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The 2017 México Tsunami Record, Numerical Modeling and Threat Assessment in Costa Rica

Silvia Chacón-Barrantes[1]

Abstract—An M_w 8.2 earthquake and tsunami occurred offshore the Pacific coast of México on 2017-09-08, at 04:49 UTC. Costa Rican tide gauges have registered a total of 21 local, regional and far-field tsunamis. The Quepos gauge registered 12 tsunamis between 1960 and 2014 before it was relocated inside a harbor by late 2014, where it registered two more tsunamis. This paper analyzes the 2017 México tsunami as recorded by the Quepos gauge. It took 2 h for the tsunami to arrive to Quepos, with a first peak height of 9.35 cm and a maximum amplitude of 18.8 cm occurring about 6 h later. As a decision support tool, this tsunami was modeled for Quepos in real time using ComMIT (Community Model Interface for Tsunami) with the finer grid having a resolution of 1 arcsec ($\sim$ 30 m). However, the model did not replicate the tsunami record well, probably due to the lack of a finer and more accurate bathymetry. In 2014, the National Tsunami Monitoring System of Costa Rica (SINAMOT) was created, acting as a national tsunami warning center. The occurrence of the 2017 México tsunami raised concerns about warning dissemination mechanisms for most coastal communities in Costa Rica, due to its short travel time.

Key words: 2017 México tsunami, Costa Rica, tsunami preparedness, tsunami records, tsunami real-time modeling.

1. Introduction

Since its creation, the National Tsunami Monitoring System of Costa Rica (SINAMOT) has processed 178 tsunami bulletins from the Pacific Tsunami Warning Center (PTWC): 158 on the Pacific coast and 20 on the Caribbean coast. None of those events presented a threat for Costa Rica, and only two additional tsunamis were registered on tide gauges since then: the 2015 Chile tsunami (Heidarzadeh et al. 2016; Satake and Heidarzadeh 2017) and 2017 México tsunami.

According to the National Seismological Service of México (SSN-Mexico 2017) located at the Universidad Nacional Autónoma de México (UNAM), the México M_w 8.2 earthquake occurred at 22:49, on Thursday September 7, Costa Rican local time (September 8th, 04:49 UTC). Its epicenter was located at 14.761°N and 94.103°W (red star in Fig. 1a) (SSN-México 2017). The earthquake triggering mechanism for this tsunami suggested that this was an intra-plate event with normal faulting within Cocos plate, and not an inverse-thrust plate boundary interface earthquake (Gusman et al. 2018; Okuwaki and Yagi 2017). The tsunami had a maximum runup of 2.7 m at Boca del Cielo, Chiapas, México (BC at Fig. 1), and had amplitudes and runups over 1 m only within 200 km from the epicenter (red and orange dots and diamonds in Fig. 1) (NCEI/NGDC/WDS 2017; Ramírez-Herrera et al. 2018). The maximum amplitude basin-wide of this tsunami measured by tide gauges was 1.76 m at Puerto Chiapas, México (PCh in Fig. 1) (NCEI/NGDC/WDS 2017; Ramírez-Herrera et al. 2018).

PTWC sent a first tsunami threat message only 5 min after the earthquake (PTWC 2017a). This first message estimated an M_w 8.0 and a 33 km depth, issuing a tsunami threat for México, Panamá, Ecuador and Central America (Guatemala, Honduras, El Salvador, Nicaragua and Costa Rica) based only on the epicenter distance. The estimated time of arrival (ETA) for Costa Rica was 00:18 at Cabo Santa Elena, 00:42 at Quepos and Cocos Island, and 00:46 at Cabo Matapalo, (CRT, local times) on Friday, September 8. The forecasted tsunami travel time (TTT) was only 1 h and 29 min to the nearest coastal location in Costa Rica. In the second tsunami bulletin from PTWC the earthquake magnitude was increased to M_w 8.2, but the threat level for Costa Rica was lower, forecasting maximum tsunami heights of less than

[1] RONMAC Program and SINAMOT, Depto. de Física, Universidad Nacional, Apdo. 86-3000, Heredia, Costa Rica. E-mail: silviachaconb@gmail.com

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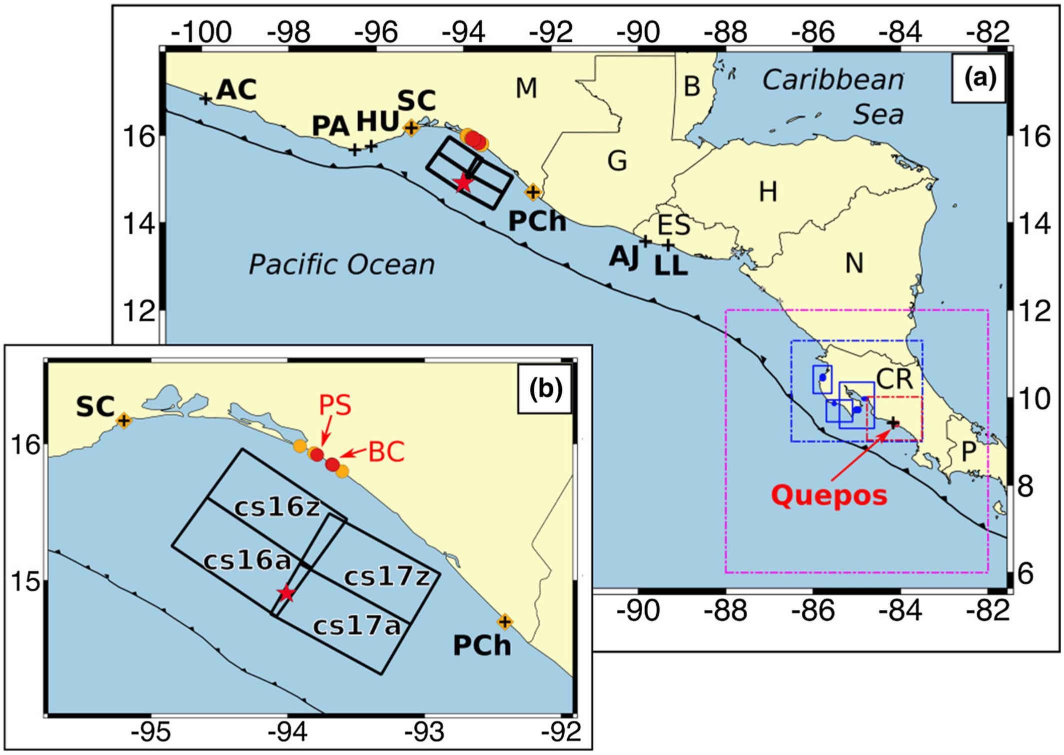

