**Natural Hazards
and Earth
System Sciences**

Tsunamigenic Ratio of the Pacific Ocean earthquakes and a proposal for a Tsunami Index

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Abstract. The Pacific Ocean is the location where two-thirds of tsunamis have occurred, resulting in a great number of casualties. Once information on an earthquake has been issued, it is important to understand if there is a tsunami generation risk in relation with a specific earthquake magnitude or focal depth. This study proposes a Tsunamigenic Ratio (TR) that is defined as the ratio between the number of earthquake-generated tsunamis and the total number of earthquakes. Earthquake and tsunami data used in this study were selected from a database containing tsunamigenic earthquakes from prior 1900 to 2011. The TR is calculated from earthquake events with a magnitude greater than 5.0, a focal depth shallower than 200 km and a sea depth less than 7 km. The results suggest that a great earthquake magnitude and a shallow focal depth have a high potential to generate tsunamis with a large tsunami height. The average TR in the Pacific Ocean is 0.4, whereas the TR for specific regions of the Pacific Ocean varies from 0.3 to 0.7. The TR calculated for each region shows the relationship between three influential parameters: earthquake magnitude, focal depth and sea depth. The three parameters were combined and proposed as a dimensionless parameter called the Tsunami Index (TI). TI can express better relationship with the TR and with maximum tsunami height, while the three parameters mentioned above cannot. The results show that recent submarine earthquakes had a higher potential to generate a tsunami with a larger tsunami height than during the last century. A tsunami is definitely generated if the TI is larger than 7.0. The proposed TR and TI will help ascertain the tsunami generation risk of each earthquake event based on a statistical analysis of the historical data and could be an important decision support tool during the early tsunami warning stage.

1 Introduction

Just after an earthquake occurs, primary earthquake information can be accessed via specialized websites, such as the homepage of the US Geological Survey (USGS 2011), and more related scientific information can be obtained from the Global Centroid Moment Tensor (Global CMT, 2011). The condition of launching tsunami warning bulletins is dependent upon a pre-calculated tsunami database in the warning systems. The Japan Meteorological Agency introduced a computer-aided simulation system in 1999 for quantitative tsunami forecasting, in which tsunami arrival times and heights are computed and stored in a database for the forecasting of tsunamis after an earthquake actually occurs (Imamura and Abe, 2009). However, the system is still not able to clearly determine whether an earthquake will generate a tsunami or not. Necessary earthquake data for considering the occurrence of a tsunami are available, including the earthquake magnitude and focal depth. Similar to earthquakes, the first attempt to establish a tsunami magnitude was conducted by Iida et al. (1967). From data of tsunamis in the Pacific Ocean, the tsunami magnitude was calculated by taking the logarithm to base 2 of a physical measurement of the tsunami, such as the maximum wave height observed at the coast or measured at the tide gauges. Abe (1979) also developed a magnitude scale defined by the logarithm of the maximum amplitude of far-field tsunami waves measured by tide gauges. These two tsunami magnitudes are widely used to express a physical property of a tsunami. The application of the tsunami magnitude has been used for the tsunamis occurring in the seas surrounding Italy (Tinti, 1991) and the Central American tsunamis (Hatori, 1995). From the point of view of the focal depth, Satake and Tanioka (1999) classified tsunamigenic earthquakes in subduction zones into three types: earthquakes at the plate interface (typical interplate

Table 1. Global tsunamis causing 3000 or more deaths. (NGDC tsunami database: http://www.ngdc.noaa.gov/hazard/tsu.shtml).

Year	Earthquake location	Magnitude M	Focal depth (km)	Estimated death or missing
365	Crete, Greece	8.0		5700
1498	Enshunada Sea, Japan	8.6	1	31 000
1586	Ise Bay, Japan	8.2		8000
1605	Nankaido, Japan	7.9		5000
1611	Sanriku, Japan	8.1		5000
1687	Southern Peru	8.5	30	*5000
1703	Boso Peninsula, Japan	8.2	1	*5233
1707	Nankaido, Japan	8.4	1	30 000
1746	Central Peru	8.0	30	4800
1755	Lisbon, Portugal	8.5		60 000
1771	Ryukyu Islands, Japan	7.4	1	13 486
1854	Nankaido, Japan	8.4		3000
1896	Sanriku, Japan	8.5	1	*27 122
1933	Sanriku, Japan	8.4	25	3000
1941	Andaman Sea, India	7.6	55	5000
1945	Makran, Pakistan	8.0		4000
1952	Kamchatka, Russia	8.5	45	4000
1976	Moro Gulf, Philippines	8.1	33	4456
2004	Banda Aceh, Indonesia	9.2	30	*227 898
2011	East Japan	9.0	24	*19 296

* May include earthquake casualties.

events), earthquakes in the outer rise within the subducting slab or overlying crust (intraplate events), and "tsunami earthquakes" that generate considerably larger tsunamis than expected from the seismic waves. The depth range of interplate earthquake sources is 10–40 km, whereas the source region of tsunami earthquakes is at a shallower extension near the trench axis. Thus, large magnitude earthquakes that occur at a shallow depth might have the potential to generate a tsunami.

