ASM Sc. J., 17, 2022

https://doi.org/10.32802/asmscj.2022.1244

Parameterising Maximum Tsunami Amplitude with Earthquake Moment Magnitude for Trans-Oceanic Tsunamis

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This study examines a relationship between earthquake size and maximum tsunami amplitude using large earthquakes of $M_w > 7.5$ that led to trans-Pacific and Indonesian tsunamis. The data were sampled from tide gauges or DART surface buoys for seven Pacific tsunamis (the 2006 Kuril, Russia, 2009 New Zealand, 2011 Tohoku-oki, Japan, 2013 Solomon Island, 2010 Maule, 2014 Iquique, and 2015 Illapel) and six Indonesian tsunamis (the 2004 Indian Ocean, 2006 Pangandaran, 2007 Bengkulu, 2010 Mentawai, 2010 Simeulue, and 2012 Northern Sumatera). We found that the size better scales with M_w instead of other measures when relating to the mean maximum amplitude η. The main finding for the trans-Pacific cases was that the M_w scale is a logarithmic function of the mean amplitude, M_w = 0.77 log η + 8.84, consistent with previous work. For the Indonesian events, it was found that M_w = 1.92 log η + 10.36, reflecting different tsunami dynamics in the Pacific and Indian Oceans. The apparent difference is thus attributable to differences in both the topographical complexity and tsunami directivity in the two oceans. This is vital as the results provide insight into the nature of tsunami propagation approaching shorelines hence useful for improved tsunami early warning.

Keywords: earthquake size; maximum tsunami amplitude; trans-oceanic tsunamis

I. INTRODUCTION

It has been long recorded that destructive tsunami waves strike most regions around the globe, particularly in countries along the perimeter of the Pacific Ocean (Goff *et. al.*, 2011; Rabinovich *et. al.*, 2013; Rabinovich *et. al.*, 2014; Zaytsev *et. al.*, 2016; Heidarzadeh *et. al.*, 2018; Goff *et al.*, 2020). Other countries positioned in the Indian Ocean (Satake *et. al.*, 2007; Rabinovich *et. al.*, 2011; Suppasri *et. al.*, 2015; Rubin *et al.*, 2017), including Indonesia are also much affected by the catastrophe. The waves are generated by varying sources, for example, volcanic activities (Giachetti *et. al.*, 2012; Day, 2015; Heidarzadeh *et al.*, 2020a), submarine landslides (Carvajal *et. al.*, 2019; Mikami *et. al.*, 2019; Nakata *et. al.*, 2020; Tappin, 2021) or earthquakes of tectonic origin (Satake *et. al.*, 2012; Satake, 2014; Fisher & Harris, 2016; Sozdinler *et. al.*, 2019; Pranantyo *et al.*, 2021). A recent seismic study (Widiyantoro *et al.*, 2020) has revealed convincing evidence of seismic gaps, which potentially trigger megathrust subduction earthquakes and possibly generate devastating tsunamis, hitting most areas in the southern coastal lines of Java Island, Indonesia.

However, none of the above previous studies has examined a relationship between earthquake magnitude and maximum tsunami amplitude, or here measured as the corresponding mean maximum amplitude. Previous work (Hanks & Kanamori, 1979; Kanamori, 1983; Delouis *et. al.*, 2009; Satriano *et. al.*, 2011; Okal, 2019) ended up with only earthquake size determination. On the other hand, recent investigations into the nature of propagating tsunami waves associated with travel time delay (e.g. Prastowo *et al.*, 2018) and tsunami energy decay (e.g. Prastowo & Cholifah, 2019) have considered tsunami parameters but with no earthquake source parameters calculated in the investigations. Hence, this study is of significance as earthquakes and tsunamis are

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correlated to each other through two dynamic parameters associated with each phenomenon.

Concern about direct measurements of a magnitude scale dates back to the work of Bäth (1981), where magnitude was thought to provide direct valuable information on the seismic energy release hence seismic moment recorded. Since then, research focusing on the relationship between the seismic moment and various scales of earthquake magnitude has developed. A mathematical relation between earthquake moment magnitude M_w and seismic moment M_o is a well-known equivalence $M_w \propto \log M_o$ (Hanks & Kanamori, 1979; Kanamori, 1983). With the scaling law for the source size and in relation to the sea surface elevation when a tsunami is generated in the ocean by an earthquake, (Okal *et al.*, 2014) found a linear relationship between the observed surface elevation η and M_o for large trans-oceanic tsunamis.