Figure 1
Regional summary. **a** Earthquake epicenter is depicted with a red star. Tide gauges are represented with crosses. AC: Acapulco, PA: Puerto Ángel, HU: Huatulco, SC: Salina Cruz, PCh: Puerto Chiapas, AJ: Acajutla, LL: La Libertad and Quepos. Measured tsunami runups over 1 m are shown as orange dots, and over 2 m runups as red dots (PS: Playa del Sol and BC: Boca del Cielo, both in México); tsunami amplitudes over 1 m are plotted with orange diamonds (NCEI/NGDC/WDS 2017; Ramírez-Herrera et al. 2018). ComMIT grids for the Costa Rican Pacific Coast are delimited with purple, blue and red rectangles. Grids A are shown as dash–dotted rectangles with resolutions of 60 arcsec (purple) and 30 arcsec (blue and red). Grids B are shown as solid thin rectangles with resolution of 5 arcsec (red and blue), grid B for low-resolution model has the same extent as grid A shown in blue. Grids are shown with more detail in Fig. 4. Countries are M: México, G: Guatemala, ES: El Salvador, H: Honduras, N: Nicaragua, CR: Costa Rica and P: Panamá. **b** Unit fault planes used to define the tsunami initial condition (black rectangles) are named cs16a, cs16z, cs17a and cs17z. The co-seismic deformation caused by the unit faults was multiplied by the mean slip and added up to obtain the tsunami initial condition

30 cm. This bulletin was issued at 23:24 (local time) on Thursday September 7, 54 min before the first ETA to the Costa Rican shores.

In this document, the author will describe the numerical modeling and threat analysis performed by SINAMOT for the 2017 México tsunami. Also, since the Quepos tide gauge was relocated, the author will attempt to verify a new set of grids. These grids were created with new bathymetric data surveyed on July 2017 offshore Marina Pez Vela in Quepos. Finally, the contribution to the Costa Rica tsunami preparedness derived from all these efforts will be discussed.

2. *2017 México Tsunami Recorded in Costa Rica*

Costa Rica has three tide gauges located at its Pacific coast, but only the Quepos gauge was working when the Mexican tsunami occurred (Fig. 1). Quepos tide gauge was deployed in 1957, being the oldest gauge that is currently operational and registering a total of 14 tsunamis so far (Chacón-Barrantes and Gutiérrez-Echeverría 2017). In December of 2014, the gauge was relocated to the entrance of Marina Pez Vela. The tsunami arrived at this gauge at 00:50 h on Friday, September 8, local time. The first peak had an amplitude of 9.35 cm and occurred at 01:07 h; the maximum amplitude was 18.8 cm at 06:58 h, both

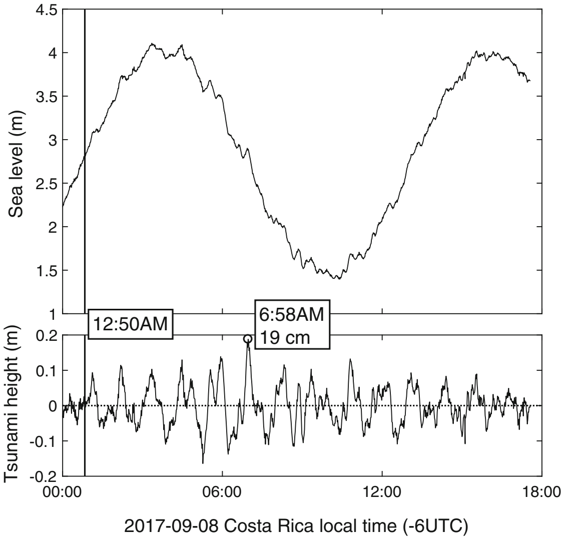

Figure 2
2017 México tsunami registered at the Quepos tide gauge. Upper panel: Original gauge record including tide. Lower panel: Filtered tsunami record

local times (Fig. 2b). PTWC forecasted maximum tsunami amplitudes of less than 30 cm for Quepos (PTWC 2017b), which matched with the observations. The tsunami signal is clear before and after the tide was removed (Fig. 2a, b respectively), with a signal-to-noise ratio of 6:1 (Fig. 3). The signal-to-noise ratio was calculated in decibels by computing the ratio of the signal summed squared magnitude to that of the noise and then converted to power ratio.

