INUNDATION DURING THE 26 DECEMBER 2004 TSUNAMI

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We summarize findings and observations from the field surveys conducted in the aftermath of the 26 December 2004 tsunami. This was the first tsunami with transoceanic impact, since comprehensive post-event hydrodynamic surveys began to be conducted in the early 1990s, with modern measurement tools. Eighteen nations were directly affected: Indonesia, Malaysia, Thailand, Myanmar, India, Sri Lanka, Oman, Yemen, Somalia, Kenya, Tanzania, Madagascar, the Maldives, the Comoros, Rodrigues, Mauritius, Reunion, Seychelles. The death toll included citizens from many other countries in Asia, Europe, the South Pacific, and the Americas, giving this tsunami the grim distinction of being the first universal natural disaster of modern times.

INTRODUCTION

Substantial progress in understanding tsunami hydrodynamics has been made over the last 15 years owing to data collected on post-tsunami field surveys which have driven basic research (Synolakis and Bernard 2006). Field surveys have been instrumental in the development of models, as tsunami science evolved differently than research in other extreme natural hazards—there have been no instrumental recordings of tsunamis in the open ocean, until recently.

Without instrumental recordings, there has been no widely applicable tsunami magnitude scale; there have been only qualitative intensity scales, not in wide use due to the variability of tsunami impact even within kilometer scales. Likewise, the absence of recordings has prevented testing and the development of modeling methodologies. By contrast, seismic recordings have not only allowed the quantification of the energy release in an earthquake, hence the Gutenberg and Richter and eventually the moment magnitude scales, but also the validation of source inversion algorithms which allow the identification of the source mechanism. In recent years, tsunami field surveys have been conducted following established protocols, as discussed in Synolakis and Okal (2005). In combination with large-scale laboratory experiments, field survey data sets have allowed model verification—the process of examining how well a particular approximation of the equations of motions can model geophysical reality.

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Operational and mitigation issues for tsunami forecasts as well as several relevant statistics are discussed by Bernard et al. (2006). The evolution of tsunami science is described by Synolakis and Bernard (2006). In summary, the state-of-modeling, just before 26 December 2004 has been sufficient to predict fairly accurately the farfield impact of the megatsunami, had the hazard been identified. The first simulation of V.V. Titov and its animations -widely [2]broadcast around the world- was eventually published with minor changes (Titov et al, 2005b, Geist et al, 2006). While as it is said, it is very difficult to predict earthquakes before they happen, it is not and was not difficult to predict the impact of scenario events and be prepared.

Below we will present a short discussion of the findings from field surveys to date. Conclusions about lessons learned and unlearned are summarized in Synolakis (2006).

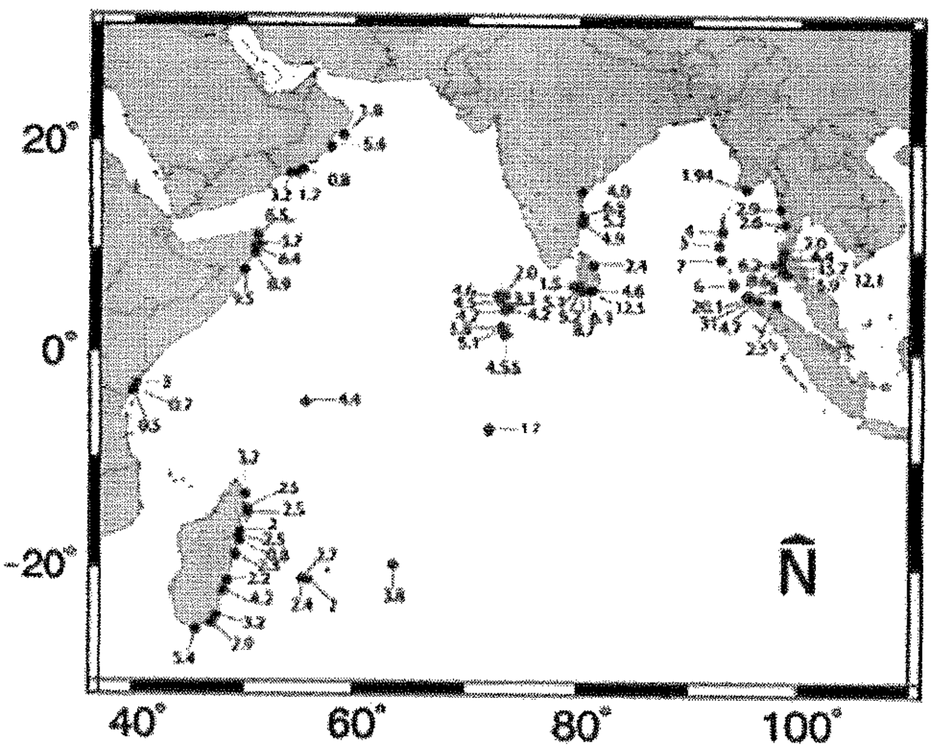

Figure 1. Runup or flow depth values around the Indian Ocean(IO) as have been reported. After Synolakis and Kong (2006).

