Coastal Engineering Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcej20

Tsunamis in the Mexican coasts during the period 2009-2018 and their behavior

Jorge Zavala-Hidalgo , Katia Trujillo-Rojas , Octavio Gómez-Ramos , Miriam Zarza-Alvarado , Felipe Hernández-Maguey & Valente Gutiérrez-Quijada

COASTAL ENGINEERING JOURNAL
2020, VOL. 62, NO. 3, 429–444
https://doi.org/10.1080/21664250.2020.1744062

Tsunamis in the Mexican coasts during the period 2009-2018 and their behavior

Jorge Zavala-Hidalgo [a], Katia Trujillo-Rojas [b], Octavio Gómez-Ramos [b], Miriam Zarza-Alvarado [b], Felipe Hernández-Maguey [b] and Valente Gutiérrez-Quijada [b]

[a]Centro de Ciencias de la Atmosfera, Universidad Nacional Autónoma de México, Mexico City, Mexico; [b]Instituto de Geofísica, Universidad Nacional Autónoma de México, México City, Mexico

ABSTRACT
The main characteristics of the tsunamis that occurred in Mexico in the period 2009–2018 and their predominant features are analyzed. During this period there were eleven tsunamis. A total of 54 time series with sea level signals associated with tsunamis were analyzed. In each case a high-pass filter was applied to remove the astronomical tide, and the computation of arrival time, travel times, distance from the source, heights, maximum amplitudes and periods were conducted. A spectral analysis was performed to determine the dominant frequencies for each tsunami and sea level station, and the decay time of the tsunami wave train was computed adjusting an exponential function. The spectral patterns were more similar for each location than for the same tsunami, which was concluded from the qualitative analysis of the spectra and their correlations. The maximum wave height occurs after 1 to 5 hours of the arrival of the first wave for local events, and between 6 to 22 hours for remote events. The characteristic frequencies and behavior for each location were identified and is expected that will be similar in future events, therefore these results may help decision makers in the implementation of risk reduction policies.

ARTICLE HISTORY
Received 11 March 2020
Accepted 13 March 2020

KEYWORDS
Tsunami along Mexican coast; tsunami behavior; sea level extremes

1. Introduction

1.1. Background of tsunami monitoring on the Mexican Coast

Mexican Pacific is a region of recurrent tsunami impact exposed to both remote and local tsunamis. The Global Historical Tsunami Database (NGDC 2019) reported around 1,600 tsunamis in the Pacific Ocean during the period 1900–2018, with at least 14 of which reached the Mexican coasts. Some of these events were studied in detail based on instrumental records and local field observations (Sanchez and Farreras 1993).

In 1985, the mission in Mexico performed by the International Tsunami Information Center (ITIC), sponsored by the Intergovernmental Oceanographic Commission (IOC), recommended that a historical survey of tsunamis in Mexico should be carried out, as a necessary component of the tsunami preparation program (Pararas-Carayannis 1987).

Following the guidelines and recommendations above, Sanchez and Farreras published in 1993 a Catalog of Tsunamis on the West Coast of México (Sanchez and Farreras 1993). The study was based on newspaper reports, sea level records, personal interviews with witnesses of the events, the review of related publications, and information from previously published catalogs.

In Sanchez and Farreras (1993), a description of the tsunamigenic earthquakes that occurred along the Mexican portion of the Mesoamerican trench was included, along with the description of the generated tsunamis and their effects on the coast of México. The document includes a description of some remote tsunamis occurred before 1950, and a more detailed description for tsunamis that impacted the Mexican Pacific coast during the period 1950 to 1985. An important contribution of the information used for the generation of this catalog came from the marigrams provided by the Servicio Mareografico Nacional (SMN) of México, operated by the Universidad Nacional Autonoma de México (UNAM), that had at that time a total of 68 records of 21 tsunamis, of which 9 were local and 12 were remote.

In recent years, several tsunamis have ocurred along the Mexican coasts which were recorded thanks to the modernization of the SMN network. This allowed monitoring important events as were the Tohoku, Japan 2011, Maule, Chile, 2010, or the Pijiiapan, México, 2017, among others. The Tohoku, Japon (2011), Maule, Chile (2010), Iquique, Chile (2014), and Illapel, Chile (2015) events have been previously analyzed (Zaytsev, Rabinovich, and Thomson 2016, 2017). Here more events are analyzed and then compared between them, with an emphasis in the specific response of each location and how they decay. In the period 2009–2018, 11 events were recorded in this network, including one in the Mexican Caribbean Sea. In this research, a careful analysis of these events is

CONTACT Jorge Zavala-Hidalgo jzavala@atmosfera.unam.mx

performed with the purpose of identifying the characteristic frequencies, amplitudes, decay time and other properties that allows to better understand the risk to tsunamis and help modeling efforts.

2. Data and methods

2.1. Data source

In 1942 the Inter-American Geodetic Survey and the Mexican National Defense Secretary conducted the first systematic measurements of sea level in Mexican ports. This network of stations was transferred in 1952 to the Institute of Geophysics (IG) of the UNAM, and at that time the National Sea Level Monitoring Service was founded. However, the network decayed in the late 80's and most of the stations stopped operating.

From 2007 to 2019 the SMN performed a modernization of the network. Currently, the sea level monitoring network has 28 stations: 12 located in the Pacific Ocean and 16 located in the Gulf of México and the Caribbean Sea. Figure 1 shows the location and name of the 28 stations. Each tide gauge station also has a benchmark network, and first-order geodetic leveling is carried out periodically for the vertical control of the tide station. Sampling of the sea level is carried out every minute with the main sensor (Radar) and every 6 with the secondary sensor (Float), the sampling of meteorological data is performed every 10 min, and the data transmission is every 5, 15 or 60 minutes. All the information collected by the stations is transmitted in near real time and received at the facilities of the SMN at UNAM, in Mexico City, and are public available on the website www.mareografico.unam.mx. Appendix A1 describes the sea level stations of SMN of which the data was used here.

2.2. Event selection

From 2007 to present, the SMN sea level network detected and recorded numerous tsunamis of seismic origin in México. From the database, the 11 most significant tsunamis, based on the recorded amplitude, that occurred between 2009 and 2018 were chosen for this study, which have associated 54 marigrams. Those cases in which the sea level disturbance produced by the tsunami were more than 10 cm in at least one site were considered. The data of each station were filtered with a Hanning filter with a window of 30 samples for the signals sampled every 6 minutes, and 140 samples for the signals sampled every minute and the residual between the raw sea level signal and the filtered signal was obtained.

2.3. Characterization of each tsunami and site

The main parameters of each tsunami, for each site in which it was recorded, were computed including: arrival time of the first wave and of the maximum height, maximum height, maximum amplitude (high minus low) and the more energetic period through a Fourier analysis. The calculation of the epicentral distance to each sea level station that recorded a tsunami was also computed using Haversine formula (Sinnott 1984).

Figure 1. Current tide gauge network of Servicio Mareografico Nacional (SMN).

With the distance and travel time, the average speed of each tsunami was calculated.

2.4. Spectral analysis

For each event, the Fourier Discrete Transform was applied to the sea level time series in order to obtain their respective Amplitude Spectra (AS), without the astronomical tide. In addition, a fraction of the time series of each sea level signal before the arrival of the tsunami was taken, and its AS was obtained in order to make a comparison with the AS of the tsunami. The spectra corresponding to each site were compared with those obtained when the tsunamis occurred computing a linear correlation. This in order to identify the characteristic frequencies associated to the tsunamis at each site of the Mexican Pacific coast.

2.5. Decay time

The residuals of the sea level signal (after removing the astronomical tides) of each event were used to analyze the decay of this energy. The maximum heights at intervals of 1 hour for local events and 2 hours for distant events were computed in order to keep only the extreme values for the analysis. Through least squares, an exponential function was adjusted to these points as shows the Equation (1).

$$M(t) = A_0 e^{-t/\tau} \quad (1)$$

Where

$M(t)$ = Local maximum residual heights

A_0 = Absolute maximum height

t = Time

τ = Decay constant

From Equation (1), the parameter τ is a constant that represents the time necessary for the maximum height A_0 to decrease by a factor of 1/e (Hayashi, Koshimura, and Imamura 2012), that is, the height at time τ will be 36.78% of the maximum height, A_0.

Once the best fit for each time series was found (Figure 2), the time τ for each one was obtained and the fraction of time between the start of the tsunami and the maximum height (Δt) was added to obtain the total time τ_f. This represents the time necessary for most of the energy to be attenuated by 63.22%.

With the time τ_f calculated for each signal, the duration of the tsunami in each sea level station was obtained, and an average duration per event was calculated. A decay analysis was performed for the Pijijiapan, 2017 event by Melgar and Ruiz-Angulo (2018) for the sea level stations of Puerto Angel, Huatulco, Salina Cruz, and Puerto Chiapas. They obtained a decay time of 3 days.