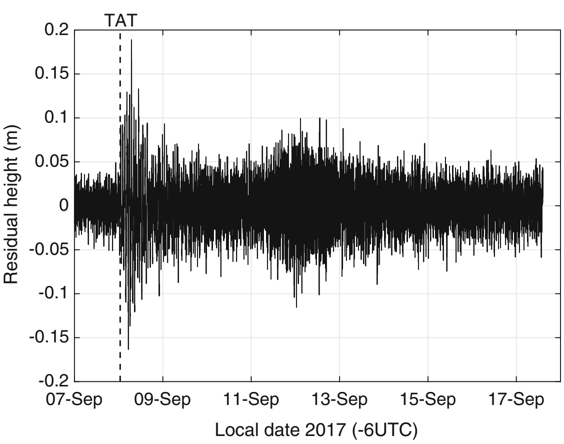

Figure 3
Filtered record of the Quepos tide gauge from September 7 to September 17, 2017. The maximum tsunami amplitudes were 18.8 cm above zero and 16.4 cm below zero. Thick dashed line shows the tsunami arrival time (TAT)

For several days after the arrival of the tsunami, the noise at the gauge seemed to be larger; this might be due to a small resonance.

3. Numerical Modeling Methodology

SINAMOT (National Tsunami Monitoring System of Costa Rica) and the RONMAC Program (Sea Level Observation Network and Coastal Threats Research Program) use several tsunami numerical models. Those models are NEOWAVE: Non-Hydrostatic Evolution of Ocean WAVE (Yamazaki et al. 2010), TUNAMI: Tohoku University Numerical Analysis Model for Investigation of near field tsunamis (Goto et al. 1997) and ComMIT: COMmunity Model Interface for Tsunami, based on MOST (Titov et al. 2011). However, for real-time tsunami forecasts, the ComMIT model is preferred.

ComMIT is a graphical user interface of the MOST numerical model (Titov et al. 2016), using a linear combination of pre-calculated unit sources (named solution) as the initial condition for the tsunami. Unit sources are fault planes with a length of 100 km, a width of 50 km, 1 m mean slip and a 90° rake, covering subduction zones within the Pacific, Atlantic and Indian basins. When a coastal earthquake occurs, the National Center for Tsunami Research (NCTR) from NOAA (National Oceanographic and Atmospheric Administration of the United States of America) publishes solutions that can be downloaded from ComMIT. Usually, the first versions of those solutions are based only on seismic information and later versions are inversions of tsunami records at deep-ocean buoys (DART). For the México tsunami, the solutions based on seismic parameters compared well with DART records. NCTR solutions are research products that are not operational; therefore, they may not be available to all users or for all tsunamis in real time. Still, SINAMOT is able to use ComMIT with its own tsunami source solutions based on observations and scale relationships if needed.

SINAMOT has established sets of nested grids for Quepos, Puntarenas, Tambor, Sámara and Potrero, in the Costa Rican Pacific coast. The extent of these grids is shown in Figs. 1 and 4. The size and

