The 15 August 2007 Peru tsunami runup observations and modeling

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[1] On 15 August 2007 an earthquake with moment magnitude (M_w) of 8.0 centered off the coast of central Peru, generated a tsunami with locally focused runup heights of up to10 m. A reconnaissance team was deployed two weeks after the event and investigated the tsunami effects at 51 sites. Three tsunami fatalities were reported south of the Paracas Peninsula in a sparsely populated desert area where the largest tsunami runup heights were measured. Numerical modeling of the earthquake source and tsunami suggest that a region of high slip near the coastline was primarily responsible for the extreme runup heights. The town of Pisco was spared by the Paracas Peninsula, which blocked tsunami waves from propagating northward from the high slip region. The coast of Peru has experienced numerous deadly and destructive tsunamis throughout history, which highlights the importance of ongoing tsunami awareness and education efforts to ensure successful self-evacuation.

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1. Introduction

[2] On August 15, 2007 at 23:40:57 UTC (~6:41 PM local time) an earthquake with moment magnitude (M_w) 8.0 occurred offshore of central Peru. Centered at 13.4°S, 76.5°W at a depth of 39 km, the event lasted 3.5 min and occurred on the interface between the South American Plate and the subducting Nazca Plate. Media reports during the first day focused entirely on the earthquake-shaking related damage and the resulting casualties (519 deaths and over 1000 injured). The bulk of the earthquake damage and human toll occurred in the towns of Pisco, Chincha Alta and Ica. Most of the destroyed buildings were unreinforced adobe houses; however churches, hospitals, schools and other public buildings were also damaged. In addition, transportation links such as the Pan American Highway, the Carretera Central, and other major routes suffered heavy damage due to landslides and liquefaction [*Earthquake Engineering Research Institute* (*EERI*), 2007]. Widespread communications and power outages occurred throughout the area, which contributed to the initial lack of information about the subsequent tsunami.

[3] The Peruvian Navy's Dirección de Hidrografia y Navegación operates a system of tide gauges along the coast and reports to the Pacific Tsunami Warning Center (PTWC). Unfortunately the earthquake damaged the nearest tide gauge, located 55km south of the epicenter at Puerto General San Martin. The tsunami was however recorded on tide gauges throughout the Pacific [*Wei et al.*, 2008]. The first PTWC tsunami bulletin was received by the Peruvian Navy headquarters in Lima at 23:53UTC (15. Aug. 2007) corresponding to the tsunami arrival time at nearest villages. The second PTWC tsunami bulletin was received in Lima at 00:19UTC (16. Aug. 2007), which is after the tsunami impact along hard hit areas. The tsunami warning dissemination was further complicated due to communication network failures after the earthquake. The Peruvian coast guard in Pisco had distributed tsunami evacuation maps based on a 7m elevation contour. All the designated temporary refuges were outside the flood zone. Fortunately, the sergeants manning the numerous outposts were alerted by the earthquake and ordered evacuations in the affected fishing villages in the short time window of 10–20 min between the earthquake and the onslaught of the tsunami. The sergeant of Rancherio, a most remote outpost on the Bahia de la Independencia, emphasized the need for reliable communication as the evacuees were stuck on top of a sand dune for the night. Unfortunately not all coastal residents were as tsunami aware. In Lagunilla, south of the Paracas Peninsula, residents did not self-evacuate after the earthquake and there was no coast guard outpost to coordinate the evacuation. Three people were caught by the waves and their bodies were eventually recovered approximately 1800 m inland. These deaths were preventable – as there was high ground less than 100 m away and Lagunilla did not suffer significant earthquake damage – if only the residents had been more cognizant of the tsunami hazard after an earthquake and initiated an immediate evacuation as executed perfectly by the Solomon Islanders on 1 April 2007 [*Fritz and Kalligeris*, 2008; *McAdoo et al.*, 2006].

