ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 31 **Number 3** **2012**

THE 2010 CHILEAN TSUNAMI: BEHAVIOR ON THE ECUADORIAN COAST AND THE GALAPAGOS ISLANDS

H. Moreano[1], P. Arreaga[2] and J. Nath[3]

[1]Instituto de Investigación Científica y Desarrollo Tecnológico, Centro de Estudios Integrales del Ambiente. Universidad Estatal Península de Santa Elena, Vía: La Libertad - Santa Elena, La Libertad.

[2]Laboratorio de Tsunamis. Instituto Oceanográfico de la Armada. Avda. de la Marina, Guayaquil.

[3]Departamento de Hidrografía, Sección Mareas. Instituto Oceanográfico de la Armada, Avda. de La Marina. Guayaquil.

E-mail: hmoreano@gye.satnet.net, parreaga@inocar.mil.ec, jnath@inocar.mil.ec

ABSTRACT

Available mareograms from ports of Ecuador and the Galapagos Islands made possible analysis and understanding of the tsunami generated by the great Chile earthquake of 27 February 2010. In general, all tidal gauges along the coastal zones at these localities begun to record sea level changes minutes after the predicted low water tide near 08:30 in the morning of February 27. The mareographic records showed waves with amplitudes ranging from 20 to 70 cm and periods of up to 2 hours. From then on the records indicated lower amplitude waves and rather short periods perhaps due to local conditions at each port. At Caleta, Aeolian and Baltra Island in the Galapagos, sea level changes begun just before low tide. Recorded waves in Academy Bay of Puerto Ayora (Santa Cruz Island) ranged at about 35 cm in amplitude and boats sat on the rocky bottom at around 07:30 (local time). Initial periods were less than 60 minutes but later were shorter - possibly because of the port's configuration. The water level fluctuations lasted for about 48 hours. Along the coast of Ecuador the tsunami wave amplitudes ranged between 20 and 70 cm the periods were longer but shorter in the Galapagos Islands. Based on initial sea level changes and the issuance of a tsunami warning at Puerto Ayora on Santa Cruz Island, there was evacuation of coastal inhabitants to safer, higher grounds.

Keywords*: Tsunami Chile 2010, Impact on Ecuador and Galapagos Islands.*

1. INTRODUCTION

The great earthquake (Mw= 8.8) occurred at 03:34 (local Chilean time) on 27 February 2010, along the south central Nazca/South American plate boundary, just offshore Maule. Its epicenter was at 35.9 S and 72.7 W and had a focal depth estimated at 35 km. It occurred as thrust-faulting along a highly stressed coastal segment of Chile's central seismic zone - extending from about 33ºS to 37ºS latitude - where active, oblique subduction of the Nazca tectonic plate below South America occurs at the high rate of up to 80 mm per year. It was the 5th most powerful earthquake in recorded history and the largest in the region since the extremely destructive May 22, 1960 magnitude M_w9.5 earthquake near Valdivia (Pararas-Carayannis, 2010). Its rupture extended nearly 500-600 km in length and the area that was affected was estimated to be 130 km wide. The quake generated destructive tsunami waves that struck the Chilean coastline and also affected distant locations elsewhere in the Pacific Ocean Basin (Cienfuegos, 2010; Comte, 2010). The tsunami was responsible for the death of nearly 500 people and caused extensive destruction along the Chilean coastal zone. Maximum run-up reached a height of 19 meters on the cliffs near the generating area but there was also major impact on bays and river mouths - like that of Maule river - where local coastal villages were swept away by the giant waves (Lagos, 2010).

The Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii issued a tsunami warning and countries like Ecuador, USA (Hawaii) and Japan - among others – and people were evacuated to higher ground. Because of the warning, there was not any loss of life elsewhere in the Pacific due to this tsunami, in contrast to the many deaths caused in Hawaii, Japan and elsewhere in the Pacific by the tsunami generated by the giant 1960 Chilean earthquake (Mw=9.5) when the warning system was still in its infancy.

