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Tsunamis recorded in tide gauges at Costa Rica Pacific coast and their numerical modeling

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Abstract Here we perform an inventory of tsunamis recorded by tide gauges in the Pacific coast of Costa Rica. This paper also reveals nine tsunami records that had not been published before, at Puntarenas tide gauge corresponding to the 1979 Colombia tsunami and at Quepos tide gauge corresponding to the 1985 Mexico twin tsunamis, the 2010, 2014 and 2015 Chile tsunamis, the 2006 Tonga tsunami, the 2011 Japan tsunami and the 2013 Solomon Islands tsunami. The original record of 1990 Cóbano tsunami at Quepos was digitized again at a higher resolution and re-processed. The arrival of 1979, 1985, 2006 and 2014 tsunamis to Costa Rica is not listed on tsunami catalogs. The maximum tsunami height obtained here after processing 1990, 2011 and 2013 records was higher than reported on catalogs. The opposite happened for the 2010 tsunami. Quepos gauge record for January 2007 was analyzed as it seemed to have registered the Kuril Islands tsunami, but the results were not conclusive due to the low sample rate and the small tsunami amplitude if any. All those eleven tsunamis were modeled and the results compared with the records. A good agreement was obtained for the Quepos gauge, although the modeled 2011 and 2013 tsunamis had a difference of 8 min on the arrival time. An acceptable agreement was obtained for the Puntarenas gauge for 1979 tsunami, considering at least the first 4 h of the marigram is lost.

Keywords Tsunami record · Costa Rican tsunamis · Numerical model verification · Tide gauges

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1 Introduction

According to tsunami catalogs, in Costa Rica tsunamis have happened very sporadically and without major consequences in most cases (Molina 1997; NCEI/NGDC/WDS 2017). Traditionally, Costa Rican shores were sparsely populated, which could be the main reason for the scarce reports. There are only two deaths officially related to tsunamis, both in 1991 at the Caribbean coast, but unfortunately the tide gauge was not working at that time. At the Pacific coast, few local tsunamis have happened. The 1950 Nicoya tsunami caused run-ups of several meters near the source (Protti et al. 2001) but was unnoticed for the rest of the Pacific coastline, having a maximum height of only 10 cm at Puntarenas tidal gauge (NCEI/NGDC/WDS 2017). Similar behavior was observed for the 1992 Nicaragua tsunami, which had maximum run-up of nearly 10 m near the source in Nicaragua (NCEI/NGDC/WDS 2017), and about 4 m at Costa Rica locations near the Nicaraguan border (Fernández-Arce et al. 1993) but was also unobserved on the rest of the coastline. We consider 1992 Nicaragua tsunami as local because the earthquake rupture area extended almost to the Costa Rican border, even when occurred offshore Nicaragua. At least 19 tsunamis, both local and far field, have been registered at tide gauges in Puntarenas and Quepos, on the Costa Rica Pacific coast.

The US Geological Survey (USGS) deployed the first tide gauge in Costa Rica in Limón, Caribbean coast, in 1940; and at the Pacific coast in Puntarenas and Quepos in 1941 and 1957, respectively. Their goal was determining the tidal planes. Their local counterpart was the National Geographic Institute (IGN), who periodically sent the records (paper rolls) to USGS. Once processed, USGS returned the rolls to IGN who stored them until about 1993, 1979 and 1996 when Limón, Puntarenas and Quepos conventional stations were, respectively, uninstalled. Unfortunately, the paper rolls before 1969 were destroyed, and there are many gaps on the records in the last few years before the gauges were dismantled. After Hurricane Mitch hit Central America in 1998, Limón and Quepos tide gauges were re-installed with digital sensors and satellite data transmission. RONMAC Program of the Universidad Nacional (UNA) has been in charge of the sea level stations in Costa Rica and they installed two more gauges at Los Sueños (Herradura) and Papagayo (Costa Rica Central and North Pacific) during the past few years.

From paper records, USGS extracted hourly averages permanently and maximum wave height when a tsunami occurred, before sending them back to Costa Rica. Consequently, the maximum heights of tsunamis between 1941 and 1966 were registered at Puntarenas and/or Quepos gauges (NCEI/NGDC/WDS 2017), but the original marigrams are not available.

In the existing paper rolls from old tide gauges, after 1969, we recently discovered records of the arrival of three tsunamis to Puntarenas and Quepos unknown so far. The new gauge at Quepos also recorded six tsunamis in 2006, 2010, 2011, 2013, 2014, 2015 and possibly in 2007. None of these records have been published before. In the case of the 1979, 1985, 2006 and 2014 tsunamis, not even the maximum heights recorded in Costa Rica were included in international tsunami catalogs. The old Quepos gauge also recorded the small 1990 Cóbano tsunami (Gutiérrez and Soley 1991), which was modeled numerically in Chacón-Barrantes and Protti (2011).

In this paper, we make a review of the existing tsunami records in Costa Rica and model the eleven mentioned tsunamis to compare with the observations.

2 Records of historical tsunamis in the Costa Rica Pacific coast

Nowadays Costa Rica has three tide gauges at the Pacific coast: Quepos, Los Sueños and Papagayo; but until 1979 there was a gauge in Puntarenas as well (Fig. 1). Only two gauges recorded tsunamis so far: Puntarenas and Quepos.

Several tsunamis were reported on the Costa Rica Pacific coast without being recorded by any tide gauge. Some of them local: in 1579, 1854, 1905 and 1992 (Molina 1997; NCEI/NGDC/WDS 2017), and one far field: 1906 Colombia Mw 8.8 (Molina 1997). During 1992, the tide gauges at Puntarenas and Quepos were not working; the rest of those tsunamis occurred before any tide gauge was installed.

2.1 Tsunamis before 1969

As mentioned before, for the tsunamis recorded before 1969 only the maximum height recorded is available and not the marigram (Table 1). Some of those tsunamis were originated locally: two in 1941, one in 1950 and another one in 1952 (Fig. 1). Among them, only the 1950 Nicoya tsunami was large enough to be witnessed at plain sight. This tsunami was recorded at Puntarenas tide gauge with a maximum height of approximately 10 cm, and it was also reported to have been a couple of meters height at the western coast of the Nicoya Peninsula, near its generation region (Protti et al. 2001).

