It is too soon to know if Indian Ocean populations are better prepared today than they were last December.

The Megatsunami of December 26, 2004


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From 1992 to 2002, tsunamis in the wake of large, but not gigantic, earthquakes, caused significant damage to coastal areas about once a year. These tsunamis resulted in more than 3,000 fatalities, 2,100 in 1998 alone from the catastrophic tsunami in Papua New Guinea. But these events were dwarfed by the December 26, 2004, megatsunami, with a final death toll that may exceed 230,000. By some accounts, the death toll is higher than for all other tsunamis in the past 300 years combined.

Tsunami hazard mitigation involves detection, forecasting, and emergency preparedness. Direct tsunami detection is now possible through tsunameters. Real-time forecasting requires not only validated numerical models, but also a reliable database of inundation parameters against which models can be tested through simulations of tsunami generation, propagation, and interaction with the shoreline. Emergency preparedness requires an understanding of the crucial characteristics of flooding, namely run-up, inundation, and overland flow depth. Mitigation measures must also be based on past experience, which can help identify flow phenomena and locales with complexities that are often impossible to anticipate.

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The National Science Foundation (NSF) has contributed significantly to the development of comprehensive 2+1-dimensional inundation numerical models and large-scale laboratory experiments. NSF has also funded workshops for comparing the results of numerical models with both laboratory models and field data for validation (Liu et al., 1991; Synolakis, 2004). With current technologies, real-time tsunami forecasting can be done through a combination of tsunami detection buoys (tsunameters) operated by National Oceanic and Atmospheric Administration (NOAA)-Pacific Marine Environmental Laboratory (PMEL) and the MOST (method of splitting tsunami) numerical model (Titov and Synolakis, 1998). In this paper, we highlight the most important results of past surveys, particularly how they have contributed to our understanding of the factors that determine the destructive impact of waves on coastal communities. We also discuss briefly how field results have contributed to the development of numerical models and how lessons learned from earlier catastrophes might have saved lives in December 2004.

Field Surveys

In the past decade, systematic post-tsunami field surveys have been undertaken by international teams of scientists (ITSTs), generally within a few weeks of the disaster. Figure 1 shows the locations of these surveys. The objective of a tsunami field survey is to quantify the inundation pattern and determine the run-up height and inundation-depth distribution along the stricken coastline. Combined with validated numerical codes, these data sets can help us predict inundation in nearby areas, if the same seismic zone ruptures at a comparable location in the future. Through hydrodynamic inversion, we may be able to determine if this is the worst-possible event expected in the area and whether there may be a transoceanic tsunami in a future rupture.

Comparisons of field data and model predictions may also help explain why an event may initially appear anomalous (e.g., when tsunami damage seems incommensurate with the size of the parent earthquake). Field observations sometimes lead to the identification of new offshore hazards, which can improve inundation maps, such as those that have been developed for Hawaii, Japan, and most parts of California, Oregon, Washington, and Alaska. Figure 2 shows still images from animations of landslide-triggered tsunamis attacking southern California (Figure 2a) and the tsunami that attacked Papua New Guinea in 1998 (Figure 2b); these animations led to further studies on the hazards of landslide tsunamis. Inundation maps help local authorities prepare for emergencies and decide where to locate schools, hospitals, fire stations, and other critical facilities.