3. Tsunami events

Of the 11 tsunamis studied, 7 were generated by distant earthquakes. The first was the Samoa tsunami (Figure 3) that occurred on September 30 2009 due to an earthquake of magnitude Mw 8.1 caused by a normal fault in the interaction of the Pacific plate and the Australian plate (USGS, Earthquake Hazards Program 2009). Three tsunamis from Chile were recorded, generated in the subduction zone between the Nazca and South American plates in the Maule region, on February 27 2010 (Figure 4), in Illapel on September 16 2015 (Figure 5) and Iquique on April 1 2014 (Figure 6), associated with earthquakes that had magnitudes of Mw 8.8, 8.3, and 8.2 respectively. All were caused by inverse faults (USGS, Earthquake Hazards Program 2010, 2014, 2015). Also, the Tohoku tsunami, in Japan, that occurred on March 11 2011 (Figure 7), whose earthquake had the greatest magnitude among the events analyzed here (Mw 9.1). It was caused by the subduction of the Pacific plate under the North American plate by a reverse fault (Duputel et al. 2012). The Champerico, Guatemala tsunami, on November 7 2012 (Figure 8) caused by an earthquake of magnitude 7.4. The earthquake was caused by a shallow reverse fault, close to the subduction zone between the Cocos plate, the Caribbean plate and the North American plate (USGS, Earthquake Hazard Program 2012). Finally, the most recent remote tsunami recorded, and the only one observed on the

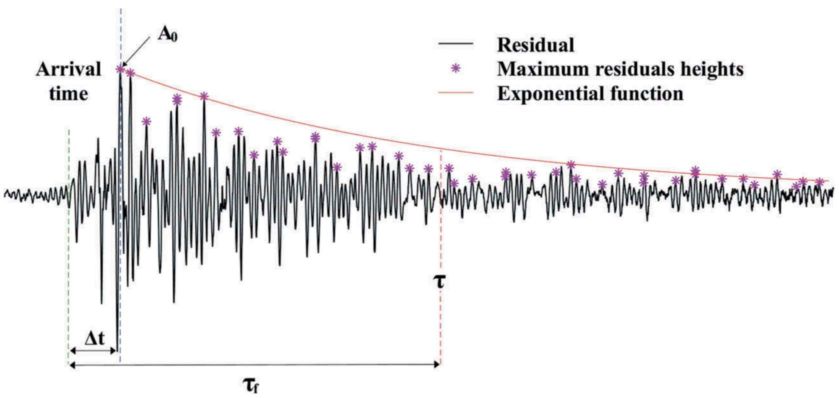

Figure 2. Adjustment of the exponential curve to the residual of the time series during the arrival of the tsunami of Pijijiapan, Chis., at the Puerto Chiapas station, where parameters A_0, τ, τ_f and Δt are shown.

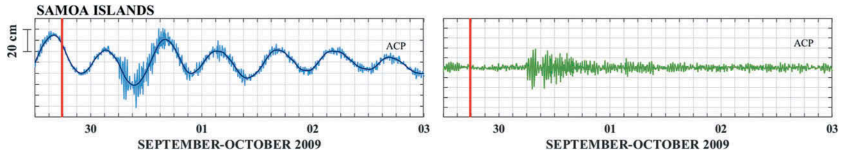

Figure 3. Sea level records series with anomalies caused by the Samoa Islands tsunami (17:48 GMT, Sep/29/2009). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). ACP (Acapulco). The red line indicates the time of the earthquake.

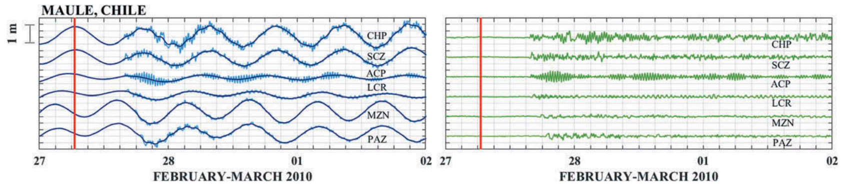

Figure 4. Sea level records series with anomalies caused by the Maule, Chile tsunami (06:34 GMT, Feb/27/2010). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). CHP (Puerto Chiapas), SCZ (Salina Cruz), ACP (Acapulco), LCR (Lazaro Cardenas), MZN (Mazatlan), PAZ (La Paz). The red line indicates the time of the earthquake.

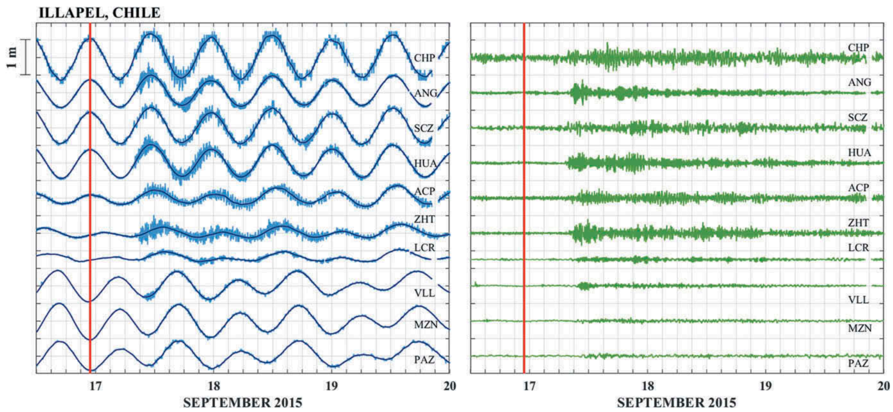

Figure 5. Sea level records series with anomalies caused by the Illapel, Chile tsunami (22:52 GMT, Sep/16/2015). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). CHP (Puerto Chiapas), SCZ (Salina Cruz), HUA (Huatulco), ANG (Puerto Angel), ACP (Acapulco), ZHT (Zihuatanejo), LCR (Lazaro Cardenas), VLL (Puerto Vallarta), MZN (Mazatlan), PAZ (La Paz). The red line indicates the time of the earthquake.

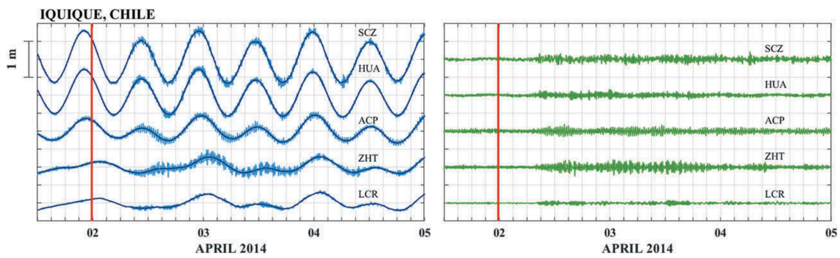

Figure 6. Sea level records series with anomalies caused by the Iquique, Chile tsunami (23:46 GMT, Apr/01/2014). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). SCZ (Salina Cruz), HUA (Huatulco), ACP (Acapulco), ZHT (Zihuatanejo), LCR (Lazaro Cardenas). The red line indicates the time of the earthquake.

coasts of the Atlantic Ocean during the 2009–2018 period, was the one generated by the earthquake of the Great Swan Islands, Honduras, on January 10 2018 (Figure 9), caused by a shallow strike-slip fault and a Mw 7.6 earthquake. It was located close to the boundaries of the North American and Caribbean plates (USGS, Earthquake Hazard Program 2018). This tsunami generated the smallest disturbance in the sea level registered along the Mexican coasts of the events studied. However, it was

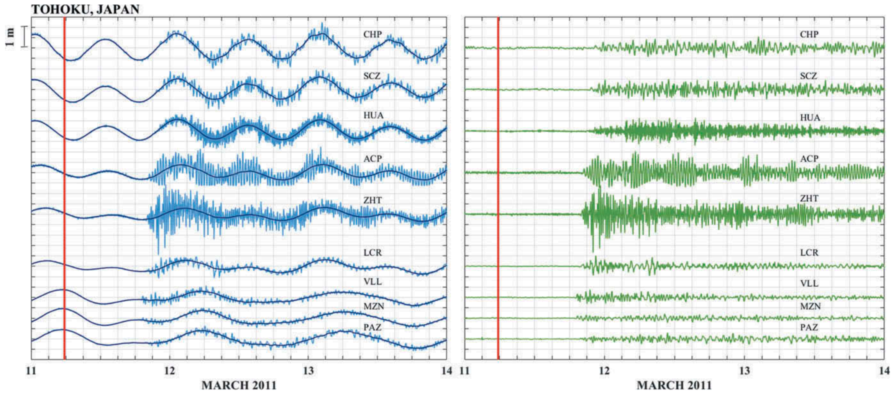

Figure 7. Sea level records series with anomalies caused by the Tohoku, Japan tsunami (05:46 GMT, Mar/11/2011). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). CHP (Puerto Chiapas), SCZ (Salina Cruz), HUA (Huatulco), ANG (Puerto Angel), ACP (Acapulco), ZHT (Zihuatanejo), LCR (Lazaro Cardenas), VLL (Puerto Vallarta), MZN (Mazatlan), PAZ (La Paz). The red line indicates the time of the earthquake.