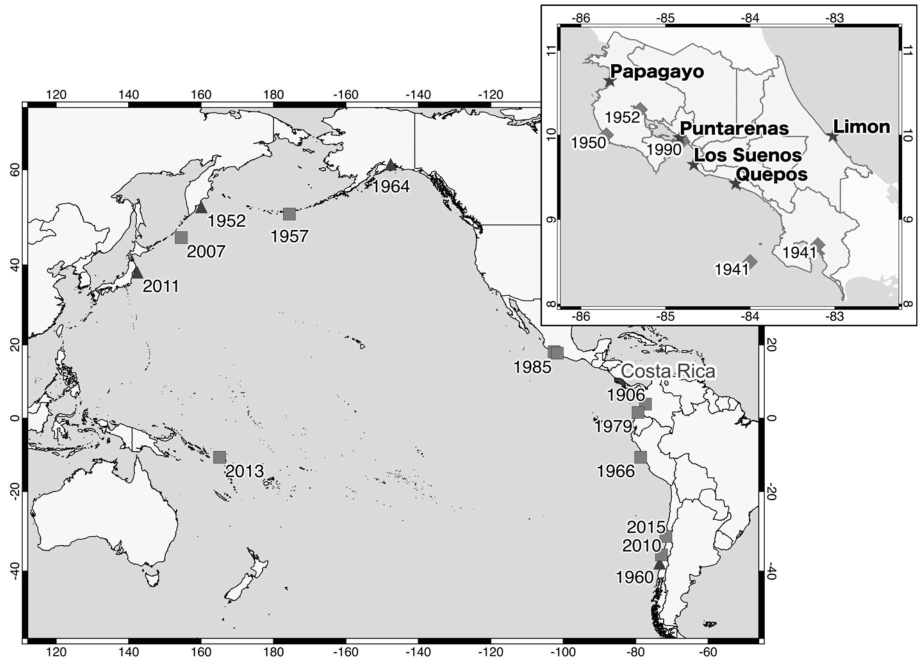

Fig. 1 Far-field tsunamis in the Pacific Ocean with records in Costa Rica. *Triangles* show tsunamis caused by Mw > 9.0 earthquakes and *squares* tsunamis caused by Mw < 9.0 earthquakes. For the 1906 tsunami, there are only witnesses' reports and no records in gauges (NCEI/NGDC/WDS 2017). In the insert, the epicenter of local tsunamis recorded at gauges (*diamonds*) and the position of tide gauges (*stars*) are shown

Table 1 Tsunami records at Costa Rican Pacific tide gauges before 1969 (NCEI/NGDC/WDS 2017)

Nr.	Date	Source	Mw	Tide gauge	Height (cm)
1	1941-12-05	Costa Rica–Panamá border	7.6	Puntarenas	23
2	1941-12-06	Costa Rica–Panamá border	6.9	Puntarenas	10
3	1950-10-05	Nicoya (Costa Rica)	7.8	Puntarenas	10
4	1952-05-13	Tempisque (Costa Rica)	6.9	Puntarenas	10
5	1952-11-04	Kamchatka	9.0	Puntarenas	30
6	1957-03-09	Aleutian Islands, USA	8.6	Puntarenas	12
7	1960-05-22	Chile	9.5	Puntarenas	43
				Quepos	55
8	1964-03-28	Alaska, USA	9.2	Puntarenas	15
				Quepos	20
9	1966-10-17	Peru	8.1	Quepos	20

Quepos and Puntarenas gauges also recorded tsunamis arriving from all around the Pacific Basin (Fig. 1). The 1952 Kamchatka Mw 9.0 tsunami was recorded at the tide gauge in Puntarenas with a maximum height of 30 cm. The 1960 Chile Mw 9.5 tsunami was recorded at Puntarenas tide gauge with a maximum height of 43 cm and at Quepos gauge of 55 cm. The 1964 Alaska Mw 9.2 tsunami was recorded also at both tide gauges in Puntarenas and Quepos, with a maximum height of 15 and 20 cm, respectively, as well as the 1966 Peru Mw 8.1 tsunami at Quepos tidal gauge with a maximum height of 20 cm. All those values were obtained from NGDC catalog (NCEI/NGDC/WDS 2017).

2.2 Tsunamis after 1969

Recently discovered paper records show the arrival of the 1979 Colombia Mw 7.9 tsunami and the 1985 México Mw 8.0 and 7.6 tsunamis to Puntarenas and Quepos tide gauges, respectively, as well as the original 1990 Cóbano Mw 7.0 tsunami marigram at Quepos. Those records were digitized and detided here.

The 1979 Colombian earthquake occurred at about 1:59 am Costa Rican time (7:59 UTC). It should have arrived to Puntarenas at about 4:00 am local time. Unfortunately, the tide gauge in Puntarenas was not working since the night before and started recording a small tsunami at about 8:00 am. The tide gauge in Quepos was not working that year.

In September 1985, two earthquakes hit the Pacific Coast of Mexico within 36 h. On September 19, a Mw 8.0 earthquake occurred at 7:18 am Costa Rican time (13:18 UTC), and on September 20, a smaller earthquake Mw 7.6 ruptured southeast of the first shock at 7:37 pm Costa Rican time (01:37 UTC of September 21). Both tsunamis were recorded at Quepos tide gauge with small amplitudes.

The 1990 Cóbano Mw 7.0 small tsunami was recorded at Quepos tide gauge. The paper marigram was digitized at a 10 min sample rate and published by Gutiérrez and Soley (1991). However, as that sample rate was too low for tsunami records, here we digitized again the paper record at a higher sample rate and re-processed it.

In November 2006, an Mw 8.3 thrust earthquake occurred at Kuril Islands, followed by an outer rise Mw 8.1 earthquake in January 2007. The tsunami caused by 2006 earthquake was larger than the one caused by 2007 earthquake (Fujii and Satake 2008). Cocos Island is a Costa Rican national park located at 500 km southeast from mainland. Park rangers reported to the authors the arrival of 2007 tsunami to the Island, strong enough to damage a couple of small boats, but they did not observe the 2006 tsunami which was larger, very likely because it arrived during the night time. Unfortunately, Quepos gauge was not working in November 2006. It was working in January 2007 and it might have registered the tsunami, although the amplitude seems to be too small.

Three Chilean tsunamis have been recorded at Costa Rica gauges during the past decade. The Mw 8.8 tsunami of 2010 was recorded at the Quepos tide gauge with small amplitude. However, at Coco's Island, the tsunami was clearly observed by the park rangers as a bore at Genius River mouth. The 2014 Mw 8.1 and the 2015 Mw 8.3 tsunamis were recorded at Quepos as well. The 2015 tsunami also provoked strong currents at Genius River mouth at Cocos Island, which were filmed by the park rangers.