Taking the essential results of previous work (Hanks & Kanamori, 1979; Kanamori, 1983; Okal *et al.*, 2014) and using far-field tsunami data, (Heidarzadeh *et al.*, 2018) reported that M_w was a logarithmic function of η. It follows that it is possible to predict tsunami height or termed here as tsunami amplitude during its propagation from a given source size. Thus, this study is aimed at parameterising mean maximum amplitude η with the M_w scale for most distant observations of the trans-Pacific events except for Indonesian tsunamis, where the data from far-field monitoring are available with only a limited number. Despite the different data availability, this study is of fundamental interest in the sense that tracking tsunami stages of its development in the open ocean from remote areas on land is particularly important for enhanced tsunami early warning.

II. METHODS

The secondary data used in this study were acquired from field measurements of sea surface elevation recorded by Deep-ocean Assessment Reports of Tsunamis (DART) surface buoys and pressure gauges, routinely monitoring instruments for tsunami passage operated by the National Oceanic and Atmospheric Administration (NOAA), the US government (http://ngdc.noaa.gov).

The data have incorporated the moment magnitudes M_w of large earthquakes, the observed mean of maximum tsunami amplitudes η of selected trans-Pacific tsunamis, and the associated epicentral distances d measured from the source point. The η definition is similar to the far-field, deep-ocean tsunami amplitudes reported by Heidarzadeh *et al.* (2018). In the present study, the term 'maximum amplitude' refers to a vertical distance measured from sea surface as reference to the highest peak. Cases considered here are seven tsunamis across the Pacific Ocean (the 2006 Kuril, Russia, 2009 New Zealand, 2010 Maule, Chile, 2011 Tohoku, Japan, 2013 Solomon, 2014 Iquique, Chile, and 2015 Illapel, Chile events) and six Indonesian tsunamis (the 2004 Indian Ocean – well known as the 2004 Aceh, 2006 Pangandaran, 2007 Bengkulu, 2010 Simeulue Island, 2010 Mentawai, and 2012 Northern Sumatera events). All tsunami occurrences examined in the current study are generated by subduction earthquakes of $M_w > 7.5$. The η used in this study were averaged over space and time of all the DARTs and gauges positions and obtained from mostly far-field stations located further than 3,200 km from the epicentre in the Pacific events, following Prastowo and Cholifah (2019). For Indonesian events, the η data were obtained from near- and far-field tsunami observations.

The followings are theories used in connecting the M_w scale to the η data. Firstly, a simple relation relating M_w to M_o was given by

$$M_w = 0.667 \times (\log M_o - 16.1) \tag{1}$$

applied for both shallow and deep earthquakes (Hanks & Kanamori, 1979; Kanamori, 1983). In cases where monitoring stations located in the perimeter of 10° or approximately 1,100 km away from the epicentre were used to collect tsunami waveforms, the corresponding data were classified into near-field tsunami observations. However, as previously stated, all the datasets in this study were collected from mostly distant tsunamis, independent of the source depth and mechanisms.

Another simple equation that relates the seismic moment M_o to the mean maximum amplitude η of a tsunami was suggested by Okal *et al.* (2014) as follows,

$$\log \eta = \log M_o - f(\Delta, \Phi) \tag{2}$$

where $f(\Delta, \Phi)$ is a function depending upon the relative distance Δ from the epicentre and the azimuth position of a monitoring station from the epicentre Φ. Here, we are not primarily concerned with f despite its crucial role in the η measurements. Rather, we note that $\eta \propto M_o$ bringing an idea into a derivation of a simple mathematical relation between M_w and η (Heidarzadeh *et al.*, 2018) as follows,

$$M_w = 0.665 \log \eta + 8.245 \quad (3)$$

where M_w is a logarithmic function of η. Thus, Equation (3) is here re-examined using empirical data of tsunami monitoring from lists of seven trans-Pacific tsunamis (see Table 1) and six Indonesian events (see Table 2).