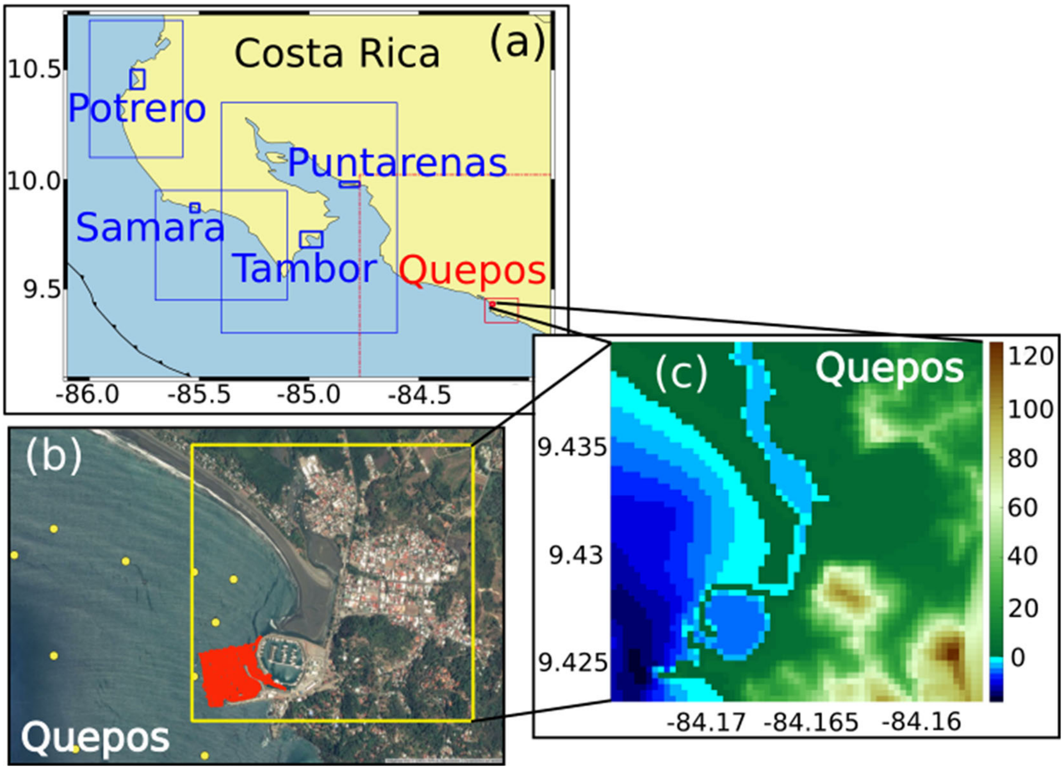

Figure 4

a Grid A for Quepos is shown as a dash–dotted red rectangle with 30 arcsec resolution. Grids B are shown as solid thin rectangles with a resolution of 5 arcsec (red and blue). Grids C are shown as thick rectangles with a resolution of 1 arcsec (red and blue) at Potrero, Sámara, Tambor and Puntarenas. Some of the grid sets share grids A and/or B. Grids of the same set have the same color. **b** The red dots show the MOPT bathymetric survey outside Marina Pez Vela in Quepos, and the yellow dots are from the only nautical chart available for the region. The yellow rectangle shows the extent of the grid C for Quepos. **c** Grid C bathymetry for Quepos in meters

Table 1

ComMIT nested grids sizes for each location and the 8-h tsunami simulation running time

Location	Grid A	Grid B	Grid C	Simulation time for 8 h of tsunami (min)
Quepos	152 × 120	110 × 80	64 × 62	0.75
Puntarenas	361 × 277	577 × 757	325 × 91	51
Tambor	361 × 277	577 × 757	361 × 260	55
Sámara	361 × 277	433 × 361	146 × 146	23
Potrero	361 × 277	307 × 451	226 × 316	13
Low-resolution grids[a]	406 × 469	1087 × 1126	–	46

[a]Low resolution refers to a set of grids meant to identify locations with a higher tsunami threat. For this set of grids, tsunami inundation was not simulated

resolution of the grids are detailed in Tables 1 and 2. SINAMOT also has a set of low-resolution nested grids covering most of the Costa Rican Pacific Coast (Fig. 1, Tables 1, 2). However, all these grids were designed to develop tsunami evacuation maps and computation time was not considered in the design. The bathymetric data used for the grids were obtained from bathymetric surveys, together with nautical

Table 2

Resolution of ComMIT nested grids for each location

Location	Grid A (arcsec)	Grid B (arcsec)	Grid C (arcsec)
Quepos	30	5	1
Puntarenas	30	5	1
Tambor	30	5	1
Sámara	30	5	1
Potrero	30	5	1
Low-resolution grids[a]	60	12	–

[a]Low resolution refers to a set of grids meant to identify locations with a higher tsunami threat. For this set of grids, tsunami inundation was not simulated

charts and global bathymetry from GEBCO (IOC/UNESCO et al. 2003). The topography was obtained from 1 m resolution LIDAR data, property of the National Emergency Commission of Costa Rica (CNE), combined with GEBCO global topography.

The first version of the Quepos grid C was built using only nautical charts and LIDAR data, and had a resolution of 4 arcsec, which is approximately 120 m. Data agreed well with tsunami records from nine small tsunamis before the tide gauge's relocation (Chacón-Barrantes and Gutiérrez-Echeverría 2017). Data agreement with the 2015 Chile tsunami was poor (Chacón-Barrantes and Gutiérrez-Echeverría 2017). In July of 2017, the Costa Rican Ministry of Public Works and Transportation (MOPT) performed a bathymetric survey offshore the harbor (red dots in Fig. 4b). The resolution of that survey is very good, but unfortunately it only covered a very limited region outside of the Marina. From nautical charts, there are only four data points inside the desired domain (yellow dots in Fig. 4b). Although the LIDAR data have 1 m resolution, the coverage does not include the Marina, and there is no information about the height and width of the docks, or about the depths inside the Marina. Considering the Marina dimensions and the available data, a 1 arcsec grid (approx. 30 m) was built covering the harbor and its surroundings (Fig. 4c). A better resolution was not possible to obtain due to the aforementioned lack of data about the inside and the area to the north of the Marina.

3.1. Real-Time Tsunami Modeling

Real-time tsunami modeling is a powerful tool that provides tsunami amplitude estimations for warning purposes, even if these are rough estimations. For the 2017 México tsunami, SINAMOT performed a real-time tsunami modeling similar to the 2015 Chile tsunami modeling (Chacón-Barrantes 2016). As explained before, ComMIT uses a linear combination of pre-calculated unit sources to construct the tsunami initial condition, as co-seismic deformation and tsunami propagation are linear phenomena. Unit sources are fault planes of 100 km × 50 km with a mean slip of 1 m. Then, each unit source is multiplied by a coefficient representing the mean slip estimated for that plane and added up. For the Mexican tsunami SINAMOT used the source solution published at 22:53 (Costa Rican time) by NCTR, consisting of the following unit sources combination: 2.805 × cs16a + 2.805 × cs17a. Expressions "cs16a" and "cs17a" are the names of the unit sources used, shown in Fig. 1a, each one having a 2.805 m mean slip. In this document, we present the results of the modeling that was generated at the Quepos tide gauge.

3.2. Post-tsunami Modeling

On the morning of September 8, local time, a new modeling was performed using the new solution, published about 1 h after the earthquake: 1.981 × cs16a + 1.981 × cs16z + 1.981 × cs17a +1.981 × cs17z. In this solution, more fault planes were used (Fig. 1a), each one with a smaller mean slip. The goal of this post-tsunami modeling was to analyze the performance of both solutions comparing synthetic marigrams with tsunami observations at Quepos, to assess how reliable the first solutions are for regional tsunamis. By that time, other solutions based on tsunami inversion had been obtained. Unfortunately, those published solutions had restricted access, meaning that the author was not able to use them even months after the earthquake.