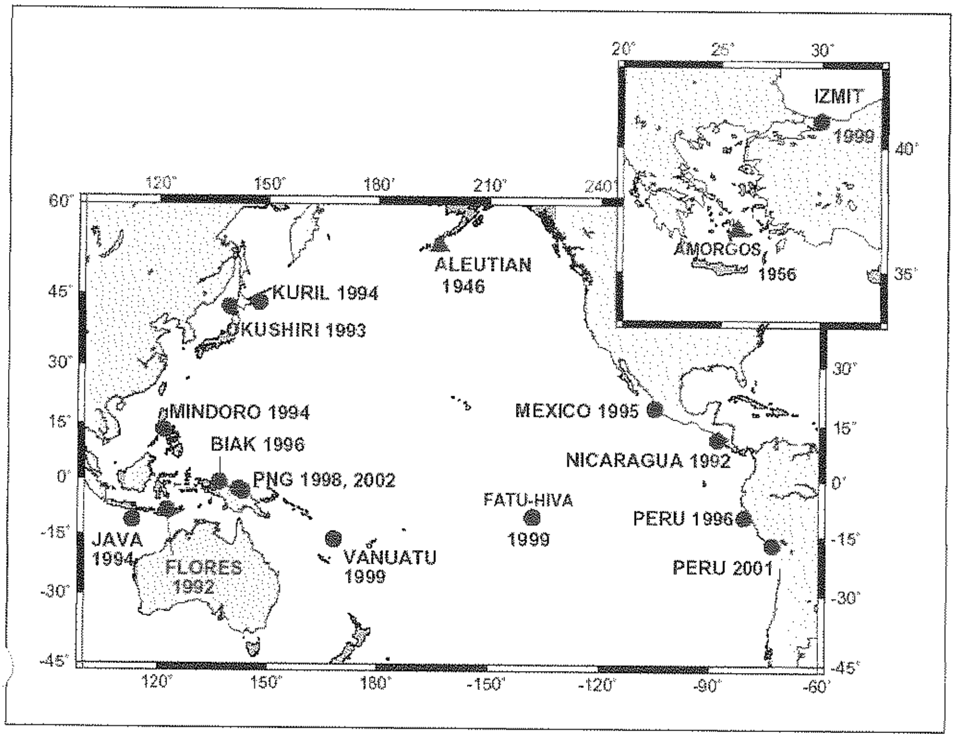

FIGURE 1 Location of field surveys of tsunamis in 1992–2002.

Although the scientific rationale behind tsunami surveys is evident, ITSTs must strike a delicate balance between the necessity of acting promptly to recover ephemeral field data and the obvious priority of search-and-rescue operations in the immediate aftermath of a disaster. In this context, we note that most tsunami watermarks are short-lived and may be lost after a single large storm. In addition, earth-moving equipment may destroy vegetation that holds clues to

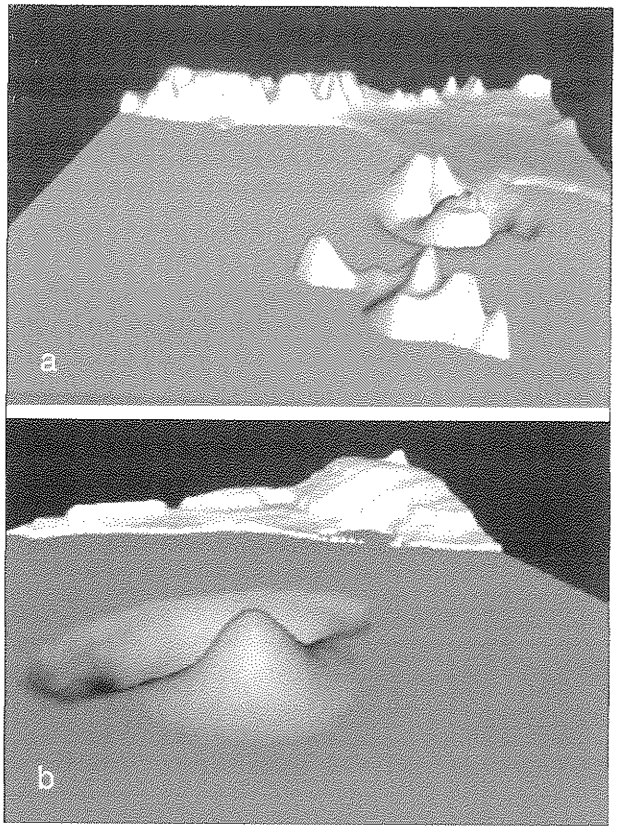

FIGURE 2 Still images of landslide waves attacking Southern California (a) and a similar landslide wave attacking Papua New Guinea (b) in 1998.

the direction and intensity of tsunami currents, and eyewitnesses usually move to safer areas or are relocated. To complicate matters further, once an official version of events circulates, all eyewitnesses tend to report identical information, as people tend to trust what they hear or read in the press more than what they have seen with their own eyes.

Based on past experience, therefore, surveys are most useful within two to three weeks of the event, allowing sufficient time for search-and-rescue efforts but still giving the ITST access to the scene. The work of ITSTs is generally unobtrusive, and teams have always been met with enthusiastic support by local people, who are not only hopeful that surveys will lead to benefits for their communities, but who also ask many interesting and difficult questions that contribute to the surveys.