In 2011, the Quepos tide gauge recorded a small tsunami after the Mw 9.1 earthquake in Japan. At Coco's Island, the tsunami funneled up the Genius River and at least 1 m of wave height can be inferred from the video taken by the park rangers. In 2013, a small tsunami was also registered in Quepos after the Mw 7.9 Solomon Islands earthquake. The 2006 Tonga Mw 8.0 tsunami was also recorded in Quepos with small amplitude, but the record was not known until now, as well as the record of the 2014 Chile tsunami.

3 Methodology

In this work, we focus on tsunamis arriving to Costa Rica Pacific shore for which marigrams are available: eleven tsunamis between 1979 and 2015.

3.1 Processing of marigrams

The paper marigrams of 1979, 1985 and 1990 tsunamis were scanned and digitized with an arbitrary height axis, as there was no height scale in the paper rolls. At that time, for both Puntarenas and Quepos, the sensor was a US Coast and Geodetic Survey Standard Automatic Gauge with a floating device, a continuous analogue record Leupold–Stevens, according to GLOSS Handbook.

Once digitized, the sea level axis was calibrated with the tide predictions for each station and date (Fig. 2). A high-pass filter was applied cutting at a period of 2.5 h. The paper roll corresponding to 1985-09-20 and 21 shows some inconsistencies on the time axis with the predicted tide. It was not possible to correct them, but their influence on the tsunami record was negligible.

The marigram of the 1990 Cóbano tsunami was digitized and detided in Gutiérrez and Soley (1991). However, the digitalization was done at a 10-min sample rate. Here we digitized the paper marigram again at a 30-s sample rate, and detided it.

In Quepos, a Suttron station was installed in late 1990s. The radar sensor recorded the 2006 and 2010 tsunamis, while the pressure sensor recorded the 2007, 2011, 2013, 2014 and 2015 tsunamis (Figs. 3, 4). The marigrams of 2006 and 2007 tsunamis were recorded at 6 min sample rate and all the marigrams after 2010 at 1 min sampling rate. They were filtered out using the same procedure as the paper records to eliminate the tide. An additional low-pass filter was applied cutting at a 3-min period to eliminate the noise from the 1985, 2013 and 2014 records.

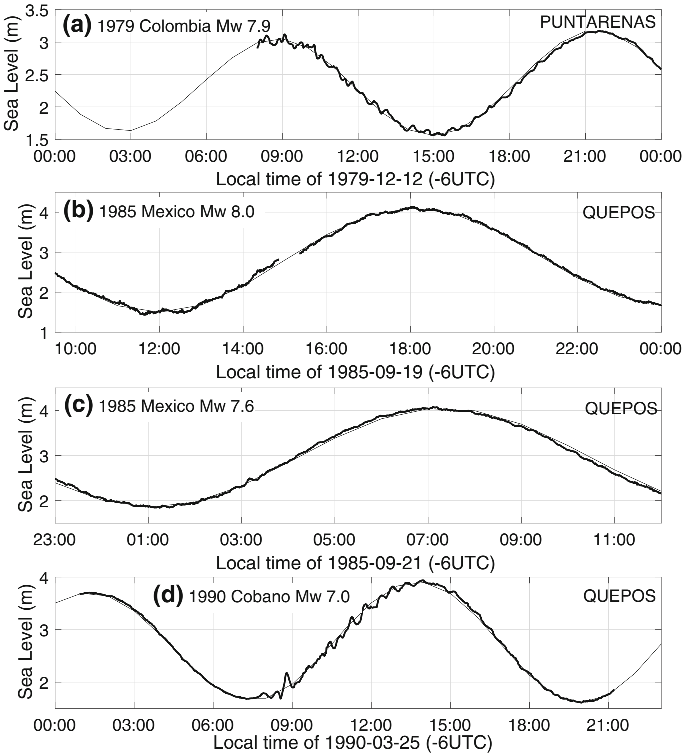

Fig. 2 Digitized marigrams of **a** the 1979 Colombia Mw 7.9 tsunami at Puntarenas and **b** 1985 México Mw 8.0, **c** 1985 México Mw 7.6 and **d** 1990 Cóbano tsunami at Quepos. The records are shown with a *thick line* and tide predictions with a *thin line*. All times are local (−6 UTC). About first 4 h of the 1979 marigram is lost; however, the tsunami was clearly recorded. The first 1985 tsunami is well defined in the marigrams, but it was hard to locate the second tsunami as it occurred only about 36 h after the first

3.2 Numerical model

Community-Based Model Interface for Tsunami (ComMIT) is a graphic user interface (GUI) of MOST numerical model (Titov et al. 2011). It was designed to perform tsunami hazard assessments in the aftermath of the 2004 Indonesia tsunami as a joint effort of United Nations Educational, Scientific and Cultural Organization (UNESCO), US Agency for International Development (USAID) and National Oceanic and Atmospheric Administration of the United States (NOAA). The seismic source can be defined by a linear combination of pre-calculated unitary sources or by user-defined seismic parameters.

ComMIT solves linear shallow water equations in the incorporated 4 arc-min propagation grid covering the whole Pacific Ocean. Then, the user defines three inundation grids nested online between them and offline to the propagation grid. Nonlinear shallow water equations are solved for the inundation grids. In this case, the inundation grids had resolutions of 60, 12 and 4 arc-s, for both Puntarenas and Quepos, named A, B and C. Grids A and B were the same for both locations. The bathymetry of the model was obtained combining GEBCO-08 data up to 200 m depth and digitized nautical charts for depths less than 200 m. However, in both Puntarenas and Quepos the data on the nautical charts are outdated and not suitable for detailed inundation studies. The topography was obtained

