

## Twin Tsunamis Triggered by the 12 January 2010 Haiti Earthquake

HERMANN M. FRITZ,<sup>1</sup> JEAN VILMOND HILLAIRE,<sup>2</sup> EMANUEL MOLIERE,<sup>3</sup> YONG WEI,<sup>4,5</sup> and FAHAD MOHAMMED<sup>1</sup>

**Abstract**—On 12 January 2010, a magnitude  $M_w$  7.0 earthquake occurred 25 km west–southwest of Haiti’s capital Port-au-Prince causing an estimated 316,000 fatalities, thereby exceeding any previous loss of life from a similar size earthquake. In addition, tsunami waves triggered by the earthquake caused at least three fatalities at Petit Paradis due to a complete lack of tsunami awareness. The International Tsunami Survey Team (ITST) was deployed within weeks of the event and covered the greater Bay of Port-au-Prince and more than 100 km of Hispaniola’s southern coastline. The collected survey data include more than 21 tsunami heights along with observations of coastal land level change. Maximum tsunami heights of 3 m have been measured for two independently triggered tsunamis.

**Key words:** Haiti, Dominican Republic, Caribbean, tsunami, earthquake, field survey, numerical modeling.

### 1. Introduction

On 12 January 2010 at 21:53:10 UTC (4:53:10 pm local time), the Enriquillo-Plantain Garden Fault (EPGF) ruptured after 240 years of inactivity, resulting in a magnitude  $M_w$  7.0 earthquake in the vicinity of Port-au-Prince, Haiti. The epicenter of the earthquake was located at 18.443°N, 72.571°W, 25 km WSW of Port-au-Prince at a shallow depth of 13 km (HAYES *et al.*, 2010; NETTLES and HJÖRLEIFSDÓTTIR, 2010). According to the Government of Haiti, the

earthquake resulted in 316,000 people killed, 300,000 injured, 1.3 million displaced out of a population of 9.7 million, and more than 300,000 houses destroyed or critically damaged in the Port-au-Prince area and in much of southern Haiti (GOH 2010; DESROCHES *et al.*, 2011). Other estimates suggest substantially lower numbers of casualties, perhaps as low as 100,000. By all estimates, the numbers of casualties exceed any previous loss of life from a similar size earthquake (BILHAM, 2010). Most of the fatalities were crushed by collapsing unreinforced buildings. Survivors sustained severe trauma but had little access to tertiary care (WALTON and IVERS, 2011). The devastating societal impact of the earthquake is reflected in the creation of the new Haitian-Creole onomatopoeic term “Goudou–Goudou” for the earthquake (BELLEGARDE-SMITH, 2011). The earthquake created a tremendous medical disaster with near-total destruction of the Haitian health care system. Initial injuries in Haiti were primarily low-velocity, high-force trauma and wound infections (AMUNDSON *et al.*, 2010; WALK *et al.*, 2011). In contrast, drowning and water-related injuries were the primary cause of immediate death in the 2004 Indian Ocean tsunami (SYNOLAKIS and KONG, 2006; FRITZ and BORRERO, 2006). The earthquake triggered independent twin tsunamis along the coastlines inside the Gulf of Gonâve and along Haiti’s south coast resulting in wave induced flooding and damage to coastal infrastructure. The tsunami waves caused at least three fatalities at Petit Paradis inside the Gulf of Gonâve due to a complete lack of tsunami awareness. Hence, about 1 per 100,000 fatalities are attributed to the Haitian tsunamis, while during the 2010 Chile earthquake the split was one tsunami to four earthquake fatalities (FRITZ *et al.*, 2011), and the 2011 Japan tsunami accounted for 92.5 % of the fatalities (FRITZ *et al.*, 2012). During the 2010 Haiti tsunamis, the Pacific Tsunami Warning

<sup>1</sup> School of Civil and Environmental Engineering, Georgia Institute of Technology, Savannah, GA 31407, USA. E-mail: fritz@gatech.edu

<sup>2</sup> Université Quisqueya, Port-au-Prince, Haiti. E-mail: hvilmond@yahoo.fr

<sup>3</sup> Ecole Nationale de Géologie Appliquée, Port-au-Prince, Haiti. E-mail: chapeshai@yahoo.fr

<sup>4</sup> Pacific Marine Environmental Laboratory, NOAA, Seattle, WA 98115, USA. E-mail: yong.wei@noaa.gov

<sup>5</sup> Joint Institute for the Study of Atmosphere and Ocean (JISAO), University of Washington, Seattle, WA 98105, USA.

Center (PTWC) responded and issued a first message 10 min after the earthquake, but all communications to Haiti were interrupted by the earthquake and none of the Haitian contact points could be reached.

Haiti, along with the Dominican Republic, shares the island of Hispaniola (76,480 km<sup>2</sup>) and occupies roughly the western third (27,450 km<sup>2</sup>) of the island (Fig. 1). Oblique convergence between the Caribbean and North American plates is partitioned between thrust motion along the north Hispaniola fault zone and two major east–west trending, strike-slip fault systems: the Septentrional fault system in northern Haiti and the Enriquillo–Plantain Garden fault (EPGF) system in southern Haiti (MANAKER *et al.*, 2008; CALAIS *et al.*, 2010). The EPGF fault zone starts offshore to the west of Haiti, bisects Haiti's southern peninsula and then extends into the Dominican Republic and towards the Muertos trough. Several earthquakes were recorded by French historian MOREAU DE SAINT-MÉRY (1750–1819) during the French Colonial period (MOREAU DE SAINT-MÉRY, 1958). During the last 500 years, large earthquakes have occurred in Hispaniola (SCHERER, 1912; TABER, 1922). The 12 January 2010 Haiti  $M_w$  7.0 earthquake represents the largest event to rupture the EPGF system since the 21 November 1751 and 3 June 1770 earthquakes, which caused severe damage in

Port-au-Prince (PRENTICE *et al.*, 2010). A large earthquake on 18 October 1751 is associated with the offshore Muertos fault (ALI *et al.*, 2008). Large historical earthquakes in 1564 and 1842 occurred along the Septentrional fault in northwestern Hispaniola (KELLEHER *et al.*, 1973). The 1842 event triggered a tsunami that affected the Port-de-Paix region in northern Haiti. They were followed by a tsunamigenic sequence of  $M_w$  7.5 to 8.1 events between 1946 and 1953 in the northeast of the Dominican Republic (MANN *et al.*, 1995). On 4 August 1946 an  $M_w$  8.1 earthquake struck off the northeastern shore of Hispaniola resulting in a destructive tsunami with 1,790 fatalities in the Dominican Republic and observed runup in Puerto Rico (O'LOUGHLIN and LANDER, 2003). Examples of historical tsunamis in the Caribbean further west along the EPGF zone include the disastrous 1692 Port Royal landslide generated tsunami in Jamaica, caused by a slump into Kingston harbor killing some 2,000 (ELLIS, 1892; PAWSON and BUISSET, 1975), and a smaller tsunami associated with the 1907 Kingston earthquake (FULLER, 1907). At least ten significant tsunamis have been documented in the northern Caribbean since 1498, six of which are known to have resulted in loss of life (O'LOUGHLIN and LANDER, 2003; PARSONS and GEIST, 2008). Rapid population increase in the Caribbean