In general, the displacement and fault size of an earthquake can be estimated by an empirical relation based on historical tsunami magnitude data, such as Wells and Coppersmith (1994), Okada and Tanioka (1998) and Papazachos et al. (2004). After the primary earthquake information is obtained, namely location, magnitude and focal solution (including focal depth and strike, dip and rake angle), other fault parameters, such as displacement and fault size, can also be estimated. These parameters are used as input in tsunami generation models to calculate the vertical seafloor displacement, which later becomes a tsunami initial level. The calculation is based on the two extensively used theories of Mansinha and Smylie (1971) and Okada (1985). The Asian Disaster Preparedness Center (ADPC) (2009) ascertained that the maximum and minimum displacements are equal for results calculated from both theories and that only minor differences could be observed in the overall shape of the computed deformation fields. Moreover, the effect of focal depth, dip and rake angles on the ocean bottom deformation

was shown by Ruangrassamee (2006) who calculated deformation for focal depth varying from 10 to 100 km by applying the Mansinha and Smylie theory. The results show remarkably different effects on the vertical seafloor displacement. Therefore, it is supported that earthquake magnitude and focal depth play an important role in the generation of a tsunami. In addition, the sea depth at the location where an earthquake occurs also plays an important role for tsunami generation. This is because a large seafloor displacement in a deep sea induces the displacement of a large amount of sea water that later has a higher potential to generate a tsunami. This study proposes a new term, the "Tsunamigenic Ratio" (TR) that is defined as the ratio between the number of earthquake–generated tsunamis and the total number of earthquakes. The Tsunamigenic Ratio will help ascertain the tsunami generation risk of each earthquake event based on a statistical analysis of the historical data if the earthquake magnitude, focal depth and sea depth are known.

2 Tsunamis in the Pacific Ocean

The National Geophysical Data Center (NGDC) tsunami database at the National Oceanic and Atmospheric Administration (NOAA) provides 2400 events (NOAA, 2011c). The global distribution of these tsunami sources is 63 % in the Pacific Ocean, 21 % in the Mediterranean Sea, 5 % in the Atlantic Ocean, 4 % in the Caribbean Sea, 6 % in the Indian

Table 2. Tsunamis causing deaths from greater than 1000 km from the source location. (NGDC tsunami database: http://www.ngdc.noaa.gov/hazard/tsu.shtml).

Year	Earthquake location	Magnitude M	Focal depth (km)	Estimated death or missing		Distant locations that reported casualties
				Local	Distant	
1837	Southern Chile	8.5		0	16	USA (Hawaii)
1868	Northern Chile	8.5	25	*25 000	1	New Zealand, Southern Chile
1877	Northern Chile	8.3	40	Hundreds	Thousands	Fiji, Japan, Peru, USA (Hawaii)
1923	Kamchatka, Russia	8.3	19	2	1	USA (Hawaii)
1946	Alaska, USA	8.1	50	5	160	USA (California, Hawaii)
1960	Central Chile	9.5	33	1000	283	Japan, Philippines, USA (California, Hawaii)
1964	Alaska, USA	9.2	23	106	18	USA (California, Oregon)
2004	Banda Aceh, Indonesia	9.3	30	*175 827	52 071	Bangladesh, India, Kenya, Maldives, Myanmar, Seychelles, Somalia, South Africa, Sri Lanka, Tanzania, Thailand, Yemen
2011	East Japan	9.0	24	19 294	2	Indonesia and USA (California)

* May include earthquake casualties.

Ocean and 1 % in the Black Sea. Most of these tsunamis were generated by earthquakes (83 %) or earthquakes that caused landslides (6 %). The remaining events were caused by landslides (2 %), volcanic eruptions (6 %), and unknown sources (3 %). If the casualty number of 3000 is selected to classify an event as a deadly tsunami, there are 16 of such events in the Pacific region out of the total of 20 events, as shown in Table 1. The earthquake that induced deadly tsunamis did not necessary have large magnitudes only, but also occurred at shallow regions less than 50 km. In Japan, where the number of casualties is the highest, the focal depth of some earthquakes is as shallow as less than 10 km (Sato, 1995). Damage to people's lives in the past was not only caused by local tsunamis but also by distant tsunamis, with transoceanic tsunami causing deaths greater than 1000 km far from the source over the Pacific Ocean, as shown in Table 2. In the Pacific Ocean, one can find eight events out of nine global events. In some events, the distant tsunami caused a higher number of casualties in the remote area than in the local area. Most of the distant tsunamis originated from earthquakes with a magnitude greater than 8.3 that occurred at the eastern Pacific side, such as in Chile and in the US, and caused damage to the western side, such as in Japan, the Philippines and New Zealand. Though Japan suffered a great loss of lives from local tsunamis generated by earthquakes with magnitude smaller than 8.5 before the 2011 event, earthquakes at the shallow region generated higher vertical ocean bottom deformation and resulted in a powerful tsunami (Satake and Tanioka 1999), such as the 1986 Sanriku and the 1946 Alaska cases (Kanamori 1972). In contrast, gigantic earthquakes with a magnitude 9.0 or greater in Chile, Alaska, Indonesia and Japan had damage potential across the Pacific Ocean.

Moreover, most tsunamigenic earthquakes occur along subduction zones or trenches where the sea depth is as deep as many thousands meters.