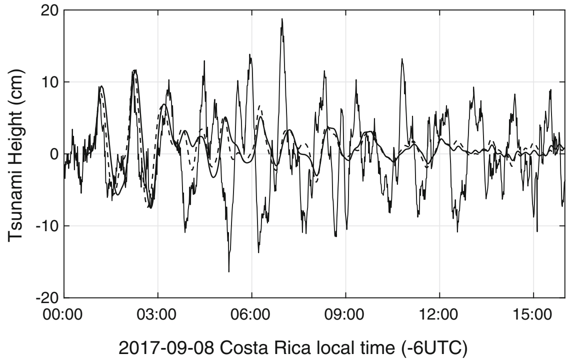

Figure 5
Comparison of the 2017 México tsunami record at the Quepos gauge (solid thin line) with model results using the first solution (dashed thick line) and the final solution (solid thick line)

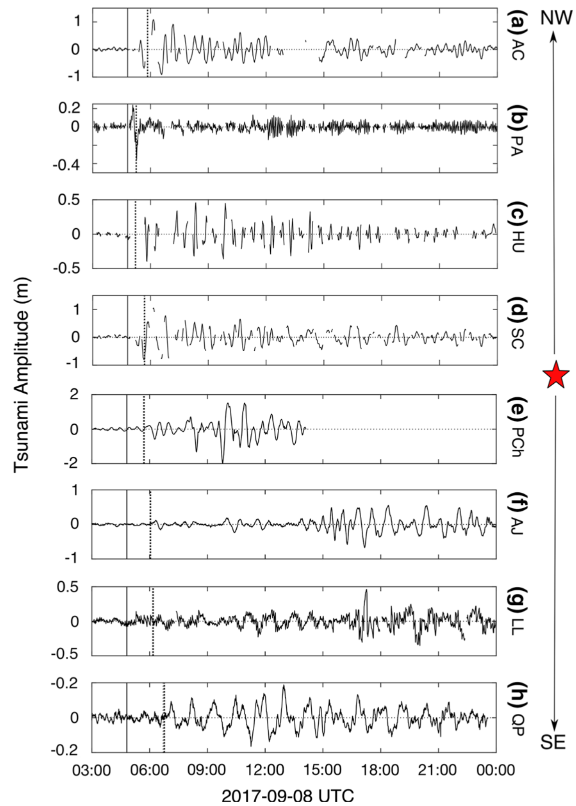

Figure 6
Filtered records of the 2017 México tsunami at gauges within 690 km north and south the epicenter and at Quepos. **a** AC: Acapulco (México), **b** PA: Puerto Ángel (México), **c** HU: Huatulco (México), **d** SC: Salina Cruz (México), **e** PCh: Puerto Chiapas (México), **f** AJ: Acajutla (El Salvador), **g** LL: La Libertad (El Salvador) and **h** QP: Quepos (Costa Rica). Gauges locations are shown in Fig. 1. Vertical lines mark the earthquake time (solid line) and the forecasted arrival time by PTWC (dotted line). Arrows show the orientation of the gauges in relation to the epicenter (NW: northwest and SE: southeast), depicted with a red star. Mexican records were provided by the Servicio Mareográfico Nacional de México and El Salvador records by the Ministry of Environment and Natural Resources (MARN), all of which were downloaded from the IOC/UNESCO website

4. *Modeling Results and Discussion*

Figure 5 compares the tsunami record at the Quepos gauge (thin line) with the model results at the gauge location using the first (thick solid line) and the second (thick dashed line) published seismic solutions. For both, the model adequately replicated only the first two peaks and troughs of the tsunami. All model results failed to replicate the maximum tsunami amplitude at Quepos that occurred 6 h after the first arrival.

Coarse resolution and lack of proper bathymetric data prevented accurate modeling within the Marina. The grid resolution was not enough to replicate the interaction between the tsunami and the Marina. The width of the harbor entrance is about 29 m, and the grid resolution is 1 arcsec, about 30.7 m; thus, the entrance had to be widened in the model. A finer grid would be required to adequately model the harbor. The author recommends a bathymetric survey around and inside the Marina to perform a more precise modeling. Until then, it is not possible to verify the model setup for the new gauge location.

The maximum amplitude occurring so late after the first arrival might have been caused by trapped waves in addition to (or instead of) a local effect, as the same behavior was observed at other gauges. Adriano et al. (2018) refers to trapped waves along the coastline of the Tehuantepec Gulf as the reason for the tsunami recorded at Salina Cruz (México) to have a higher amplitude 50 min after the first arrival. Figure 6 shows 21-h records of this tsunami at seven tide gauges located within 690 km from the epicenter and at the Quepos gauge (1250 km away from the epicenter). The data from Mexican gauges was obtained from the National Tide Service at UNAM (Servicio Mareográfico Nacional, SMN-UNAM), while the data from El Salvador gauges was obtained from the Ministry of Environment and Natural Resources (MARN). The record at Puerto Chiapas, México, was requested directly to SMN-UNAM and has a shorter duration of 11 h. All the other tsunami records were downloaded from the IOC/UNESCO website (IOC/UNESCO 2018a), from SMN-UNAM tide gauges. The locations of the gauges are shown as black crosses in Fig. 1. Solid vertical lines in Fig. 6 show the earthquake time, and dotted thick lines show the forecasted ETA for each station. To forecast ETAs, PTWC uses a point source at the epicenter coordinates instead of a real finite source. Consequently, there may be important differences between real and forecasted ETAs for local and regional tsunamis, depending on the epicenter location within the fault plane and relative to the region of interest (Chacón-Barrantes et al. 2017).

