002 correction formula. Our analysis so far indicates that these issues require careful consideration of several factors not captured by either formulae, such as the possible regional variations of the $M_{wp}$ values seen in Figs. 3, 4, 5, and still clearly visible in Fig. 7, even after correcting the $M_{wp}$ values via the application of the new formula.

Despite underestimations sometimes exceeding a whole magnitude unit for the largest earthquakes, however, the PTWC has never failed to issue the appropriate tsunami bulletin when the situation required it. This results from having conservative warning criteria designed to take into account magnitude underestimations at the heart of the center's standard operational procedures[5] (SOP). In the Pacific warning system, these SOPs called for the issuance of a regional warning for all areas within 1000 km of the epicenter for any earthquake with a magnitude between 7.6 and 7.8 inclusive, and the issuance of an expanding tsunami warning and watch[5], each covering areas within 3 and 6 hours to initial impact[5], respectively, for any earthquake with a magnitude equal to or larger than 7.9.

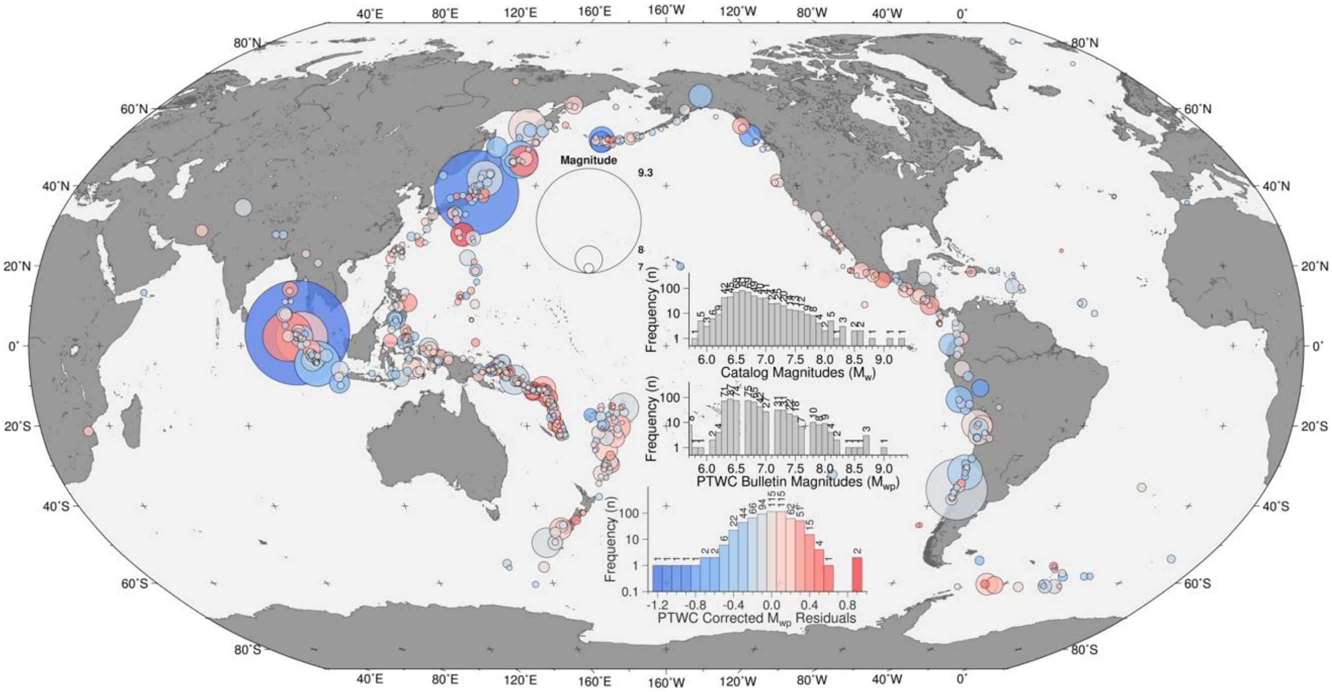



Fig. 7 – Spatial distribution of magnitude residuals after applying correction coefficients calculated from a new magnitude dependent formula derived from the $M_{wp}$ magnitudes reported in the PTWC bulletins.