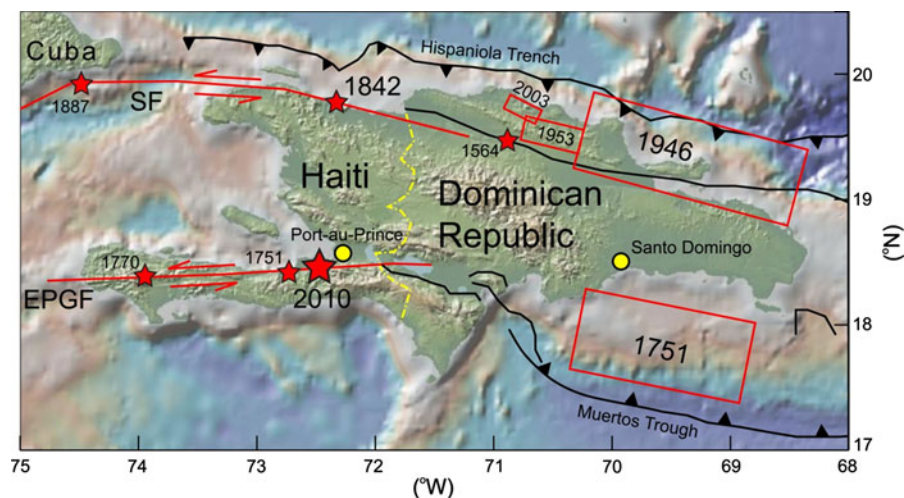


Figure 1

Tectonic setting of Hispaniola Island with selected historic earthquakes. EPGF Enriquillo–Plantain Garden Fault; SF Septentrional Fault (Ali *et al.*, 2008; Calais *et al.*, 2010)

exposes more coastal residents to future tsunami events (GRINDLAY *et al.*, 2005).

## 2. Post-Tsunami Reconnaissance

The Haiti and Dominican Republic survey took place from 31 January to 7 February 2010. The International Tsunami Survey Team (ITST) covered more than 100 km of coastline inside the Gulf of Gonâve from Petit-Goâve to Luly and more than 100 km of Hispaniola's south coast between Pedernales, Dominican Republic and Jacmel, Haiti. The survey team documented tsunami runup, flow depth

and inundation, wave induced deposition or erosion, structural damage and interviewed eyewitnesses using established protocols (SYNOLAKIS and OKAL, 2005). The Hispaniola survey data includes 21 runup and flow depth measurements shown in Fig. 2 and Table 1. Measured data were corrected for predicted tide levels at the time of tsunami. Predicted tidal ranges at Port-au-Prince and Jacmel are typically on the order of 0.6 m such as on 12 January 2010. The tsunami impacts peaked with maximum tsunami heights exceeding 3 m both at Petit Paradis inside the Bay of Grand-Goâve on the north coast of Haiti's southern peninsula and at Jacmel on Haiti's south coast.

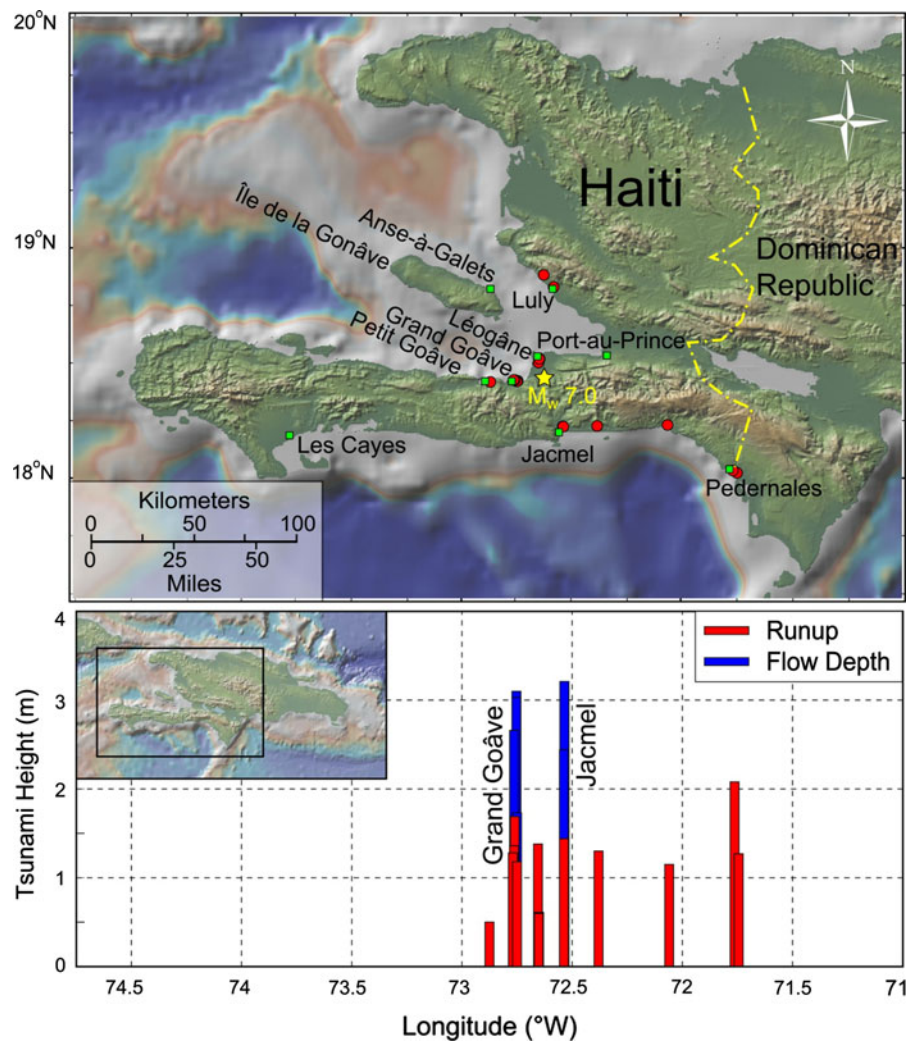


Figure 2

Tsunami flow depths and runup heights measured along coastlines in the Gulf of Gonâve and along Hispaniola's south coast

Table 1

*Tsunami dataset recorded in Haiti and the Dominican Republic by the International Tsunami Survey Team (ITST) from 3 to 7 February 2010*