2. Post-Tsunami Field Observations

[4] An initial survey by Peruvian Naval Authorities noted evidence of flooding along a stretch of coastline from Paracas up to Miraflores in Lima and raised the importance of a scientific reconnaissance. The post-tsunami field survey was coordinated through the Peruvian Navy's Dirección de Hidrografia y Navegación and took place from September 4–7. The survey covered approximately 275 km of Pacific coastline from Lima in the north to the desert region at

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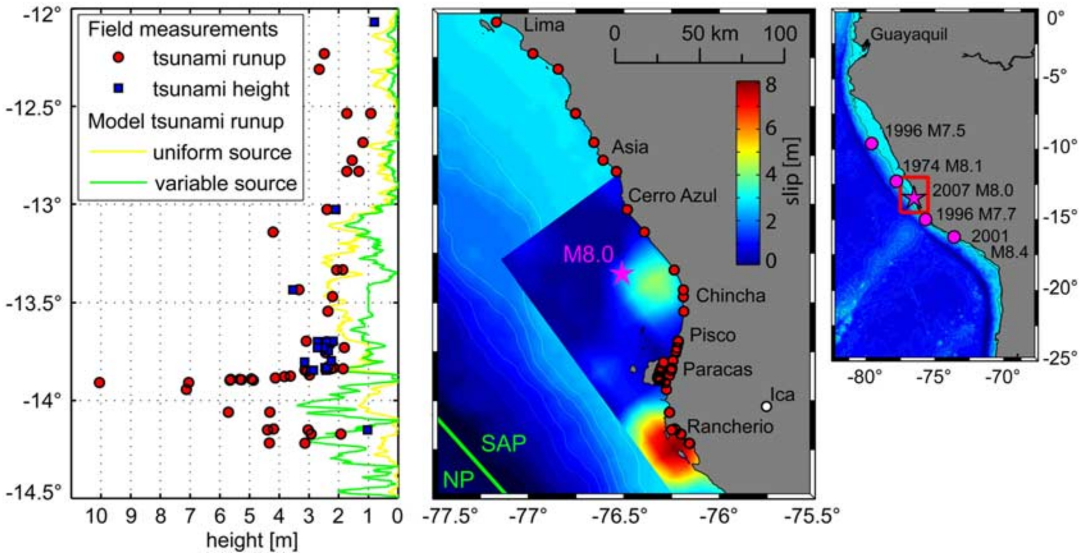

Figure 1. Measured tsunami heights and runup compared against uniform and variable source numerical simulations along the coast of central Peru; main fault line with tectonic plates (NP, Nazca Plate; SAP, South American Plate); earthquake epicenter estimate (http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007gbcv/); surface projection of the slip distribution superimposed on ETOPO2 bathymetry (http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007gbcv/finite_fault.php); and location map with selected historic earthquakes.

Bahia de la Independencia 50 km south of Paracas (Figure 1). The team measured local flow depths and tsunami heights, maximum runup, inundation distances, recorded structural damage and interviewed eyewitnesses per established methods [*Synolakis and Okal*, 2005; *Dengler et al.*, 2003]. Eyewitnesses described two to three main waves with mostly an initial recession corresponding to a leading depression N-wave as described by *Tadepalli and Synolakis* [1994].

[5] 51 transects were recorded from the waterline to the inundation limit and adjusted for tide levels upon tsunami arrival as shown in Table S1.[1] The tsunami runup distribution peaks south of the Paracas Peninsula with a 10 m runup spike on Playa Yumaque and sustained runup in excess of 7 m along 5 km of coastline (Figure 2). Fortunately, the tsunami was largest in a mostly uninhabited desert area (Figure 3a). The nearest permanent settlements of Rancherio and Lagunilla, described previously as good and bad examples of tsunami awareness, were strongly affected by the waves. At Lagunilla the tsunami flooded up to 2 km inland over extremely flat terrain with up to 4 m runup at the inundation limit and 5 to 6 m runup heights at the location of the village on the shoreline (Figure 3b). More than twenty boats were washed ashore and deposited up to 1.3km inland (Figure 3c). The Paracas peninsula resembles the Xaafuun peninsula in Somalia given the maximum inundation and death toll at the leeside [*Fritz and Borrero*, 2006]. Similar runup heights and flow depths during the 2004 Indian Ocean tsunami resulted in much higher death tolls in Sri Lanka [*Liu et al.*, 2005], attributable to the higher population density there.