## 3.3 Review of PTWC's Performance for the Four Largest Earthquakes in the Last Fifty Years

To illustrate how PTWC's tsunami warning criteria work, we will briefly discuss how they applied or would apply to the four largest earthquakes in the world during the last fifty years, namely, the 2004 $M_w$=9.3 Sumatra, the 2010 $M_w$=8.8 Chile, the 2011 $M_w$=9.1 Japan, and the 2012 $M_w$=8.6 Sumatra earthquakes.

For the 2004 Sumatra ($M_w$=9.3) earthquake the PTWC had initially estimated its moment magnitude as 8.0 and sent an observatory message to that effect 11 minutes and 10 seconds after origin time. The PTWC then issued a tsunami information bulletin (TIB) containing the same parameters for the Pacific 15 minutes after origin time. Sixty-five minutes after origin PTWC issued another TIB for the Pacific that updated the magnitude to 8.5. The scientists on duty understood the potential danger presented by the event, and tried to reach some emergency manager contacts in the Indian Ocean basin. In addition, by relaying messages through the U.S. State Department, some east African countries received useful warnings. Had this earthquake occurred in the Pacific, the initial 8.0 magnitude estimation would have sufficed for the PTWC to issue the aforementioned expanding warning and watch[5] within 11 to 15 minutes from origin time. This initial tsunami bulletin would have put Indonesia, Malaysia, Myanmar, and Sri Lanka into a warning, and most of the rest of the Indian Ocean into a watch. Had the Indian Ocean had a tsunami warning system with the same procedures and capabilities as in the Pacific, then designated national agencies would have received notification, which in turn would have allowed them to trigger the evacuation of coastal populations to safe areas where time permitted. Monitoring of sea level gauges would have verified the size and extend of the tsunami, and this would have in turn extended the warning to India, the Maldives, the east coast of Africa, and all other affected coasts in the Indian Ocean. This sequence of events would have happened in spite of having an initial underestimation of the earthquake's magnitude by 1.3 magnitude units. Tragically, the Indian Ocean had no such system in place, and this ultimately led to the loss of so many lives.

For the Chile 2010 earthquake ($M_w$=8.8) the PTWC initially estimated its magnitude as 8.5, and 11 minutes and 44 seconds after origin time issued a tsunami bulletin that placed Chile and Peru in a warning, and Ecuador in a tsunami watch. In addition, the PTWC scientists on duty made phone calls to the countries nearest to the epicenter to confirm receipt of the tsunami warning, and exchange information regarding the sea level data. After receiving both, reports, and data confirming the presence of a tsunami wave propagating across the ocean, the PTWC placed the whole Pacific Basin under a tsunami warning. The PTWC continued monitoring the network of water level gauges available in the Pacific until it cancelled the warning the next day, over 27 hours after origin time. For this large earthquake the PTWC underestimated its magnitude by only 0.3 magnitude units. Even much larger underestimations of the initial magnitude, however, would not have prevented the PTWC from issuing the same series of tsunami bulletins.

For the 2011 ($M_w$=9.1) Japan earthquake, the PTWC followed the established protocol and initially used the 7.9 magnitude computed and disseminated by the Japan Meteorological Agency (JMA). This resulted in an expanding tsunami warning and watch issued by PTWC 8 minutes and 37 seconds from origin time that placed most of the northwest Pacific in either a warning or a watch. PTWC's second tsunami bulletin issued 57 minutes after origin time updated the magnitude to 8.8. The PTWC continued to monitor the tsunami waves as they propagated across the Pacific until it cancelled the warning the next day, over 24 hours after origin time. Notice that although initially underestimated by 1.2 magnitude units, the PTWC tsunami bulletin based on JMA's magnitude still put all immediately threatened areas in a warning in less than 9 minutes, and it extended the warning to the rest of the Pacific well in advance of any tsunami impacts outside of Japan.