Pt.	Site	Latitude (°N)	Longitude (°E)	$z + h$ (m)	$R$ (m)	$I$ (m)	Date and time surveyed (UTC)	Watermark
1	Grand-Goâve, P.P.	18.42975	-72.74990	1.73		20.0	3-Feb-2010 20:22	WL, EW
2	Grand-Goâve, P.P.	18.42971	-72.74988		1.18	25.0	3-Feb-2010 20:34	WL, EW
3	Grand-Goâve, P.P.	18.42825	-72.75294	3.10		13.4	3-Feb-2010 20:50	RD, BO
4	Grand-Goâve, P.P.	18.42801	-72.75333	3.03		30.9	3-Feb-2010 21:03	MI, EW
5	Grand-Goâve, P.P.	18.43116	-72.76031		1.69	52.3	3-Feb-2010 21:43	WL, EW
6	Grand-Goâve, P.P.	18.43355	-72.76340	2.66		22.6	3-Feb-2010 22:09	MI, EW
7	Grand-Goâve, P.P.	18.43342	-72.76351		1.36	41.4	3-Feb-2010 22:13	WL, EW
8	Grand-Goâve	18.43343	-72.76892		1.28	15.1	6-Feb-2010 20:59	WL, EW
9	Petit-Goâve	18.42491	-72.87511		0.50	0.0	6-Feb-2010 19:05	EW
10	Léogâne	18.50939	-72.65493		1.38	17.6	6-Feb-2010 22:05	WL, EW
11	Léogâne	18.52472	-72.65009		0.61	8.1	6-Feb-2010 23:01	WL, EW
12	Léogâne	18.52458	-72.65193		0.60	7.8	6-Feb-2010 23:09	WL, EW
13	Luly	18.83597	-72.57781		N.W.	0.0	7-Feb-2010 17:01	EW
14	Luly	18.88849	-72.62262		N.W.	0.0	7-Feb-2010 17:31	EW
15	Pedernales, D.R.	18.02799	-71.74437		1.27	7.1	4-Feb-2010 19:25	EW
16	Anse-à-Pitres	18.03825	-71.76272		2.08	10.4	5-Feb-2010 13:51	EW
17	Belle-Anse	18.23713	-72.05963		1.15	3.2	5-Feb-2010 20:14	EW
18	Cayes-de-Jacmel	18.23390	-72.38004		1.30	19.2	6-Feb-2010 13:03	EW
19	Jacmel	18.23234	-72.53714	2.44		24.5	6-Feb-2010 14:08	RD, EW
20	Jacmel	18.23269	-72.53706		1.44	63.5	6-Feb-2010 14:00	WL, EW
21	Jacmel	18.23146	-72.53503	3.21		13.4	6-Feb-2010 14:40	MI, EW

Codes to nature of measurements:  $h$  flow depth above terrain,  $z$  terrain elevation,  $z + h$  flow depth above sea level at tsunami arrival time,  $R$  runup,  $I$  inundation; codes to nature of watermarks: *BO* boat, *EW* eyewitness, *MI* mudline inside, *RD* rafted debris, *WL* wrack line; Abbreviations: *D.R.* Dominican Republic, *N.W.* negative wave (draw down only), *P.P.* Petit Paradis

### 3. Coastal Landslide Tsunami in Bay of Grand Goâve

A coastal landslide generated tsunami was surveyed at Petit Paradis inside the Bay of Grand Goâve located 45 km west-southwest of Port-au-Prince (<http://www.nature.com/news/2010/100225/full/news.2010.93.html>). Approximately 400 m of coastline failed co-seismically resulting in a land loss of up to 100 m in cross-shore direction based on pre- and post-earthquake satellite imagery shown in Fig. 3. The landslide generated tsunami was only observed along adjacent coastlines within a few kilometers both to the east and west of the landslide source. The tsunami peaked with maximum tsunami heights exceeding 3 m at Petit Paradis less than a kilometer to the east of the landslide source. The cross-shore inundation distances remained below 100 m. Several independent eyewitnesses confirmed the co-seismic nature of the coastal landslide and the subsequent tsunami arrival within less than a minute of the earthquake. The eyewitness reports indicate a single main wave with a flooding duration of tens of seconds. The sub-minute wave period and

tsunami arrival time at Petit Paradis along with the coastal land loss and localized tsunami impact identify a coastal submarine landslide as tsunami source (Fig. 4a–d). Sub-minute to minute wave periods have been determined for other landslide tsunamis such as Lituya Bay, Alaska, in 1958 (FRITZ *et al.*, 2009). Multibeam and chirp surveys mapped the submarine sediment deformations and offshore landslide tracks in the Bay of Grand Goâve (HORNBAACH *et al.*, 2010). The triggered tsunami waves caused at least three confirmed fatalities, damaged houses and destroyed fishing boats at Petit Paradis. Eyewitnesses observed the three victims consisting of two boys at pre-school age accompanied by their grandfather standing in the field staring at the engulfing landslide to be washed away by the tsunami seconds later. The victims did not try to evacuate. Unfortunately, the people of Haiti had neither the ancestral knowledge nor educational awareness of tsunami hazards that saved many natives from near-field tsunamis in the Solomon Islands in 2007 (FRITZ and KALLIGERIS, 2008). In addition, coastal land-level changes in the submeter range are documented along coastlines near the epicenter along the



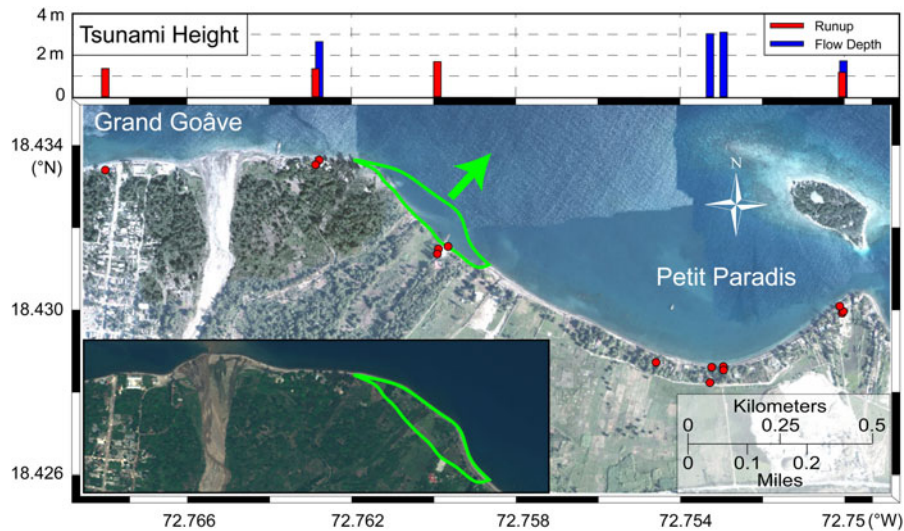


Figure 3

Coastal landslide at Petit Paradis with measured tsunami heights along the Bay of Grand Goâve (pre- and post-earthquake images of coastline)

Gulf of Gonâve. Coastal uplift was observed at Léogâne located 30 km west of Port-au-Prince and subsidence at Petit Goâve located 10 km west of Grand Goâve (Fig. 4e–g). Numerous non-tsunamigenic sites with liquefaction and lateral spreading were identified (GREEN *et al.*, 2011; OLSON *et al.*, 2011). A fast-tide like oscillation with submeter tsunami height was reported by eyewitnesses at Luly located 50 km north of Grand-Goâve (Fig. 4h).