[6] In the town of Paracas, there was damage to a pier due to sand liquefaction resulting in differential pile settlement of up to 0.3 m, while the floating pier deck was uplifted by the tsunami and stuck at an elation of 2.5 m (Figure 3d). North of the Paracas Peninsula the tsunami runup had characteristic runup heights of 3 m. Nevertheless boats were washed into the streets in Pisco and the Tambo de Mora prison was partially flooded in Chincha Alta. The prison compound walls collapsed due to the earthquake, setting free 600 prisoners prior to the onslaught of the tsunami. Similarly Indonesia's super security prison on Nusa Kambangan was inside the tsunami flood zone during the 17 July 2006 Java tsunami earthquake [*Fritz et al.*, 2007]. Critical infrastructure such as hospitals, schools, and prisons should be located outside of flood zones.

[7] This Peru earthquake represents a unique opportunity to characterize the collateral tsunami impact in the immediate aftermath of a destructive earthquake. Community-based education and awareness programs are particularly essential to help save lives in locales at risk from near-source tsunamis [*Sieh*, 2006]. This is of particular importance for Peru given the fairly frequent near source moderate size tsunamis such as the 2001 Camana tsunami in southern Peru [*Okal et al.*, 2002], the 1996 Chimbote tsunami in northern Peru [*Bourgeois et al.*, 1999], the small November 1996 Nazca tsunami, and the October 1974 tsunami in the same area as the 2007 event [*Kulikov et al.*, 2005]. Relative to previous earthquakes and tsunamis affecting this part of Peru, this event ranks towards the smaller end of the spectrum in terms of both overall seismic moment and observed effects at Pisco [*Okal et al.*, 2006]. The 2007 earthquake has a smaller seismic moment than the 1974 event (0.9 vs. 1.5×10^{28} dyne-cm), however the tsunami effects at Pisco were equivalent or more severe in 2007 ($\sim$3 m vs. $\sim$2 m). One witness, a 58 year-old sergeant at the Rancherio Coast Guard outpost, had experienced several tsunamis at that location. By his estimation, relative to the most recent event, the 1974 tsunami was

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033494.