All gauges located southeast of the epicenter reported the maximum tsunami amplitude between 4 and 11 h after the ETA. The only station northwest of the epicenter showing a similar behavior was Huatulco (México), where maximum amplitude was reported about 3 h after the ETA. At the Puerto Chiapas tide gauge (México), the maximum amplitude was recorded 5 h after the first arrival, a time difference similar to the one reported in Quepos. At Acajutla (El Salvador), the maximum amplitude was recorded about 12 h after the first arrival. At La Libertad (El Salvador), the maximum amplitude was recorded about 10 h after the ETA. Adriano et al. (2018) used tsunami records up to 160 min after the earthquake, and consequently did not observe or reproduce this effect with their numerical model.

ComMIT did not replicate this effect, at least for the Quepos gauge. The reason might be the coarse resolution of the outer propagation grid, fixed at 4 arcmin. Also local effects might be responsible, many comparisons of MOST models with gauge data for previous events showed fairly good comparison with later waves amplitude (Rabinovich et al. 2017; Tang et al. 2012). Inaccuracies on the tsunami sources used might also be at least partially responsible. Future work to explore the reason of the “maximum amplitude delay effect” should include the use of a different numerical model with finer resolution on the outer grid, as well as an initial condition obtained from the results of tsunami inversion and/or more accurate seismic parameters.

5. Threat Analysis for Costa Rica Due to the 2017 México Tsunami

SINAMOT is part of the RONMAC Program from the National University of Costa Rica, as well as IMARES (Unit of Maritime Engineering, Rivers and Estuaries) from the University of Costa Rica. The RONMAC Program has performed numerical simulations for over 50 tsunamis around the Pacific basin to determine which of those tsunamis represent a higher threat for Costa Rica, and also to establish which Costa Rican regions are facing a higher threat. Those simulations were part of a Tsunami Evacuation Maps Development Project that is currently under way. Also, SINAMOT performs between three and four internal exercises per year using some of those scenarios. Several of the considered scenarios took place along the Pacific coast of México, so it was concluded that those do not represent a major threat due do directivity. For example, the M_w 8.0 1985 México tsunami had a maximum amplitude of 3 m basin-wide, but only 8.5 cm at the Quepos tide gauge, which was located 2207 km away from the epicenter (Chacón-Barrantes and Gutiérrez-Echeverría 2017). However, standard operating procedures (SOP) were followed during the 2017 México event, as it was done for all other events.

SINAMOT performed real-time tsunami modeling using ComMIT, which showed that Costa Rica was not located in the direction of the tsunami maximum energy (Fig. 7). The maximum tsunami heights obtained using a rigid wall approach were about 40 cm at external grids, which are similar to the maximum heights forecasted by PTWC (PTWC 2017b). Figure 8 shows the maximum tsunami heights offshore, which were obtained for grid A (Fig. 8c) and B of Potrero (Fig. 8a), Sámara (Fig. 8b) and Tambor and Puntarenas (Fig. 8d). The maximum tsunami heights were obtained for the Gulf of Papagayo, located at the southwestern coast of the Nicoya Peninsula and Esterillos (at the Central Pacific coast). Based on these results, flooding was discarded, but the potential risk of dangerous currents remained. Running times of the five models performed on a personal computer for the Costa Rican coastal locations were between 0.75 and 55 min for 8 h of tsunami time (Table 1). The set of grids was prepared