The essential elements of the database of post-tsunami surveys include measurements of *run-up*, *inundation*, and *flow depth*. Run-up is the maximum vertical elevation of a point located on initially dry land that is inundated by the waves. Inundation is the maximum horizontal penetration of waves in the direction normal to the beach during the flooding. The data point characterizing water penetration can be based either on a watermark, such as a line of debris deposited either on land or in vegetation, or on eyewitness reports. The local flow depth is inferred from watermarks on walls or from debris left dangling from trees or posts. Figure 3 shows an example from Sri Lanka after the recent tsunami. In most cases, a record is kept of the precise time of measurements so they can be correlated with tide-gauge measurements of the still waterline at the time of the event.

Post-tsunami surveys also include geotechnical documentation of tsunami flows based on quantifications of the amount and direction of sedimentation or erosion and the nature of granular deposits. These data can be used for quantitative reconstructions of the currents involved in the inundation (Gelfenbaum and Jaffe, 2003).

Through interviews with eyewitnesses, we record the experiences of survivors, both to document the physical properties of the waves (e.g., their number, intervals in time, and the occurrence of down-draws, which leave no watermarks). Some eyewitnesses have volunteered

FIGURE 3 Debris dangling from trees is used as watermarks to infer flow depths. Hambandote, Sri Lanka, 2004.

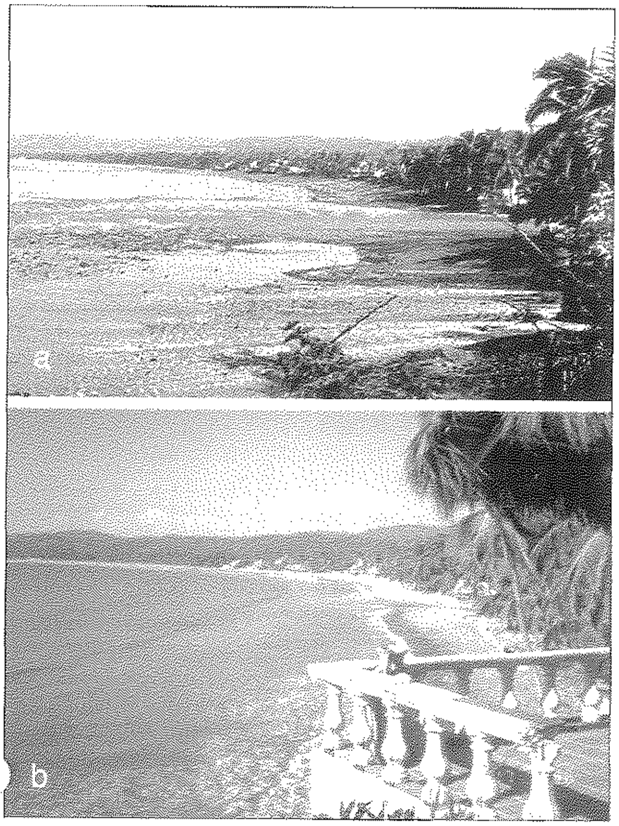

FIGURE 4 Photographs of the leading depression wave (shoreline recession) in Manzanillo, Mexico, in 1995, during (a) and after (b) the event.

dramatic photographs. Figure 4, for example, shows the shoreline recession following the 1995 Manzanillo tsunami. These photographs resolved the question of whether leading-depression N-waves were hydrodynamically stable (Tadepalli and Synolakis, 1996). Interviews also help document human responses (e.g., whether the tsunami was recognized and whether the area was evacuated before or upon arrival of the waves). Whenever possible, interviews with eyewitnesses are videotaped and permanently archived, after informed consent.

An important aspect of the work of ITSTs is outreach to local communities. Working closely with community leaders, local teachers, nongovernmental organizations, or United Nations authorities, we hold meetings in town halls, churches, schools, and hospitals, and we make presentations to local populations. Figure 5 shows a meeting in Vanuatu during the 1999 survey. During recent field surveys, meetings were held in Indonesia, Sri Lanka, Maldives, Kenya, Somalia, and possibly elsewhere. In a more casual way, ITSTs talk continuously with groups of residents who simply congregate around the scientists.