According to the problem and information stated above, the characteristics for the next tsunami are still unclear. This study will quantify the characteristics of earthquake-generated tsunamis using the historical events in the Pacific Ocean. The proposed Tsunamigenic Ratio (TR) is defined as the ratio between the number of earthquake–generated tsunamis and the total number of earthquakes (Suppasri et al., 2011a, b). This idea is the same as that proposed by Okada and Tanioka (1998), but their study was limited to Japan and did not provide much detailed information. Gusiakov (2005) proposed the Tsunami Efficiency (TE) in the Pacific Ocean as the ratio between the number of tsunamis, including those generated by landslides and of unknown origins, and the total number of the coastal and submarine earthquakes. However, the TE value may exceed 1, and it does not reflect the characteristics most likely to occur as the earthquake-generated tsunami. By considering the earthquake magnitude, focal depth and sea depth as the primary parameters in the generation of a tsunami, this study can provide more information on the tsunami generation ratio if future earthquake-related parameters are known.

3 Earthquake data and processing method

Earthquake-generated tsunamis and earthquake events can be accessed by the NGDC global significant earthquake database website (NOAA, 2011b). On the data selection page, we can select whether the earthquake event was associated with tsunami or not. Therefore, the historical earthquake

events are divided into two groups: tsunami-associated events and tsunami-non-associated events. Tsunami related information for the tsunami-associated events can be accessed by the Global Historical Tsunami Database website (NOAA, 2011c). Consequently, the TR value is calculated for each specific range of earthquake magnitude, focal depth and sea depth. However, the earthquake magnitude is not compatible with the earthquake magnitude scale because the primary earthquake magnitude can be measured using several different scales. The primary magnitude is chosen from the available magnitude scale in this order: the moment magnitude (M_w), the surface wave magnitude (M_s) and the body wave magnitude (M_b). Nevertheless, Scordilis (2006) derived relationships between M_s and M_w and between M_b with M_w. The M_s–M_w relation has a bilinear changing slope at $M_w = 6.2$, while the M_b–M_w relation can be plotted until 6.2. That means that the earthquake magnitude, M, can also be defined as either M_w or M_s. Based on the tsunami data in Japan, Okada and Tanioka (1998) mentioned that an earthquake with focal depth deeper than 90 km could not generate a tsunami. Moreover, most tsunamis were generated when the Japanese earthquake magnitude, M_j, was greater than 7.0 ($M_w = 6.9$) and occurred at a very low ratio if M_j was smaller than 6.2 ($M_w = 6.3$). Gusiakov (2005) used 1201 events of the coastal and submarine earthquakes with magnitude $M_s \geq 7.0$ and focal depth ≤ 100 km that occurred in the Pacific Ocean during the last 100 years (from 1901 to 2000). In addition, the term "coastal" means that they also took into account the earthquakes located within 100 km in-land for the events with $7.0 \leq M_s \leq 8.0$ and 200 km in-land for the events with $M_s > 8.0$.

The Pacific Ocean is geographically divided into 9 regions: New Zealand-Tonga (NZT), New Guinea-Solomon (NGS), Indonesia (IND), the Philippines (PHI), Japan (JAP), Kuril–Kamchatka (K–K), Alaska-Aleutians (A–A), Central America (CAM) and South America (SAM), following the zoning used in the NGDC map (Lockridge and Smith, 1984; Gusiakov, 2005). Table 3 summarizes the information on the boundaries for each region, and the map is illustrated in Fig. 1. This study considers the NGDC database, which contains earthquake events from 200 BC to 2011 (more precisely from year −193 to 2011). Regarding the level of completeness of earthquake and tsunami catalogs and the accuracy of parameters that greatly vary over time, four different time periods can be distinguished: pre-instrumental (prior 1900), early instrumental (1900–1962), instrumental (1963–1990) and modern instrumental (1991 to 2011). The earthquake events exclude an event when the epicenter was located farther than 50 km from a shoreline. In some cases, fault width of megathrust earthquakes in subduction zones can be as large, for instance, as 150 km for $M = 9.3$ of the 2004 Sumatra Earthquake (Suppasri et al., 2011c) and 200 km for $M = 9.0$ of the 2011 Great East Japan Earthquake (Suppasri et al., 2012c). However, maximum width of continental faults for $M < 7.5$ earthquake estimated using a formula proposed by
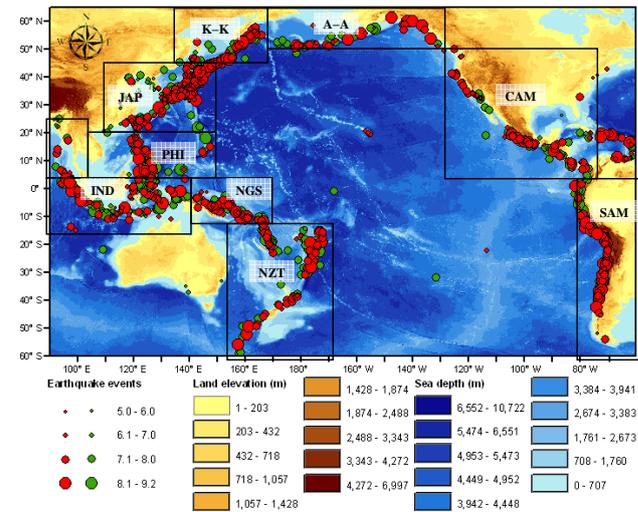
Fig. 1. Earthquake events in the Pacific Ocean (red: with tsunami events and green: without tsunami event).