III. RESULTS AND DISCUSSIONS

A. The Epicentre Distributions for Trans-Pacific and Indonesian Tsunamis

Figures 1 and 2 exhibit the epicentre distributions for the trans-oceanic tsunamis (the Pacific and Indonesian events) considered in the present study. Note that the epicentres are given in different colours but having the same star symbol. The figures are made available using ArcGIS online basemaps (https://arcgis.com/home/group.html). All cases depicted are considered recent tsunamis that occurred within the last twenty years. Four of the seven trans-Pacific included here (three Chilean and Japanese events) were those reported earlier by Heidarzadeh *et al.* (2018). All the Indonesian cases were located near the Sumatera and Java subduction zones, marking the presence of a converging zone of the subducting Indo-Australian plate beneath the Eurasian plate.

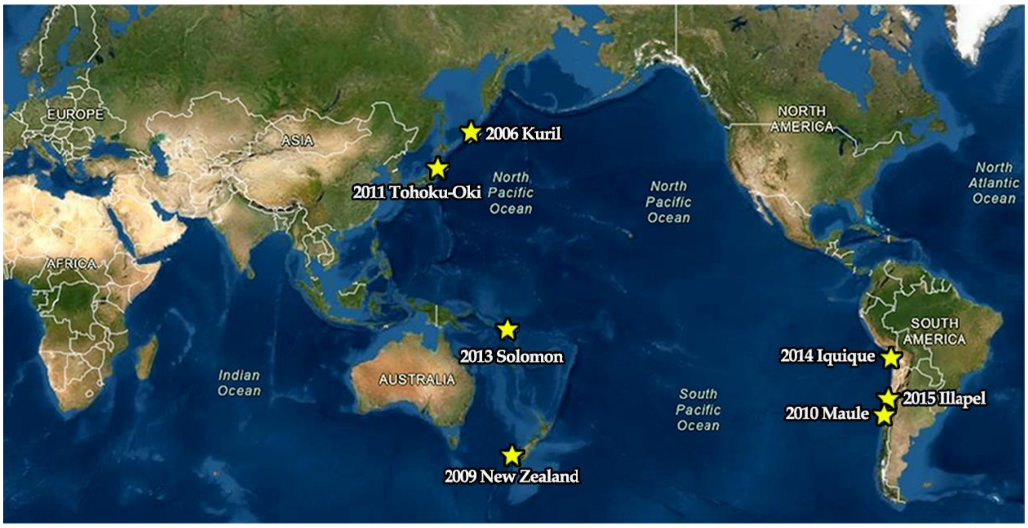

Figure 1. A geographical map showing the distribution of seven trans-Pacific tsunami epicentres examined in this study

Figure 2. A geographical map showing the distribution of six Indonesian tsunami epicentres examined in this study

B. Trans-Pacific Tsunamis

From the seven tsunamis across the Pacific, data acquisition and processing were carried out but not being provided in details here owing to a large number of numerical values involved. Therefore, with no substantial amounts of reduced information on tsunami occurrences under consideration we present the data in a short-listed table of data descriptions with limited only from five points of measurement for each case, as shown in Table 1. As the buoys used to monitor tsunami passage in the present study were surface buoys, information on the depth is neither important nor considered relevant to the parameterisation process, compared to other quantities listed in Table 1. All tsunamis are generated by tectonic earthquakes of $M_w > 7.5$.

Table 1. List of far-field observations from the trans-Pacific tsunami occurrences used in this study