TSUNAMI SURVEYS IN THE INDIAN OCEAN

Sumatra

The very first survey appears to be that of Borrero (2005a, 2005b) in Banda Aceh. Dr. Jose Borrero was the first scientist to enter the most severely stricken area in the entire Indian Ocean(IO) on January 3, 2006. Near Medan in NE Sumatra, the runup was 2.5 m. Banda Aceh, at the northern tip of Sumatra, horizontal inundation reached 4 km at places, while the flow depth near the shoreline was > 9 m. The scene was reminiscent of the devastation at Babi and Riangroko in the Flores 1992 event (Yeh et al. 1993), at Rajekwesi in 1994 (Synolakis et al. 1995), and at Sissano, Papua, New Guinea in 1998 (Kawata et al. 1999), only the devastation in Sumatra was far more extensive.

The severest damage was reported in Lhongka, just south of Banda Aceh, where bark stripped from trees along the coast suggests flow depths in excess of 13 m. In a cement factory about 1 km inland, the inferred flow depth was about 20 m aboveground. Close by, a 90-m coal-carrying barge was deposited about 160 m inland. The maximum runup was estimated 30-36m.

An interesting observation by Borrero et al. (2006a,b) was the study of the change in the velocity of the advancing wave front as inferred from an amateur video filmed outside the Grand Mosque near the center of Aceh, where the flow depth was 2.5 m. By locating the exact same locations that the videos were shot during the event, and using particle image velocimetry techniques, they inferred the front first moving at ~2 m/sec. then suddenly accelerated to speeds >5 m/sec.

Malaysia, Thailand, Myanmar, and Bangladesh

Yalciner et al. (2005) have reported on the damage in Malaysia. The tsunami reached Langkawi to the south and Penang to the north and directly across the Malay Peninsula and reached Penang Island 4 hours after the earthquake. In both locations, the tsunami manifested itself as a leading depression wave, with a maximum positive amplitude of up to 3 m. They noted that the death toll of 50 on the island is not justified, given the overall minor damage, and attributed to the difficulty to rapidly evacuate over sandy seawalls of > 2 m just behind sandy beaches.

In Thailand, Siripong (2006) has reported that while Patong Beach on Phuket Island received most of the media attention because of the density of foreign tourists, the largest runup of >15 m was observed at Cape Coral in Phang-nga province, about 120 km north of Patong. The west side of Phuket experienced high runup, exceeding 5 m in most places, and in the bays where beach resorts were situated, the runup reached 9 m.

For Patong, Dalrymple and Kriebel (2005) have noted that damage was reduced behind wide and vegetated sand dunes. Further, "all along the business district of Patong Beach, the seawall had regularly spaced openings for pedestrian access to the beach. Damage to inland shops appeared to correlate to these openings." While this is at first unexpected, because tsunamis are such long waves that they should not be sensitive to such small topographic features, this has been observed earlier in El Transito, Nicaragua (Synolakis et al. 2005). Further, Kanoglu and Synolakis (1998) have commented on how the maximum runup of long waves is very dependent on the last coastal topographic segment that the tsunami encounters.

Satake et al (2006) describe the survey of the coast of Myanmar. At the Ayeyarwaddy Delta 25 people died, and more than 1,000 were affected, yet the tsunami flow depths did not exceed 2.3 m. The area is a typical delta flat with numerous tributaries, and overland flow can easily spread from many directions. The tsunami runup reportedly did not exceed the highest possible tide mark, something that the team interpreted as implying that the runup did not exceed the high storm line. The measurements explain why 71 casualties were reported in Myanmar versus the 5,395 dead in adjacent Thailand, a difference that initially was greeted with suspicion in the media. Satake et al. (2006) speculate that the smaller impact—at least in southwest Myanmar—may be due to the numerous islands in the Myeik Archipelago, north of the Thailand/Myanmar border. The fairly small offshore depths in the archipelago may also be a factor, as well as the directivity of the source.