Papazachos et al. (2004) is about 25 km and about 100 km for $M < 8.5$ earthquake in subduction zones. Therefore, sea depth for these in-land earthquakes is reasonably assumed to be obtained by taking a sea depth value at a point where the distance is within 50 km perpendicularly far from the epicenter. The method of extracting coastal earthquakes was adapted from the tsunami casualty estimation method developed by Suppasri et al. (2012a, b). They applied the concept of image processing and the Laplacian mask over the global bathymetry data of Pacific region. Shorelines of every 2-min grid from ETOPO2 (NOAA 2011a) can be found by the mentioned method. The coastal zone is then expanded until it reaches 50 km. For tsunami event selection from the NGDC database, the code "1 = Earthquake" was used from the total of 12 codes describing the tsunami cause, and the codes "4 = definite tsunami" and "3 = probable tsunami" were used from the total of six codes describing the tsunami event validity. Consequently, the TR is calculated from an earthquake event with a magnitude ranging from 5.0 to 9.0, focal depth up to 200 km and sea depth down to a depth of 7000 m.

4 Tsunamigenic Ratio of the Pacific Ocean earthquakes

The total numbers of tsunami events for the four different time periods mentioned above are 466, 499, 337 and 381, respectively, as summarized in Table 4a. The average TR in the Pacific Ocean for each region in each time period can be calculated using the total number of tsunami-associated event (a), of tsunami-non-associated event (b), and of event (c) (Table 4a). TR was calculated by dividing "a" by "c" with resulting TR value of 0.46, 0.41, 0.47 and 0.40 for the four periods, respectively. It can be seen from Table 4a that

Table 3. Tsunamigenic regions along the Pacific Ring of Fire.

Regions	Abbreviations	Lower-Left point	Upper-Right point
New Zealand-Tonga	NZT	60° S 155° E	12° S 168° W
New Guinea-Solomon	NGS	12° S 141° E	5° N 170° E
Indonesia	IND1	15° S 90° E	5° N 141° E
	IND2	5° N 90° E	25° N 105° E
Philippines	PHI	5° N 105° E	20° N 150° E
Japan	JAP	20° N 110° E	45° N 150° E
Kuril-Kamchatka	K–K	45° N 135° E	65° N 170° E
Alaska-Aleutians	A–A	50° N 170° E	65° N 128° W
Central America	CAM	5.5° N 128° W	50° N 75° W
South America	SAM	60° S 82° W	5.5° N 65° W

Table 4a. Average tsunamigenic ratio TR along the Pacific Ring of Fire by separating data into four periods.

Reg.	Prior 1900				1900–1962				1963–1990				1991–2011			
	a	b	c	TR	a	b	c	TR	a	b	c	TR	a	b	c	TR
NZT	5	0	5	1.00	15	35	50	0.30	15	13	28	0.54	24	9	33	0.73
NGS	4	0	4	1.00	25	17	42	0.60	21	15	36	0.58	11	6	17	0.65
IND	41	14	55	0.75	18	39	57	0.32	10	40	50	0.20	30	76	106	0.28
PHI	6	58	64	0.09	17	30	47	0.36	9	15	24	0.38	8	18	26	0.31
JAP	104	79	183	0.57	74	68	142	0.52	59	31	90	0.66	43	41	84	0.51
K–K	4	5	9	0.44	11	19	30	0.37	11	1	12	0.92	9	3	12	0.75
A–A	5	2	7	0.71	5	14	19	0.26	10	3	13	0.77	7	0	7	1.00
CAM	14	59	73	0.19	21	58	79	0.27	9	43	52	0.17	11	56	67	0.16
SAM	30	36	66	0.45	18	15	33	0.55	14	18	32	0.44	10	19	29	0.34
Total	213	253	466	0.46	204	295	499	0.41	158	179	337	0.47	153	228	381	0.40

Note: a = tsunami-associated events, b = tsunami-non-associated events and c = total number of events.

TR prior to 1900 (pre-instrumental) fluctuates quite a bit: from 0.09 in PHI to 1.00 in NZT and NGS. K–K and A–A have high TR of more than 0.75 for both 1963–1900 and 1991–2011. CAM has the lowest TR of about 0.20 for the whole time period. Table 4b summarizes number of events and TR for accumulated data for the total period and also for periods 1990–2011, 1963–2011 and 1991–2011. TR in Table 4b is approximately 0.40 for all time spans, meaning that value of TR is consistent with time, while different by region. In general, JAP provides the largest number of the tsunami-associated (a) events (280 out of 728 events) and of total (c) events (499 out of 1683 events), which is about one-third of the total data. If the time span is considered until the pre and early instrumental periods, NZT, NGS, JAP, K–K and A–A are regions where TR is about 0.5–0.6. On the other hand, if only the instrumental and modern instrumental periods are considered, TR for those regions is increased as high as 0.6–0.8. TR for IND and PHI is approximately the same of about 0.3, while TR for CAM and SAM is 0.2 and 0.4, respectively.