Comparison of the 2010 and 1960 Chilean tsunamis indicated substantial differences in source mechanisms, energy release, ruptures, spatial clustering and distributions of aftershocks, as well as in geometry of subduction and extent of crustal displacements on land and in the ocean – which could also account for energy trapping and differences in far-field effects (Pararas-Carayannis, 2010).

Shortly after the earthquake the U.S. National Oceanic and Atmospheric Administration (NOAA) issued the map shown in Fig. 1, which shows the tsunami's propagation and arrival times in hourly increments as well as estimated wave amplitudes in centimeters. As shown, the tsunami's travel time to the Galapagos was 6 hours with estimated height of 40 cm and for the coast of Ecuador about 5 hours with a height estimated at 20 cm.

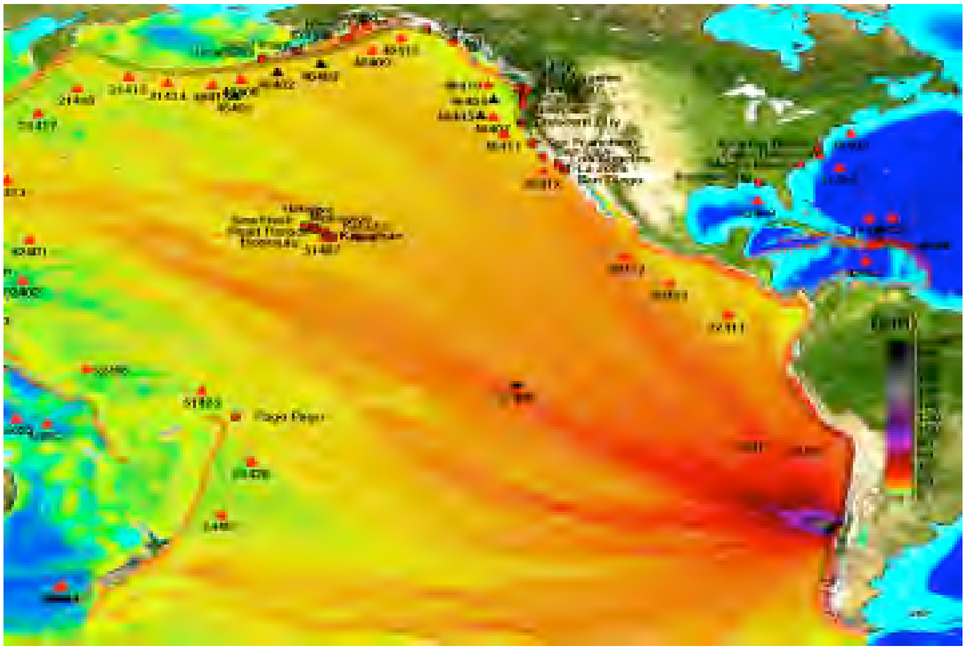

Fig. 1 Propagation map of the Chilean tsunami of 27 February 2010 across the Pacific Basin issued by U.S. - NOAA. The brown lines are travel times and the colors show energy focusing and estimated tsunami wave amplitudes.

2. OBJECTIVE

Given this background of the tsunami, the objective of the present study was to analyze the tide gauge records at five coastal ports along Ecuador and of two more records from the Galapagos Island in order to understand the behavior of the tsunami in both geographical areas and particularly for each port in order to arrive at conclusions that would allow the National Secretary for Risk Management (SNGR Spanish acronyms), the local governments and local universities to adopt prevention, and mitigation measures that would help reduce future casualties and property damage.

3. DATA COLLECTION AND FILTERING

The Instituto Oceanográfico de la Armada (INOCAR) of Ecuador maintains a network of tide gauges along its continental coast and in the Galapagos Islands. Specifically tide gauges exist at ports in Esmeraldas, Manta and La Libertad, as well at Bahia de Caraquez at the Chone River estuary and Puerto Bolivar at the Jambeli Archipelago. Tide stations in the Galapagos Islands are located at the Aeolian Inlet (Baltra Island) and at Academy Bay of Puerto Ayora (Santa Cruz Islands). Sea level records of the already mentioned ports are included in the present paper. Table 1 shows details on the locations of all these gauges that recorded the 27 February 2010 Chile tsunami.