Synolakis and Kong (2006) have written that in adjacent Bangladesh to the west of Myanmar, the impact was reportedly mild, with two children dead, one of whom was in a boat. The earthquake was strongly felt in Chittakong, about 220 km southwest of Dhaka, the capital, where seiching was reported in Dhanmondi Lake.

India and the Andaman and Nicobar Islands

Yeh et al. (2006) reported the tsunami impact in southeast India, across from the source region. They estimated an effective wave length of 430 km between the first and second wave, with a period of about 40 minutes. Notably, they attempted to differentiate between local splashup and flow depths. The runup was "fairly uniform" from 2.2 to 5.5 m along the 600-km coastline that the survey covered. Tragically, despite the relatively smaller runup than was observed in Sri Lanka, Thailand, or Aceh, 8,600 people died. The authors commented on how it appeared that most victims drowned in flow depths of 1.5 to 2 m.

Eskijian (2006) has reported on the damage to Chennai ports on the Indian mainland and to Port Blair in South Andaman island. Chennai had no prior warning, no action plan, and was totally unprepared. By contrast, in Port

Blair, vesssels followed an emergency protocol vessels were able to depart, and there was little damage to the port infrastructure, as a direct result of the tsunami. The tsunami arrived in Chennai 1 hour and 25 minutes after reaching Port Blair. Eskijian (2006) speculated that the satellite dish had rotated due to the seismic shaking. Synolakis (2005) has argued that some communications are known to have survived, and it remains unexplained why there was no warning issued for the mainland or Sri Lanka. Tens of thousands might had been spared.

Sri Lanka

Goff et al. (2006) and Liu et al. (2005) have reported on the damage in Sri Lanka. 13% of the coastal housing was completely or partially destroyed. The tsunami arrived as a leading elevation wave a little over two hours after the earthquake at 3:10 UT, 9:10 A.M. local time. One to three waves were reported, depending upon the location. The maximum tsunami elevation ranged from 10 m in Trincomalee on the northeast side of the island to 7 m in Kalmunai further south, to 4.6 m in Yala, which was yet further near the southern tip of Sri Lanka, inside a national park. Interestingly, in Yala, while the flow elevation was not among the largest reported in Sri Lanka, the devastation was complete. Most if not all of the residents of the only local hotel died, because it was literally razed. As the team surmised through later interviews with survivors elsewhere, sand dunes fronting the hotel had been removed to enhance the views of hotel guests, obviously with catastrophic results.

Oman and Yemen

Okal et al. (2006a) surveyed the tsunami effects in Oman and recorded maximum heights on "the order of" 1–3 m, with a single value of 5.4 m at Al Shuaayr that was attributed to splash. The larger runup values of 2–3.3 m were grouped in southwest Oman, from Dhalkut to Taqah.

The port of Salalah is one of the major container terminal facilities in the Middle East. According to reports obtained from the harbor master and several other port employees, the 285-m freighter Maersk Mandraki broke its moorings and started drifting for a period of several hours, both outside and inside the harbor. All efforts to free the freighter via tugboats were in vain. The freighter eventually settled outside the harbor, beaching on a sand bar. Similarly, the 292-m-long Maersk Virginia, comparable in size to the Mandraki, was rocked by the tsunami as it was attempting to enter the harbor, to the extent that the captain had to wait about seven hours outside before proceeding; during that time, the vessel was being pulled toward the breakwater, which it struck, causing minor damage. Miraculously, the Mandraki did not collide with other ships or with harbor structures. It is interesting to note that the runup in areas surrounding the port was less than 1 m, underscoring the substantial impact that even small tsunamis can have in modern ports.

Otherwise, there are sparse reports for the tsunami impact elsewhere. H. Fritz and E.A. Okal have recently surveyed Socotra island in Yemen and have reported runup up to 5.3m.

Somalia, Kenya, Tanzania, and South Africa

Clearly, the hardest and most perilous survey undertaking was in Somalia, reported by Fritz and Borrero (2006b). They surveyed the coastal towns of Eyl, Bandarbeyla, Foar, Xaafuun, and Bargaal. Hardest hit was a 650-km stretch of the Somali coastline between Garacad and Xaafuun. In all towns, at least four waves were observed. The tsunami killed 300 people and caused extensive destruction of shelters, houses, water sources, fishing boats, and equipment. Most of the victims were reported along the Xaafuun Peninsula. The town of Xaafuun was completely flooded, with depths up to 2 m, runup of 4–6 m, up to 11 m/sec. flooding currents, and 700-m inundation distances—it suffered widespread destruction. The livelihoods of many people residing in towns and small villages along the Somalia coastline. The highest runup height in Somalia "of almost 9 m" was recorded in Bandarbeyla.