Name of Tsunami	Location of the Buoys		Epicentral Distance d (km)	Maximum Amplitude (m)	The Mean Amplitude η (m)
	Longitude	Latitude			
2009 New Zealand	157.87° W	21.31° N	8,284	0.030	0.033
(M_w 7.8)	155.06° W	19.73° N	8,253	0.040	
(166.58° E, 45.75° S)	155.83° W	20.04° N	8,248	0.030	
	159.36° W	21.95° N	8,285	0.025	
	117.17° W	32.71° N	11,614	0.038	
2013 Solomon	157.87° W	21.31° N	5,392	0.100	0.113
(M_w 8.0)	155.83° W	20.04° N	6,378	0.140	
(165.14° E, 10.74° S)	120.76° W	35.18° N	9,298	0.150	
	121.89° W	36.61° N	9,252	0.095	
	177.36° W	28.21° N	4,727	0.080	
2014 Iquique	73.42° W	20.47° S	287	0.350	0.162
(M_w 8.2)	168.39° W	23.11° S	9,905	0.175	
(70.82° W, 19.64° S)	124.18° W	41.75° N	8,763	0.142	
	145.58° W	43.28° N	10,339	0.130	
	148.69° E	38.71° N	15,696	0.014	
2015 Illapel	166.54° W	53.88° N	13,108	0.240	0.214
(M_w 8.3)	174.17° W	52.23° N	13,558	0.170	
(71.65° W, 31.57° S)	160.50° W	55.34° N	12,789	0.200	
	122.98° W	37.99° N	9,397	0.210	
	124.18° W	41.75° N	9,975	0.250	
2006 Kuril	159.36° W	21.95° N	5,043	0.400	0.281
(M_w 8.3)	157.87° W	21.31° N	5,203	0.190	
(153.27° E, 46.58° N)	162.33° W	55.06° N	3,201	0.180	
	122.98° W	37.99° N	6,634	0.310	
	155.83° W	20.04° N	5,453	0.325	
2010 Maule	139.00° W	9.80° S	7,234	1.790	0.954
(M_w 8.8)	156.48° W	20.90° N	10,823	0.980	
(72.90° W, 36.12° S)	119.69° W	34.41° N	9,231	0.530	
	140.10° W	8.90° S	7,390	0.950	
	155.83° W	20.04° N	10,712	0.520	

Name of Tsunami	Location of the Buoys		Epicentral Distance d (km)	Maximum Amplitude (m)	The Mean Amplitude η (m)
	Longitude	Latitude			
2011 Tohoku-oki	155.10° W	19.70° N	6,306	1.410	1.504
(M_w 9.0)	155.83° W	20.04° N	6,221	1.220	
(142.37° E, 38.30° N)	156.48° W	20.90° N	6,112	1.740	
	120.76° W	35.18° N	8,206	1.880	
	177.40° W	28.60° N	3,856	1.270	

Table 1 indicates a non-linear dependence of the mean maximum amplitudes measured as η upon the moment magnitudes M_w for all tsunamis across the Pacific in ordered magnitudes. The data reveal that the observed amplitudes do not vary with the epicentral distance, reflecting tsunami directivity likely to be a key role in determination of tsunami heights, as also suggested by Prastowo *et al.* (2018). Some authors have considered wave dispersion effects on tsunami propagation (Glimsdal *et al.*, 2013), ocean irregular bottom topography and vertical stratification (Allgeyer & Cummins, 2014), and the initial phase reversal of tsunami development (Watada *et al.*, 2014). However, all of these factors are considered unimportant as they do not relate to the size of earthquake, with which the η data are correlated. In order to obtain further confirmation on the relation between the M_w scale for the trans-Pacific tsunamis examined here and the observed η, we then provide in Figure 3 a plot of $M_w - \eta$ scaling for the data listed in Table 1.