#### 4. Tsunami Observations on the South Coast of Hispaniola in Haiti and the Dominican Republic

Tsunami and earthquake observations were documented along more than 100 km of Hispaniola's south coast between Pedernales, Dominican Republic and Jacmel, Haiti (Fig. 5). The tsunami impact peaked with maximum tsunami heights exceeding 3 m at Jacmel on Haiti's south coast and tsunami runup of more than 1 m was still observed at Pedernales in the Dominican Republic. Jacmel, which is near the center of the south coast, represents an unfortunate example of a village and harbor located for protection from storm waves but remains vulnerable to tsunami waves with runup doubling from the entrance to the head of the bay. Inundation and tsunami damage were limited to <100 m inland at Jacmel. The 12 January 2010

earthquake itself caused heavy damage and several hundred fatalities at Jacmel. Along Hispaniola's south coast, eyewitnesses reported one to four main waves usually with an initial recession, which could correspond to a leading depression N-wave of TADEPALLI and SYNOLAKIS (1994). At most locations on Hispaniola's south coast, the first wave arrived within 15 min of the earthquake and wave period estimates range from 5 to 10 min, which is in stark contrast to the sub-minute wave period observed locally at Petit Paradis. The fishermen at Pedernales gathered on the board-walk and recorded the tsunami with cell-phone videos. The people of Haiti and the Dominican Republic exhibited a complete lack of tsunami awareness despite the 1946 Dominican Republic tsunami at Hispaniola's northeast coast. In sharp contrast, Sri Lankan UN soldiers on duty at Jacmel self-evacuated given the memory of the 2004 Indian Ocean tsunami (LIU *et al.*, 2005).

#### 5. Numerical Modeling

To simulate the measured tsunami runup, we used the tsunami inundation model MOST (TITOV and GONZALEZ, 1997; TITOV and SYNOLAKIS, 1998). MOST is a model suite using nonlinear shallow water equations with telescoped grids to compute tsunami wave dynamics in its generation, propagation and

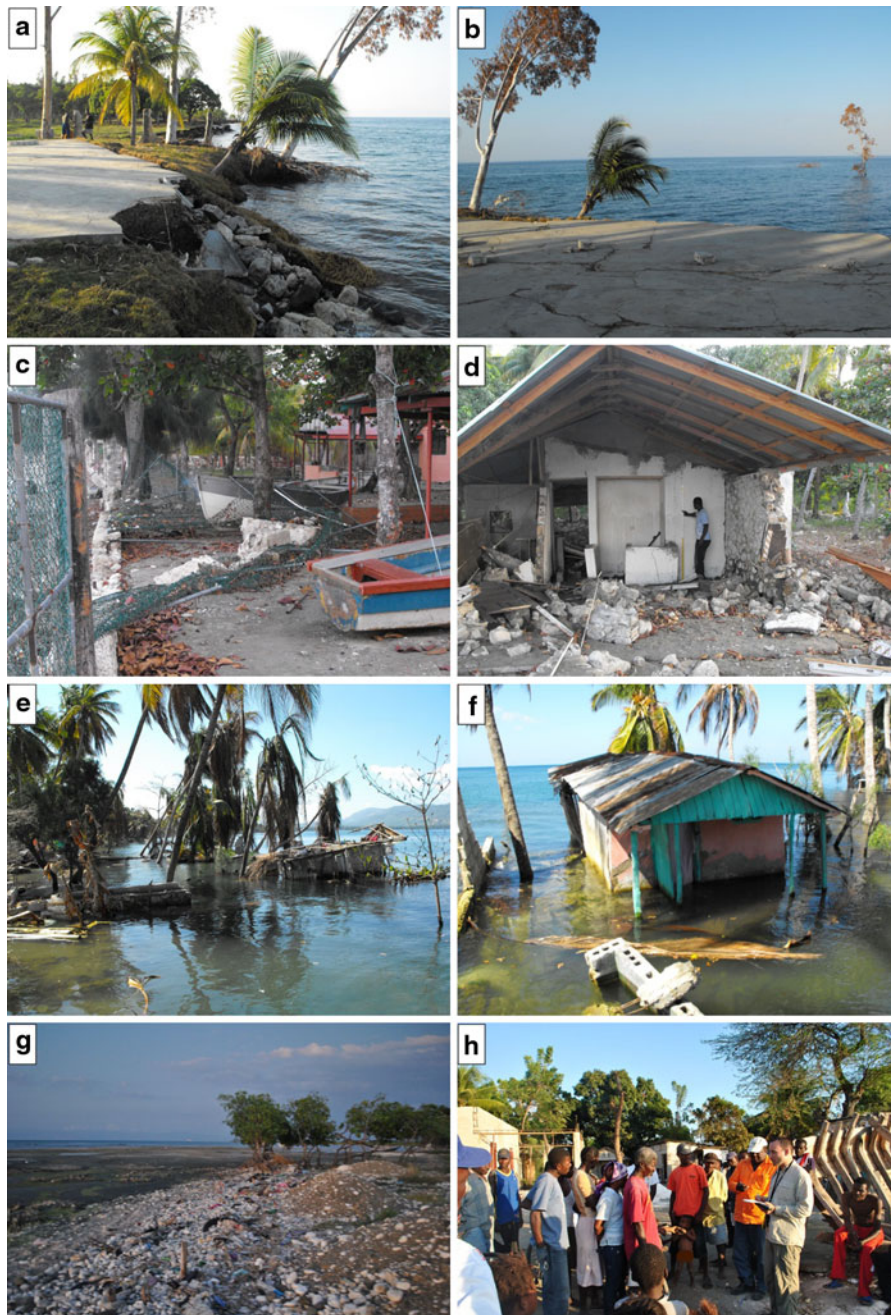


Figure 4

Gulf of Gonâve survey: **a, b** landslide scarp with tree located 70 m offshore; **c** tsunami damaged residential house with watermarks and flow depth measurement; **d** fishing boat washed ashore and through fence by tsunami waves; **e, f** subsidence at Petit Goâve; **g** coastal uplift with mangroves at Léogâne; **h** eyewitness interview at Luly

inundation. The MOST model has been extensively tested against a number of laboratory experiments and benchmarks, and was successfully used for simulations of many historical tsunami events (SYNOLAKIS

*et al.*, 2008; TANG *et al.*, 2009, 2012; TITOV, 2009; USLU *et al.*, 2011; WEI *et al.*, 2008, 2012). MOST is a standard tsunami inundation model used in the NOAA tsunami forecast system to provide modeling