Tsunamigenic ratios for each region are then plotted against the three parameters that have related potential to generate a tsunami (Fig. 2): earthquake magnitude (Fig. 2a), focal depth (Fig. 2b) and sea depth (Fig. 2c). From Fig. 2a, greater earthquake magnitude has a greater potential to generate a tsunami because the TR at $M = 6.0$ is approximately 0.20 and increases to 0.50 at $M = 7.5$ and to more than 0.80 at $M = 8.5$. Influence from the focal depth is shown in Fig. 2b. Shallower focal depth has high potential for tsunami generation. A TR of 0.80 can be found when the focal depth is less than 30 km and gradually reduces to below 0.20 when the depth is deeper than 100 km. Sea depth at a point of each earthquake epicenter, which is considered as a representative value of the whole rupture area for quick information after an earthquake occurrence, is obtained from the global bathymetry data (ETOPO2), and the plot is shown in Fig. 2c. In general, TR increases when sea depth is increased, and the TR increases rapidly when the sea depth is as deep as 1000 m, and varies from 0.40 to 0.70 when the sea depth is deeper than 1000 m. This large variation can be seen in all

Table 4b. Average tsunamigenic ratio TR along the Pacific Ring of Fire by separating data into four periods.

Reg.	Prior 1900–2011				1900–2011				1963–2011				1991–2011			
	a	b	c	TR	a	b	c	TR	a	b	c	TR	a	b	c	TR
NZT	59	57	116	0.51	54	57	111	0.49	39	22	61	0.64	24	9	33	0.73
NGS	61	38	99	0.62	57	38	95	0.60	32	21	53	0.60	11	6	17	0.65
IND	99	169	268	0.37	58	155	213	0.27	40	116	156	0.26	30	76	106	0.28
PHI	40	121	161	0.25	34	63	97	0.35	17	33	50	0.34	8	18	26	0.31
JAP	280	219	499	0.56	176	140	316	0.56	102	72	174	0.59	43	41	84	0.51
K–K	35	28	63	0.56	31	23	54	0.57	20	4	24	0.83	9	3	12	0.75
A–A	27	19	46	0.59	22	17	39	0.56	17	3	20	0.85	7	0	7	1.00
CAM	55	216	271	0.20	41	157	198	0.21	20	99	119	0.17	11	56	67	0.16
SAM	72	88	160	0.45	42	52	94	0.45	24	37	61	0.39	10	19	29	0.34
Total	728	955	1683	0.43	515	702	1217	0.42	311	407	718	0.43	153	228	381	0.40

Note: a = tsunami-associated events, b = tsunami-non-associated events and c = total number of events.
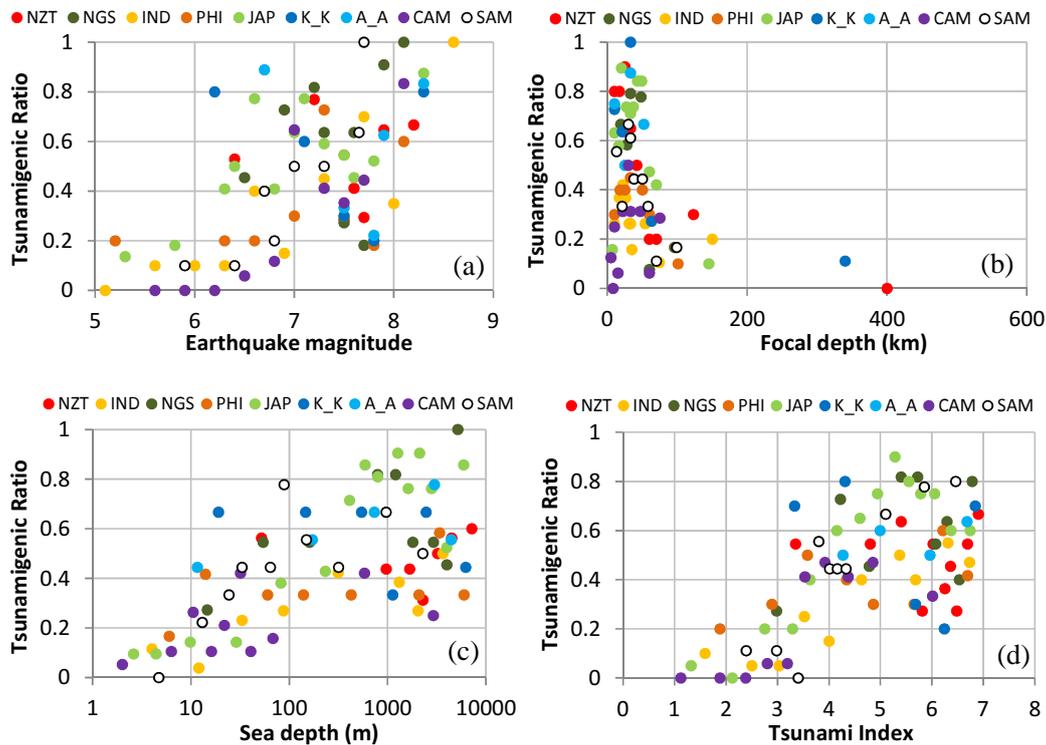
Fig. 2. Tsunamigenic ratio for each region.