Not surprisingly, we have found considerable differences in sensitivity to tsunami hazards among populations of various regions. In the most earthquake-prone areas, such as the coast of Peru, local residents feel many earthquakes every year, and most of them have been or will be exposed to a perceptible tsunami in their lifetimes. As a result, the concept of tsunami hazard is passed along by ancestral tradition, and people are well educated in this respect; self-evacuation upon noticing anomalous behavior of the sea is a well developed reflex. Evacuation contributed significantly to the relatively low death toll from the 1999 and 2001 Peru tsunamis (Okal et al., 2002).

ITST presentations stress three fundamental facts regarding tsunamis and their mitigation: (1) tsunamis are natural phenomena, part of Earth's normal geological processes, and they do and will recur; (2) any local earthquake felt strongly enough to disrupt people's activities could produce significant changes in sea level and should dictate the evacuation of low-lying areas; and (3) any withdrawal of the sea is a harbinger of the destructive return of an inundating wave and should trigger an immediate evacuation of the beaches. Based on local conditions, we suggest guidelines for choosing evacuation areas and emphasize the need for vigilance for several hours, because the overall duration of a tsunami cannot be safely predicted from the first arrivals. We also distribute pamphlets, if possible in local languages, summarizing tsunami hazards and simple mitigation guidelines. To local government and civil defense authorities, we stress the importance of sensible controls of development in low-lying areas and

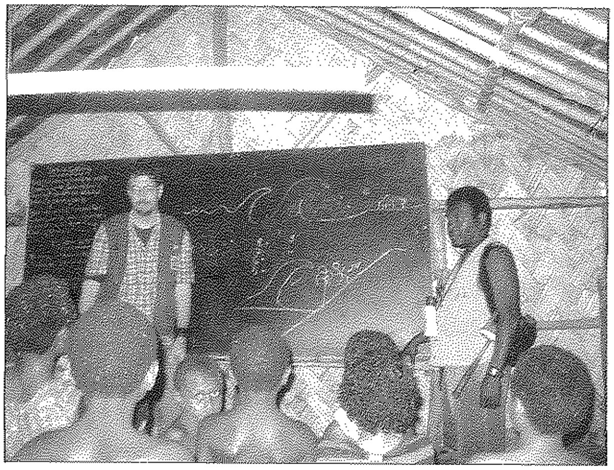

FIGURE 5 Photograph from Vanuatu showing eyewitness interviews and public outreach meeting.

of educating people about tsunami hazards through various exercises, such as yearly drills like the ones conducted in Japan and Peru.

On a more formal level, ITSTs have enthusiastically invited the participation of scientists from the affected countries not only to provide them with *in situ* training during and after the survey, but also to establish a basis for closer international cooperation. Local scientists also contribute regularly to data analyses and are joint authors of most publications resulting from field surveys.

Progress to Date

Based on pre-Sumatran events, significant advances were made in numerical codes for predicting tsunami evolution, and, indeed, most inundation maps in the United States are based on codes that have been validated by large-scale laboratory experiments and field data. Thus, NOAA-PMEL is now able to forecast tsunamis in real time and predict inundations with tested numerical codes. Leading depression N-waves have replaced solitary waves as the prevailing paradigm for theoretical analyses of tsunamis. Based on large-scale experiments of moving blocks, direct numerical simulations (DNSs) have been done using the Navier-Stokes equations of landslide generation and run-up, at least for laboratory-scale models (Liu et al., 2005b). However, using hydrodynamic inversion to infer seafloor motion from run-up or inundation remains largely unexplored.