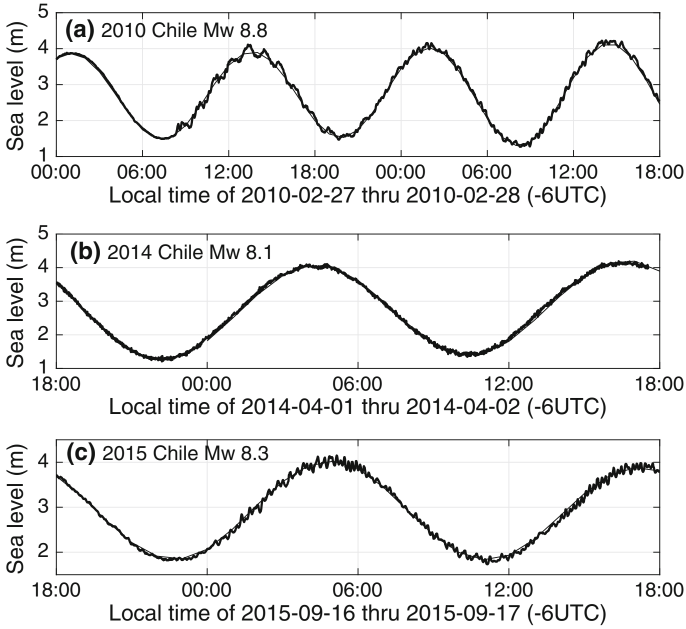

Fig. 3 Marigrams of the **a** 2010 Chile Mw 8.8, **b** 2014 Chile Mw 8.1 and **c** 2015 Chile Mw 8.3 tsunamis at Quepos. The records are shown with a *thick line* and tide predictions with a *thin line*. All times are local (−6 UTC)

from high-resolution LIDAR data owned by the Costa Rica National Emergency Commission (CNE).

3.3 Tsunami sources

We considered eleven historical scenarios, one local: 1990 Cóbano Mw 7.0 and ten far-field tsunamis: 1979 Colombia Mw 7.9, 1985 México Mw 8.0, 1985 México Mw 7.6, 2006 Tonga Mw 8.0, 2007 Kuril Islands Mw 8.0, 2010 Chile Mw 8.8, 2011 Japan Mw 9.0, 2013 Solomon Islands Mw 7.9, 2014 Chile Mw 8.1 and 2015 Chile Mw 8.3. The seismic sources employed for tsunamis after 2006 are included in the ComMIT model as linear combination of unitary sources obtained from the inversion of tsunami records at DART buoys (Deep-Ocean Assessment and Reporting of Tsunamis) and tide gauges.

For the 1979 and 1985 tsunamis, the seismic sources were approached using ComMIT unitary sources based on the parameters given in UNAM Seismology Group (1986) for México, and a personal communication with the Observatorio Sismológico del Suroeste de Colombia (OSSO). For the 1979 Colombia earthquake, four unitary sources (cs41a, cs41b, cs42a and cs42b) were employed for a total area of 200 × 100 km^2 with a mean slip of 2.7 m. For the first 1985 México tsunami, two unitary sources (cs06a and cs07a) with a total area of 200 × 50 km^2 were considered with a 2.8 m mean slip. For the second 1985 tsunami, one unitary source (cs09b) covering 100 × 50 km^2 was employed with a 3.3 m mean slip.

For the only local tsunami modeled, 1990 Cóbano, a customized seismic source was employed following the parameters given in Chacón-Barrantes and Protti (2011).

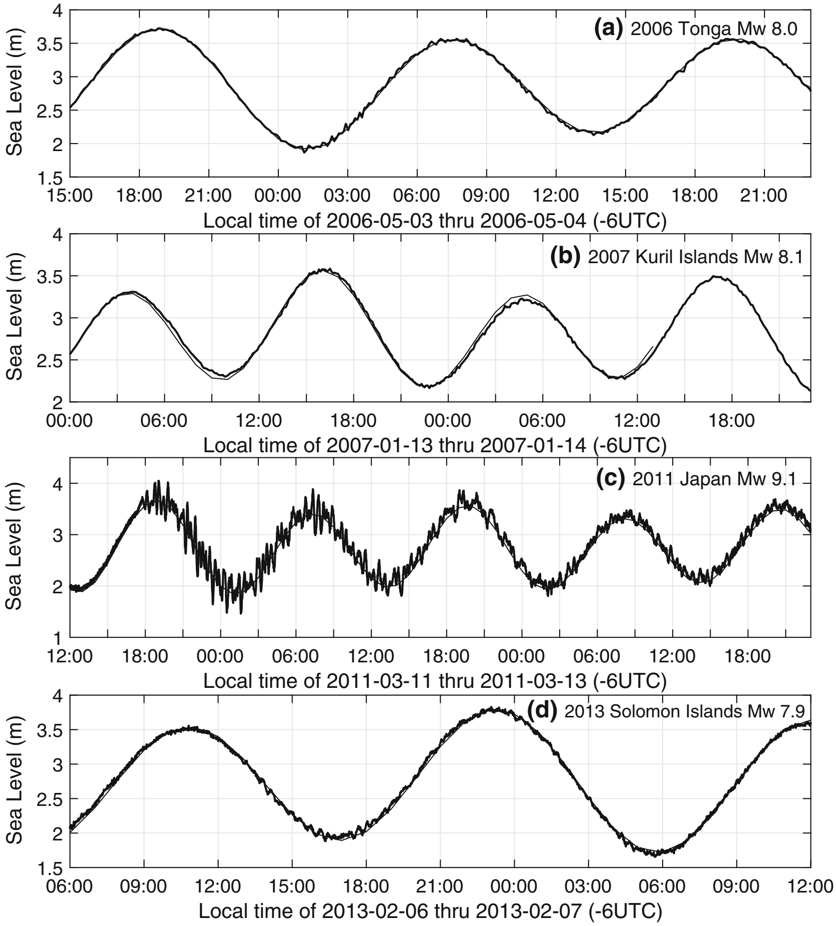

Fig. 4 Marigrams of the **a** 2006 Tonga Mw 8.0, **b** 2007 Kuril Islands Mw 8.1, **c** 2011 Japan Mw 9.0 and **d** 2013 Solomon Islands Mw 7.9 tsunamis at Quepos. The records are shown with a *thick line* and tide predictions with a *thin line*. All times are local (−6 UTC)

4 Results

As mentioned before, paper marigrams of the 1979 Colombian Mw 7.9 tsunami and both 1985 México tsunamis (Mw 8.0 and 7.6) were recently found. The marigrams were processed to extract the tsunami signal, which is very clear for the 1979 tsunami (Fig. 5a). This tsunami was recorded in Puntarenas, but unfortunately about the first 4 h of the marigram is lost. The remaining record shows a maximum height of 13.5 cm, and the model calculated a maximum tsunami height of 13.2 cm (Fig. 5a; Table 2).