Table 1. Tide gauges locations on the continental coast of Ecuador and at the Galapagos Archipelago

PORT	LATITUDE	LONGITUDE	CHARD/EDITION	COMMENTS
Esmeraldas	00-57-29 N.	079-38-46 W.	IOA-10010/2010	Main Pier (APE).
Bahía de Caráquez Chone Estuary	00-36-26 S.	080-25-22 W.	IOA-1031/2007	Río Chone Estuary County Pier
Manta	00-55-53 S.	080-43-18 W.	IOA-10401/2008	Main Pier (APM).
La Libertad	02-13-04 S.	080-54-23 W.	IOA.10520/2008	Main Pier (SUINLI).
Puerto Bolívar Jambeli Estuary	03-15-35 S.	080-00-05 W.	IOA-10811/2006	Jambelí Estuary, Estero Santa Rosa, Main Pier (APPB).
Baltra Island Galapagos.	00-26-06 S.	090-17-06 W.	IOA. 20213/2011	Aeolian Inlet, Navy Pier
Santa Cruz Island Galapagos.	00-44-48 S.	090-19-00 W.	IOA-20310/2009	Academy Bay, Navy Pier

Each record was statistically filtered and an assessment was made on astronomical effects, atmospheric pressure, Kelvin and storms waves that may have affected the recordings. Based on this assessment it was concluded that these had minimal or no effect. Neither the Chone estuary nor the Estero Santa Rosa had any significant inflow of fresh water to influence the recording. Furthermore there was no impact of spring tide such as the one which occurred a month later on March 28 when the moon was full. Therefore, the records of the above mentioned tide stations represented almost pure oscillations generated by the tsunami.

4. ANALYSIS

Table 2 shows the arrival time of the first tsunami crest at each tide gauge station and the time of low water for Saturday, 27 February 2012 for each of the seven ports - as predicted by the tide table issued by INOCAR. Also, the same table includes the amplitudes and periods of the tsunami generated oscillations as recorded by the mareographs (Figures 2 and 3). From the analysis of the records, it is established that the first tsunami wave crest at three stations along the Ecuadorian coast arrived after low water, while at Bahía de Caraquez and Puerto Bolívar; the first oscillation enters both estuaries before low tide. The time delay in arrival may be the result of natural hydraulic estuarine conditions.

Table 2. Details of the tsunami arrival. LW: Low water (Tide table 2010) R: Zone Time 5 S: Zone time 6.

PORT	ARRIVAL TIME	TIME LW	AMPLITUDE (cm.)	PERIOD (min.)
Esmeraldas	09H30 R	08H28R	20-30	120
Bahía de Caráquez	08H30 R	08H56R	30-50	60-120
Manta	10H00 R	08H35R	25-30	90-120
La Libertad	08H50 R	08H38R	35-70	120-150
Puerto Bolívar	09H00 R	O9H24R	35-50	60-110
Isla Baltra	07H00 S	07H28S	25-35	30-60
Isla Santa Cruz	07H00 S	07H28S	25-35	30-60

The first wave recorded at the port of Manta (located between Esmeraldas and La Libertad) shows arrival at 10:00, almost an hour later than at La Libertad to the south and half an hour later than at Esmeraldas to the north. However, all tide gauges at all ports recorded oscillations with periods ranging from 90 to 150 minutes and amplitudes ranging from 20 to 70 cm. The inconsistency in arrival times could be due to effects of refraction and diffraction, which can be attributed to local bathymetry and coastal geomorphology. Manta is located on an east – west trending coastline and faces north, while La Libertad is located in the interior of Santa Elena Bay. Therefore, waves coming from the south would have to refract considerably before arriving at both ports. Also, it should be noted that the tide gauge record at La Libertad of the 1960 Chilean tsunami showed amplitudes and periods of 1.54 m. and 36 minutes respectively (Rizzo 1977) and it also occurred at low water.