For the 2012, Sumatra earthquake ($M_w$=8.6), the PTWC estimated its magnitude as 8.7 and issued an Indian-Ocean-wide tsunami watch 8 minutes and 36 seconds after origin time. This earthquake ranks as the largest strike-slip earthquake ever recorded. In addition to $M_{wp}$, by 2012 the PTWC had already added two more analysis tools to its arsenal: the *W*-phase magnitude estimation method after Kanamori and Rivera[7], and the Real-time Inundation Forecast of Tsunamis[7] (RIFT) modeling tool. The *W*-phase centroid moment tensor (CMT) solution for this event indicated a mixed thrust-strike slip fault mechanism 23 minutes after origin time. The tsunami waves forecast using these new fault parameters showed that this earthquake could only generate a tsunami much smaller than originally predicted assuming a pure thrust mechanism. Twenty minutes later the PTWC scientists on duty received a revised *W*-phase CMT solution using depth searching (since incorporated into the PTWC *W*-phase algorithm) from the USGS. That solution showed that the earthquake had a pure strike-slip fault mechanism, for which modeling confirmed that the tsunami presented little danger. A magnitude 8.3 aftershock 2 hours and 5 minutes after the main shock, which itself posed a potential tsunami threat, further complicated the situation by forcing the tsunami watch to last longer. Meanwhile, the scientists on duty waited until having access to the first sea level readings from the region. After confirming the presence of only small tsunami waves that posed no hazard, the PTWC cancelled its tsunami watch for the Indian Ocean 4 hours and 10 minutes after origin time.

This brief review of how the PTWC's Pacific warning criteria have, or could have applied to four of the largest seismic events in the last 20 years highlights the fact that even underestimations of earthquake magnitudes by as much as 1.3 magnitude units did not prevent, or would not have prevented the PTWC from issuing the required tsunami warning, even for the Indian Ocean during the 2004 Sumatra earthquake. The regional watch issued for the Indian Ocean basin in the aftermath of the 2012 $M_w$=8.6 Sumatra earthquake eight years later, for instance, relied on extrapolation to this region of the same PTWC warning criteria in effect decades earlier for the Pacific basin. Unlike the 2004 Sumatra earthquake, however, the 2012 earthquake off the west coast of northern Sumatra occurred at a time when the Indian Ocean region had established a tsunami warning system that facilitated the reception and dissemination of the tsunami watch issued by the PTWC. This highlights the very often-ignored fact that the PTWC has applied, and still continues to apply, very conservative tsunami warning criteria based on pre-established magnitude thresholds as a way to cope with the limitations of the analysis tools at its disposal.

The *W*-phase method[6] represents a major contribution to PTWC's performance in terms of accuracy and completeness, as it provides very accurate moment magnitude and fault mechanism determinations, both essential pieces of data for constraining a tsunami forecast. Notwithstanding, the $M_{wp}$ method, although less accurate or complete, still has the advantages of speed and simplicity. While getting the results of a *W*-phase CMT inversion still takes 20~30 minutes, the $M_{wp}$ method provides a faster magnitude estimate within 10 minutes or less from origin time. In the case of very large earthquakes, such as the four discussed above, an $M_{wp}$ magnitude estimation of 7.9 or larger sufficed, and still suffices, to warrant an initial tsunami warning. Moreover, advances in tsunami modeling at the PTWC have led to the adoption of even more conservative tsunami warning criteria. These new criteria for the Pacific basin, for instance, now require the issuance of a tsunami threat message for any earthquakes in the Pacific with an estimated 7.1 or larger magnitude.