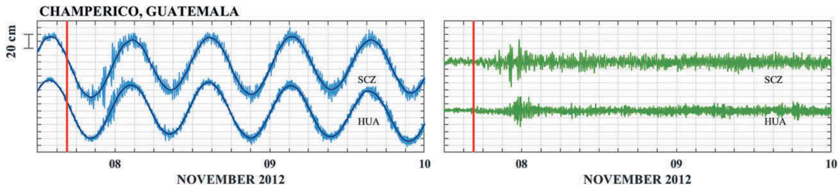

Figure 8. Sea level records series with anomalies caused by the Champerico, Guatemala tsunami (16:35 GMT, Nov/07/2012). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). SCZ (Salina Cruz), HUA (Huatulco). The red line indicates the time of the earthquake.

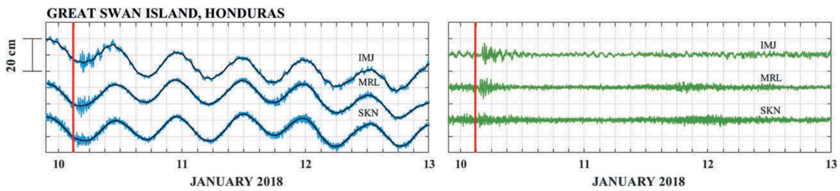

Figure 9. Sea level records series with anomalies caused by the Great Swan Island, Honduras tsunami (02:51 GMT, Jan/10/2018). (Left) sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). IMJ (Isla Mujeres), MRL (Puerto Morelos), SKN (Sian Ka'an). The red line indicates the time of the earthquake.

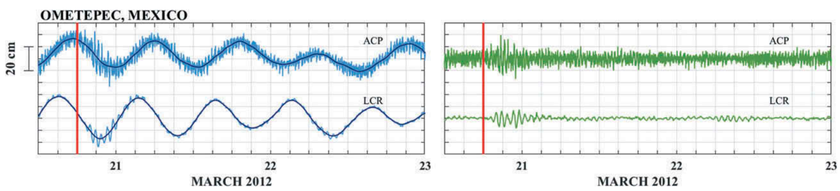

Figure 10. Sea level records series with anomalies caused by the Ometepec, Gro., Mex. tsunami (18:02 GMT, Mar/20/2012). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). ACP (Acapulco), ZHT (Zihuatanejo), LCR (Lazaro Cardenas). The red line indicates the time of the earthquake.

considered in this research due to the infrequent occurrence of tsunamis along the Mexican Caribbean Sea and the Gulf of Mexico.

Among the local events, 3 local tsunamis generated in the Mexican Pacific Ocean were recorded. On March 20 2012, a tsunami occurred in the state of Guerrero, due to an earthquake Mw 7.5 near Ometepec (Figure 10), in the subduction zone between the Cocos and North American plates. In the same subduction zone, earthquakes of April 21 2013 generated near the coast of Lazaro Cardenas, Michoacan (Mw 5.9), April 18 2014 in Petatlan, Guerrero (Mw 7.2), and on September 8th,

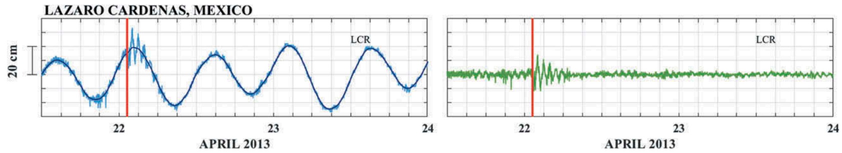

Figure 11. Sea level records series with anomalies caused by the Lazaro Cardenas, Mich., Mex. tsunami (01:16 GMT, Apr/22/2013). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). LCR (Lazaro Cardenas). The red line indicates the time of the earthquake.

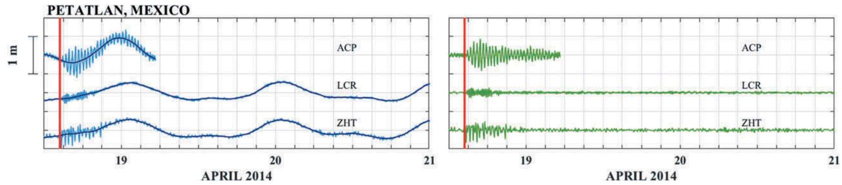

Figure 12. Sea level records series with anomalies caused by the Petatlan tsunami (14:27 GMT, Apr/18/2014). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). ACP (Acapulco), ZHT (Zihuatanejo), LCR (Lazaro Cardenas). The red line indicates the time of the earthquake. The red line indicates the time of the earthquake.

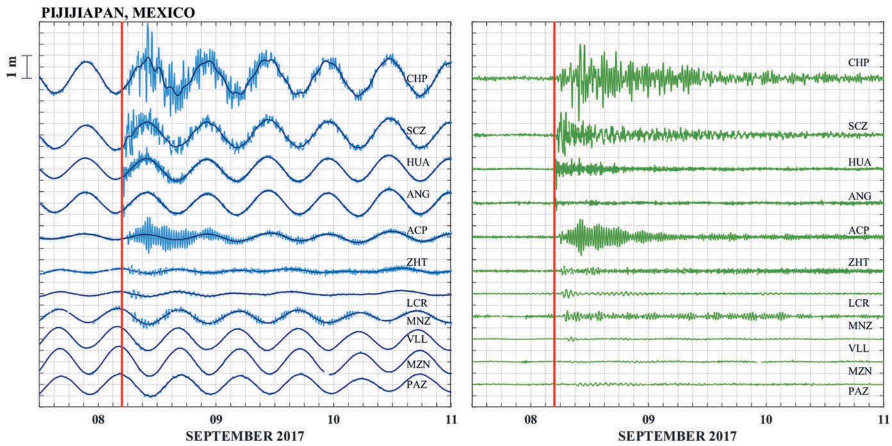

Figure 13. Sea level records series with anomalies caused by the Pijijiapan, Chis., Mex. tsunami (04:49 GMT, Sep/08/2017). (Left) Sea level records (blue) and low pass filtered signal (black). (Right) Residuals (green). CHP (Puerto Chiapas), SCZ (Salina Cruz), HUA (Huatulco), ANG (Puerto Angel), ACP (Acapulco), ZHT (Zihuatanejo), LCR (Lazaro Cardenas), MNZ (Manzanillo), VLL (Puerto Vallarta), MZN (Mazatlan), PAZ (La Paz). The red line indicates the time of the earthquake.

2017 in Pijijiapan, Chiapas (Mw 8.2) (Jimenez 2018). The first two were generated by inverse faults while the third was generated by a normal fault. All of them caused tsunamis that were observed along the coasts of Mexico (Figures 11–13, respectively) (SSN 2012, 2013, 2014, 2017).

4. Results

4.1. Tsunamis general characteristics

The Table 1 shows the main characteristics obtained from the tsunamis. The maximum wave heights and amplitudes of each event are highlighted with black-bold.

Of all the analyzed events, the one that produced the greatest disturbance in the sea level was the 2017 Pijijiapan, Chiapas tsunami, which generated a maximum amplitude of 3.4 m at the Puerto Chiapas station. Note that this station is the closest to the epicenter (183 km) (Table 1).

On the other hand, the 2011 Tohoku tsunami produced sea level anomalies with an amplitude of 3.22 m at the Zihuatanejo station located 10,909 km from the origin of the tsunami (Table 1). The maximum amplitudes were recorded more frequently in the stations of Acapulco, Zihuatanejo and Puerto Chiapas for both local and remote events.

In most of the events it was observed that the first wave height is not the greatest and usually it occurs several hours after the first arrival. The fraction of time between the first arrival and the maximum height, previously, defined as Δt, was smaller for local tsunamis (1 to 5 hours) while for distant tsunamis Δt was between 6 to 22 hours. The stations with Δt greater than 5 hours were Salina Cruz, Mazatlan, Huatulco, Puerto Chiapas and Lazaro Cardenas.