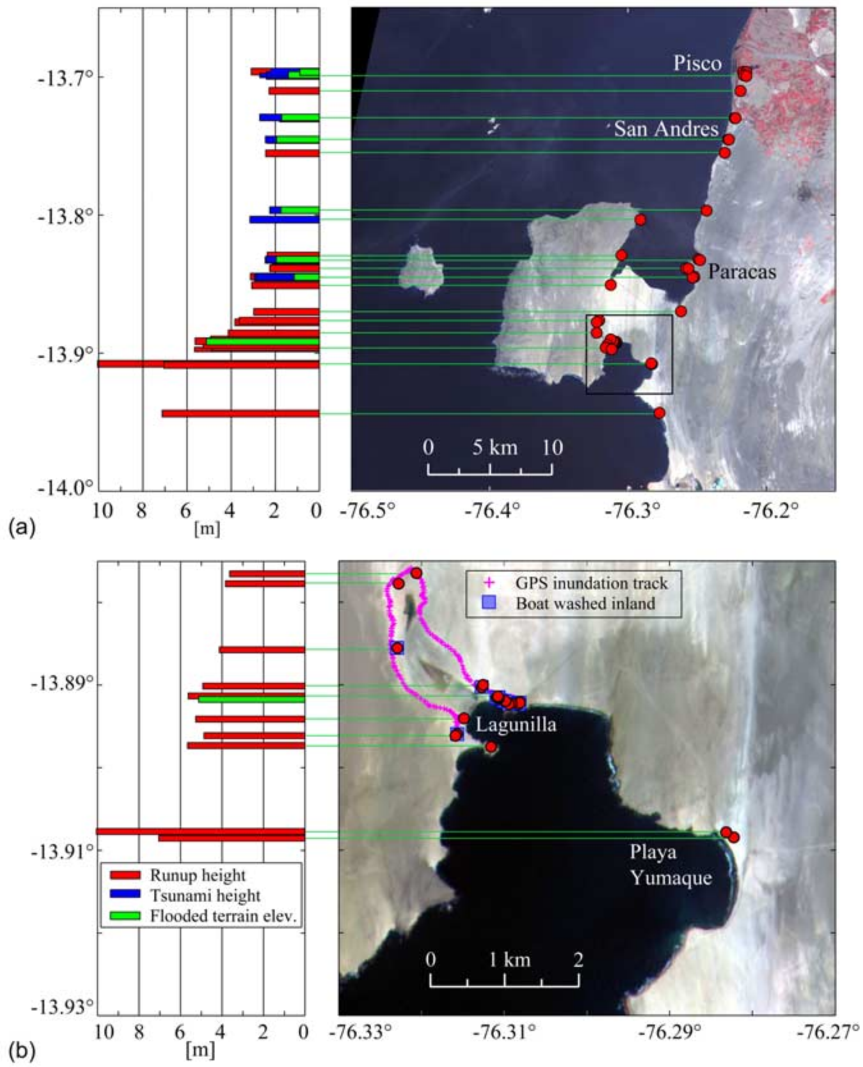

Figure 2. Measured tsunami heights and runup: (a) Paracas Peninsula and Pisco and (b) Playa Yumaque with maximum runup and Lagunilla with the maximum inundation; background ASTER satellite image (8 November 2007).

slightly smaller while the 12 November 1996 Nazca earthquake generated a tsunami approximately one-third the size of 2007. He did not observe any tsunami resulting from the 2001 Camana earthquake.

3. Numerical Modeling

[8] To simulate the measured tsunami runup, we used the tsunami inundation model MOST, which solves the 2 + 1 non-linear shallow water equations in rectangular or spherical coordinates [*Titov and Synolakis*, 1998]. Shortly after the event, seismic inversion models suggested the presence of a high slip patch near the coastline, south of the Paracas Peninsula [*Ji and Zeng*, 2007]. The subsequent field survey confirmed that this region experienced the highest runup as a result of the earthquake.

[9] Because of the lack of high-resolution bathymetry, it is not reasonable to expect a match to the measured tsunami runup as coarse bathymetry grids generally result in an underprediction of measured tsunami runup heights [*Synolakis and Bernard*, 2006]. For this study, only the global 2-minute bathymetry and topography data set was readily available. The bathymetry data was interpolated to a system of three nested grids of 1 arcminute, 20 arcseconds and 6 arcseconds, respectively.

[10] Two different source models were used to initialize the tsunami propagation and runup model (Table 1). Both sources assumed earthquake rupture with uniform slip across rectangular fault planes. Source 1 used a single fault segment while Source 2 assumed two fault planes. Source 2 partitioned ~80% of the total seismic moment on to the southern fault plane to better approximate the earthquake slip distribution as estimated through the inversion of teleseismic data. Plots of the offshore tsunami wave heights and final deformation fields are shown in Figure 4.

[11] The deformation fields shown in Figures 4b and 4c were used in MOST to initialize a full hydrodynamic simulation of the tsunami effects. The modeled runup for each source is shown in comparison to the measured field data in Figure 1. The model results are generally deficient in matching the magnitude of the overall runup. The uniform rectangular source produces runup that matches observed

Figure 3. (a) Tsunami runup induced slump and wrackline on Playa Tunga along Bahia de la Independencia's desert coastline. (b) The fishing village of Lagunilla completely destroyed by the tsunami resulting in 3 deaths out of 7 inhabitants, while survivors reported no significant earthquake damage. (c) A fishing boat washed more than 1.3 km inland in the flood zone with up to 2 km inundation near Lagunilla in the background. (d) Paracas marina tsunami height measured based on a floating dock stuck in an uplifted position.

values throughout the central part of the survey region, however this source does not provide a good fit to the data to the north, or most notably, south of the Paracas Peninsula. The runup predicted by Source 2 on the other hand, more closely follows the distribution of the measured field data although it is still deficient by a factor of 3.

[12] While the results represent an underprediction, important conclusions can still be made about the nature of this particular tsunami source. An earthquake model with a strongly partitioned source and two distinct slip patches provides a better fit to the observed runup distribution. These results are in contrast to recent observations and modeling of the September 12, 2007 earthquake ($M_w = 8.4$) and tsunami in the Bengkulu region of Sumatra [*Borrero et al.*, 2007]. In that event, detailed slip distributions were shown to be less important in predicting overall tsunami runup. In the case of the Bengkulu earthquake and tsunami, the primary deformation areas were located some 50–150 km offshore while the deformations in Peru are centered much closer (<50 km) shore. Also in Sumatra, the coastline is generally straight and parallel to the source region without any major features, such as the Paracas Peninsula, to block the propagation of tsunami waves to the north or south.