The 1985 tsunamis occurred within 36 h of each other; consequently, we cannot discard interference between them. The first 1985 tsunami record had a maximum height of 8.5 cm, and the model resulted in a maximum height of 6.5 cm (Fig. 5b; Table 2). The second tsunami was small, and the gauge record on those days was quite noisy, very likely due to subsequent reflections of the first tsunami; therefore, the arrival of the second 1985 tsunami to Quepos is not clear (Fig. 6). Using the modeled arrival time for the second 1985

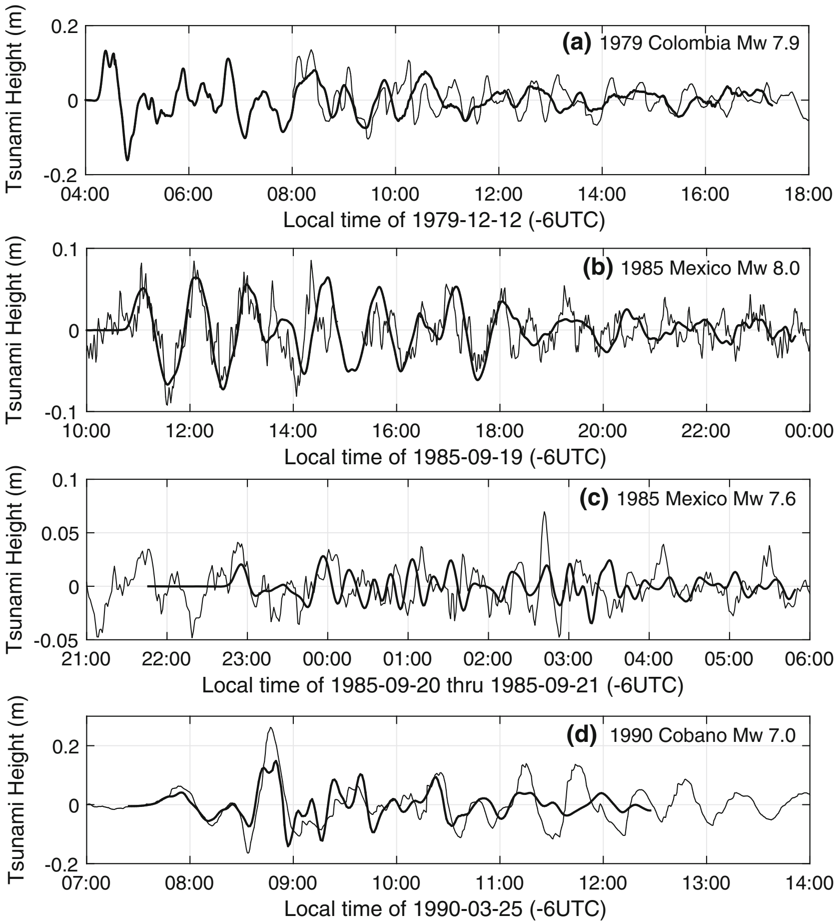

Fig. 5 Model results (*thick line*) compared to filtered records (*thin line*) of the **a** 1979-12-12 Colombia tsunami at Puntarenas, **b** the 1985-09-19 México tsunami, **c** the 1985-09-21 México tsunami and **d** the 1990-03-25 Cóbano tsunami at Quepos. In all cases, local time (−6 UTC) is shown. The largest peak of the second 1985 México tsunami was not well reproduced by the model. This peak might be a consequence of the superposition of the two tsunamis

tsunami, we determined a maximum height of 6.9 cm for the recorded tsunami and a maximum height of 2.8 cm was modeled (Fig. 5c; Table 2). Yet, there is a peak at about 21:40 of comparable height that might be the real first arrival, remaining of the first tsunami or just noise.

As mentioned before, the 1990 Cóbano tsunami was already modeled by Chacón-Barrantes and Protti (2011). However, the tsunami record employed in that work was digitized by Gutiérrez and Soley (1991) at a 10 min sample rate (Fig. 7). Here, the record was digitized again at 30 s sample rate and detided using the same procedure as the other historical records. The maximum observed tsunami height obtained by Gutiérrez and Soley (1991) was 0.71 ft (21.3 cm), and the maximum obtained here was 26 cm. The numerical modeling of this tsunami resulted in a maximum tsunami height of 15 cm.

Table 2 Maximum observed and modeled tsunami heights for the historical scenarios considered (after 1969). Maximum height reported before at G: Gutiérrez and Soley (1991), N: NCEI (2017)

Nr.	Date	Place	Mw	Obs. max. height (cm)	Mod. max. height (cm)	Location	Height at tsunami catalogs (cm)	Sampling rate
10	1979-12-12	Colombia	7.9	13.5+[1]	13.2	Puntarenas	–	Paper roll digitized at 30 s
11	1985-09-19	México	8.0	8.5	6.5	Quepos	–	Paper roll digitized at 30 s
12	1985-09-21	México	7.6	7.0	2.8	Quepos	–	Paper roll digitized at 30 s
13	1990-03-25	Cóbano	7.0	26	15	Quepos	21.3 (G)	Paper roll digitized at 30 s
14	2006-05-03	Tonga	8.0	7.9	9.6	Quepos	–	6 min
15	2007-01-13	Kuril Is.	8.1	2.9?[2]	3.6	Quepos	–	6 min
16	2010-02-27	Chile	8.8	19.6	27.0	Quepos	24 (N)	1 min
17	2011-03-11	Japan	9.1	53.8	44.2	Quepos	50 (N)	1 min
18	2013-02-06	Solomon Is.	7.9	7.0	5.6	Quepos	4 (N)	1 min
19	2014-04-01	Chile	8.1	3.6	2.2	Quepos	–	1 min
20	2015-09-16	Chile	8.3	17.8	7.9	Quepos	15 (N)	1 min

[1] About the first 4 h of the marigram is lost, therefore the maximum tsunami height was very likely larger than this value

[2] It was not possible to conclude if this was an actual tsunami record

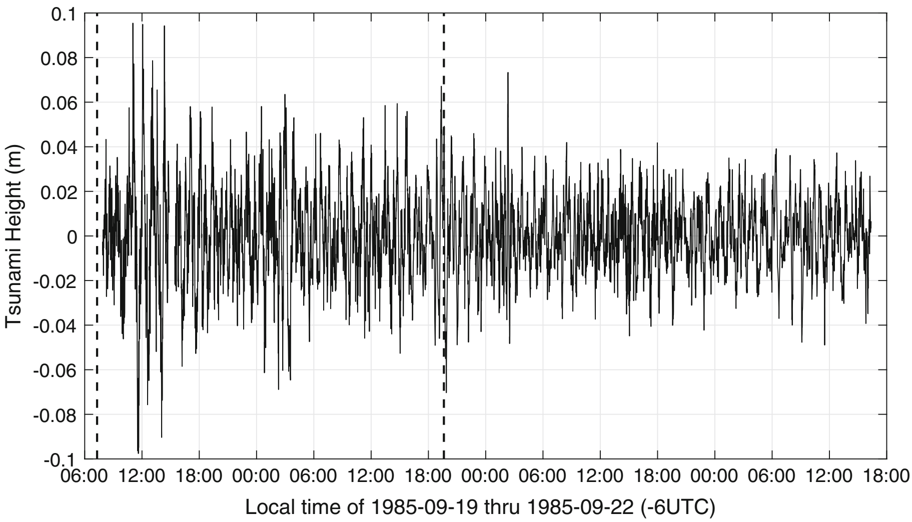

Fig. 6 Filtered gauge records from 1985-09-19 through 1985-09-22 at Quepos. *Dashed lines* show the earthquakés time span. All times are local (−6 UTC). It seems to be superposition of both tsunamis