At Puerto Bolívar, the tsunami crest arrived at 09:00, before low water and had periods of 120 minutes and amplitudes of 35 cm. After mid-day, three additional peaks with shorter periods and amplitudes were recorded but it appears that these were in response to local conditions – since the estuary has a west and north mouth and waves can enter in and out from both sides. At Bahía de Caráquez, the initial crest is recorded at 08:30 with similar periods and amplitudes as in Puerto Bolivar, but they both decreases as the day goes on and this behavior may respond to the own estuarine hydraulics and morphology.

At the Galápagos Islands, the first tsunami peak occurred at 07:00, half an hour before low water. The oscillations were of shorter periods and amplitudes than those recorded along the coasts of

Continental Ecuador. However, at Academy Bay at Puerto Ayora on Santa Cruz Island in the Galapagos, in the next hour after the first tsunami wave arrived, there were sea level oscillations, which caused yachts and small boats to seat on the rocky bottom of the harbor (Tagle, 2010). When the third wave arrived at this port in the subsequent hour, all boats were once again floated and by 09:00 sea level oscillations were of shorter amplitudes and periods - probably due to the tsunami or to local resonance response of the bay or perhaps to both. By midnight sea level activity returned to normal at Academy Bay.

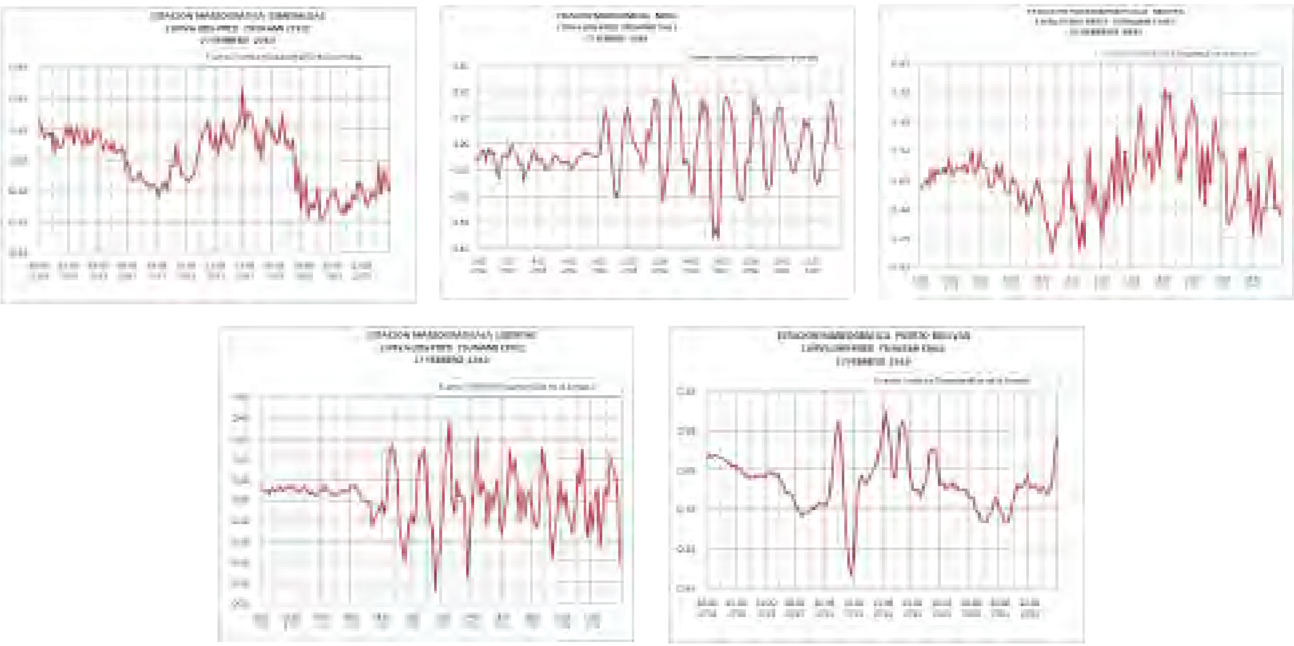

Figure 2. Mareograms from the continental ports of Ecuador where the astronomical tide has been filtered, thus records show tsunami oscillations only. Amplitudes and periods differ because of each port's geometry and morphology (for details see text).