figures shown. For the entire Pacific Ocean, the plots were made using all data and were separated into three different time periods, 1900–2011 (green line), 1960–2011 (blue line) and 1991–2011 (red line), respectively, as shown in Fig. 3–c, with different affecting parameters, earthquake magnitude (Fig. 3a), focal depth (Fig. 3b) and sea depth (Fig. 3c). Power function was applied for regression analysis to fit the data because it provides higher R^2 in all cases. A comparison of data accuracy and correlation can be made among three different time periods using the R^2 values. It can be seen from the regression analysis that values of R^2 in all cases have improved when more precise data (during 1960–2011 or 1991–2011) are used. The curves obtained from the regression analysis can be used for the future estimation of TR for each different time span when earthquake magnitude, focal depth and sea depth are known.
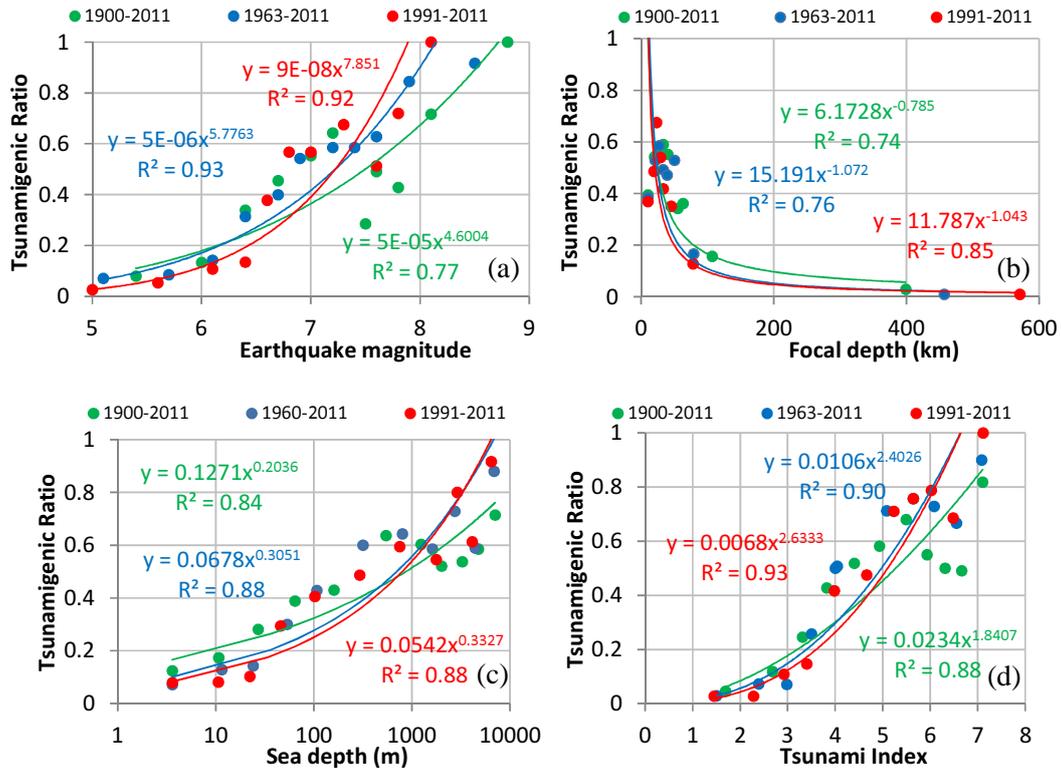
Fig. 3. Tsunamigenic ratios of the entire Pacific region for three different periods with regression analysis using power function.
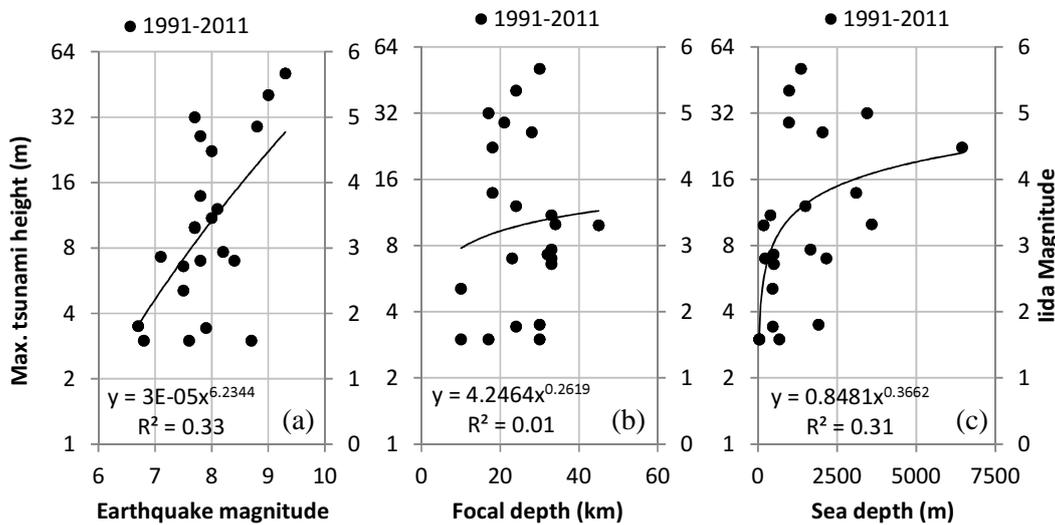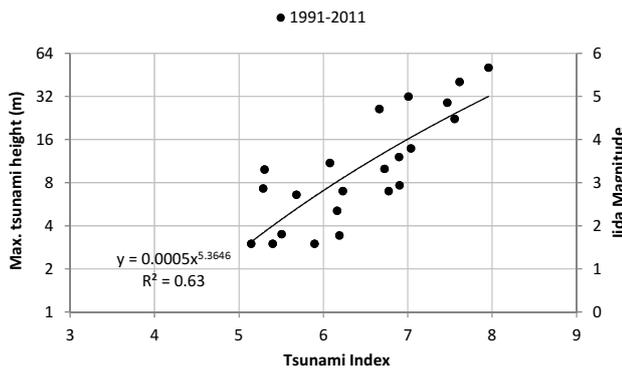