In Table 2 a summary of the duration of each event is presented

Table 1. Tsunami and earthquake main characteristics of each event; the seismic information was provided by the Servicio Sismológico Nacional (SSN) of UNAM and the USGS Earthquake Hazard Program, the code for the sea level monitoring stations (SLS) is the same used by the SMN; the arrival and maximum sea level high times are in GMT; the travel times correspond to the period between the earthquake and the arrival of the first wave. The distances between the earthquake epicenter and the location to the sea level stations were computed following the Haversine equations for distances on the earth's surface; the wave height and the wave amplitude were computed from the residuals, the tsunami period is the one with more energy in the spectral analysis; the mean speed was computed from the period of time taken by the first wave and the distance between the SLS and the source, cases in which the travel speed is very different than expected are indicated by **. The decay time of the events (τ) were computed following Equation (1) and the event time τ_f (Figure 2).

Earthquake Information (*Name, Country, Date, Time (GMT), Magnitude*)	Code Stations	First Wave Arrival Time (GMT)	Max. Height Arrival Time (GMT)	First Wave Travel Time (hr)	Max. Height Travel Time (hr)	Source Distance (Km)	Max. Amplitude (m)	Max. Wave Height (m)	Tsunami Period (min)	Mean Speed (Km/hr)	Event Duration (hr)
Swan Islands, Honduras	IMJ	04:12	04:39	01:21	01:48	541.1	**0.13**	**0.073**	23	400.8	06:29
Jan/10/2018, 02:51	MRL	03:45	05:07	00:54	02:16	517.6	**0.13**	**0.055**	25	575.1	07:01
(Mw 7.6)	SKN	03:33	04:37	00:42	01:46	464.0	0.094	0.045	15	622.9	-
Pijijiapan, Mexico	CHP	05:36	10:04	00:47	05:15	183.1	**3.4**	**1.5**	25	233.7	32:15
Sep/08/17, 04:49	SCZ	05:13	07:10	00:24	02:21	195.5	**1.9**	**1**	17	488.8	37:13
(Mw 8.2)	HUA	04:58	09:53	00:09	05:04	243.8	1.4	0.51	10	1625.3 **	36:15
	ANG	04:56	05:04	00:07	00:15	275.3	0.58	0.24	5	2359.7 **	04:19
	ACP	05:44	10:03	00:55	05:14	662.1	1.6	0.79	29	722.3	21:45
	ZHT	06:04	06:51	01:15	02:02	857.7	0.42	0.24	21	686.2	87:01
	LCR	06:13	07:11	01:24	02:22	931.1	0.40	0.2	55	665.1	21:45
	MNZ	06:30	07:29	01:41	02:40	1 185.1	0.47	0.25	30	704.0	70:00
	VLL	07:04	08:18	02:15	03:29	1 349.2	0.17	0.08	55	599.6	04:37
	MZN	07:48	21:30	02:59	16:41	1 597.0	0.13	0.06	43	535.3	-
	PAZ	09:06	15:19	04:17	10:30	2 000.0	0.16	0.08	60	466.9	-
Illapel Chile.	CHP	07:47	15:43	08:53	16:49	5 601.7	**0.84**	**0.43**	30	630.6	82:04
Sep/16/15, 22:54	SCZ	07:40	01:09 (Sep/18)	08:46	26:15	5 872.0	0.51	0.23	17	669.8	84:04
(Mw 8.4)	HUA	07:17	20:17	08:23	21:23	5 873.3	0.64	0.31	9	700.6	52:10
	ANG	08:17	10:46	09:23	11:52	5 882.3	**0.74**	**0.38**	5	626.9	37:09
	ACP	07:47	14:01	08:53	15:07	6 168.3	0.5	0.27	29	694.4	58:22
	ZHT	08:00	11:50	09:06	12:56	6 332.8	**0.77**	**0.4**	16	695.9	60:27
	LCR	08:06	21:39	09:12	22:45	6 395.3	0.24	0.12	15	695.1	60:29
	VLL	09:44	10:38	10:50	11:44	6 822.3	0.26	0.11	50	629.8	46:46
	MZN	09:45	20:35	10:51	21:41	7 123.4	0.22	0.1	51	656.5	68:57
	PAZ	10:25	15:46	11:31	16:52	7 445.0	0.18	0.08	61	646.5	-
Petatlan, Mexico	ACP	14:52	16:54	00:24	02:27	166.7	**0.85**	**0.43**	29	416.8	15:21
Apr/18/14, 14:27	ZHT	14:38	17:36	00:11	03:17	70.4	0.56	0.22	21	384.0	08:46
(Mw 7.2)	LCR	14:43	18:17	00:15	03:50	128.4	0.27	0.13	15	513.6	08:57
Iquique, Chile.	SCZ	07:54	03:22 (Apr/03)	08:08	27:36	4 791.3	0.38	0.21	17	580.8	183:32
Apr/01/14, 23:46	HUA	07:11	23:56	07:25	24:10	4 811.4	0.3	0.16	10	648.7	70:10
(Mw 8.2)	ACP	07:18	14:07	07:32	14:21	5 153.2	**0.36**	**0.19**	27	684.1	101:27
	ZHT	07:50	00:42 (Apr/03)	08:04	24:56	5 334.1	**0.46**	**0.21**	21	661.3	61:40
	LCR	08:23	12:58 (Apr/03)	08:37	37:12	5 402.5	0.17	0.08	15	627.0	79:39
Lazaro C., Mexico Apr/22/13, 01:16 (Mw 5.9)	LCR	01:23	02:05	00:07	00:49	14.2	**0.25**	**0.14**	54	121.7	16:13
Champerico, Guatemala	HUA	18:44	23:54	02:09	08:19	429.4	**0.69**	**0.33**	9	199.7	97:54
Nov/07/12, 16:35 (Mw 7.4)	SCZ	18:56	22:03	02:21	06:28	495.6	0.44	0.2	17	210.9	97:00

(*Continued*)

Table 1. (Continued).

Earthquake Information (*Name, Country, Date, Time (GMT), Magnitude*)	Code Stations	First Wave Arrival Time (GMT)	Max. Height Arrival Time (GMT)	First Wave Travel Time (hr)	Max. Height Travel Time (hr)	Source Distance (Km)	Max. Amplitude (m)	Max. Wave Height (m)	Tsunami Period (min)	Mean Speed (Km/hr)	Event Duration (hr)
Ometepec, Mexico Mar/20/12, 18:02 (Mw 7.5)	ACP	18:46	20:45	00:44	02:43	166.8	**0.34**	**0.2**	29	227.5	10:44
	LCR	19:12	23:36	01:10	05:34	437.1	0.14	0.07	54	429.9	18:52
Tohoku, Japan. Mar/11/11, 05:46 (Mw 9.1)	CHP	22:06	08:42 (Mar-12)	16:20	26:56	11 816	1	0.53	28	723.4	165:18
	SCZ	21:36	11:00 (Mar-12)	15:50	29:14	11 497	0.97	0.47	32	726.1	101:51
	HUA	21:14	15:36 (Mar-12)	15:28	33:50	11 443	1.32	0.63	9	739.8	43:43
	ACP	20:22	05:18 (Mar-12)	14:36	23:32	11 095	**1.78**	**1.03**	28	759.9	50:14
	ZHT	20:05	23:19	14:19	17:33	10 909	**3.22**	**1.38**	16	762.0	48:31
	LCR	20:00	22:30	14:14	16:44	10 840	0.97	0.50	53	761.6	42:32
	VALL	19:10	21:30	13:24	15:44	10 399	0.79	0.41	50	776.0	36:52
	MZN	19:12	10:18 (Mar-12)	13:26	28:32	10 115	0.43	0.21	28	753.0	71:25
	PAZ.	19:45	10:49 (Mar-12)	13:59	29:03	9 748	0.55	0.29	61	697.1	80:34
Maule, Chile.Feb/27/10, 06:34 (Mw 8.8)	CHP.	15:30	23:06	08:56	16:32	6 012.8	**1.2**	**0.55**	27	673.1	23:17
	SCZ	15:36	04:30 (Feb-28)	09:02	21:56	6 269.9	0.73	0.41	28	694.1	63:29
	ACP	15:42	19:30	09:08	12:56	6 537.9	**0.9**	**0.47**	29	715.8	52:58
	LCR	15:54	18:42	09:20	12:08	6 754.3	0.76	0.39	53	723.7	67:42
	MZN	17:18	03:06 (Feb-28)	10:44	20:32	7 476.1	0.34	0.2	51	696.5	75:11
	PAZ	18:21	00:17 (Feb-28)	11:47	17:43	7 780.8	0.57	0.25	61	660.3	52:09
Samoa IslandsSep/29/09, 17:48 (Mw 8.1)	ACP	06:06	07:54	12:18	14:06	8 693.9	**0.41**	**0.19**	29	706.8	28:37

Table 2. Average duration in hours considering all stations that recorded the event (minimum and maximum observed) on the Mexican Pacific coast in the period 2009–2018. The distant tsunamis are marked with *.