## 3.4 Distribution of PTWC Tsunami Bulletin Latencies

Figure 8 illustrates the worldwide distribution of the PTWC bulletin latencies for the 647 earthquakes under consideration. As we can observe, most symbols appear in warmer colors, indicating message delays of no more than 15 minutes from origin time. Most of the message latencies over 15 minutes from origin time correspond to earthquakes that occurred prior to 2003, before PTWC made the $M_{wp}$ magnitude estimation method[8] part of its routine operations. The timeline in Fig. 9 shows the reduction of message latencies along the years. Blue indicates magnitude underestimations, while red indicates magnitude overestimations using the same color scale as in Figs. 3, 4, 5, 6, and 7. The table at the bottom of Fig. 9 shows a reduction of the message delay times from over an hour in 1998 to around 6 minutes both in 2015 and the first quarter of 2016. Figure 9 also illustrates that prior to 2002 most of the PTWC bulletins reported underestimated magnitudes. This appears related to the use, at the time, of the $M_S$ magnitude, a method known to saturate for earthquakes with moment magnitudes around $M_w$=7.8 or larger. The $M_{wp}$ method has indeed performed much better (and much faster), but its tendency to underestimate the size of the largest earthquakes remains an issue. Notwithstanding, Fig. 9 corroborates that the introduction of the $M_{wp}$ method represented an undeniable improvement to the PTWC daily operations.