Fig. 4. Relationship between the earthquake magnitude/focal depth/sea depth and the maximum tsunami height and Iida magnitude of recent tsunamis causing death events.

5 Proposal for a Tsunami Index

According to the previous Fig. 2a–c, greater earthquake magnitude has a high possibility of tsunami occurrence (generally $M > 7.0$), shallower focal depth has high possibility of tsunami occurrence (generally focal depth < 100 km), and deeper sea depth has high possibility of tsunami occurrence (generally sea depth > 1000 m). Combining the above three parameters would help provide a better understanding of tsunami generation mechanism. Consequently, a new parameter that includes the effect of the three parameters is

Fig. 5. Relationship between the tsunami index and the maximum tsunami height and Iida magnitude of recent tsunamis causing death events.

proposed in a dimensionless form, called the Tsunami Index (TI), as expressed in Eq. (1).

$$TI = Magnitude + \log\left(\frac{Depth_{sea}}{Depth_{focal}}\right) \qquad (1)$$

From the equation, the range of the tsunami index varies from 0 to about 10.0 (extremely lowest to highest theoretical case). For example, TI = 0 when magnitude = 5.0, focal depth = 100 km and sea depth = 10^{-3} km, and TI = 10.0 when magnitude = 9.0, focal depth = 1 km and sea depth = 10 km.

The results with smaller variation are plotted in Fig. 2d and Fig. 3d. In general, R^2 for TI is higher than R^2 for earthquake magnitude, focal depth and sea depth itself. In other words, a combination of the three mentioned parameters as proposed with introduction of TI helps reinforce the relationship between these parameters and the tsunami generation. In case of TI, R^2 increases from 0.88 (data during 1900–2011) to 0.90 (data during 1960–2011) and to 0.93 (data during 1991–2011). The TR starts from the tsunami index (TI) equal to 2.0, increases to 0.50 when TI is at 5.0 and reaches 0.80 when TI becomes 7.0. In general, when period 1900–2011 is considered, the coefficient of determination, R^2 increases from 0.77 (earthquake magnitude), 0.74 (focal depth) and 0.84 (sea depth) to 0.88 when the TR are plotted against the proposed TI. In addition, R^2 for the case when only the modern instrumental period (red line) is considered is as high as 0.93. It can be noticed from the results that the blue and red lines are similar in most parameters and get along with the TR results, as explained in the previous section and in Table 4b. For the whole Pacific region, TR is more than 0.5 when TI is larger than 5 and TR reach 1.0 when TI is almost 8. The blue and red lines in Fig. 3 are steeper than the black line, implying that the recent tsunamis caused greater tsunami generation potential than they did in the past hundred years. Although the TR during 1991–2011 (0.40) is slightly less than the TR prior 1900 (0.46) (Table 4a), the TR during 1991–2011 gradually becomes higher

when the TI is greater than 5. In other words, a tsunami is almost definitely generated if a computed TI is greater than 7.0 (for example, magnitude > 8.0, focal depth < 10 km and sea depth > 1000 m). This means that the TR of the recent events is higher than the historical events when a powerful tsunami is expected to be generated.

This section also discusses and compares "hazards" (the maximum tsunami height and the TR). Recent tsunamis causing death events during 1991–2011 are summarized in Table 5. Most of them were generated with an earthquake magnitude greater than 7.5, which is 19 from the total of 22 events. The range of TI value from 5.14 to 7.96 was calculated based on the previously mentioned data and plotted against the maximum tsunami height (up to 50 m). Figure 4 shows a plot of 22 events during 1991–2011 with information on earthquake magnitude, focal depth, sea depth, tsunami height and Iida tsunami magnitude (M_I) (Iida et al., 1967). The relationship between the maximum tsunami height and the TI for tsunamis during 1991–2011 is shown in Fig. 5. Although a relationship between TI and TR using these three parameters is unclear, R^2 obtained from the plot using data from 1991–2011 against the proposed TI is increased from 0.33 to 0.63 (Fig. 5). However, there are some important points that might cause uncertainty in this calculation, such as the lack of instrumental records in the past. For instance, the total number of earthquakes prior to 1900 is only 466, whereas there were already 381 events during 1991–2011 from the total of 1217 during 1900–2011 (Table 4b). Modern technology, such as earthquake measurement technology and high-resolution satellite images, help to increase the accuracy of earthquake and tsunami information. For example, better earthquake magnitude and focal depth can now be obtained. For the tsunami height, a better transportation system also supports accessibility to highly affected areas. Although an effect from global warming is still unclear, the measured maximum tsunami height of the recent tsunamis (1991–2011) might be closer to the actual maximum tsunami heights.