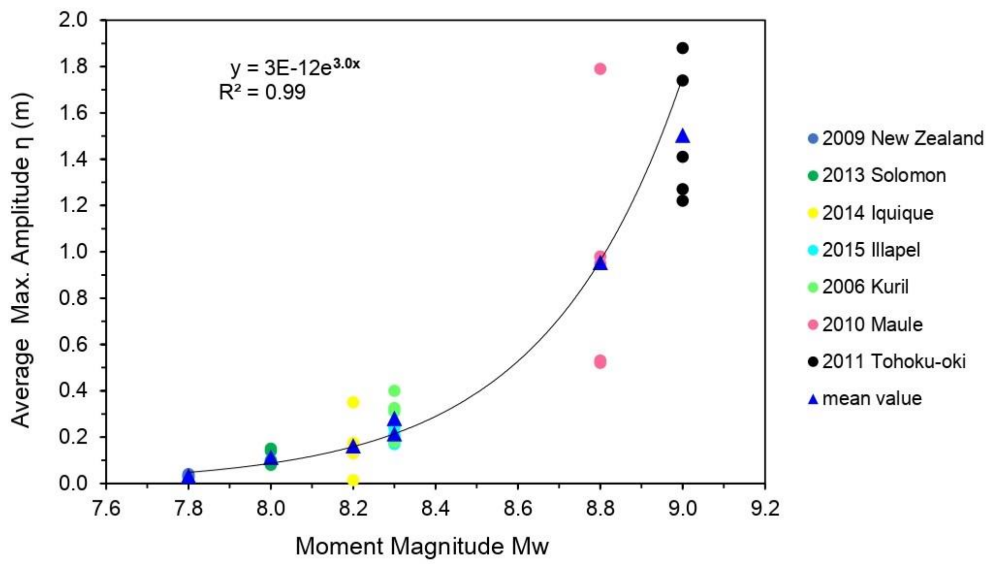

Figure 3. Plot of η against M_w for the trans-Pacific events using far-field observations

It is clear from Figure 3 that the mean amplitudes η for the distant tsunami observations extracted from each event vary with the moment magnitude records M_w in such a way to be similar to that of previously found by Heidarzadeh *et al.* (2018). Within the context of far-field monitoring throughout the Pacific-wide basin, we then obtain a parametric equation from a spreadsheet, representing a linear correlation between the earthquake moment magnitude and the logarithmic scale of the mean maximum amplitude. The resulting equation is provided by M_w = 0.77 log η + 8.84, with a high level of confidence denoted by the coefficient of correlation, R^2 = 0.99. This result for tsunamis across the Pacific is in good agreement with that written as Equation (3) of previous work (Heidarzadeh *et al.*, 2018). Insignificant differences in the multiplying factor of log η and the constant between the empirical equation derived from this study and Equation (3) of Heidarzadeh *et al.* (2018) are owing to differences in the number of field data used for each event and in the number of tsunami cases considered.

However, it is then surprising to find that the far-field maximum amplitude of a tsunami wave is independent of the distance of points of measurements, as for a particular case in some points further the observed amplitude is even larger than that recorded in places relatively close to the epicentre. This finding is actually contrary to the general descriptions of energy decay with distance based upon the measurements of sea surface elevation (Prastowo & Cholifah, 2019) although two tsunamis reported in their study are included. It should be noted here that the independence of the η data for far-field observations on the distance may possibly be caused by, in some ways, the amount of energy lost to ocean dissipation varies with different directions of tsunami propagation. This is due to the complexity of ocean topography and bathymetry effects induced by vertical seafloor deformation (Glimsdal *et. al.*, 2013; Allgeyer & Cummins, 2014). Once again, all the difficulties regarding these geophysical disturbances are beyond the focus of this study. Thus, we can say here for the trans-Pacific that the moment magnitude M_w and η data are correlated to each other for distant observations by means of the M_w scale is a logarithmic function of the apparent mean maximum amplitude η.

C. Indonesian Tsunamis

To go further with all the above findings, we examine six Indonesian tsunami occurrences, where most of them were generated in the Sumatera subduction zone and only one was induced by tectonic event in the Java subduction zone. Here, we do not include recent Indonesian events, the 2018 Palu Bay and 2018 Sunda Strait tsunamis for different reasons. As widely known, the 2018 Palu Bay tsunami was triggered by a strike-slip earthquake of M_w7.5 (e.g. Gusman *et. al.*, 2019; Nagai *et al.*, 2021) whereas the 2018 Sunda Strait tsunami was associated with a volcanic eruption a day before (e.g. Ren *et. al.*, 2020; Heidarzadeh *et al.*, 2020b). While there is no reliable data from field surveys of unexpected tsunami heights at offshores and onshores in the Palu Bay tsunami, there is no relevant moment magnitude scale reported in the Sunda Strait event. These difficulties are in line with the findings of the so-called hard lessons learned from the 2018 Indonesian catastrophes (Titov, 2021).

Similar to the trans-Pacific, all generating earthquakes are seismic events with the measured magnitudes of $M_w > 7.5$. The same procedures as the previous ones for the trans-Pacific hold also for the Indonesian tsunamis except for field data from tsunami wave monitoring, where both near-field ($d < 3{,}200$ km) and far-field ($d \geq 3{,}200$ km) tsunami observations are included. Again, the depth information is not provided in Table 2 for the same reason as in Table 1.