From what is known, trained tsunami observes along coastal areas of continental Ecuador reported fairly accurately on the stage of the astronomical tide and distinguished the subsequent superimposed sea level variations after tsunami arrival. However, such superimposition on sea level by the tsunami may have gone unnoticed by amateur observers. This was not the case in ports of the Galapagos Islands, such as Academy Bay in Puerto Ayora, where shorter tsunami periods and wave amplitudes allowed better observations of strong incoming and outgoing currents to the extend that anchored boats just seated for a while on the rocky bottom. Fortunately, the prevailing low tide at the time prevented major flooding or property damage of the coastal zone. Also, proper evacuation of the people to higher ground ensured their safety.

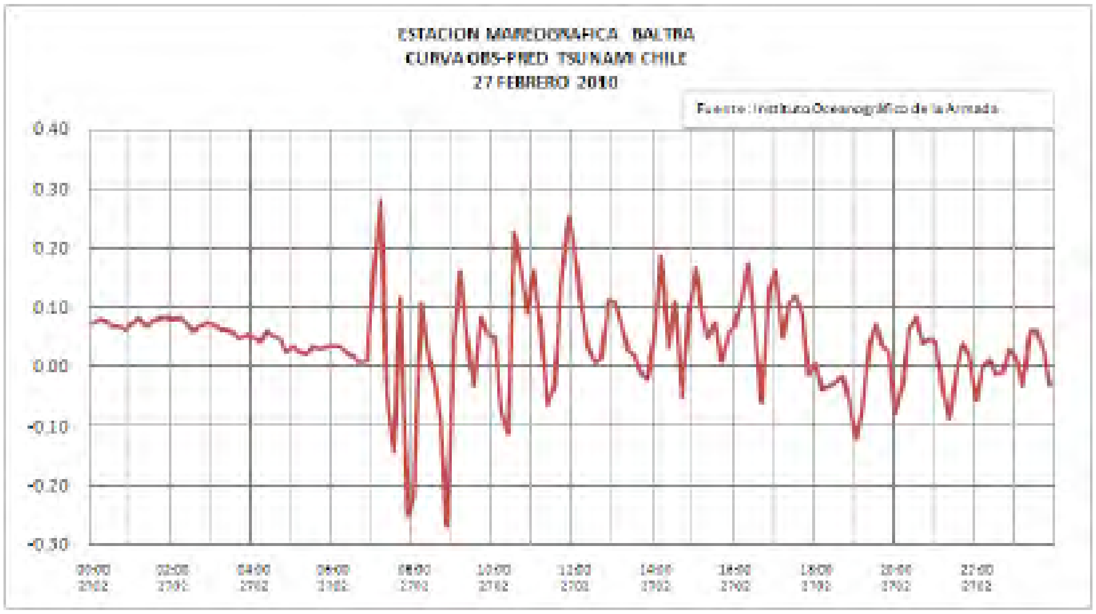

Figure 3: Mareogram of the Baltra Island tide gauge (at the Aeolian Inlet) in the Galapagos with astronomical tide filtered out. Note that amplitudes and periods are shorter from those recorded by tide stations on the continent. Stability of sea level was attained near midnight. For details see text.

5. DISCUSSION

Fortunately, the tsunami of 27 February 2010 generated in Chile did not have a major impact along the coasts of continental Ecuador and of the Galapagos Islands for the following reasons:

> Because of the great distance from the source region, it took from 5 to 6 hours for the tsunami to reach the mainland Ecuadorian coast and the Galapagos Islands. Thus, there was sufficient time for officials of the National Secretary for Risk Management to adopt the necessary safety measures and issue a warning for evacuation of the people at Puerto Ayora (Santa Cruz Island in the Galapagos) to higher ground, while at the country's continental coast, the Comités de Operaciones de Emergencia (COE) kept a close watch as the event was evolving.
>
> The timely regional tsunami warning issued by the Pacific Tsunami Warning Center (PTWC) based on data from coastal stations and DART buoys, helped the National Agencies for Risk Management to act promptly and effectively in Ecuador.
>
> The United States Geological Survey (USGS) provided at its web page reliable data and seismic records that were useful in assessing the tsunami risk.