6　Application of Tsunamigenic Ratio and Tsunami Index

Application of TR and TI can be explained as follows. A tsunami is very likely to be generated if a calculated TI is greater than 7.0. Moreover, 6 levels can be classified for an early tsunami warning: tsunami advisory (TI < 3 and TR < 0.1), small tsunami (TI < 4 and TR < 0.3), moderate tsunami (TI < 5 and TR < 0.5), major tsunami (TI < 6 and TR < 0.7), destructive tsunami (TI < 7 and TR < 0.9) and devastating tsunami (TI ≈ 8 and TR ≈ 1.0), as shown in Table 6. One good example of using TI is that TI can express the increasing trend of maximum tsunami height over the recent tsunamis causing death, while earthquake magnitude, focal depth, and sea depth itself cannot because low values

Table 5. Recent tsunamis causing death from 1991 to 2011 and related information.

Year	Location	Deaths	Earthquake magnitude	Tsunami Index	Maximum tsunami height (m)	Tsunami Magnitude
1991	Costa Rica	2	7.6	5.14	3.0	1.58
1992	Nicaragua	170	7.7	5.30	9.9	3.31
1992	Flores Sea, Indonesia	1169	7.8	6.66	26.2	4.71
1993	Okushiri, Japan	208	7.7	7.01	32.0	5.00
1994	Java, Indonesia	250	7.8	7.04	13.9	3.80
1994	Halmahera, Indonesia	1	6.8	5.40	3.0	1.58
1994	Mindoro, Philippines	81	7.1	5.29	7.3	2.87
1995	Mexico	1	8.0	6.08	11.0	3.46
1996	Sulawesi, Indonesia	9	7.9	6.19	3.4	1.78
1996	North Peru	12	7.5	6.16	5.1	2.35
1996	Irian Jaya, Indonesia	110	8.2	6.90	7.7	2.94
1999	Vanuatu	5	7.5	5.68	6.6	2.72
2001	Southern Peru	26	8.4	6.23	7.0	2.81
2004	Sumatra, Indonesia	227 898	9.3	7.96	50.9	5.67
2005	Sumatra, Indonesia	10	8.7	5.89	3.0	1.58
2006	Seram, Indonesia	4	6.7	5.50	3.5	1.81
2006	Java, Indonesia	802	7.7	6.76	10.0	3.32
2007	Solomon Islands	52	8.1	7.05	12.1	3.60
2009	Samoa Islands	192	8	7.54	22.4	4.48
2010	Southern Chile	156	8.8	7.43	29.0	2.81
2010	Sumatra, Indonesia	431	7.7	6.97	7.0	4.86
2011	East Japan	19 294	9.0	7.61	40.5	5.34

Table 6. Decision support for early tsunami warning using tsunami index and the proposed tsunami intensity and tsunami magnitude.

Tsunami Index			Tsunami Intensity		Tsunami height (m)	Tsunami magnitude M_I
Index TI	Generation ratio TR	Tsunami description	Intensity I	Intensity definition		
3	0.1	Advisory	I–V	Not felt – Strong	1	0
4	0.3	Small	VI	Slightly damaging	2	1
5	0.5	Moderate	VII–VIII	Damaging – Heavily damaging	4	2
6	0.7	Major	IX–X	Destructive – Very destructive	8	3
7	0.9	Destructive	XI	Devastating	16	4
8	1.0	Devastating	XII	Completely devastating	32	5

of R^2 are obtained (Fig. 4a–c). This result is verified and has a somewhat good agreement with the tsunami magnitude (Iida et al., 1967) in Fig. 5 and can be expressed together with the tsunami intensity and corresponding tsunami height (Papadopoulos and Imamura, 2001) in Table 6 when the logarithmic scale (base 2) is used for the tsunami height.

7 Conclusions

The Pacific Ocean is the location where two-thirds of the tsunamis have occurred. Countries surrounding the Pacific Ocean suffered from many tsunamis that caused a great number of deaths. This study utilized the historical tsunami database in the Pacific to compute the TR, which is defined as the ratio between the number of earthquake-generated tsunamis and the total number of earthquakes. The average TR in the Pacific Ocean is about 0.40, whereas the TR for

each region varies depending on the selected data period, pre-instrumental (prior 1900), early instrumental (1900–1962), instrumental (1963–1990) and modern instrumental (1991 to 2011). The TR for each region was calculated and shows the relationship between three influential parameters: earthquake magnitude, focal depth and sea depth. The results show that a greater magnitude earthquake at shallower focal depths has a high potential to generate tsunamis with a large tsunami height. The tsunami index (TI) was proposed to express the influence on tsunami generation and maximum tsunami height of the three parameters summarized above in one parameter and to successfully increase the coefficient of determination, R^2. This study indicates that recent submarine earthquakes had a higher potential to generate a tsunami with larger tsunami heights than during the entire last century. TR and TI are verified and can be well expressed together with the early proposed tsunami magnitude and tsunami intensity. The proposed TR and TI might be an important parameter for a decision support tool during the early tsunami warning stage or for future tsunami risk assessments.

Edited by: S. Tinti
Reviewed by: V. K. Gusiakov and another anonymous referee

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