Table 2. List of near- and far-field observations from the Indonesian tsunamis used in this study

Name of Tsunami	Location of the Buoys		Epicentral Distance d (km)	Maximum Amplitude (m)	The Mean Amplitude η (m)
	Longitude	Latitude			
2006 Pangandaran	115.22° E	8.77° S	870	0.120	0.074
(M_w 7.7)	122.22° E	18.00° S	1,883	0.020	
(107.32° E, 9.22° S)	95.33° E	5.83° S	1,376	0.060	
	73.17° E	6.77° N	4,186	0.110	
	96.89° E	12.12° S	1,186	0.060	
2010 Mentawai	58.87° E	20.68° N	5,243	0.040	0.054
(M_w 7.8)	60.60° E	25.30° N	5,333	0.040	
(100.11° E, 3.48° S)	66.98° E	24.81° N	4,769	0.060	
	72.39° E	7.30° S	3,101	0.060	
	81.20° E	8.56° S	2,168	0.070	
2010 Simeulue	109.94° E	14.02° S	2,307	0.003	0.064
(M_w 7.8)	88.55° E	8.86° N	1,194	0.007	

Name of Tsunami	Location of the Buoys		Epicentral Distance d (km)	Maximum Amplitude (m)	The Mean Amplitude η (m)
	Longitude	Latitude			
(97.13° E, 2.36° N)	97.82° E	0.55° N	216	0.170	
	100.37° E	0.90° S	512	0.070	
	98.50° E	0.53° S	356	0.070	
2007 Bengkulu	96.89° E	12.12° S	987	0.110	0.142
(M_w 8.5)	73.53° E	4.19° S	3,090	0.120	
(101.37° E, 4.44° S)	73.17° E	6.77° N	3,373	0.130	
	98.77° E	1.73° N	745	0.160	
	103.25° E	0.25° S	511	0.190	
2012 Northern Sumatera	88.79° E	6.26° N	645	0.125	0.166
(M_w 8.6)	88.55° E	8.86° N	882	0.070	
(93.06° E, 2.33° N)	95.33° E	5.83° S	943	0.400	
	73.17° E	6.77° N	2,261	0.150	
	96.89° E	12.12° S	1,663	0.085	
2004 Aceh	98.77° E	1.73° N	356	0.430	0.358
(M_w 9.1)	96.89° E	12.12° S	1,719	0.330	
(95.98° E, 3.30° N)	115.74° E	31.83° S	4,434	0.350	
	54.00° E	17.00° S	5,136	0.330	
	25.63° E	33.95° S	870	0.120	

Again, Table 2 shows a likely non-linearity in the relation between the mean maximum amplitudes η and the moment magnitudes M_w for the Indonesian tsunamis listed. The observed amplitudes clearly do not vary with the distance, prompting a role played by tsunami directivity and tsunami heights, as also suggested by Prastowo *et al.* (2018). There may be additional factors affecting tsunami heights in the open ocean, including wave dispersion effects (Glimsdal *et al.*, 2013), bottom topography and vertical stratification (Allgeyer & Cummins, 2014), and the initial phase reversal of tsunami development (Watada *et al.*, 2014). As with the previous cases, these factors are considered insignificant and hence ignorable. The relation between the M_w scale for the Indonesian events in this study and the mean amplitude η is provided in Figure 4 in the form of a plot of $M_w - \eta$ scaling for the data listed in Table 2.

Figure 4 exhibits that the mean amplitudes η for the Indonesian tsunamis vary with the moment magnitudes M_w, similar to the trans-Pacific. Using a spreadsheet, we derive a parametric equation, representing the log-linear relation between the observed M_w and η data. The resulting equation is given by M_w = 1.92 log η + 10.36, with a high level of confidence denoted by R^2 = 0.95. The fact that the resulting equation for this case has the same log-linear correlation as that for the trans-Pacific indicates that the $M_w - \eta$ scaling likely behaves self-consistent, independent of observational distance of monitoring and pathways of tsunami propagation. The apparent differences in the multiplying factor of log η and the constant between the equation derived for the trans-Pacific and the Indonesian tsunamis are owing to differences in the topographic complexity and tsunami wave directivity in the two oceans.