Weiss and Bahlburg (2006) have reported the impact on the Kenyan coastline. The area around Mombasa was largely spared, due to an offshore reef. In Malindi, which is not protected by a reef, runup ranged up to 3 m, with 40-m inundation distances.

For Tanzania, Synolakis and Kong (2006) have reported that ten people were killed, an unknown number of people were missing, and an oil tanker temporarily ran aground in Dar es Salaam harbor and damaged an oil pipeline. The Tanzanian Guardian newspaper site reported on 27 December 2004 that "two ships were swept out of Dar es Salaam port by powerful tidal waves, creating tension and confusion among port authorities and city residents," while the police commander "...said yesterday the victims drowned as they were swimming in the Indian Ocean at a number of beaches in the city."

In South Africa, the Cape Times reported that one person drowned at the "main beach" at Blue Horizon Bay near Port Elizabeth. A barman in Struisbaai, at Cape Agulhas at the southernmost tip of Africa, reported the wave arriving at about 7:30 P.M. local time and wrote "It was quite amazing. The water from the sea had pulled right back, leaving a sandy beach. About five minutes later, the water suddenly rose very high, about 1.5 metres. There were a lot of people on the beach, and they all ran for cover."

Madagascar, the Mascarene Islands, Seychelles, the Maldives, and Diego Garcia

Okal et al (2006b) reported the impact of the megatsunami in Madagascar. This was a difficult survey in terms of coastal access, as the team had to backtrack inland to revisit the next beach. They interviewed more than 100 eyewitnesses and measured runup and inundation at 52 sites. The tsunami arrived around 9:00 UTC, noon local time, 8–8.5 hours from the epicentral time, which is in good agreement with Titov et al. (2005b). Unusual water motions lasted all day, and the interval between waves was about 15–20 minutes. Eyewitnesses described how they visited the beaches after the unusual shoreline recession that followed the first wave—a testament to the universality of human impulses, only here they were less disastrous, due to the size of the wave. Furthermore, the team described the erratic response of residents to an alert after the 28 March 2005 event, which produced a mostly minimal tsunami, and they noted the urgent need for educational efforts in tsunami hazard mitigation.

A very important observation was made at the port of Toamasina. At the time when the first wave arrived, about 12:30 P.M., the local runup during the event did not exceed 60 cm. Yet, at about 7:00 P.M., a 50-m freighter broke its moorings and wandered within the harbor for the next 3 hours, eventually becoming grounded on a sand bar. Similar observations were made in Le Port, Reunion, and Salalah, Oman, and they underscore the importance of remaining vigilant for several hours in far-field locales after a teletsunami.

The Indian Ocean has numerous island chains. Impact has been reported in the Maldives, the Mascarenes, and the Seychelles. Fritz et al. (2006a) described the tsunami inundation in the Maldives. The country stretches 823 km from north to south and 130 km from east top west, with 1,190 islands grouped into 26 natural atolls. Open seas or deep channels with a depth of more than 200 m separate the atolls. Only 0.33% of its 13,423 km^2 is land, with only 200 islands inhabited and a population of 270,101. H. Fritz and C.E. Synolakis undertook extensive public outreach with lectures on tsunami hazard mitigation that were broadcast over the public radio and TV stations of the republic.

Consistent with other reports in the Maldives, the first of three waves arrived in Male as an leading-elevation N-wave (LEN (Tadepalli and Synolakis 1994) at about 9:15 A.M. local time. Witnesses described a gradual rise in sea level from all directions. While seawalls limited inundation, the reaction of residents in Male was—regrettably—as observed elsewhere in the IO, with children basking in the spray of water as the tsunami struck the seawall.

The hardest-hit islands were Vilufushi and Madifushi. The former had a population of 1,886 and is barely 1 km long and up to 300 m wide, flat, with an elevation of about 1 m and bounded by a coral reef roughly 1 km offshore. The death toll was 18, with 192 houses damaged. The tsunami washed over the island, with a flow depth was 4 m. A broken clock recorded the arrival time at 9:26 A.M., which is consistent with research by Titov et al. (2005b).

The second-highest flow depth of 3.1 m outside Vilufushi was recorded in Kandholhudhoo in the Raa atoll. However, here the residents were warned by telephone about 15 minutes before the arrival, and only three persons died. An amateur video shows the tsunami attack as a flood, in sharp contrast to similar videos from Thailand and Aceh.