Figure 5

Haiti south coast survey: Port of Jacmel during (a) tsunami draw down on 12 January 2010 and (b) on normal day; c tsunami flooding of the road next to the UN barracks at Jacmel; d rapid surveying of tsunami height at the flooded UN barracks with a laser range finder; e earthquake damage at Jacmel; f deforestation for charcoal in the mountains along Haiti's south coast; g landslide along "Route Nationale 102" (the main road connecting Haiti and the Dominican Republic); h eyewitness interview at Anse-à-Pitres across the border from Pedernales; (a-c) photo credit: Captain Geethika of the Sri Lankan UN blue helmets

assistance to Tsunami Warning Centers for their forecasting operations. NGDC has developed a 9-arcsec bathymetry grid that contains no topographic elevation for Gulf of Mexico and Caribbean Sea. This

grid, however, has relatively sparse coverage in the Caribbean and may not contain accurate bathymetric information, especially in the coastal area of north-western Caribbean Sea (NATIONAL GEOPHYSICAL DATA

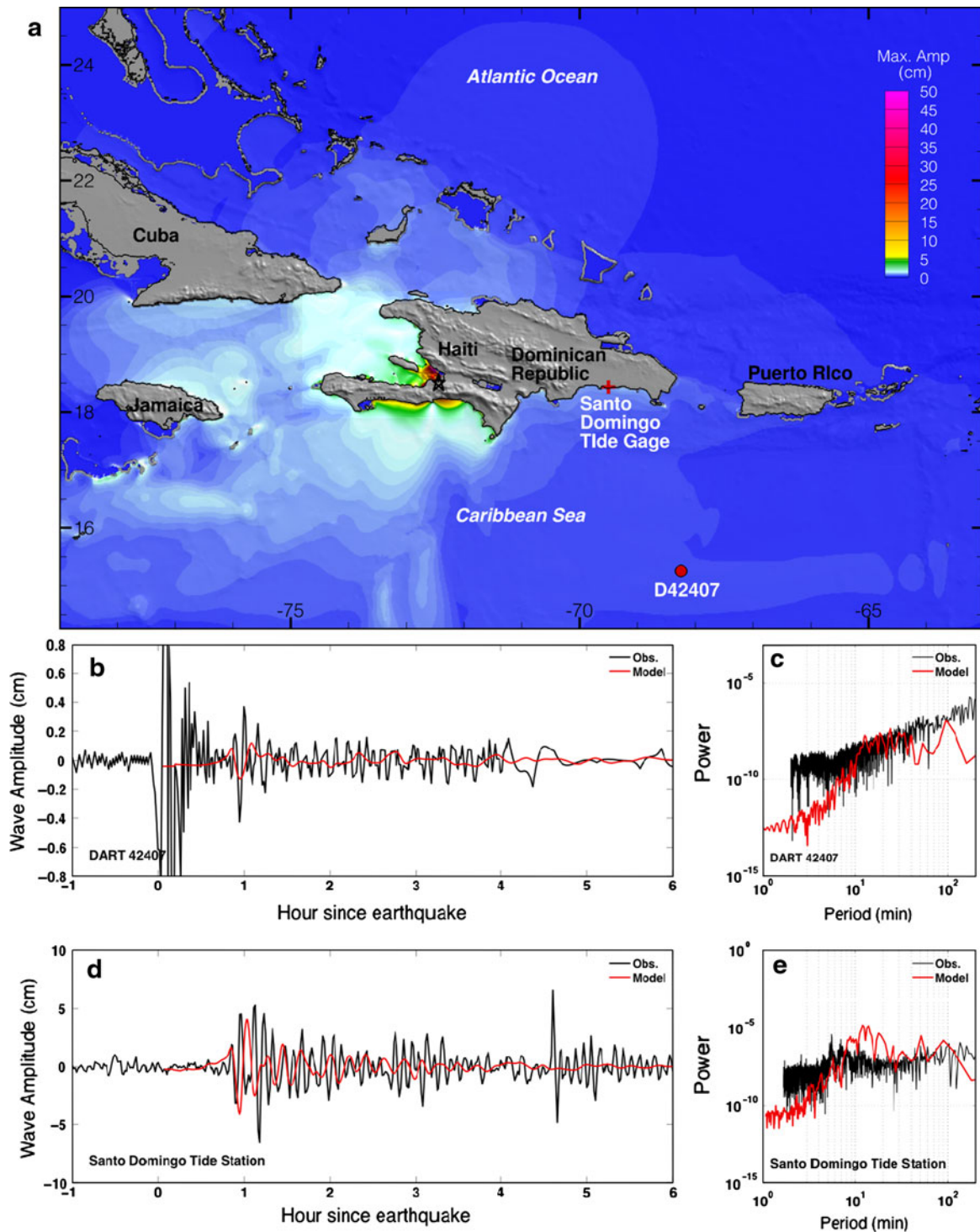


Figure 6

**a** Computed maximum tsunami amplitude in Haiti vicinity based on the NEIC source model. Tsunami recordings and model comparison of **(b)** wave amplitude and **(c)** spectrum at DART buoy 42,407 about 600 km southeast of the earthquake source. Tsunami recordings and model comparison of **(d)** wave amplitude and **(e)** spectrum at the Santo Domingo tide gauge located 300 km east of the earthquake source



CENTER, 2005). This dataset was combined with the Shuttle Radar Topography Mission (SRTM) 90 m elevation to generate all the grids for tsunami inundation modeling. Models were developed here to study the tsunami impact at Santo Domingo and Pedernales in Dominican Republic and Jacmel in Haiti. While sharing a common outmost grid of 1 arcmin ( $\sim 1.85$  km) resolution to account for the tsunami propagation in northwestern Caribbean Sea, these models employ an 18-arcsec ( $\sim 550$  m) grid to cover Haiti and western Dominican Republic (Figs. 7, 8 insets), and a local 3-arcsec ( $\sim 90$  m) grid (Figs. 7, 8) to compute the tsunami inundation.

The computed tsunami waves based on different source models were compared with deep-ocean observations in the Caribbean, a coastal tide gauge at Santo Domingo, Dominican Republic, and post-tsunami survey results in Haiti. Figure 6a shows that the NEIC source model underestimated the tsunami

waves on the south shore of Haiti near Jacmel, where the post-tsunami survey discovered up to 3 m tsunami height in Jacmel and up to 2 m runup in southeastern Haiti at the border with the Dominican Republic (Fig. 2). The ground shaking caused by the seismic waves was quickly detected within a couple of minutes of the earthquake, shown as high-frequency spikes in Fig. 6b, by a DART 42407 about 600 km southeast of the earthquake source. The computed time series of the NEIC model agrees well with the arrival time and approximate amplitude recorded by DART 42407 (Fig. 6b). Spectrum analysis of the recorded time series at DART 42407, however, reveals that a dominant wave period was hardly distinguishable from the background noise, which probably can be attributed to weak tsunami signal and low signal-to-noise ratio. The modeled time series shows the most dominant wave periods are about between 12 to 24 min (Fig. 6c).