TSUNAMI EVENT	DURATION (h)
SWAN ISLAND, HONDURAS, 2018	**7** *(6:29–7:01)*
PIJIJIAPAN, MEXICO, 2017	**32** *(4:19–87:01)*
ILLAPEL, CHILE, 2015*	**60** *(37:09–84:04)*
PETATLAN, MEXICO, 2014	**11** *(8:46–15:21)*
IQUIQUE, CHILE, 2014*	**98** *(70:10 – 183:32)*
LAZARO CARDENAS, MEXICO, 2013	**16** *(16:13)*
CHAMPERICO, GUATEMALA, 2012	**97** *(97:00–97:54)*
OMETEPEC, MEXICO, 2012	**15** *(10:44–18:52)*
TOHOKU, JAPAN, 2011*	**70** *(36:52–165:18)*
MAULE, CHILE, 2010*	**55** *(23:17–75:11)*
SAMOA ISLANDS, 2009*	**28** *(28:37)*

The decay of distant tsunamis was longer than those from local sources (Table 2). Sites where tsunami waves remain for longer periods, from both local or distant sources, were Puerto Chiapas, Salina Cruz, Acapulco, Zihuatanejo, and Lazaro Cardenas, while the sites where tsunami waves take less time to decay are Puerto Angel and Puerto Vallarta.

The methods proposed here were not applied in cases in which the disturbances in the sea level were not significantly different with respect to the sea conditions previous to the event. Those cases were Sian Ka'an in the event of Honduras, 2018; Mazatlan in the event of Illapel in 2015; and La Paz in the events of Pijijiapan, 2017 and Illapel, 2015.

4.2. Amplitude spectrum

Comparing the AS of different tsunamis recorded for the same sea level station, it was found that there is great similarity between them. This similarity can be visually observed, and was corroborated with the calculated correlations (Appendix A2).

For the Puerto Chiapas station, at least 3 main frequencies in all tsunamis were identified, (Figure 14). From the sea level signals, periods between 20 and 30 minutes were visually obtained for the tsunamis that arrived at this station, while in the AS, the maximum frequency amplitudes were in that interval (0.03–0.04 cpm (cycles per minute), 33–25 min) and established as the dominant frequencies that would be expected from a tsunami that arrives in this area. A frequency peak of 0.0073 cpm (137 min) present in all the recorded events is also observed in Puerto Chiapas, with considerable amplitude in the events of Pijijiapan (2017) and Maule, Chile (2010).

The tide station of Puerto Angel was installed in 2012. The events of 2013 and 2014 did not generate disturbances at the sea level of this location. Only two events were recorded (2015 and 2017), whose spectra are observed in Figure 15. The spectra of these events have a high correlation (0.9) with dominant frequencies of 0.21 cpm. corresponding to a period of 5 min.

At Huatulco station, two main frequencies were recognized: 0.1 and 0.11 cpm (Figure 16) corresponding to periods of 10 and 9 minutes, as well as secondary frequencies corresponding to periods of 13, 14 and 29 minutes that were present in all the tsunamis analyzed. The best correlations were obtained between the spectra of Tohoku, Illapel and Iquique, being of the order of 0.59 to 0.70.

At Acapulco sea level station, the main frequency was 0.034 cpm (period of 29 min) and clearly occurred in all the recorded events. Secondary frequencies were also distinguished in the 5 distant

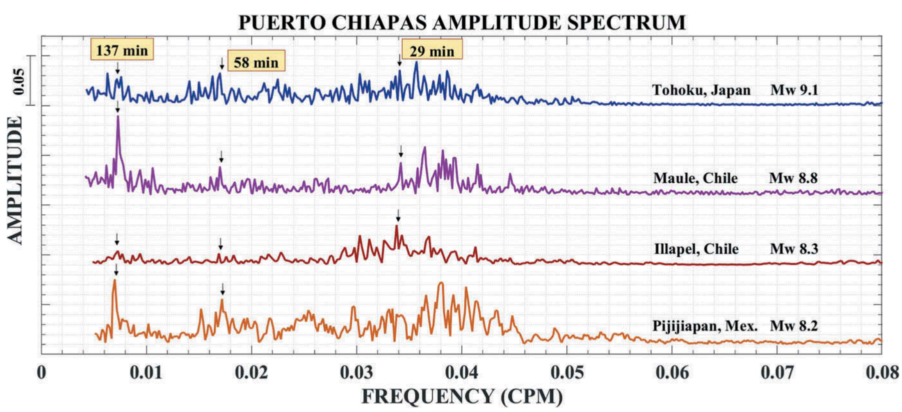

Figure 14. Amplitude spectra of Tsunamis at the sea level station of Puerto Chiapas (CHP). Spectra of Tohoku, Japan (2011), Maule, Chile (2010), Illapel, Chile (2015) and Pijijiapan, Mex. (2017) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

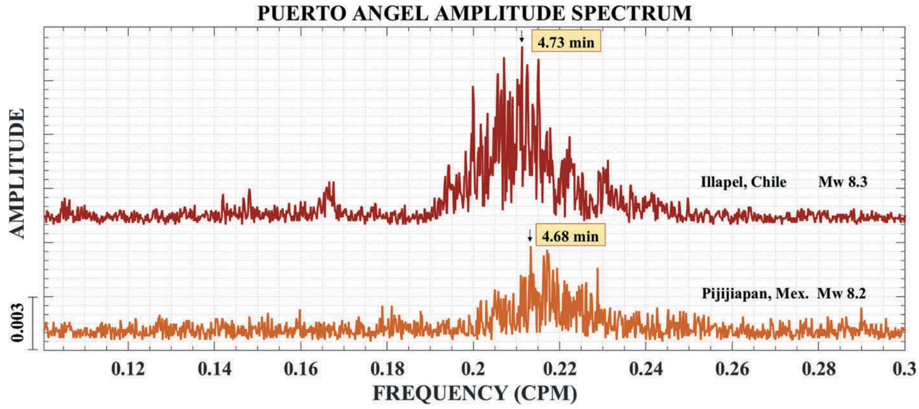

Figure 15. Amplitude spectra of Tsunamis at the sea level station of Puerto Angel (ANG). Spectra of the Illapel, Chile (2015) and Pijijiapan, Mex. (2017) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

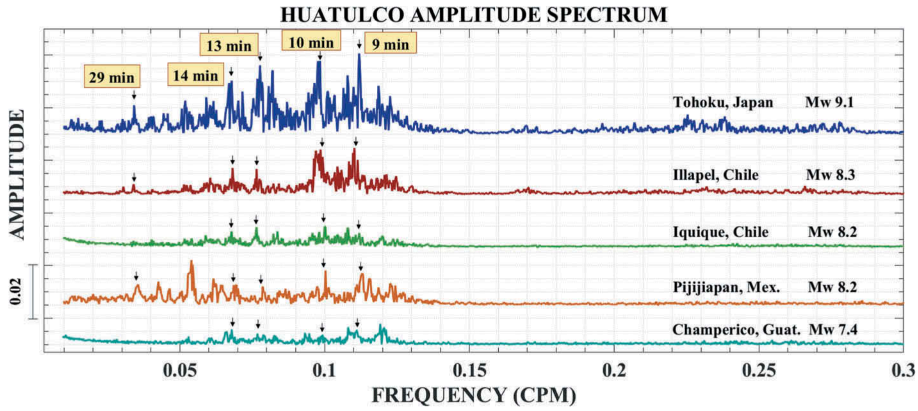

Figure 16. Amplitude spectra of Tsunamis at the sea level station of Huatulco (HUA). Spectra of Tohoku, Japan (2011), Illapel, Chile (2015), Iquique, Chile (2014), Pijijiapan, Mex. (2017), and Champerico, Guatemala (2012) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

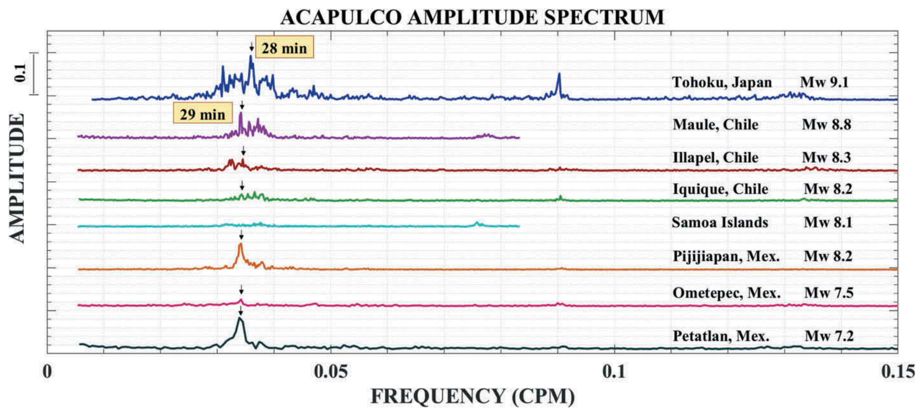

Figure 17. Amplitude spectra of Tsunamis at the sea level station of Acapulco (ACP). Spectra of Tohoku, Japan (2011), Maule, Chile (2010), Illapel, Chile (2015), Iquique, Chile (2014), Samoa (2009), Pijijiapan, Mex. (2017), Ometepec, Mex. (2012) y Patatlan, Mex. (2014) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

tsunami events that are not observed in the local tsunamis. It should be noted that a correlation of 0.91 was obtained between the local events of Petatlan and Pijijiapan (Figure 17).