> The fact that the tsunami struck the continentals Ecuadorian coast and the Galapagos Islands just before or after low water, limited damage to only a few boats at Academy Bay but no major damage or loss of life were reported anywhere.

In evaluating tsunami vulnerability, a point of concern is that water masses in bays, estuaries and inlets can be affected by tsunami oscillations, thus resulting in secondary undulations and energy trapping based on natural modes of oscillation (resonance effects), local bathymetry and coastal configuration in each case. Such interaction in enclosed or semi-enclosed bodies of water could have significant impact on run-up, particularly if the tsunami occurred during high tide. For such occasions where such interaction occurs, the risk of flooding and damage increases and a numerical simulation model may help understand wave behavior and potential impact – thus help in taking better mitigation measures. Such study showing tsunami transformation into a resonant oscillation or seiche was carried out for Monterey Bay (Breaker et al, 2011).

The tsunami of 27 February 2010 confirmed a conclusion by another study (Espinoza1990) that less dangerous tsunamis to the Ecuadorian maritime zone are those from distant sources and that the more dangerous are local tsunamis - such as the one generated by the great 31 January 1906 earthquake along the Esmeraldas coast near the Yaquina Transform Fault or the Manglares Basin (Collot, et al., 2009). Until recently the 1906 event was considered to be one of the six strongest earthquakes of the last century.

Great tsunamigenic earthquakes usually occur along certain regions along active subduction zones, characterized by great trenches. The tsunamis that are generated can have a destructive far-field impact in the entire Pacific Basin. Examples of such great tsunamigenic earthquakes are those of 1960 (Mw=9.5) and of 2010 (Mw=8.8) along the southern segment of the Perú-Chile trench, and of the 1964 Alaska earthquake (Mw=9.2) along the eastern end of the Aleutians trench (Ryan, Huene & Kirby. 2012). Other active subduction zones along the Japanese coast and the Mariana Islands are known to generate tsunamigenic earthquakes of varied magnitude. Ecuador is vulnerable to such great tsunamis of distant origin – particularly if they arrive during high tide or in conjunction with in-situ storm waves. In such cases, flooding and destruction would be much greater. Also, Ecuador vulnerable to local destructive tsunamis generated from earthquakes sources mostly located along the Peru-Chile trench, the Yaquina Transform Fault, the submarine canyons on the continental margin and at the Galapagos Hot spot.

The ocean bottom morphology of Ecuador's continental margin, the Galapagos Hot Spot and Platform and the Carnegie Ridge and their potential for the generation of tsunamigenic earthquakes have been reviewed and assessed (Goyes, 2009; Collot, et al., 2009). There is also the potential for tsunami generation from collapse such as that of the submarine volcano Roca Redonda near Isabela Island. Tsunami waves from such volcanic sources in the Galapagos Archipelago could reach coastal region within an hour or less after generation and may be more destructive to the islands than those generated from distant events along Ecuador's maritime zone. Obviously, there is a need to research to a greater extend such tsunami source areas and develop guidelines for warning as well as for educational programs of preparedness.

6. CONCLUSIONS

Earthquake epicenter, magnitude, tsunami propagation map and geometry of ports are parameters that determine tsunami wave periods and amplitudes recorded by tide gauges. Fortunately, both the 1960 and 2010 Chilean tsunamis occurred at low tide along the Ecuadorian coast and the Galapagos Islands. However, it is possible that the next tsunami from Chile or anywhere else may arrive at high tide or perhaps coincide with a higher sea level associated with the El Niño phenomenon. Therefore, it is important that a proper assessment is made for each port using detailed topographic data to evaluate under different scenarios, tsunami run-up/backwash and consequent collateral impacts.