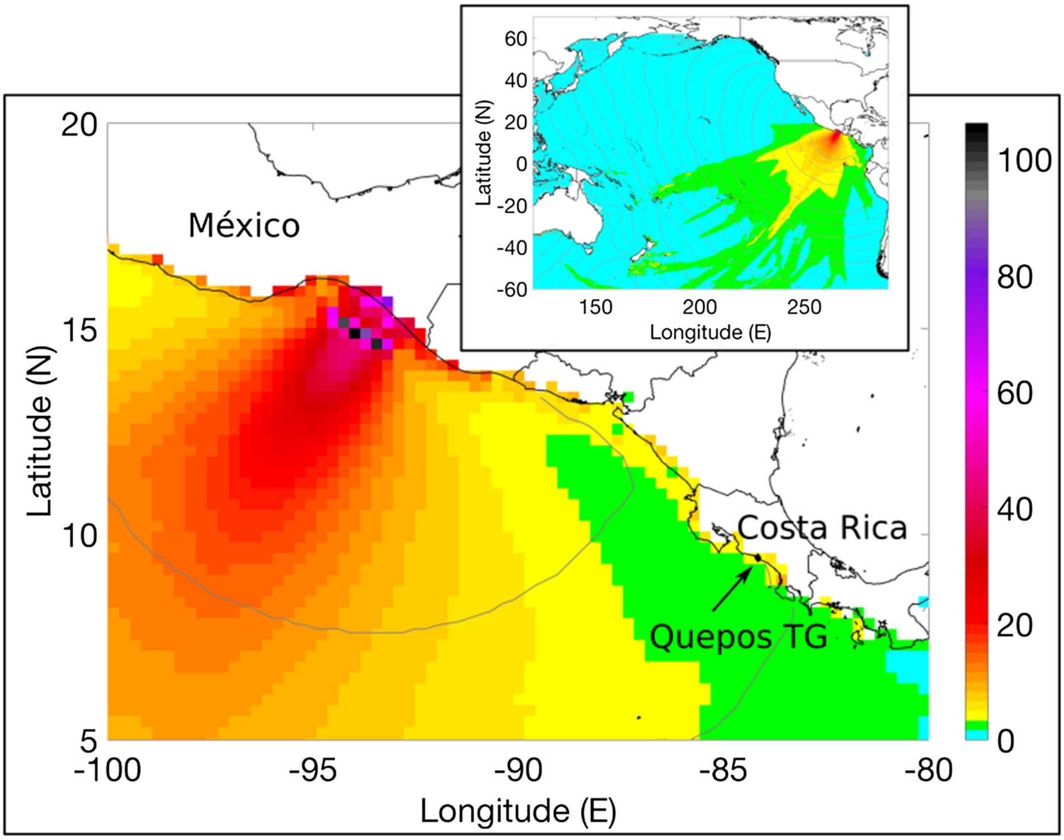

Figure 7
Energy directivity plot of the 2017 México tsunami. Gray lines indicate travel time contours every hour. The black diamond indicates the location of Quepos' tide gauge (TG). The insert shows the energy directivity plot for the entire Pacific Ocean

for tsunami evacuation maps development, without considering the running times. Intermediate grids cropping for most of the grids set might result in faster running times if used for real-time tsunami forecasts. ComMIT is certainly a very useful tool for real-time tsunami forecasts not only in Costa Rica, but also in other countries. The author recommends that more updates to the tsunami source solutions become available to improve the quality of real-time forecasts, including DART inversions for all ComMIT and its related platform Tweb users (Bernard and Titov 2015; Burger et al. 2013, 2014, 2016; Kamb et al. 2014).

The first SINAMOT Report issued at 23:13 on September 7 (local time) indicated a high probability of minor impact. SINAMOT indicated that strong currents might occur at places that are prone to amplification of tsunami currents, such as Genius River mouth on Coco's Island, Ballena National Marine Park and Potrero Bay, Guanacaste. The report indicated no possibility of tsunami flooding along the Costa Rican coast. When the second PTWC Bulletin increased the earthquake magnitude and lowered the threat level for Costa Rica, SINAMOT issued a second report on September 7 at 23:36 confirming the findings of the first report.

6. Tsunami Literacy and Tsunami Preparedness in Costa Rica

The total population of Costa Rica was estimated to be 4,947,490 inhabitants as of June 2017 (INEC 2017), with about half-million living in the Pacific and Caribbean coasts. However, Costa Rica attracts millions of tourists to its beaches all year long, due to

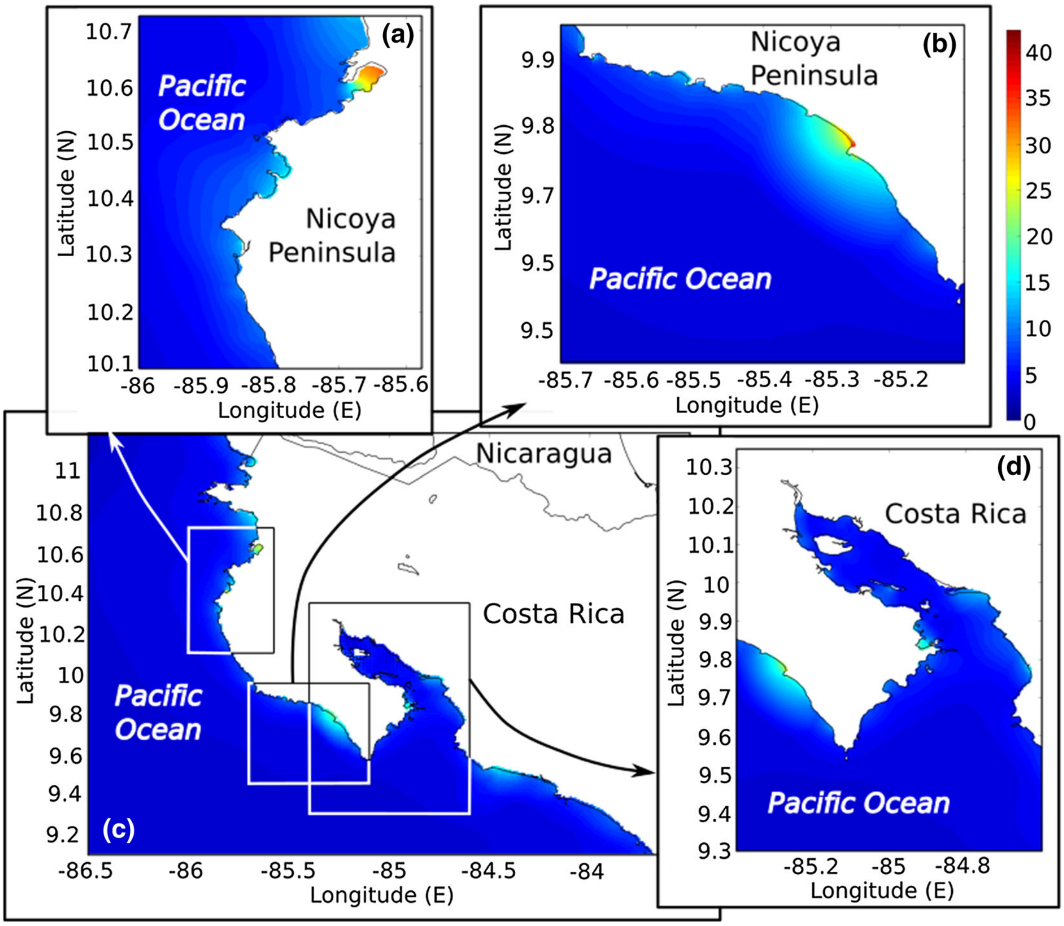

Figure 8
Maximum tsunami height offshore, in centimeters, obtained for grid B of **a** Potrero, **b** Sámara and **d** Tambor. Also, for **c** Grid **a** of those sets