4. Conclusions

[13] The rapid deployment of the survey team to central Peru after the 15 August 2007 event led to the recovery of important data on the characteristics of tsunami impact in the near field. As with all near field tsunamis, the waves struck within minutes of the massive ground shaking. Spontaneous evacuations coordinated by the Peruvian Coast Guard minimized the fatalities and illustrates the importance of community-based education and awareness programs. The residents of the fishing village Lagunilla were unaware of the tsunami hazard after an earthquake and did not evacuate, which resulted in 3 fatalities. Despite the relatively benign tsunami effects at Pisco from this event, the tsunami hazard for this city (and its liquefied natural gas terminal) cannot be underestimated. Between 1687 and

Table 1. Source Parameters Used to Generate Earthquake Deformation Fields

	Seg.	L, km	W, km	Slip, m	Depth, km	Strike, deg	Dip, Deg	Rake, Deg	M_o, dyn-cm
Source 1	A	115	57.6	3.4	10	324	27	64	0.11×10^{29}
Source 2	A	66	33	8.5	10	324	27	64	0.91×10^{28}
	B	59	20	3.7	10	324	27	64	0.21×10^{28}

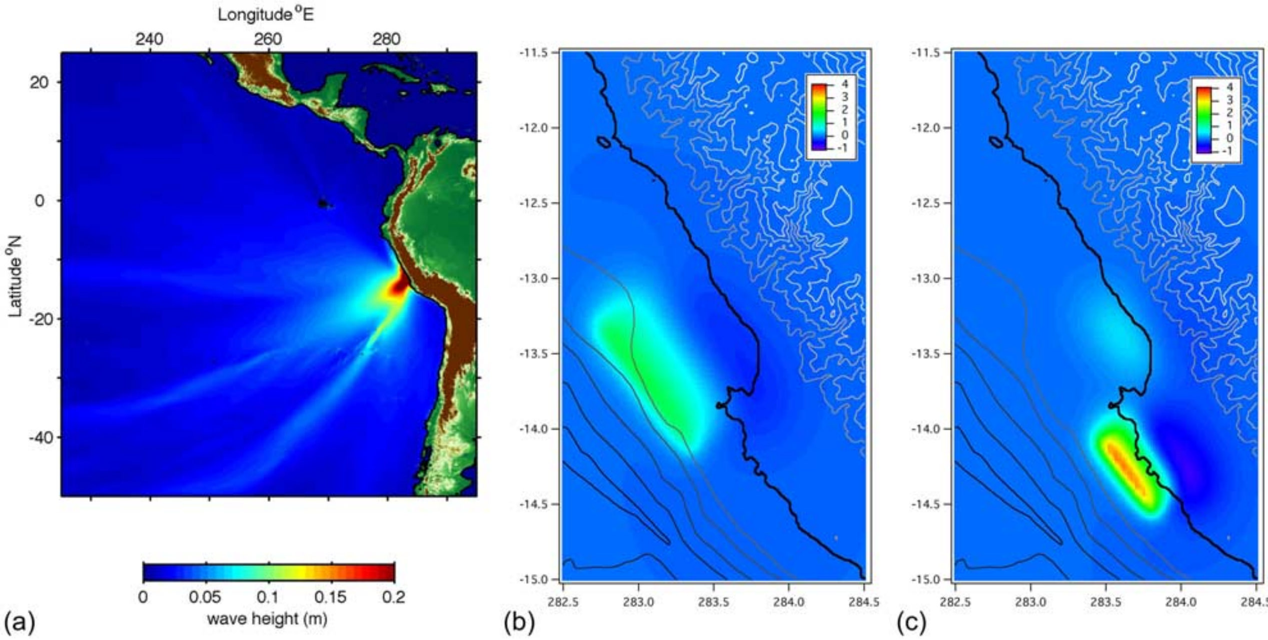

Figure 4. (a) Maximum estimated tsunami wave heights in the Pacific Ocean near Peru computed using the MOST-model based on the uniform source described in Table 1. Earthquake deformation fields for the (b) uniform and (c) composite sources (Table 1).

1868, the city of Pisco was destroyed 4 times by tsunami waves [*Okal et al.*, 2006]. Since then, two events (1974 and 2007) have resulted in partial inundation and moderate damage. The fact that potentially devastating (up to 10 m) tsunami runup heights were observed immediately south of the peninsula only serves to underscore this point.

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