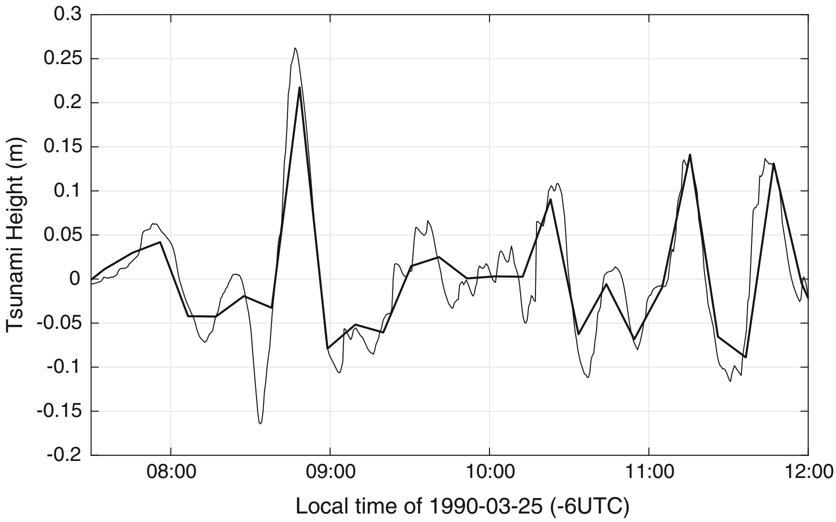

Fig. 7 *Thick line* shows the 1990 Cobano tsunami marigram digitized at a 10 min sample rate and detided by Gutiérrez and Soley (1991). *Thin line* shows the same marigram digitized here at 30 s sample rate and detided. Higher sample rate allowed re-defining the tsunami maximum height of 26 cm instead of 21.3 cm previously reported by Gutiérrez and Soley (1991)

In Fig. 8, the marigrams and model results for the Chilean tsunamis at Quepos tide gauge are compared. For the 2010 tsunami, the maximum observed height was 19.6 cm and the maximum simulated height was 27 cm. For 2014 and 2015 tsunamis, the maximum heights recorded were 3.6 and 17.8 cm and the maximum heights obtained with the model were 2.2 and 7.9 cm, respectively.

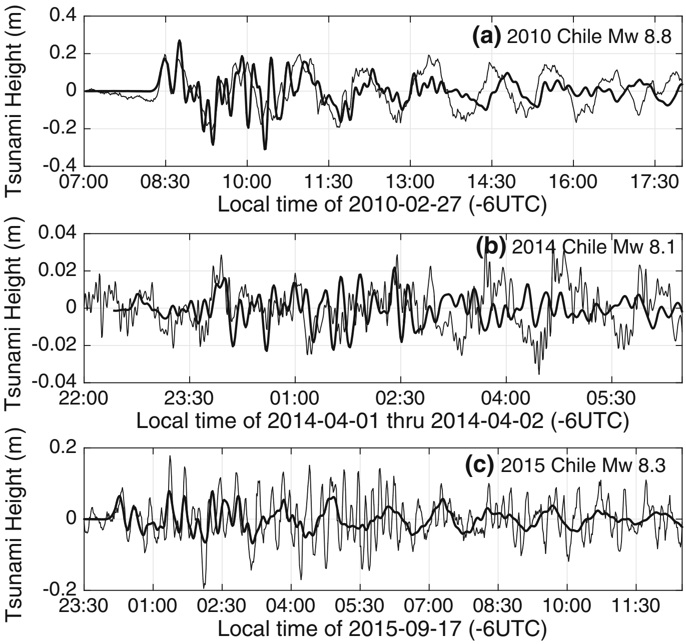

Fig. 8 Model results (*thick line*) compared to filtered records (*thin line*) of the **a** 2010 Chile Mw 8.8, **b** 2014 Chile Mw 8.1 and **c** 2015 Chile Mw 8.3 tsunamis. In all cases, local time (−6 UTC) is shown. Good agreement obtained except for 2015: The tidal gauge was relocated in December 2014

For the 2011 Japan and 2013 Solomon Islands tsunamis (Fig. 9), the maximum heights recorded were 53.8 and 7 cm, respectively, and the maximum heights obtained with the model were 44.2 and 5.6 cm. For these two cases the modeled tsunami arrived 8 min earlier compared with the records, not shown in the figure. No delay was obtained for any other tsunamis, including the 2006 Tonga tsunami, for which the observed maximum height was 7.9 cm versus a modeled maximum height of 9.6 cm. For the 2007 Kuril Islands tsunami, the original gauge records appeared to show the tsunami arrival (Fig. 4b), but once the filter was applied the tsunami seemed to have amplitudes comparable to noise. The maximum height of the filtered records is 2.9 cm and the maximum modeled tsunami height was 3.6 cm.

5 Discussion

The 2015 Chile tsunami showed the largest differences between the modeled and observed heights. In late 2014, Quepos tide gauge was relocated inside a recently built marina, and the up to date bathymetry of the marina and its surroundings was not available for this study, being very likely the reason for the differences between observed and modeled tsunami. Still, the results of the model are within the order of magnitude of the recorded tsunami for that case and the modeled waveform adjusted well to the records.