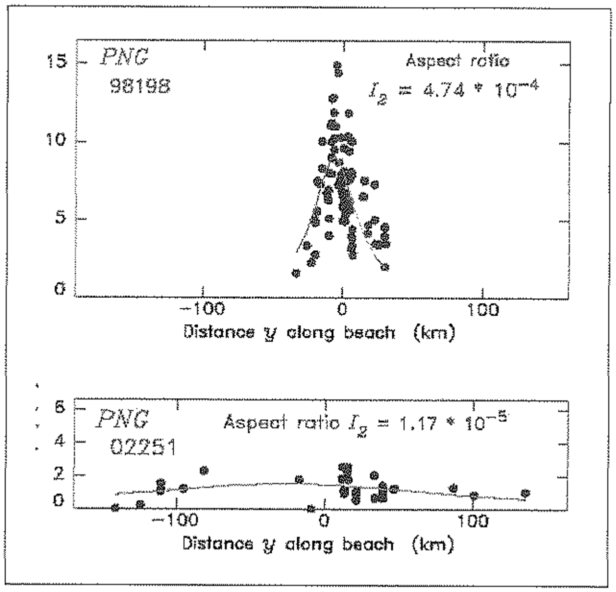

FIGURE 6 Comparison of run-up distribution in the long-shore direction for the 1998 Papua New Guinea landslide tsunami and the 2002 Papua New Guinea tectonic tsunami.

Based on differences between the run-up distribution in the long-shore direction of the Papua New Guinea tsunamis in 2002 and 1998 (Figure 6), Okal and Synolakis (2004) inferred that data sets of run-up amplitudes in the near field can be used to identify the source (dislocation or landslide) of a tsunami. They proposed that two dimensionless quantities ($I_1 = b/\otimes\upsilon$ and $I_2 = b/a$) behave as invariants, characteristic of the class of tsunami source (dislocation or landslide) but largely independent of the exact parameters describing these sources. They argued that one measure of the maximum run-up, b, should be principally controlled by the slip on the fault, $\otimes\upsilon$; the long-shore extent, a, of the inundation should reflect the lateral extent of the source. Noting the fundamentally different distribution fields of underwater deformation for dislocations and landslides, and particularly that the strain release in an earthquake is limited by the strength of crustal rocks, Okal and Synolakis (2004) showed that I_2 (as well as I_1 when $\otimes\upsilon$ is sufficiently well known) can be used as a discriminator of the nature of a tsunami source. A simple rule of thumb is that dislocation sources cannot have aspect ratios, I_2, greater than 10^{-4}. The analysis confirms the widely known but unpublished Plafker rule, which suggests that the run-up is never more than twice the slip, except in areas where extreme coastal steepness contributes to tsunami evolution (Plafker, 1997).

The methodology outlined above has been extended to study older events with triggers and unusually large tsunamis that have remained vexing mysteries, notably the Unimak, Aleutian Islands, tsunami of April 1, 1946 ($M_0 = 9 \times 10^{28}$ dyne-cm), and the Amorgos, Greece, tsunami of July 9, 1956 ($M_0 = 5 \times 10^{27}$ dyne-cm) (Okal et al., 2002).

Sumatra, Indonesia, December 26, 2004

The Sumatran earthquake and tsunami, which are feared to have caused more than 230,000 deaths, struck on December 26, 2004. The moment estimate ($M_0 = 1.3 \times 10^{30}$ dyne-cm), based on the measurement of split modes of free oscillations of Earth, is about three times larger than the 4×10^{29} dyne-cm measured from traditional long-period surface waves. Thus, the Sumatran earthquake was the second largest ever instrumentally reported, larger than the 1964 Alaskan event ($M_0 = 8.2 \times 10^{29}$ dyne-cm), but smaller than the 1960 Chilean earthquake ($M_0 > 2 \times 10^{30}$ dyne-cm), assuming their reported moments reflect their true size (Stein and Okal, 2005).