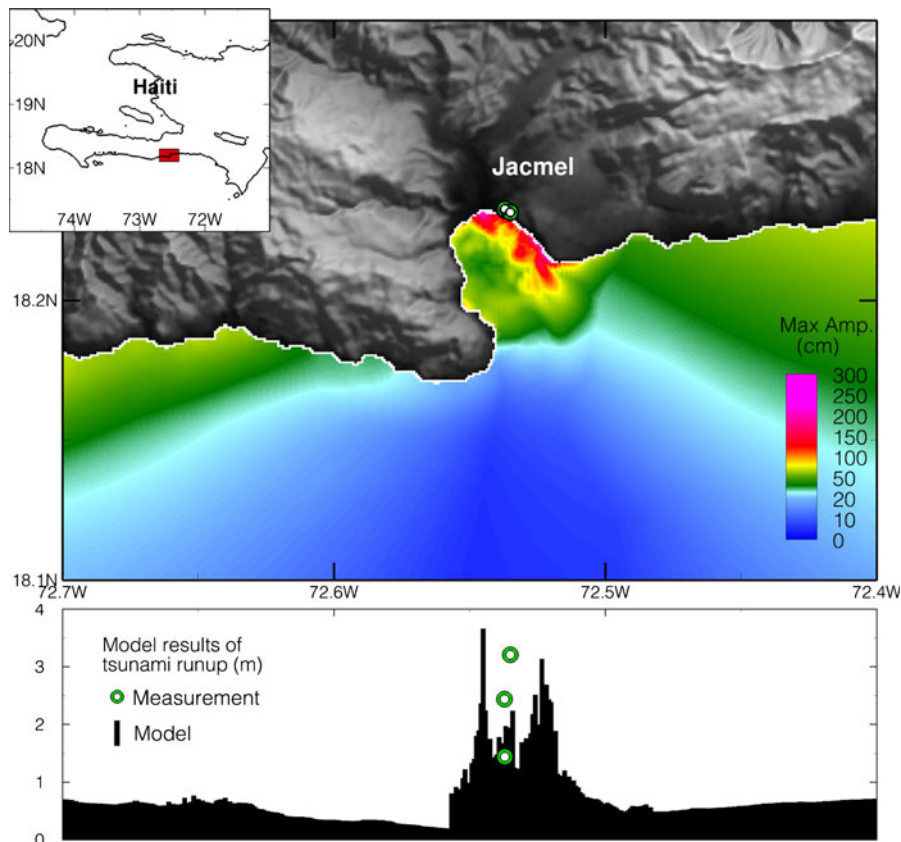


Figure 7

Computed tsunami runup heights at Jacmel from a 3'' inundation model using the scaled NEIC source model. The *black bars* in the lower panel are the computed runup heights along the shoreline

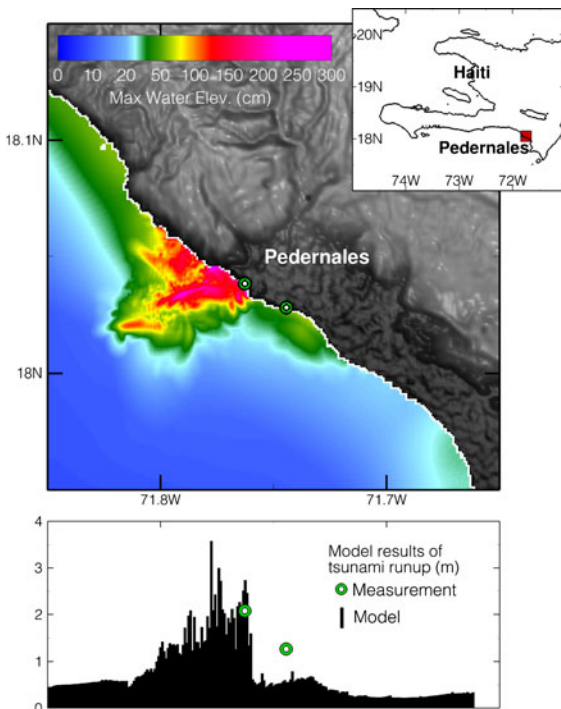


Figure 8

Computed tsunami runup heights at Anse-à-Pitres (Haiti) and Pedernales (Dominican Republic) from a 3'' inundation model using the scaled NEIC source model. The *black bars* in the *lower panel* are the computed runup heights along the shoreline

A high-resolution model at Santo Domingo, located on the south coast of the Dominican Republic and about 300 km east of the earthquake source, shows good comparison with the tsunami amplitude recorded by the Santo Domingo tide gauge, 4 cm for the maximal wave amplitude (Fig. 6d). The spectrum of the tide gauge records suggests tsunami wave periods of about 5 to 8 minutes inside Santo Domingo harbor (Fig. 6e). The model results, however, over-predicted with wave periods of 12 to 14 min. The difference in wave period may be an indication that the tsunami source needs to be further investigated and the possibility of submarine landslides considered. Different rupture models proposed in some recent studies (HAYES *et al.*, 2010; HORNBAACH *et al.*, 2010; CALAIS *et al.*, 2010) indicated a complex rupture during the Haiti earthquake that probably includes simultaneous or near-simultaneous motion on strike-slip and thrust structures, and landslides. The tsunami modeling tests with these source models, however, underestimate the tsunami impact on Haiti's south shore by an order of

magnitude. The favorable amplitude comparisons and slightly-over-predicted wave periods in Fig. 6 suggest that the NEIC solution is a workable source model, but still needs further improvement to reflect the tsunami footprints observed in both the Gulf of Gonâve and the south shore of Haiti. NEWMAN *et al.* (2011) discussed a regional rigidity scale factor that accounts for the discrepancy between tele-seismically inverted slip and the true regional slip that may be subdued when traveling through the lower crust. While keeping a constant  $M_0$ , this scale factor resulted in a slip weighted  $5.6 \pm 1.0$  across the fault during the 2010 Mentawai earthquake. Analogously we found a 4-time scaled model from the NEIC source (Table 2) well predicts the more than 3 m tsunami heights observed at Jacmel (Fig. 7). The computed tsunami wave period is estimated to be about 6 to 7 min, and fits well with the reported data. The modeling results at Jacmel indicate a wave oscillation may have been triggered by the tsunami wave inside Jacmel Bay lasting for hours, and the resonance may be one of the reasons responsible for the tsunami wave period of minutes. The scaled model also predicted 2 m tsunami runup at Anse-à-Pitres (Haiti) on the southeast shore of Haiti across the border from Pedernales in the Dominican Republic. It's worth noting that the SRTM 90-m data was the best-available topography used in this study, and its vertical topographic uncertainty up to 16 m may play a role in the underestimation of tsunami runup in the original NEIC solution.

Table 2

<i>Source parameters of modeled tsunami</i>	
Earthquake parameters <sup>a</sup>	Value
Longitude	72.559°W
Latitude	18.423°N
Length	43.0 km
Width	27.0 km
Dip	64°
Rake	25°
Strike	71°
Slip	5.8 m
Depth	10 km

<sup>a</sup> Earthquake parameters are adjusted based on NEIC source to best fit tsunami measurements

## 6. Conclusions

The rapid deployment of a survey team to Haiti after the 12 January 2010 event resulted in the recovery of important data on the characteristics of tsunami impact as well as information on coastal land level changes. The tsunami arrival times recorded by the DART buoy and the Santo Domingo tide gauge indicate that the tsunami on Hispaniola's south shore was triggered instantly with the earthquake, while the public attention was mostly focused on the Gulf of Gonâve and the Bay of Port-au-Prince. The tsunami flooding inside the Gulf of Gonâve is attributed to a coastal submarine landslide at Petit Paradis, while the source of the tsunami on the south shore of Hispaniola remains to be determined. As with most near-field tsunamis, the waves struck prior to official warnings reaching coastal residents. The lack of self-evacuations resulted in three tsunami fatalities and demonstrated the pivotal importance of community-based education and awareness programs (SYNOLAKIS and BERNARD, 2006).