The 2014 Chile and 2007 Kuril Islands tsunamis had the smallest amplitudes among the records analyzed here. The filtered record of Quepos gauge during the expected arrival of 2007 Kuril Islands tsunami showed a maximum height of 2.9 cm. However, due to the low sampling rate (6 min) and the low amplitude, it was not possible to separate the tsunami

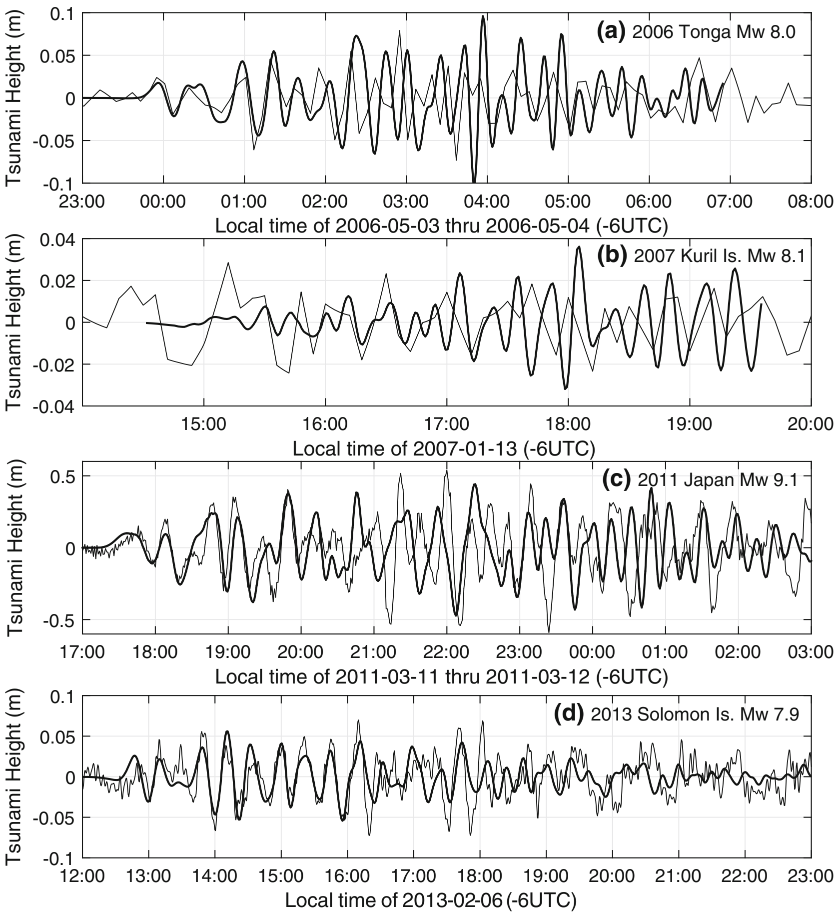

Fig. 9 Model results (*thick line*) compared to filtered records (*thin line*) of the **a** 2006 Tonga Mw 8.0, **b** 2007 Kuril Islands Mw 8.1, **c** 2011 Japan Mw 9.0 and **d** 2013 Solomon Islands Mw 7.9 tsunamis. Both 2011 and 2013 simulated tsunamis arrived with 8 min delay to Quepos, which were corrected in the figure. In all cases, local time (−6 UTC) is shown. It is not possible to conclude if 2007 tsunami was actually recorded at Quepos, due to small wave heights and low sample rate

signal from the noise. Also the model results did not agree with the supposedly recorded waveform, and then we could not conclude on the maximum tsunami height observed. On the opposite, for the 2014 Chile tsunami it was possible to identify the tsunami signal based on the model results, probably because the higher sampling rate.

Apparently Chilean tsunamis do not represent a major threat for Costa Rican shores, based on historical records. Four Chilean tsunamis were recorded in Costa Rican gauges so far, and the maximum tsunami heights were about half a meter, even including the largest earthquake measured worldwide, the 1960 Mw 9.5. Among these four tsunamis, the 2014 generated in the North of Chile had the smallest earthquake magnitude and the smallest maximum height recorded at Quepos. The 2010 and 2015 tsunamis had a similar maximum height at Quepos, despite their difference in magnitude, indicating the influence of directivity effects (Fig. 10). Following this, Costa Rica might be more vulnerable to tsunamis generated on central and south Chile.

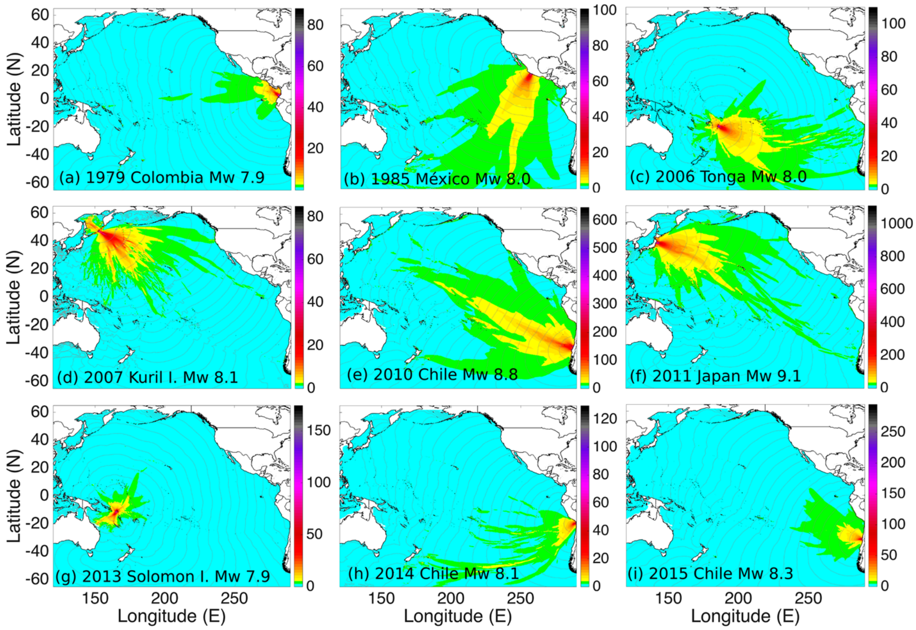

Fig. 10 Energy plots of nine historical far-field tsunamis simulated here: **a** 1979 Colombia Mw 7.9, **b** 1985 México Mw 8.0, **c** 2006 Tonga Mw 8.0, **d** 2007 Kuril Islands Mw 8.1, **e** 2010 Chile Mw 8.8, **f** 2011 Japan Mw 9.1, **g** 2013 Solomon Islands Mw 7.9, **h** 2014 Chile Mw 8.1 and **i** 2015 Chile Mw 8.3 tsunamis. *Color scales* are different for each subplot as the goal is to show tsunami directivity

On the contrary, large earthquakes originated at the southwest Pacific might have important effects on Costa Rican shores despite the distance. According to NGDC catalog (NCEI/NGDC/WDS 2017), 2006 Tonga tsunami had maximum amplitude of 27 cm at American Samoa and at Crescent City, California, USA. That tsunami arrived to Quepos with a maximum height of almost 8 cm, a comparable maximum height to the 2013 Solomon Islands tsunami that had a maximum height of 11 m near its source. Even when 8 cm is not significant in terms of threat, it was only a third of the maximum height recorded for that tsunami in the near field, even after crossing the entire Pacific Ocean.