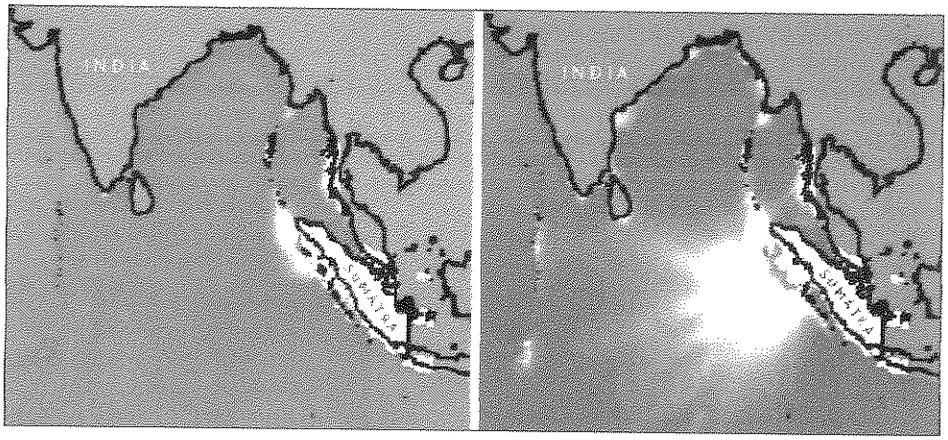

FIGURE 7 *Maps of maximum wave heights during the March 28, 2005, event, showing the effect of the islands on Nias and Simeulue off Sumatra. Without the islands, the simulations suggest the tsunami would have been much larger, underscoring the need for direct tsunami detection.*

In the Sumatran earthquake, the location of the slow slip is still uncertain, but a likely explanation is that it occurred over the entire 1,200-kilometer length of the rupture zone, as suggested by aftershocks. The southern third was probably a region of faster slip, and the rupture moved slower as it moved northward. The tsunami run-up in the near field on Sumatra is 25 to 30 meters, which implies a slip of 12 to 15 meters, by the rule of thumb that run-up does not usually exceed twice the fault slip.

An interesting question is whether the slow slip contributed to the tsunami excitation. This possibility is suggested by the successful simulations of the amplitude of the tsunami on the high seas, as detected by the JASON satellite, using the MOST code (Titov and Synolakis, 1998) and a source that includes the northern segment (V. Titov and D. Arcas, research scientists, NOAA-PMEL, personal communication).

Stein and Okal (2005) argued that, if the entire aftershock zone has already slipped significantly, there is no immediate danger of a large tsunami being generated by slip on this segment of the plate boundary; however, the danger of a great earthquake to the south remains. Their conjecture was borne out during the March 28, 2005, event, which indeed ruptured to the south but caused no significant tsunami in the far field, possibly because of the presence of two islands off Sumatra (Figure 7) that limited tsunamigenesis, as reported by Arcas and Synolakis (Kerr, 2005).

With satellite imagery, we can now make unprecedented comparisons of an area before and after an inundation. Using geographic information systems (GIS) layers with existing topographic maps and satellite images of Banda Aceh, Borrero (2005) was able to locate precisely the inundation and infer flow directions and inundation heights (Figure 8).

Lessons Learned and Not Learned

In the aftermath of the horrific tsunami of December 2004, many attempts will be made to place blame or quickly "fix" problems (Synolakis, 2004). We will not attempt such a deconstructionism here, nor comment on what, if anything, the four warning centers in the Pacific might have done differently, other than to note that they had no operational responsibility in the Indian Ocean. Clearly, the evacuation warnings following the March 28, 2005, event (just three months later) showed that nations in the Indian Ocean are more prepared now, at least to issue evacuation warnings. But this is only a start. The evolving ad hoc Indian Ocean tsunami warning system must avoid recommending unnecessary evacuations or risk losing the confidence of coastal populations.

The images from Sri Lanka, India, and Thailand that have filled our television screens—and the descriptions by survivors—are all too familiar, at least to those of us who have conducted tsunami field surveys. They reminded us of Nicaragua and Flores in 1992, East Java in 1994, Irian Jaya in 1996, Biak in 1996, Papua New Guinea in 1998, and Vanuatu in 1999, countries with similar landscapes and coastal construction.

The responses of some local residents and tourists in the great Sumatran tsunami, however, were not familiar. In one report, swimmers approaching the beach felt the current associated with the leading depression wave but hesitated to get out of the water because of the "noise" and the fear that if there was an earthquake they would be safer away from buildings. They had to be told by tourists from Japan—where an understanding of tsunamis is now almost hard-wired into the genes—to run to high ground. In Phuket, many pictures show tourists casually watching the onslaught of the tsunami within 100 meters or less of the coastline, and in Sri Lanka tourists and locals rushed to explore the exposed seafloor after the leading depression wave receded. Undoubtedly most of them perished. Obviously, neither tsunami folklore, nor pictures of the tsunami in Manzanillo had reached the public worldwide.

In another report, vacationers spending the day on Phi Phi Island in Thailand were taken back to Phuket one hour after the event began. As we learned from the 1960 Chilean and 1993 Okushiri tsunamis, waves can persist for several hours. Thus, transporting tourists back to the hazard zone was nothing less than grossly irresponsible.