At Zihuatanejo three important frequencies corresponding to periods of 32, 21, and 16 minutes were identified. For this station, the behavior in the frequency domain is similar for both distant and local tsunamis (Figure 18).

In Lazaro Cardenas sea level station (Figure 19), the behavior of the frequency spectra was similar for those of local origin, with correlation coefficients of 0.78 and

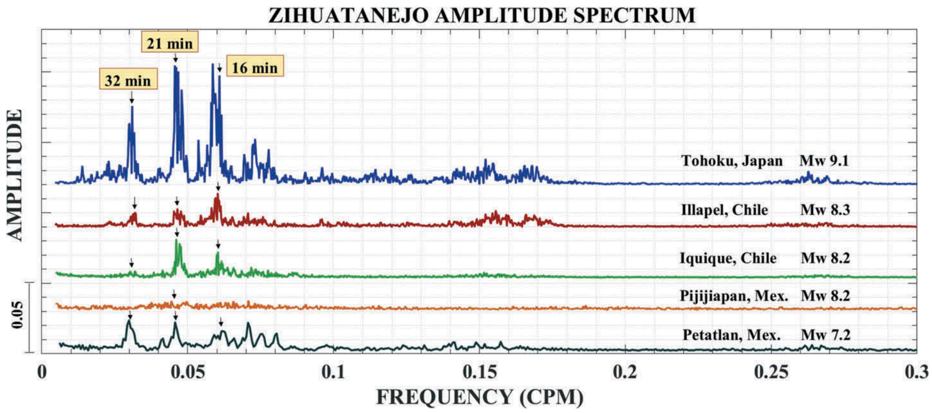

Figure 18. Amplitude spectra of Tsunamis at the sea level station of Zihuatanejo (ZHT). Spectra of Tohoku, Japan (2011), Illapel, Chile (2015), Iquique, Chile (2014), Pijijiapan, Mex. (2017), and Patatlan, Mex. (2014) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

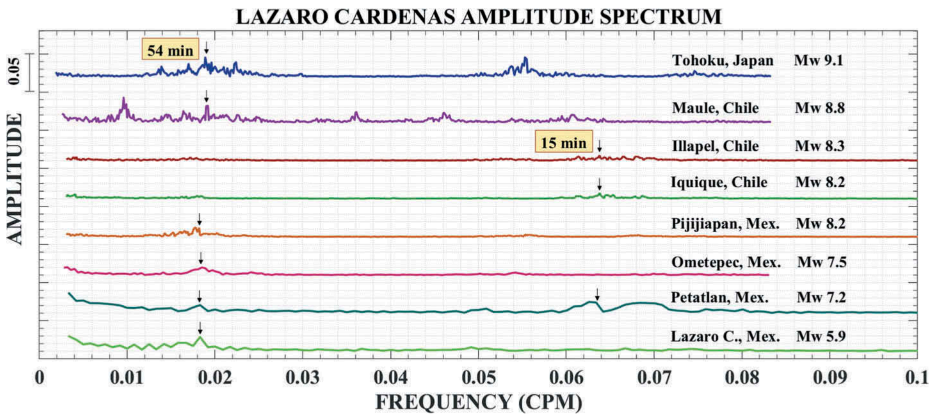

Figure 19. Amplitude spectra of Tsunamis at the sea level station of Lazaro Cardenas (LCR). Spectra of the Tohoku, Japan (2011), Maule, Chile (2010), Illapel, Chile (2015), Iquique, Chile (2014), Pijijiapan, Mex. (2017), Ometepec, Mex. (2012), Patatlan, Mex. (2014) and Lazaro Cardenas, Mex. (2013) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

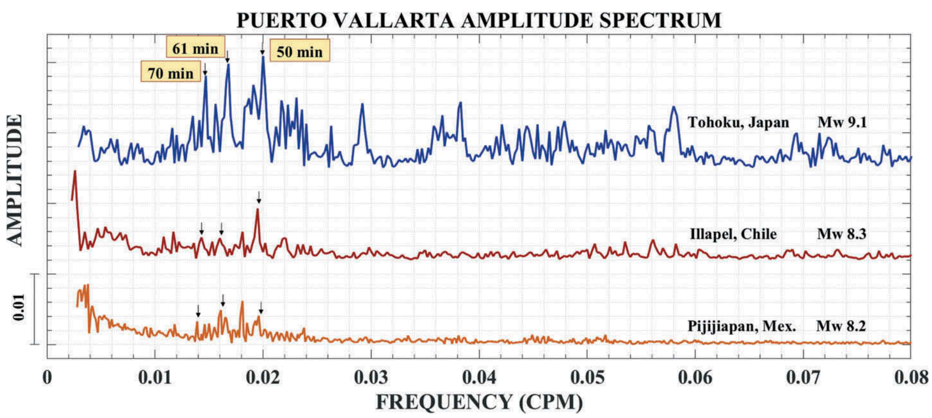

Figure 20. Amplitude spectra of Tsunamis at the sea level station of Puerto Vallarta (VLL). Spectra of the Tohoku, Japan (2011), Maule, Chile (2010), Illapel, Chile (2015), Iquique, Chile (2014), Pijijiapan, Mex. (2017), Ometepec, Mex. (2012), Patatlan, Mex. (2014) and Lazaro Cardenas, Mex. (2013) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

0.80, and differ from those of distant tsunamis. Similar to Acapulco, there are secondary frequencies with peaks in 0.066 and 0.018 cpm (periods of 15 and 55 min).

In the Puerto Vallarta sea level station (Figure 20), the three recorded events have a dominant frequency of 0.02 cpm (50 min period). The spectra of the events

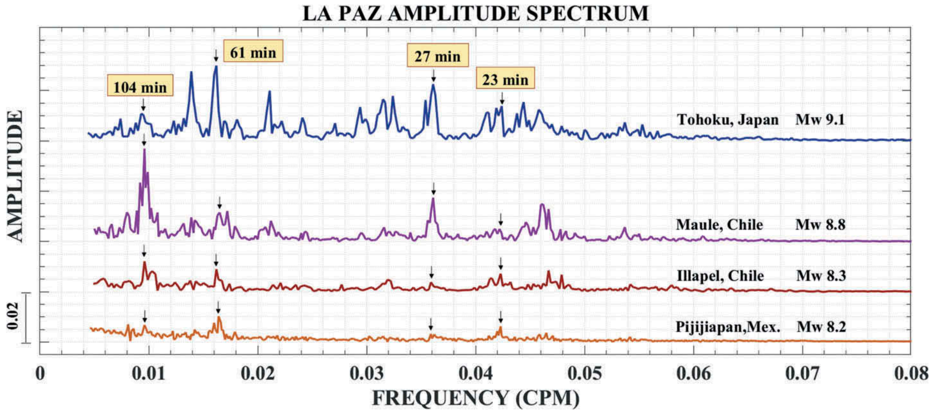

Figure 21. Amplitude spectra of Tsunamis at the sea level station of La Paz (PAZ). Spectra of Tohoku, Japan (2011), Maule, Chile (2010), Illapel, Chile (2015) and Pijijiapan, Mex. (2017) are shown. The corresponding Mw of the source earthquakes and the frequencies (periods) that are persistent throughout different events are indicated.

of Illapel and Pijijiapan had the largest correlation (0.64).

At La Paz sea level station, 4 tsunamis were recorded. In these events the frequencies associated with largest amplitude were 0.016 and 0.037 cpm corresponding to the periods of 61 and 27 min. However, during the 2010 Maule, Chile event, the frequency of 0.0096 cpm equivalent to a 1 hour and 44 minutes had more amplitude than in the other events. As in the case of the Puerto Vallarta station, the events of Illapel (2015) and Pijijiapan (2017) behaved very similarly to each other with a correlation coefficient of 0.74 (Figure 21).

Comparing the amplitude spectra of the sea level signals in their normal state and the signal disturbed by the tsunami, it was observed that both spectra contain almost the same main frequencies although they differ in amplitude.