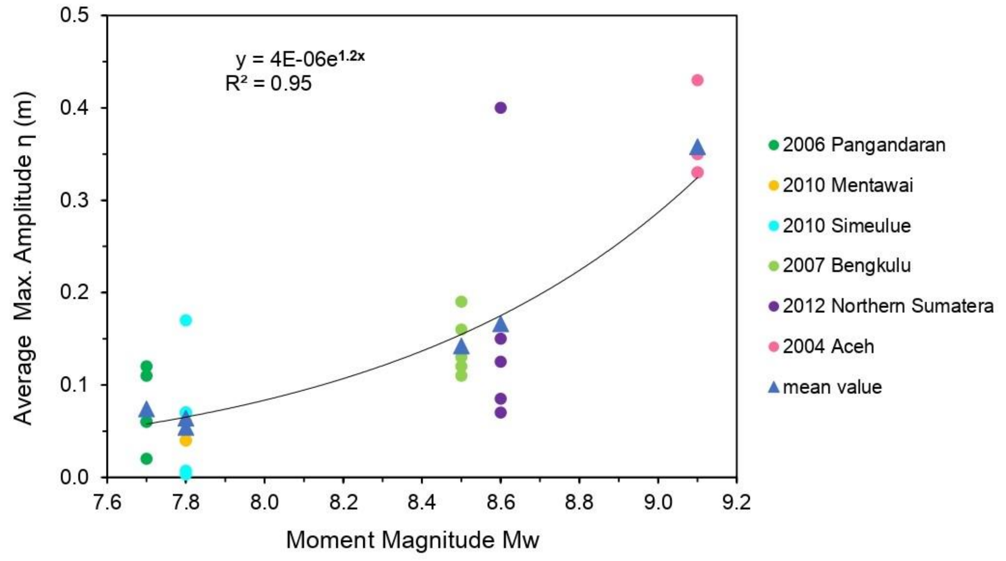

Figure 4. Plot of η against M_w for the Indonesian events using near- and far-field observations

As with the trans-Pacific events, we find no clear relations between tsunami travel distances away from the epicentre and the corresponding maximum amplitudes. Thus, all previous arguments applied for the trans-Pacific also hold for the Indonesian tsunamis, meaning that the amount of dissipated energy varies with tsunami pathways, *i.e.*, different directions of tsunami propagation. In this context, we assume that the effects of irregular ocean bottom topography and island barriers induce tsunamis originating from noticeable source regions in the Pacific and Indian Oceans to undergo distinct rates of energy dissipation, the same argument as discussed in relevant previous work (Rabinovich *et. al.*, 2011; Rabinovich *et al.*, 2013). Again, these induced disturbances are beyond the focus of this study. Therefore, to this end we can conclude that for all the trans-Pacific and Indonesian tsunamis examined in the present study, the $M_w - \eta$ scaling obeys the log-linear relation $M_w - \log \eta$, independent of fields of tsunami observation and consistent with previous findings of relevant research (Hanks & Kanamori, 1979; Kanamori, 1983; Okal *et. al.*, 2014; Heidarzadeh *et al.*, 2018).

IV. CONCLUSION

The present work has successfully parameterised the mean maximum amplitudes acquired for most distant observations with the moment magnitudes. For the large earthquake-induced tsunamis across the Pacific Ocean, initiated by strong ground shaking with $M_w > 7.5$, the M_w scale is proved to be a logarithmic function of the mean wave amplitude η measured with an additional factor related to fractional distances from the epicentre. It follows that the maximum amplitude η depends only on the moment magnitude M_w, in good agreement with previous work. From the data collected and the corresponding analysis, the empirical equation for the trans-Pacific is found to be M_w = 0.77 log η + 8.84, consistent with previous work. For the Indonesian tsunamis with similar sizes, the equation is of M_w = 1.92 log η + 10.36. The apparent difference in the two empirical equations indicates that distinct tsunami propagation characteristics in the Pacific and Indian Oceans are present but the details of the different characteristics are beyond the scope of the present study.

V. ACKNOWLEDGEMENT

The authors would like to thank NOAA, the US government accessed at http://ngdc.noaa.gov from which the data used in this study were acquired. The present work has also benefited from https://keisan.casio.com/exec/system/1224587128 for all online calculations of the distance between two places on the spherical Earth's surface.

VI. AUTHORS' STATEMENT

The authors declare that no funds or other financial supports were received during the work. The authors also declare that there is no conflict of interest regarding this work.

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