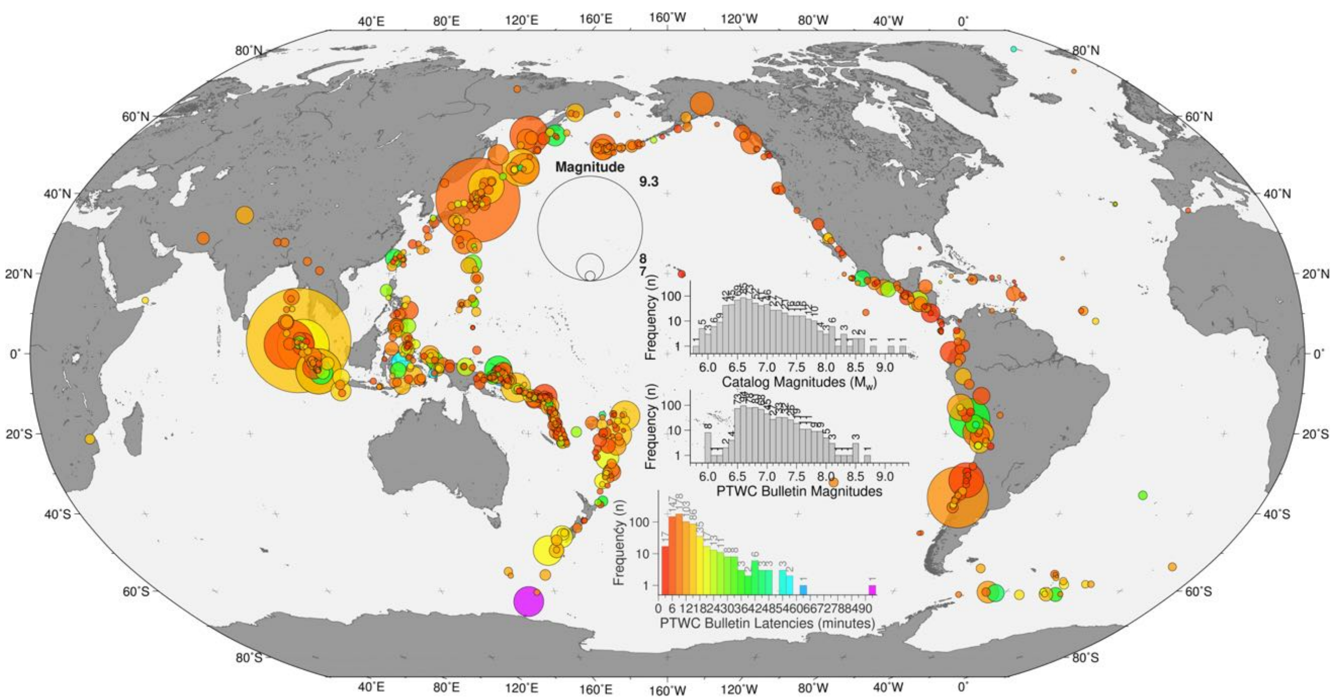
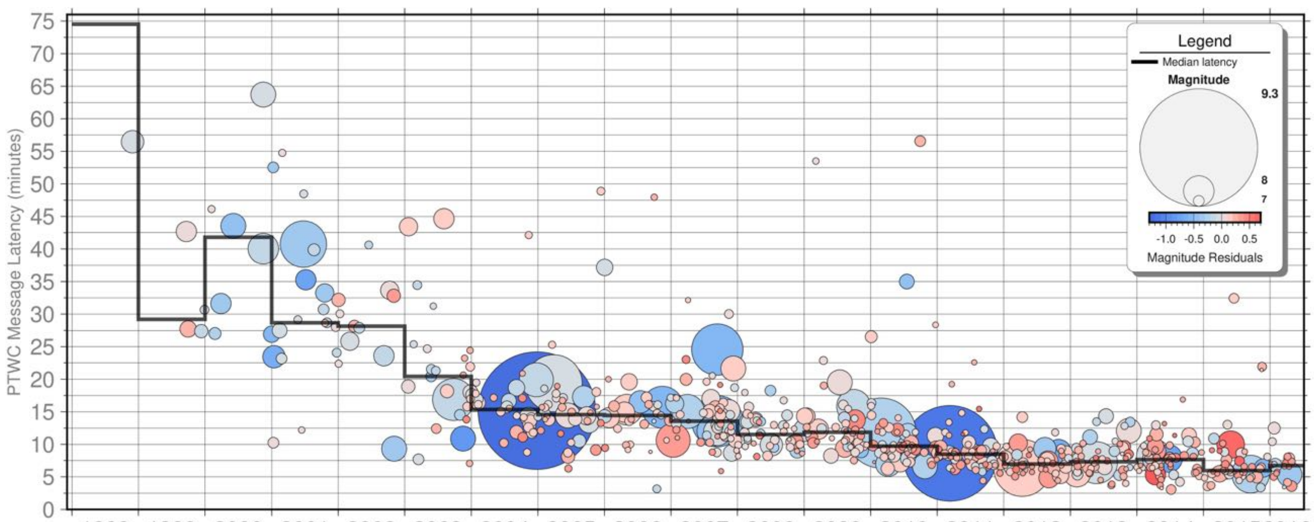



Fig. 8 – Spatial distribution of the PTWC tsunami bulletin latencies from the origin times listed in the catalog for the 647 earthquakes shown in Fig. 1.

At present, the PTWC applies other magnitude estimation methods that provide more accurate, though slower, results. These include the mantle magnitude method, and the *W*-phase method. This last method provides the PTWC with a very reliable earthquake magnitude, as well as the fault mechanism. These pieces of information serve as input for running tsunami simulations, and become essential to provide a reasonably constrained tsunami forecast for threatened coasts as fast as possible. As of May 2016 the initial tsunami bulletin issued by PTWC for any seismic event, however, still relies on evaluating the $M_{wp}$ magnitude estimate based on the application of the same tried and true magnitude threshold criteria[5]. A more accurate tsunami forecast and evaluation follows this initial bulletin once the *W*-phase CMT inversion results become available within 20 to 30 minutes from origin time. Their availability then makes it possible to run more accurate tsunami simulations based on more accurate magnitude estimations, and a description of the geometry of the causative fault.




| | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | 2 | 4 | 6 | 19 | 11 | 25 | 30 | 38 | 31 | 56 | 42 | 44 | 57 | 59 | 48 | 52 | 58 | 46 | 18 |
| $x_{min}$ | 56.47 | 27.38 | 27.02 | 10.25 | 9.32 | 7.07 | 8.78 | 6.28 | 3.17 | 5.88 | 8.13 | 7.53 | 6.28 | 4.42 | 4.45 | 3.73 | 3.07 | 3.37 | 3.43 |
| $x_{max}$ | 92.57 | 42.68 | 63.72 | 54.75 | 40.62 | 44.65 | 42.13 | 48.88 | 47.95 | 32.15 | 18.25 | 53.5 | 56.57 | 22.58 | 14.18 | 14.33 | 16.88 | 32.43 | 12.48 |
| $\bar{x}$ | 74:31 | 32:06 | 42:00 | 31:27 | 27:51 | 21:08 | 15:59 | 15:23 | 15:37 | 14:36 | 11:52 | 13:07 | 11:47 | 8:57 | 7:22 | 7:45 | 7:44 | 7:46 | 6:40 |
| $x_d$ | **74:31** | **29:11** | **41:47** | **28:40** | **28:08** | **20:25** | **15:20** | **14:33** | **14:25** | **13:33** | **11:30** | **11:51** | **9:43** | **8:28** | **6:58** | **7:19** | **7:39** | **5:57** | **6:44** |
| $\sigma$ | 25:31 | 7:11 | 12:51 | 11:51 | 8:00 | 9:23 | 5:44 | 6:37 | 8:04 | 4:54 | 2:34 | 6:56 | 7:54 | 3:08 | 1:48 | 2:28 | 2:32 | 5:14 | 2:14 |

Fig. 9 – Timeline of PTWC tsunami bulletin latencies in minutes and the corresponding yearly statistics calculated from data for the 647 earthquakes under consideration.

Other factors driving the PTWC gains in speed when issuing the initial tsunami bulletins include 1) The gradual increase in the number of stations it monitors in near-real time to over 600, 2) Improvements of the PTWC internet and computer hardware infrastructure, 3) An operational mind shift among PTWC scientists based upon analyses of past performance, regarding when to consider the preliminary earthquake parameters good-enough to issue a tsunami bulletin in the shortest possible time. After 2008, for instance, the PTWC doubled its I/O bandwidth, which in turn allowed access to more seismic data. The combined influence of these factors along time gradually resulted in the apparent gains in message speed seen in Figs. 8 and 9.

## 4. Acknowledgements

We acknowledge the contributions made by numerous present and past members of the Pacific Tsunami Warning Center's operational staff, who along the years implemented improvements, responded to and quickly analyzed these earthquakes, and sent the appropriate message products. We also acknowledge the Generic Mapping Tools (GMT)[11] team for providing the versatile software package used to create all the maps and graphs included in this paper.

## 5. Conclusions

We compiled a database of 647 initial tsunami bulletins issued by the Pacific Tsunami Warning Center (PTWC) between 1998 and April 2016. We validated the earthquake parameters reported in the PTWC bulletins with more authoritative source parameterizations provided in the earthquake catalogs of the NEIC and the GCMT project. Analysis of the spatial distribution of the epicentral location offsets, magnitude residuals, and message latencies, as well as some of their essential statistics allow us to draw the following conclusions:

1. Since 1998 the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii has gradually reduced the time needed to issue a tsunami bulletin for the regions in its area of responsibility (AOR) from as much as 1 hour and 14 minutes in 1998 to a median of 6 minutes in 2015, and 6 minutes and 44 seconds during the first quarter of 2016. This more than 90% reduction of the message latencies helps to effectively warn coasts nearest a tsunamigenic earthquake, where the generated tsunami waves usually have the greatest impact, as well as to give coasts further away more time to prepare for their arrival.