At first sight, the Maldivian archipelago, with elevations of less than 2 m above sea level, appears extremely vulnerable. While early reports of only about 82 people killed and 26 missing seemed unbelievable, the survey helped identify one of the reasons for this outcome. The Maldives do not have a large continental shelf, thus limiting tsunami shoaling significantly. This behavior was implicit in the Kanoglu and Synolakis (1998) study, which calculated analytically the wave runup around islands, and in the study by Lautenbacher (1970), who calculated the wave diffraction. In essence, the Maldives experienced the tsunami with little amplification with respect to its deep-water signature.

Okal et al. (2006c) surveyed the Mascarene islands, i.e., Rodrigues, Mauritius, and Reunion. Reunion lacks a continuous fringing reef. Mauritius is about 200 km east-northeast of Reunion and features an almost continuous coral reef. Rodrigues is 600 km from Mauritius and a developed coral reef system.

Most witnesses described a series of three waves. A leading elevation wave of small amplitude arrived first, with the third crest being the largest. The runup ranged from 0.5 to 2.9 m, with a single 3.8-m value measured at Petit Gravier, in southwest Rodrigues, where otherwise the runup was 2.9 m, which was also the highest value of this survey among 35 measurements.

An interesting observation was the motions of MSC Uruguay, anchored in Le Port in east Reunion. She broke her moorings four hours later than the arrival of the first wave, in a manner reminiscent of accounts in Salalah, Oman and Toamasina, Madagascar. This delay could be attributed to harbor resonance whose onset is triggered by the arrival of waves with periods close to those of the port, and not necessarily by the first wave.

Jackson et al. (2005) have described the impact in the Seychelles. Two people died as the tsunami arrived during low tide. In the capital Mahe, facing west, the runup ranged from 1.6 to 4.4 m. Fish and coral debris covered the first 200 m of the south runway of the airport. In the bay of Anse la Mouch on the west side, the tsunami penetrated about 400 m inland at some places, despite thick vegetation. The flow depth reached 3 m in Anchor Cafe, above the mean water level, even though the cafe was 1.5 m above sea level. Interestingly, the authors calculated a surge velocity in the range of 3–6 m/sec at the shoreline. Recall, the 2-5m/sec front velocities estimated 3km inland in Banda Aceh.

Synolakis and Kong (2006) have reported on Diego Garcia. It is horseshoe-shaped, about 63 km long, with a maximum elevation of 7 m. At the southern end, there is a lagoon 20 km long and 9 km wide, with depths ranging from 20 m to 30 m. The island is exclusively leased to a U.S. military base, in the

Chagos Archipelago. The official U.S. Navy comment remains that there was no impact. One web site reports a 1.9-m wave. The most comprehensive report from an Internet blog said "Around 0700 we felt the earthquake. I thought it was one of our B-1 bombers taking off just a little closer than usual...Around 10:00 after our worship service folks came into the Chapel Center saying the lagoon had been emptied of water. The water's return to the lagoon was a bit leisurely coming back and did slosh over some parts of the island. The only damage done was one of the lines to a ship was broken when the water returned and flipped the vessel around." It is likely that the first wave was not noticed, as elsewhere in the far field, such as Oman, but in contrast to the Mascarene islands. which are closer to Diego Garcia. It is striking that the observation of the lagoon emptying was not taken as a sign for immediate evacuation. Whether it was the offshore topography with no continental shelf like the Maldives, or the directivity of the source, the personnel and residents in Diego Garcia were very lucky indeed.

The observations reported here are summaries from a summary paper summarizing papers and other publications, newspaper web sites, and Internet blogs. We will only dwell on a few key observations.

DISCUSSION

Hundreds of photos are available of tourists in Phuket just casually watching the onslaught of the tsunami within 100 m of the shoreline. Undoubtedly, most perished. Neither the pre-existing tsunami folklore, recorded in numerous popular science books since 1946, nor the telling photos from Manzanillo, Mexico (Borrero et al. 1995), and the change of the scientific paradigm of tsunamis in terms of the leading wave had reached the broader public, worldwide. This is yet another warning for public education campaigns.