its tropical weather and beautiful natural resources. Costa Rican coasts have been sparsely populated until recent times. Consequently, there have been reports of only 32 tsunamis since 1579, both local and distant and on both shores. People possess the empirical knowledge of running to highlands if a strong local earthquake is felt along the coasts, but regional and distant tsunamis do not have natural warnings, so those require a warning and evacuation order to be issued.

On August 15, 2007, due to an M_w 8.0 earthquake in Perú (Fritz et al. 2008), PTWC issued tsunami bulletins indicating a possible tsunami threat for Central America. International Latin American news media reported tsunami warnings for all Central American territories. SINAMOT did not exist at that time, and the country did not have any tsunami protocols at any level. Given the media coverage, CNE contacted two oceanographers (who later became part of the SINAMOT founders) that recommended people to evacuate the coasts due to the lack of additional information and protocols. This recommendation led to chaos among the coastal population and caused panic at those locations where evacuation was not straightforward. People did not know how far, how high, how fast or for how long they had to evacuate. On September 5, 2012, an M_w 7.6 earthquake originated offshore of the Nicoya Peninsula (Yue et al. 2013) and triggered self-evacuations of most coastal populations along the Peninsula. Fortunately, the subsequent tsunami had negligible amplitudes, but once again people evacuated too late, too far away and stayed away from the coast for too long. On April 1 2014, another "tsunami warning" hit the international Latin American news, caused by an M_w 8.2 earthquake in Northern Chile (Suzuki et al. 2016). This time, authorities decided to wait and see the tsunami evolution before recommending any evacuations. Right after this tsunami, SINAMOT was created to ensure that proper tsunami protocols would be followed after any potential tsunamigenic event.

Since then, SINAMOT has become the referential source for any tsunami events. News media used to ask questions to other institutions (seismic, meteorological and oceanographical), which did not have any specific tsunami expertise. People did not know where to search for information when faced with a tsunami rumor. Nowadays, and by the time of this publication, SINAMOT's Facebook profile (SINAMOT 2017) has more than 17,000 followers and reports all the potential tsunamigenic events. The site posts information about anniversaries of historical tsunamis recorded in Costa Rica, as well as general tsunami information. The 2017 México tsunami was the second tsunami getting media coverage since SINAMOT was created. However, in this case the media coverage was extensive afterward. The earthquake occurred at 10:49 pm local time, and the tsunami arrived at Quepos approximately 2 h later, around 1 am. Only a couple of radio stations reported the tsunami watch in real time. The next morning though, main TV news reported the earthquake and tsunami starting at 6 am, local time. The media coverage was better this time: the press had learned that only local authorities can issue an official warning. They also learned that even small tsunamis can be potentially dangerous events at certain locations (Ugarte 2017).

In México, the tsunami early warning did not reach small coastal towns, except one with a naval station (Ramírez-Herrera et al. 2018). Other countries have experienced problems related to tsunami warning dissemination in the past, for example during the 2017 Mediterranean and the 2004 Indian Ocean tsunamis (Heidarzadeh et al. 2017; Perry 2007), and Costa Rica still needs to increase its tsunami preparedness. There are no sirens or any other rapid warning dissemination methods within coastal communities during the nighttime. Costa Rica has over 600 beaches, not all are populated, but there is only one tsunami-ready community (Horan et al. 2010; IOC/UNESCO 2018b). Hence, only one coastal community has verified and certified mechanisms to ensure warning dissemination and proper evacuation procedures.

7. Conclusions

In this work, the response to the 2017 México tsunami in Costa Rica was analyzed in terms of tsunami warnings and real-time forecasts. Also, the tsunami record at the Quepos tide gauge was de-tided and compared with model results and PTWC forecast values. SINAMOT used ComMIT with the initial conditions given by NCTR, based on seismic parameters. For the Quepos tide gauge, the model successfully replicated the first two peaks of the tsunami, but not the maximum amplitude recorded 6 h after the first arrival. The differences between the model results with the initial conditions given 4 min and 1 h after the earthquake were minimal, both based on seismic parameters. To the author's knowledge, another tsunami initial condition was obtained by NCTR via tsunami inversion, but it is not available for all users. The author recommends that more updates become available for ComMIT and Tweb users, including results from tsunami inversions. The several hours delay in the maximum tsunami amplitude was also observed in three stations southeast and one northwest of the epicenter; which might be due to trapped waves and/or special characteristics of the initial condition. More numerical simulations are recommended to account for this effect on future warning decisions.

Costa Rica shows considerable improvements in its tsunami preparedness. However, it still needs to review its tsunami warning standard operating procedures for regional tsunamis with reduced arrival times (less than 3 h). If the 2017 México tsunami had posed a threat to the country, warning spreading might have been impossible for some communities, due to its occurrence time, arrival time and the lack of proper warning dissemination mechanisms.

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