Contrast these reactions with those of the inhabitants of Vanuatu in 1999. In Baie Martelle, a rather pristine enclave with no electricity or running water, the locals watch television once a week when a pick-up truck with a satellite dish, a VCR, and a TV stops by their village. Only months earlier, the residents had watched a UNESCO video of a tsunami. Thus, when they felt the ground shake during the earthquake, they ran to a nearby hill. The tsunami swept through, at night, razing the village to the ground, but only 1 percent (5 people) of the 500 inhabitants died.

Consider what was learned from the 1992 Nicaraguan tsunami, where the damage was extensive in El Transito but less so in adjacent Playa Hermosa because of an opening in the reef fronting most of the central coast of Nicaragua. In El Transito, the opening was about 20 meters wide, allowing for easy navigation to the beach; hence the rapid development of El Transito as a fishing village. When the tsunami hit, the wave funneled through and inundated the region fronting the opening, which, sadly, was where most of the human activity was concentrated.

At Aonae, Japan, during the 1993 tsunami, a manmade sand dune and about 50 concrete dolos (wave protectors) channeled the tsunami into the populated portions of the town and protected the unpopulated areas. As Liu et al. (2005a) report, in Sri Lanka, the "Sumudra Devi," a passenger train out of Colombo, was derailed and overturned by the tsunami almost halfway between Galle and Colombo killing more than 1,000 people. In the immediate fronting area, there had been significant coral mining related to tourism development, and the reef that might have protected that area was reported to have suffered large losses. Tsunami run-up in the area was nearly 8 meters; compare this to 10 meters in El Transito, where about 100 people died.

Consider, too, the consequences of poor land use. The Papua New Guinea tsunami in 1998 is perhaps best known among scientists because of its landslide source (Synolakis et al., 2002). In numerous documentaries produced since then, Sissano Lagoon has become infamous for its death toll and its serene but deadly topography. Villagers lived on a narrow sand spit sandwiched between the Bismark Sea on the north and Sissano Lagoon on the south. Once the tsunami hit, there were no escape routes. The wave overran the sand spit resembling a classic open-channel flow over a sill. Similar conclusions had been drawn from Pancer in Java during the 1994 East Javan tsunami. Although scientists had repeatedly warned that such locations in tsunami-prone areas were death traps, thousands of people were killed in December in south Sri Lanka where many locations resemble Sissano. For example, in Hambandote, hundreds of buses, many allegedly carrying passengers, were reportedly swept into the lagoon behind the town. Some were still visible there when the ITST arrived (Figure 9).

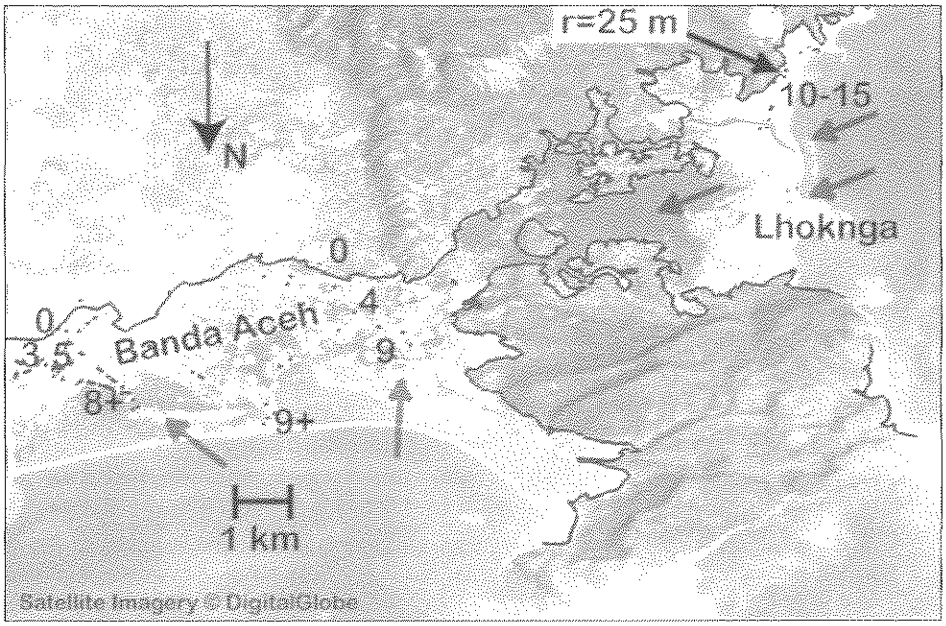

FIGURE 8 Satellite images superposed on inundation measurements show the direction of the tsunami attack in Banda Aceh.