For all the cases studied, frequencies with larger amplitudes observed without tsunami coincide with those obtained from the spectra obtained in the series of the tsunami period. Therefore, when a tsunami arrives at the coast, it is influenced by the geographical characteristics of the coast and the bathymetry favoring oscillations with similar frequencies of those obtained without a tsunami (Figures 22 and Figures 23).

The dominant tsunami frequency for each station was defined to be the one present in all events with the largest amplitude (Table 3).

5. Discussion and conclusions

Larger tsunami wave amplitudes were recorded in the sea level stations of Acapulco, Zihuatanejo and Pto. Chiapas for both local and remote events; while in the stations of Pto. Angel, Salina Cruz, Lazaro Cardenas and Mazatlan the tsunami waves amplitudes were smaller. La Paz had also smallest amplitudes but, because of its location, it is very likely that is due to its less exposed to tsunamis.

For local tsunamis the time difference between the arrival time of the first wave and the wave with maximum height was from 1 to 5 hours while for distant

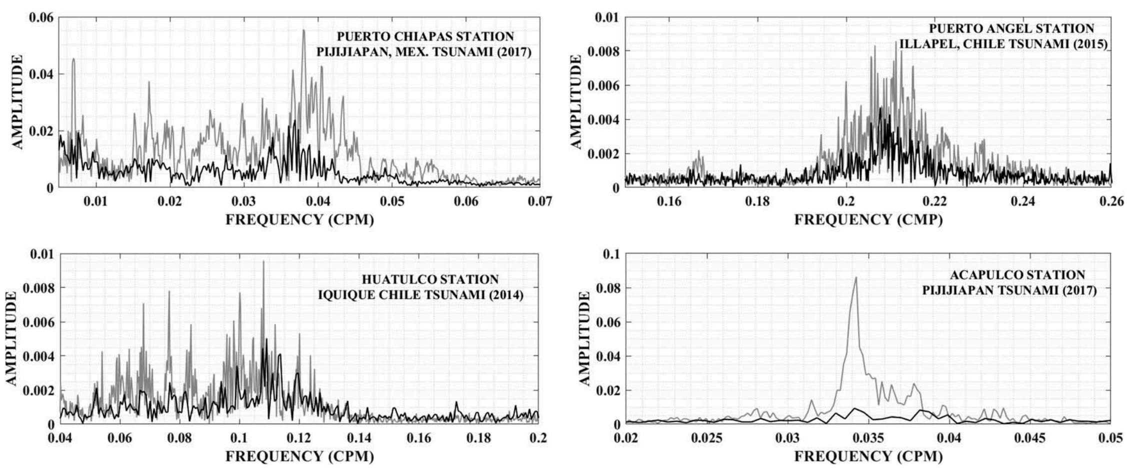

Figure 22. Amplitude spectra obtained from a series that record a tsunami (gray line) and Amplitude spectra from the sea level before the arrival of the tsunami.

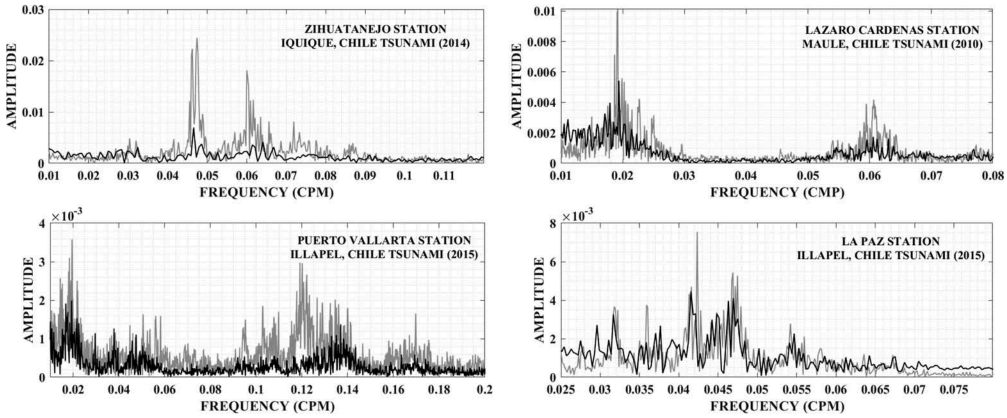

Figure 23. Amplitude spectra obtained from a series that record a tsunami (gray line) and the sea level before the arrival of the tsunami.

Table 3. Main tsunami periods found in the AS of each tidal station.

TIDE STATION	MAIN TSUNAMI PERIOD (min)
PUERTO CHIAPAS, CHIS.	25/30
SALINA CRUZ, OAX.	17
HUATULCO, OAX.	9/10
PUERTO ANGEL, OAX.	5
ACAPULCO, GRO.	29
ZIHUATANEJO, GRO.	16/21
LAZARO CARDENAS, MICH.	15/54
PUERTO VALLARTA, JAL.	50
LA PAZ, BCS.	27/61

tsunamis, the arrival time difference was from 6 to 22 hours, and the perturbation last longer for distant tsunamis than for tsunamis produced by local sources. So that for a large-scale tsunami the flood hazard may prevail for a long time, in particular in the case of distant tsunamis.

Oscillations that remain longer time for local and distant sources are Puerto Chiapas, Salina Cruz, Acapulco, Zihuatanejo and Lazaro Cardenas, while the areas where the tsunami energy took less time to decay were Puerto Angel and Puerto Vallarta.

The spectral of the noise (non-astronomical tide frequencies) for segments of the time series when there were no tsunamis coincides in the peak characteristic frequencies observed during the tsunamis, but with smaller amplitude.

The spectra from different events for the same location have high correlations regardless of the site of origin (may have different amplitudes but with peaks and lows in similar frequencies). The similarity allows to determine the characteristic frequencies of the tsunamis in each zone and the periods that can be expected for future tsunamis that arrive at the Mexican Pacific coast were established. Puerto Vallarta, Lazaro Cardenas, Puerto Chiapas y Acapulco, have peak frequencies larger than 30 min which is characteristic of the flooding waves, in addition to their amplitude. Small peak periods were observed in Puerto Angel, Huatulco and Salina Cruz. These results may help to evaluate the numerical models of different tsunami scenarios, also may help policy makers to elaborate plans for risk reduction.

Acknowledgments

The authors would like to acknowledge the Servicio Mareografico Nacional of the Universidad Nacional Autonoma de México, for the sea level data used in this research. The data can be downloaded from www.mareografico.unam.mx. Authors also would like to acknowledge to The Project for Hazard Assessment of Large Earthquakes and Tsunamis in the Mexican Pacific Coasts for Disaster Mitigation SATREPS, funded by JST-JICA (#1554361).

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Jorge Zavala-Hidalgo http://orcid.org/0000-0002-2737-434X

References

Duputel, Z., L. Rivera, H. Kanamori, and G. Hayes. 2012. "W Phase Source Inversion for Moderate to Large Earthquakes

(1990–2010).” *Geophysical Journal International* 189 (2): 1125–1147. doi:10.1111/gji.2012.189.issue-2.

Hayashi, Y., S. Koshimura, and F. Imamura. 2012. “Comparison of Decay Features of the 2006 and 2007 Kuril Island Earthquake Tsunamis.” *Geophysical Journal International* 190 (1): 347–357. doi:10.1111/j.1365-246X.2012.05466.x.

Jimenez, C. 2018. “Seismic Source Characteristics of the Intraslab 2017 Chiapas, Mexico Earthquake (Mw 8.2).” *Physics of the Earth and Planetary Interiors* 280 (2018): 69–75. doi:10.1016/j.pepi.2018.04.013.

Melgar, D., and A. Ruiz-Angulo. 2018. “Long-Lived Tsunami Edge Waves and Shelf Resonance from the M8. 2 Tehuantepec Earthquake.” *Geophysical Research Letters* 45 (22): 12–414. doi:10.1029/2018GL080823.

National Geophysical Data Center/World Data Service (NGDC/WDS): Global Historical Tsunami Database, NOAA. 2019. doi:10.7289/V5PN93H7.

Pararas-Carayannis, G. 1987. “International Tsunami Information Center, A Progress Report for 1985-1987.” In *XI Session of the International Coordination Group for the Tsunami Warning System in the Pacific*. Beijing, China, September. 8–12. 12 plus annexes.

Sánchez, A. J., and S. F. Farreras. 1993. Catalog of tsunamis on the Western Coast of Mexico. In *World Data Center for solid Earth Geophysics*, Publication SE-50, NOAA Boulder, Colorado.

Sinnott, R. W. 1984. “Virtues of the Haversine.” *Sky and Telescope* 68 (2): 159.