## Acknowledgments

The survey was supported logistically by ONAMET of the Dominican Republic and UNESCO-IOC. F.M. was supported by the National Science Foundation through the NSF NEESR award CMMI-0936603.

## REFERENCES

- ALI, S.T., FREED, A.M., CALAIS, E., MANAKER, D.M., and McCANN, W.R. (2008). *Coulomb stress evolution in Northeastern Caribbean over the past 250 years due to coseismic, postseismic and interseismic deformation*, *Geophys. J. Int.*, 174:904–918.
- AMUNDSON, P., DADEKIAN, G., ETIENNE, M., GLEESON, T., HICKS, T., KILLIAN, D., KRATOVIL, K., LEWIS, C., MONSOUR, M., PASIUK, B., RHODES, D., and MILLER, E.J. (2010). *Practicing Internal Medicine Onboard the USNS Comfort in the Aftermath of the Haitian Earthquake*. *Annals of Internal Medicine*, 152(11):733–738.
- BELLEGARDE-SMITH, P. (2011). *A man-made disaster: the earthquake of January 12, 2010 – a Haitian perspective*. *J. Black Studies*, 42(2):264–275.
- BILHAM, R. (2010). *Lessons from the Haiti earthquake*. *Nature*, 463:878–879.
- CALAIS, E., FREED, A., MATTIOLI, G., AMELUNG, F., JÓNSSON, S., JASMA, P., HONG, S.-H., DIXON, T., PRÉPETIT, C., and MOMPLAISIR, R. (2010). *Transpressional rupture of an unmapped fault during the 2010 Haiti earthquake*. *Nature Geoscience*, 3(11):794–799.
- DESROCHES, R., COMERIO, M., EBERHARD, M., MOONEY, W., and RIX, G.J. (2011). *Overview of the 2010 Haiti Earthquake*. *Earthquake Spectra* 27(S1):S1–S21.
- ELLIS, A.B. (1892). *The great earthquake of Port Royal (Jamaica)*. *Popular Sci.* 40:774–784.
- FRITZ, H.M., and BORRERO, J.C. (2006). *Somalia field survey of the 2004 Indian Ocean Tsunami*. *Earthquake Spectra* 22(S3):S219–S233.
- FRITZ, H.M., and KALLIGERIS, N. (2008). *Ancestral heritage saves tribes during 1 April 2007 Solomon Islands tsunami*. *Geophys. Res. Lett.*, 35, L01607, doi:10.1029/2007GL031654.
- FRITZ, H.M., MOHAMMED, F., and YOO, J. (2009). *Lituya Bay Landslide Impact Generated Mega-Tsunami 50th Anniversary*. *Pure Appl. Geophys.* 166(1-2):153-175, doi:10.1007/s00024-008-0435-4.
- FRITZ, H.M., PETROFF, C.M., CATALÁN, P., CIENFUEGOS, R., WINKLER, P., KALLIGERIS, N., WEISS, R., BARRIENTOS, S.E., MENESES, G., VALDERAS-BERMEJO, C., EBELING, C., PAPADOPOULOS, A., CONTRERAS, M., ALMAR, R., DOMINGUEZ, J.C., and SYNOLAKIS, C.E. (2011). *Field Survey of the 27 February 2010 Chile Tsunami*. *Pure Appl. Geophys.* 168(11):1989–2010, doi:10.1007/s00024-011-0283-5.
- FRITZ, H.M., PHILLIPS, D.A., OKAYASU, A., SHIMOZONO, T., LIU, H., MOHAMMED, F., SKANAVIS, V., SYNOLAKIS, C.E., and TAKAHASHI, T. (2012). *2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LiDAR*. *Geophys. Res. Lett.*, 39, L00G23, doi:10.1029/2011GL050686.
- FULLER, M.L. (1907). *Notes on the Jamaica earthquake*. *J. Geology* 15(7):696–721.
- GOH – GOVERNMENT OF THE REPUBLIC OF HAITI (2010). *Action Plan for National Recovery and Development of Haiti*, Port-au-Prince, Haiti.
- GREEN, R.A., OLSON, S.M., COX, B.R., RIX, G.J., RATHJE, E., BACHHUBER, J., FRENCH, J., LASLEY, S., and MARTIN, N. (2011). *Geotechnical Aspects of Failures at Port-au-Prince Seaport during the 12 January 2010 Haiti Earthquake*. *Earthquake Spectra* 27(S1):S43–S65.
- GRINDLAY, N.R., HEARNE, M. and MANN, P. (2005). *High risk of tsunami in the northern Caribbean*. *EOS Trans.*, AGU, 86(12): 121–126.
- HAYES, G.P., BRIGGS, R.W., SLADEN, A., FIELDING, E.J., PRENTICE, C., HUDNUT, K., MANN, P., TAYLOR, F.W., CRONE, A.J., GOLD, R., ITO, T., and SIMMONS, M. (2010). *Complex rupture during the 12 January 2010 Haiti earthquake*. *Nature Geoscience*, 3(11):800–805.
- HORNBAACH, M.J., BRAUDY, N., BRIGGS, R.W., CORMIER, M.-H., DAVIS, M.B., DIEBOLD, J.B., DIEUDONNE, N., DOUILLY, R., FROHLICH, C., GULICK, S.P.S., JOHNSON, H.E., MANN, P., MCHUGH, C., RYAN-MISHKIN, K., PRENTICE, C.S., SEEBER, L., SORLIEN, C.C., STECKLER, M.S., SYMITHE, S.J., TAYLOR, F.W., and TEMPLETON, J. (2010). *High tsunami frequency as a result of combined strike-slip faulting and coastal landslides*. *Nature Geoscience*, 3(11): 783–788.
- KELLEHER, J., SYKES, L., and OLIVER, J. (1973). *Possible criteria for predicting earthquake locations and their applications to major plate boundaries of the Pacific and the Caribbean*, *Journal of Geophysical Research*, 78(14):2547–2585.
- LIU, P.L.-F., LYNETT, P., FERNANDO, J., JAFFE, B.E., FRITZ, H.M., HIGMAN, B., MORTON, R., GOFF, J., and SYNOLAKIS, C.E. (2005). *Observations by the International Tsunami Survey Team in Sri Lanka*, *Science* 308(5728):1595.