For such assessment, it would be helpful to study tsunami wave behavior in enclosed water bodies using mathematical model simulation under different tide conditions. Such studies could help determine if the tsunami excites each particular basin – thus causing seiches, greater inundation and higher run-up. This is a challenge for researchers to undertake with the support of SNGR and local governments.

ACKNOWLEDGEMENTS

We thank Ing. Jimmy Candell Soto, Principal at the Universidad Estatal Península de Santa Elena (UPSE) and Captain Rafael Cabello Peñafiel, Director, Instituto Oceanográfico de la Armada (INOCAR), for their unconditional support for research and the enhancement of knowledge. Also, we thank Luis A. Burbano, César Barrionuevo and Jorge Briones of INOCAR's Hydrographic Department for their suggestions and comments. We thank Jorge Espinoza for his advise in making text changes, MAE's Martha Delgado de Lara for her kind revision of the English version and Maria Caza for her patience and worthy support in preparation of this document. Finally, the authors appreciate Dr. George Pararas-Carayannis' critical reading and careful editing.

REFERENCES

Breaker, L., Murty, T., Flora, S. and Hunter, C. (2011). The Response of Monterey Bay to the 2010 Chilean Earthquake. *Journal of Tsunami Society International. 30*(1), 1-23.

Breaker, L., Murty, T., Carrol, D.and Teague, J. (2011). The Response of Monterey Bay to the Great Tohoku Earthquake of 2011. *Journal of Tsunami Society International. 30*(3), 153-162.

Cienfuegos, R. (2010). Observations on morphological changes produced by the impact of the February 27 2010 tsunami along the coastline of V-VI-VII regions. *Book of Abstracts, American Geophysical Union* 18, Chapman Conference on Giant Earthquakes and their tsunamis.

Comte, D. (2010). The 2010. Chile earthquake – Variations in the rupture mode. *Book of Abstracts, American Geophysical Union* 20, Chapman Conference on Giant Earthquakes and their tsunamis.

Collot, J., Michaud, F., Alvarado, A., Mercaillou, B., Sosson, M., Ratzov, G., Migeon, S., Calahorrano, A. & Pazmiño, A. (2009). Vision general de la morfología submarina del margen convergente de Ecuador-Sur de Colombia: Implicaciones sobre la transferencia de masa y la edad de la subducción de la Cordillera de Carnegie. En *Geología y Geofísica Marina y Terrestre del Ecuador.*

Comisión Nacional del Derecho del Mar. Argudo & Asociados Impresores, Guayaquil. 47-74
Espinoza, J. (1990). Posibles efectos de un tsunami en las costas de la Península de Santa Elena – Ecuador. Instituto Oceanográfico de la Armada.

Goyes, P. (2009). Fondos marinos de soberanía y jurisdicción del Ecuador. En *Geología y Geofísica Marina y Terrestre del Ecuador.* Comisión Nacional del Derecho del Mar. Argudo & Asociados Impresores. Guayaquil. 1-8

Lagos, M. (2010). Magnitude and impact from the 2010 Chilean tsunami. *Book of Abstracts, American Geophysical Union* 29, Chapman Conference on Giant Earthquakes and their tsunamis.

Pararas-Carayannis, G. (2010). The Earthquake and Tsunami of 27 February 2010 in Chile – Evaluation of Source Mechanism and of Near and Far-field Tsunami Effects. Science of Tsunami Hazards (STH), Vol. 29, No. 2, 2010. (pages 96-126).

Rizzo, P. (1977). Catálogo de tsunamis en la costa ecuatoriana y su región insular. *Instituto Oceanográfico de la Armada*.

Ryan, H., Von Huene, R. and Kirby, S. (2012). Tsunami Hazards to U.S. Coast from Giant Earthquakes in Alaska. *EOS, Transactions, American Geophysical Union. 93*(19), 185-186.
Tagle, P. (2010). Tsunami en Puerto Ayora. *La Revista* 24, El Universo, 21 de marzo.