In addition to the photos, there are numerous videos of the advancing megatsunami. For perspective, the only available movies of tsunami evolution on dry land had been a short clip of the 1946 tsunami, amateur footage showing the 1983 Japan Sea tsunami, and brief footage of the Camana, Peru 2001 wave. Footage from Thailand shows the tsunami first slowing down as it evolves through increasingly shallower water, then accelerating past the original shoreline. In hindsight, this should had been anticipated; the wave slows down as the depth diminishes, but once on dry land it moves at first with a velocity that is related to the bore propagation speed, before decelerating again as it reaches its maximum runup. These inferences help explain the apparent mesmerizing of victims who are seen to simply stand watching the tsunami approaching—clearly its speed did not appear too threatening, until it was way too late.

Hydrodynamic propagation models are initialized with seafloor displacement estimates derived from fault solutions. Their predictions reflect the accuracy of standard elastic half-space models used to transfer fault solutions to displacement fields. Model initialization had been partially validated with smaller tsunamis, but never with megathrust events. The current state-of-the-art hydrodynamic propagation engineering codes appear to model tsunami propagation adequately. Smith et al. (2005), compares tsunami free-field signatures from satellite backscatter data with model predictions from the method of splitting tsunamis (MOST) (Titov and Synolakis 1998), which is the first-ever such comparison. Note the < 60-cm height of the tsunami as it propagates and the small steepness, which confirms the conjecture that led to the development of the LDN/LEN paradigm (Tadepalli and Synolakis 1996). These comparisons offer support for the models that had been used to estimate the impact of other megathrusts, such as in the Cascadia subduction zone.

A comparison of the inundation between the 26 December 2004 and 28 March 2005 tsunamis allows the quantitative evaluation of the utility of relying on coastal gauges. The 2005 tsunami was very small, a "no show" (Kerr 2005), yet it was triggered by a magnitude 8.7 thrust earthquake, "with similar focal mechanisms, focal depths, and epicenters only about 110 km apart" from the megatsunami source (Geist et al. 2005). If one relied on the measurement from the Cocos Island tide gauge, then one would infer that the 2005 tsunami was about one-half the size of the 2004 wave. Indeed, there was mass panic in several nations in the Indian Ocean, and the Cocos Island recording did not help cancel the evacuations or better focus the warnings. The tide gauge in Manzanillo, Mexico recorded the 2004 tsunami as being 2.8 m, as high as at the Colombo, Sri Lanka station. Without further belaboring the obvious, this observation underscore the risk of relying on tide gauge records for warning guidance. The only proven methodology for inferring the free-field height of a tsunami is tsunameters (Titov et al. 2005a).

The runup induced from the tsunami of the 8.7 March 28, 2005 earthquake substantially smaller that from the 2004 event. Geist et al. (2005) have attributed the small size of the 2005 tsunami primarily to the smaller ocean depth over the deformation zone. By contrast, Arcas and Synolakis (Kerr 2005) have argued that, since most of the deformation occurred below the islands of Nias and Simeulue, the effective water mass set into motion during the 2005 event was reduced, thereby drastically limiting the size and impact of the generated tsunami. Kanoglu and Synolakis (2006) have shown that the smaller depth appears a second order effect compared to the reduction in fluid mass set in to motion because of the islands. This clearly identifies the need to have pre-existing inundation maps for realistic scenario events, so earlier unrecognized effects such as the presence of islands in the deformation zone can be properly evaluated in advance.

The impact of smaller tsunamis on ports remains highly controversial. Borrero et al. (2005) have reported on possible impacts in the ports of Los Angeles and Long Beach, California from a locally triggered tsunami of a size larger than observed in most distant IO ports. By contrast, the destruction in

Crescent City, California from the 15 November 2006 Kuril tsunami was caused by waves of a size similar to those observed in 2004 in IO ports farfield. While the Borrero et al (2006) estimates of the economic impact have been scrutinized, it is clear that even small tsunamis can cause substantial impact in ports.

Finally, the shortcomings in the population and emergency response observed underscore the urgent need for a worldwide educational effort on tsunami hazard mitigation. Even in 2006, earthquakes in Tonga, off Kythira, Greece produced strong ground shaking but did not trigger spontaneous evacuations, as the residents were expecting official warnings. At best, official warnings would had arrived in adjacent coastlines after the first tsunami arrival. As it turned out, the Tonga event did generate a very small tsunami, the Kythira event didn't, both because the earthquake hypocenter was at depths greater than 40 km. The Central Javan tsunami of 17 July 2006 killed more than 600 people, all while officials were debating whether to issue warning. Thus, simply educating the local populations who are at risk is not enough. In an era of global citizenship, it is important that everyone can identify the precursors of a tsunami attack and knows to evacuate to high ground or inland as quickly as possible, or, if necessary, how to more safely vertically evacuate to adjacent buildings.

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