SSN. 2012. Reporte de Sismo. “Sismo del dia 20 de marzo de 2012, Oaxaca (M 7.4).” http://www.ssn.unam.mx/jsp/reportesEspeciales/Oaxaca-Guerreo −20marzo2012.pdf

SSN. 2013. Reporte de Sismo. “Sismo del dia 21 de abril de 2013, Michoacan (M 5.8).” http://www.ssn.unam.mx/sismicidad/reportes-especiales/2013/SSNMX_rep_esp_20130421_michoacan_M58.pdf

SSN. 2014. Reporte de Sismo. “Sismo del dia 18 de abril de 2014, Guerrero (M 7.2).” http://www.ssn.unam.mx/sismicidad/reportes-especiales/2014/SSNMX_rep_esp_20140418_guerrero_M72.pdf

SSN. 2017. Reporte especial de Sismo. “Sismo de Tehuantepec (2017-09-07 23:49 Mw 8.2).” http://www.ssn.unam.mx/sismicidad/reportes -especiales/2017/SSNMX_rep_esp_20170907_Tehuantepec_M82.pdf

USGS, Earthquake Hazards Program, 2009, “M 8.1 - Samoa Islands Region.” https://earthquake.usgs.gov/earthquakes/eventpage/official20110311054624120_30#executive

USGS, Earthquake Hazards Program. 2010. “M 8.8 - Offshore Bio-Bio, Chile.” https://earthquake.usgs.gov/earthquakes/eventpage/official20110311054624120_30#executive

USGS, Earthquake Hazards Program. 2012. “M 7.4 - Offshore Guatemala.” https://earthquake.usgs.gov/earthquakes/eventpage/usp000jv5f#executive

USGS, Earthquake Hazards Program. 2014. “M 8.2-94km NW of Iquique, Chile.” https://earthquake.usgs.gov/earthquakes/eventpage/usc000nzvd#map

USGS, Earthquake Hazards Program. 2015. “M 8.3-48km W of Illapel, Chile.” https://earthquake.usgs.gov/earthquakes/eventpage/us20003k7a#executive

USGS, Earthquake Hazards Program. 2018. “M 7.5-44km E of Great Swan Island, Honduras.” https://earthquake.usgs.gov/earthquakes/eventpage/us1000c2zy#executive

Zaytsev, O., A. B. Rabinovich, and R. E. Thomson. 2016. A comparative analysis of coastal and open-ocean records of the great Chilean tsunamis of 2010, 2014 and 2015 off the coast of Mexico. In *Global Tsunami Science: Past and Future*, Volume I (pp. 4139–4178). Birkhäuser, Cham.

Zaytsev, O., A. B. Rabinovich, and R. E. Thomson. 2017. “The 2011 Tohoku Tsunami on the Coast of Mexico: A Case Study.” *Pure and Applied Geophysics* 174 (8): 2961–2986. doi:10.1007/s00024-017-1593-z.

Appendix

Table A1. Tide gauge stations of SMN that were installed or modernized during the period 2009-2018.

Tide station	Latitude	Longitude	Code	Sensor type	Year of installation	Sample interval (min)
Isla Mujeres	21° 15.280′ N	86° 44.765′ W	IMJ	Radar	2017	1
Puerto Morelos	20° 52.089′ N	86° 52.009′ W	MRL	Radar	2013	1
Sian Ka'an	19° 18.758′ N	87° 26.765 ′W	SKN	Radar	2016	1
Puerto Chiapas	14° 42.738′ N	92° 24.083′ W	CHP	Float	2008	6
				Radar	2014	1
Salina Cruz	16° 10.106′ N	95° 11.806′ W	SCZ	Float	2009	6
				Radar	2013	1
Huatulco	15° 45.187′ N	96° 7.767′ W	HUA	Radar	2010	1
Puerto Ángel	15° 39.922′ N	96° 29.500′ W	ANG	Radar	2012	1
Acapulco	16° 50.276′ N	99° 54.180′ W	ACP	Float	2008	6
				Radar	2017	1
|Zihuatanejo	17° 38.171′ N	101° 33.491′ W	ZHT	Radar	2011	1
Lázaro Cárdenas	17° 56.387′ N	102° 10.683′ W	LCR	Float	2012	6
				Radar	2012	1
Manzanillo	19° 03.633′ N	104° 18.032 ′W	MNZ	Radar	2017	1
Puerto Vallarta	20° 39.476′ N	105° 14.572′ W	VLL	Radar	2016	1
Mazatlán	23° 10.885′ N	106° 25.432′ W	MZN	Float	2009	6
				Radar	2014	1
La Paz	24°16.039′ N	110° 19.970′ W	PAZ	Float	2008	6
				Radar	2017	1

Table A2. Pearson's linear correlation coefficients between the amplitude spectra of the tsunamis recorded at each tidal station. Values greater than 0.55 are highlighted with black-bold.

LINEAR CORRELATION COEFFICIENTS										
Tsunami Events	Pijijiapan, Mex.	Illapel, Chile	Petatlan, Mex.	Iquique, Chile	Lazaro C. Mex.	Ometepec, Mex.	Champerico, Guat.	Tohoku, Jap.	Maule, Chile	Samoa Islands
PUERTO CHIAPAS										
Pijijiapan, Mex.	1,00	**0,68**						0,51	**0,61**	
Illapel, Chile	**0,68**	1,00						**0,63**	0,40	
Tohoku, Jap.	0,51	**0,63**						1,00	0,54	
Maule, Chile	**0,61**	0,40						0,54	1,00	
PUERTO ANGEL										
Pijijiapan, Mex.		**0,90**								
HUATULCO										
Pijijiapan, Mex.	1,00	0,52		0,52			0,48	0,53		
Illapel, Chile	0,52	1,00		**0,59**			0,53	**0,70**		
Iquique, Chile	0,52	**0,59**		1,00			0,54	**0,61**		
Tohoku, Jap.	0,53	**0,70**		**0,61**			**0,62**	1,00		
Champerico, Guat.	0,48	0,53		0,54			1,00	**0,62**		
ACAPULCO										
Pijijiapan, Mex.	1,00	**0,62**	**0,91**	**0,63**		0,54		**0,60**	**0,79**	0,29
Illapel, Chile	**0,62**	1,00	**0,78**	0,50		**0,56**		**0,60**	**0,66**	0,47
Petatlán, Mex.	**0,91**	**0,78**	1,00	**0,64**		**0,57**		0,53	0,53	0,38
Iquique, Chile	**0,63**	0,50	**0,64**	1,00		0,30		**0,63**	**0,70**	0,39
Ometepec, Mex.	0,54	**0,56**	**0,57**	0,30		1,00		**0,58**	**0,64**	0,24
Tohoku, Jap.	**0,60**	0,60	0,53	**0,63**		**0,58**		1,00	**0,65**	0,48
Maule, Chile	**0,79**	**0,66**	0,53	**0,70**		**0,64**		**0,65**	1,00	0,45
Samoa Islands	0,29	0,47	0,38	0,39		0,24		0,48	0,45	1,00
ZIHUATANEJO										
Pijijiapan, Mex.	1,00	0,10	0,34	0,29				0,32		
Illapel, Chile	0,10	1,00	0,53	0,46				**0,57**		
Petatlán, Mex.	0,34	0,53	1,00	**0,62**				**0,73**		
Iquique, Chile	0,29	0,46	**0,62**	1,00				**0,63**		
Tohoku, Jap.	0,32	**0,57**	**0,73**	**0,63**				1,00		
LÁZARO CÁRDENAS										
Pijijiapan, Mex.	1,00	0,39	0,42	0,39		**0,78**		**0,80**	0,49	0,22
Illapel, Chile	0,39	1,00	0,20	**0,67**		0,47		0,12	0,02	0,02
Petatlán, Mex.	0,42	0,20	1,00	**0,79**		0,50		0,15	0,01	0,01
Iquique, Chile	0,39	**0,67**	**0,79**	1,00		0,42		0,40	0,04	0,04
Lázaro C. Mex.	**0,78**	0,47	0,50	0,42		1,00		**0,72**	0,53	0,31
Ometepec, Mex.	**0,80**	0,12	0,15	0,40		**0,72**		1,00	0,48	0,38
Tohoku, Jap.	0,49	0,02	0,01	0,04		0,53		0,48	1,00	0,25
PUERTO VALLARTA										
Pijijiapan, Mex.	1,00	**0,64**						0,55		
Illapel, Chile	**0,64**	1,00						0,54		
Tohoku, Jap.	0,55	0,54						1,00		
LA PAZ										
Pijijiapan, Mex.	1,00	**0,74**						**0,63**	**0,71**	
Illapel, Chile	**0,74**	1,00						**0,63**	**0,73**	
Tohoku, Jap.	**0,63**	**0,63**						1,00	**0,70**	
Maule, Chile	**0,71**	**0,73**						**0,70**	1,00	