2. The PTWC has never failed to issue a tsunami warning despite underestimating the magnitude of some large earthquakes by as much as 1.2 magnitude units. Even underestimations of earthquake magnitudes by as much as 1.3 magnitude units should not have prevented the PTWC from issuing the required tsunami warning for the 2004 Sumatra earthquake. Had the Indian Ocean established a tsunami warning system that facilitated the reception and dissemination of a tsunami warning or watch before the 2004 Sumatra earthquake, then extrapolation of PTWC's conservative warning criteria for the Pacific to the Indian Ocean would have resulted in the issuance of an expanding tsunami warning and watch for the Indian Ocean within 11 to 15 minutes from origin time, regardless of the initially low 8.0 magnitude estimate. Tragically, the Indian Ocean at the time had no tsunami warning system in place, and this ultimately led to the loss of over 200,000 lives.

3. Despite its tendency to underestimate the magnitude of the largest earthquakes, the $M_{wp}$ method still has an unsurpassed advantage in terms of speed and simplicity, which make it an essential seismic analysis tool in the context of tsunami warning operations at the US TWCs. The PTWC still relies heavily on $M_{wp}$ magnitude estimates to quickly evaluate the tsunami generating potential of an earthquake based on conservative, pre-established magnitude thresholds, and send its initial tsunami bulletin just a few minutes after origin time.

4. Implementation of the *W*-phase CMT method at the PTWC allows its scientists to obtain a very accurate magnitude and fault mechanism within 20~30 minutes from origin time. The completeness of the results, and the speed of the method when compared to more traditional CMT inversions that take hours or days to provide a result constitute a must needed and welcome improvement. Within the context of tsunami warning operations, however, the *W*-phase method still cannot compete with the $M_{wp}$ method in terms of speed, an indispensable feature for near-field tsunami warning operations. In the future, the addition of GPS data to the *W*-phase CMT inversion analysis might provide much faster results depending on the availability and quality of the GPS data.

5. The addition of tsunami modeling tools such as RIFT allows the PTWC to provide a tsunami wave forecast less than one hour after origin time. In this regard, the results from *W*-phase CMT inversion analysis turn paramount to provide a well-constrained tsunami wave forecast.

6. Analysis of 647 bulletins issued between 1998 and April, 2016 reveals that the PTWC epicentral offsets have a mean value of 25.7 km, a standard deviation of 22.8 km, and a median value of 19.1 km when compared to later catalog values.

7. The distribution of the PTWC magnitude residuals, despite having a historical median value of 0.2 magnitude units, confirmed the $M_{\mathrm{wp}}$ method tendency to incur increasingly larger underestimations the greater the earthquakes. The application of a magnitude dependent $M_{\mathrm{wp}}$ linear correction at the US TWCs does not satisfactorily resolve this issue. Moreover, the automatic application of this correction formula contributes to the overestimation of the magnitude of over 52% of moderate earthquakes. This highlights the need of either a new set of more discrete correction coefficients, or a new approach that specifically targets the $M_{\mathrm{wp}}$ underestimations.

8. We derived a magnitude dependent correction formula for $M_{wp}$ from the magnitudes actually reported in the PTWC bulletins as $M_{wp}^{*} = \left(M_{wp} - 2.077\right)/0.702$, where $M_{wp}^{*}$ denotes the corrected value. Application of this formula results in better matching with the GCMT moment magnitudes. The results of this study, however, highlight the need of further research on the shortcomings of the $M_{wp}$ method, and a more discrete treatment of their manifestation under actual operational conditions at the TWCs. More accurate magnitude estimations within ten minutes or less stands out as a critical operational need at the TWCs. The $M_{wp}$ method will continue to fill this operational need at the TWCs for as long as more robust methods such as the $W$-phase CMT cannot provide results within ten minutes or less from origin time. For effective tsunami warning purposes, particularly in the near field, the $M_{wp}$ method still emerges as the only alternative that complies with this time requirement, particularly when dealing with very large earthquakes.

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