For 2013 Solomon Islands tsunami, the NGDC catalog (2017) reported 4 cm of maximum height at Quepos and here we obtained 7 cm after the data processing (Table 2). The entry on that tsunami catalog is referenced to the data provided by the Pacific Tsunami Warning Center (PTWC), but there is no information on how the maximum height was obtained. There is also a discrepancy between maximum heights reported at NGDC catalog (2017) for 2010 and 2011 tsunamis, both entries also based on heights reported by PTWC without references on the methodology. For the 2010 tsunami, a maximum height of 24 cm is listed and we obtained 19.6 cm, and for 2011 tsunami a maximum height of 50 cm is listed and we obtained 53.8 cm. Still, these discrepancies are not significant.

As mentioned before, the simulated Japan and Solomon Islands tsunamis arrived 8 min earlier than the recorded tsunamis. This difference on arrival times did not appeared for the rest of the tsunamis simulated here, including the Tonga tsunami. The time on the marigrams was confirmed by the predicted tide in all cases. The tsunami sources employed for tsunamis after 2006 were defined by NCTR using a linear combination of unitary sources, based on an inversion of many tsunami records at tide gauges and deep-ocean buoys, and the modeled tsunamis should agree well with the recorded ones, both in height and time. The authors have no explanation for the discrepancy on the arrival time in these cases.

For the 1979 and both 1985 tsunamis, the sources employed were defined by the authors using a linear combination of ComMIT unitary sources based on information provided in the literature, and no tsunami inversion was performed. For the second 1985 tsunami, there is a larger underestimation of the maximum tsunami height despite trying several unitary sources. The highest peak of 7 cm was recorded at about 2:20 h of 1985-09-21, but the model predicted a 1.34-cm-height peak at that time. The 1985 tsunamis occurred within 36 h of each other and it was not possible to separate the records of each tsunami, particularly because the second tsunami was rather small. Inaccuracies at the source definition might be at least partly responsible for differences between the recorded and modeled tsunamis for the 1979 and the second 1985 tsunami. The tsunami heights of the first 1985 tsunami were slightly underestimated although the waveform agreed very well with the records, meaning the chosen linear combination of unitary sources worked fine.

The agreement obtained here for the record of 1979 tsunami at Puntarenas gauge was not conclusive. The model results agreed on the maximum tsunami height, but the gauge started to record the tsunami after 4 h of the supposed arrival. It is not possible to know whether the tsunami waves during the first 4 h were higher than the waves recorded, and it is not possible to know neither the accuracy of the source employed nor the model setup. Puntarenas is located inside Nicoya Gulf at a very narrow sandbar, and the merging of bathymetric and topographic data should be done very carefully. A bathymetric survey is planned for 2017 followed by the merging of bathymetric and topographic data. Better results might be achieved afterward. Also the RONMAC Program is planning to re-deploy Puntarenas gauge during 2017, in collaboration with the Meteorological Institute (IMN), allowing the recording of tsunamis in the future.

A bore formed at Genius River mouth on Coco's Island after the 2010 Chile tsunami, and a bore was also recorded in video after the 2011 Japan and the 2015 Chile tsunamis at the same place. Coco's Island is the only emerged mountain on Cocos Plate, located at about 500 km southeast from Costa Rica mainland. Unfortunately, our model is too coarse there to estimate a maximum tsunami height, but the RONMAC Program is working on deploying a tide gauge at Coco's Island in collaboration with the National Emergency Commission (CNE) and NOAA.

Having an accurate and updated national database of tsunami records is very important for threat analysis. The recovery and analysis of so far unknown tsunami records performed here contributes largely to this database for Costa Rica. Also, the re-processing of 1990 marigram allowed refining the tsunami waveform correcting the maximum observed tsunami height of 26 cm instead of 21 cm. The waveform was reproduced acceptably well by the model, although there is an underestimation of the maximum height, very likely due to uncertainties on the source. Source definition is particularly important for near-field tsunamis, and here we approximated a homogeneous slip instead of a slip distribution.

6 Conclusions

Here we released ten unpublished tsunami records at Costa Rican gauges, and re-processed one published before. The modeling of those historic tsunamis was performed: ten of them for Quepos and one for Puntarenas.

For Puntarenas, the model was not able to reproduce the tsunami waveform, but it gave reasonable tsunami maximum heights. Due to its location and geomorphology, Puntarenas is particularly sensitive to bathymetry quality. A bathymetric survey is planned for 2017 allowing a more realistic model setup. Also the tide gauge in Puntarenas will be re-installed this year.

For Quepos, the model reproduced quite well the observed tsunami waveforms before December 2014, when the gauge was relocated at a recently built marina. This marina encloses only a small portion of the coast in Quepos, and the agreement on tsunami records before the marina was very good, as well as the agreement on the tsunami waveform for the 2015 tsunami. However, it is recommended to update the model including the marina where the new tide gauge is located to be able to reproduce future tsunami waveforms recorded there.

Despite the good agreement on tsunami waveforms for most of the recorded tsunamis in Quepos, the tsunami heights were underestimated for all cases but the 2006 Tonga and 2010 Chile, for which the model overestimated the heights. These underestimations should be considered if the model setup is employed for forecast purposes. However, in all cases, the modeled height and the observed height are within the same order of magnitude.

Before this work, the Costa Rican tsunami database included 21 tsunamis entries for the Pacific coast, both local and far field. Witnesses reported seven tsunamis, and tide gauges recorded 14 tsunamis. For nine of the tide gauge records, only the maximum tsunami height is available. Only one of the five available marigrams had been published before: the 1990 local tsunami, which was re-processed here, and its maximum height updated. The other four marigrams had remained unpublished until now although their maximum height was listed in catalogs. Here we unveiled six more records of small tsunamis at tide gauges between 1979 and 2014, consisting of the complete marigram recorded, for an updated total of 27 entries, none of which has caused damages or casualties in the Costa Rica Pacific coast. This increase by about a third on the number of entries on the national tsunami database is worthy for tsunami threat analysis and model verification.

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