- MANAKER, D.M., CALAIS, E., FREED, A.M., ALI, S.T., PRZYBYLSKI, P., MATTIOLI, G., JANSMA, P., PRÉPETIT, C., and DE CHABALIER, J.B. (2008). *Interseismic plate coupling and strain partitioning in the Northeastern Caribbean*, *Geophys. J. Int.*, 174:889–903.
- MANN, P., TAYLOR, F.W., EDWARDS, R.L., and KU, T.-L. (1995). *Actively evolving microplate formation by oblique collision and sideways motion along strike-slip faults: An example from the northeastern Caribbean plate margin*, *Tectonophysics*, 246(1–3): 1–69.
- MOREAU DE SAINT-MÉRY, M.-L.É. (1958). Description topographique, physique, civile, politique et historique de la partie Française de l'île Saint-Domingue. Revised and expanded edition. Edited by B. Maurel and E. Taillemite. 3 vols. Paris: Société de l'histoire des Colonies Françaises et Librairie Larose, 1,565 pages, (in French).
- NATIONAL GEOPHYSICAL DATA CENTER (2005). East Coast and Gulf Coast and Caribbean nine second tsunami propagation grids compilation report – prepared for the NOAA Center for Tsunami Inundation Mapping Efforts (TIME), 11p.
- NETTLES, M., and HJÖRLEIFSDÓTTIR, V. (2010). *Earthquake source parameters for the 2010 January Haiti main shock and after-shock sequence*, *Geophys. J. Int.*, 183:375–380.
- NEWMAN, A.V., HAYES, G., WEI, Y., and CONVERS, J. (2011). *The 25 October 2010 Mentawai tsunami earthquake, from real-time discriminants, finite-fault rupture, and tsunami excitation*, *Geophys. Res. Lett.*, 38 (L05302), doi:10.1029/2010GL046498.
- O'LOUGHLIN, K.F., and LANDER, J.F. (2003). *Caribbean Tsunamis: A 500-Year History from 1498–1998*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- OLSON, S.M., GREEN, R.A., LASLEY, S., MARTIN, N., COX, B.R., RATHJE, E., BACHHUBER, J., and FRENCH, J. (2011). *Documenting liquefaction and lateral spreading triggered by the 12 January 2010 Haiti Earthquake*. *Earthquake Spectra* 27(S1):S93–S116.
- PARSONS, T., and GEIST, E.L. (2008). *Tsunami Probability in the Caribbean Region*. *Pure Appl. Geophys.* 165(11-12):2089–2116, doi:10.1007/s00024-008-0416-7.
- PAWSON M., and BUISSERET, D. (1975). *Port Royal, Jamaica*. Clarendon Press, Oxford (GBR).
- PRENTICE, C.S., MANN, P., CRONE, A.J., GOLD, R.D., HUDNUT, K.W., BRIGGS, R.W., KOEHLER, R.D., and JEAN, P. (2010). Seismic hazard of the Enriquillo–Plantain Garden fault in Haiti inferred from palaeoseismology. *Nature Geoscience*, 3(11):789–793.
- SCHERER, J. (1912). *Great earthquakes in the island of Haiti*. *Bull. Seismol. Soc. Am. Bull.*, 2(3):161–180.
- SYNOLAKIS, C.E., and BERNARD, E.N. (2006). Tsunami science before and beyond Boxing Day 2004, *Phil. Trans. R. Soc. A* 364:2231–2265.
- SYNOLAKIS, C.E., BERNARD, E.N., TITOV, V.V., KĀNOĞLU, U., and GONZÁLEZ, F.I. (2008). *Validation and verification of tsunami numerical models*, *Pure Appl. Geophys.* 165(11–12):2197–2228.
- SYNOLAKIS, C.E., and KONG, L. (2006). *Runup Measurements of the December 2004 Indian Ocean Tsunami*. *Earthquake Spectra*, 22(S3):S67–S91.
- SYNOLAKIS, C.E., and OKAL, E.A. (2005). 1992–2002: *Perspective on a decade of post-tsunami surveys*; in: *Tsunamis: Case studies and recent developments*, ed. by K. Satake, *Adv. Natur. Technol. Hazards*, 23:1–30, Springer.
- TABER, S. (1922). *The seismic belt in the Greater Antilles*. *Bull. Seismol. Soc. Am. Bull.*, 12(4):199–219.
- TADEPALLI, S., and SYNOLAKIS, C.E. (1994). *The Run-Up of N-Waves on Sloping Beaches*. *Proc. Roy. Soc. Lond. A* 445(1923):99–112.
- TANG, L., BERNARD, E.N., TITOV, V.V., WEI, Y., CHAMBERLIN, C.D., EBLE, M., MOORE, C., NEWMAN, J.C., SPILLANE, M., MOFIELD, H.O. and WRIGHT, L. (2012). *Direct energy estimates of the 2011 Japan tsunami using deep-ocean pressure data for real-time forecasting, submitted to J. Geophys. Res.*, in review.
- TANG, L., TITOV, V. V., and CHAMBERLIN, C. D. (2009). *Development, testing, and applications of site-specific tsunami inundation models for real-time forecasting*, *J. Geophys. Res.*, 114, C12025, doi:10.1029/2009JC005476.
- TITOV, V.V. (2009). Tsunami forecasting, Chapter 12 in *The Sea, Volume 15: Tsunamis*, Harvard University Press, Cambridge, MA and London, England, 371–400.
- TITOV, V.V., and GONZALEZ, F. (1997). Implementation and Testing of the Method of Splitting Tsunami (MOST) Model. NOAA Tech. Memo. ERL PMEL-112.
- TITOV, V.V., and SYNOLAKIS, C.E. (1998). Numerical modeling of tidal wave runup, *J. Waterw. Port Coastal Ocean Eng., ASCE*, 124(4):157–171.
- USLU, B., POWER, W., GREESLADE, D., EBLE, M., and TITOV, V.V. (2011). *The July 15, 2009 Fiordland, New Zealand tsunami: real-time assessment*. *Pure Appl. Geophys.*, 168(11):1963–1972.
- WALK, R.M., DONAHUE, T.F., SHARPE, R.P., and SAFFORD, S.D. (2011). *Three phases of disaster relief in Haiti – pediatric surgical care on board the United States Naval Ship Comfort*. *J. Pediatric Surgery*, 46(11):1978–1984.
- WALTON, D.A., and IVERS, L.C. (2011). *Responding to Cholera in Post-Earthquake Haiti*. *The New England J. Medicine*, 364(1): 3–5.
- WEI, Y., BERNARD, E., TANG, L., WEISS, R., TITOV, V., MOORE, C., SPILLANE, M., HOPKINS, M., and KĀNOĞLU, U. (2008). *Real-time experimental forecast of the Peruvian tsunami of August 2007 for U.S. coastlines*. *Geophys. Res. Lett.* 35, L04609, doi:10.1029/2007GL032250.
- WEI, Y., CHAMBERLIN, C., TITOV, V.V., TANG, L., and BERNARD, E.N. (2012). *Modeling of the 2011 Japan tsunami: lessons for near-field forecast*, *Pure Appl. Geophys.*, in review.