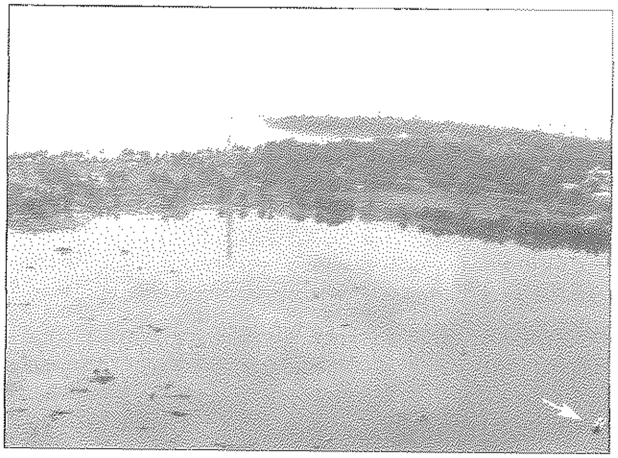

FIGURE 9 Photograph of Hambandote, Sri Lanka, showing an area sandwiched between the ocean and a lagoon. Note the bus, lower right.

Consider the response of the town of Seaside, Oregon, which has two sand spits sandwiched between the Pacific Ocean and the mainland. Based on inundation maps, which have been available for several years, and probabilistic inundation maps at 10-meter resolution, which are in the final stages of production, emergency preparedness measures have been undertaken to ensure that the people of Seaside and other Pacific towns are well informed and, hopefully, tsunami-ready.

In the 1994 East Java and 1996 Peru tsunamis, it had been observed that coastal dunes limited tsunami penetration, although no settlements were located in those specific locales. Kanoglu and Synolakis (1998) showed analytically that the last topographic slope encountered by long waves as they attack coastal topography has a noticeable effect on run-up. Yet, in Yala, Sri Lanka, a resort hotel had removed some of the dune seaward of the hotel to improve the view. In the December tsunami, the hotel was razed to the ground, and substantially higher water and greater damage were found on the hotel grounds than in neighboring areas located behind unaltered dunes. In essence, by removing some of the natural coastal protection in a localized area, a conduit was created through which the tsunami energy could flow.

As was observed during the 1992 Flores tsunami, low-lying coastlines are particularly vulnerable to tsunami attacks. When inundation maps were made in California, Eisner et al. (2001) observed that areas, such as Seal Beach, that were flooded during El Niño events also had the longest inundation distances in cyber-tsunamis. Areas where a tsunami can attack from two sides are prone to severe inundation, as was observed in 1994 in East Java and in 1996 in both Biak and Peru. Although the Great Sumatran earthquake was the fifth to hit Indonesia in 13 years, the population was unprepared and was decimated in the low-lying area between Banda Aceh and Longhka.

All over the Indian Ocean, observations of tsunami damage were similar. In numerous locations in Sri Lanka, churches and Buddhist temples were left standing. Closer to the beach in Aceh, mosques were the only structures standing in the devastated wasteland of coastal areas. In both locales, residents credited divine intervention; but places of worship are constructed "to a higher standard" than surrounding non-engineered buildings (Figure 10).

Few people knew that they should "evacuate vertically" to the second floor of these structures. In a tragic incident in Banda Aceh, a family fled its well designed, two-story villa, fearing that the building would collapse. However, the villa withstood the strong shaking unscathed. As the tsunami swept through minutes later, the father and one child died; the mother and the other child managed to climb to safety. Even in Vilufushi, the most severely impacted atoll in the Maldivian archipelago, the local school and city hall, both two-story structures, survived undamaged. People who took refuge in their own one-story houses perished. In these cases, vertical evacuation was the only choice. Sadly, the practice in Hawaii and Japan of vertical evacuation, which is often highlighted in TV documentaries, was not known to the victims.

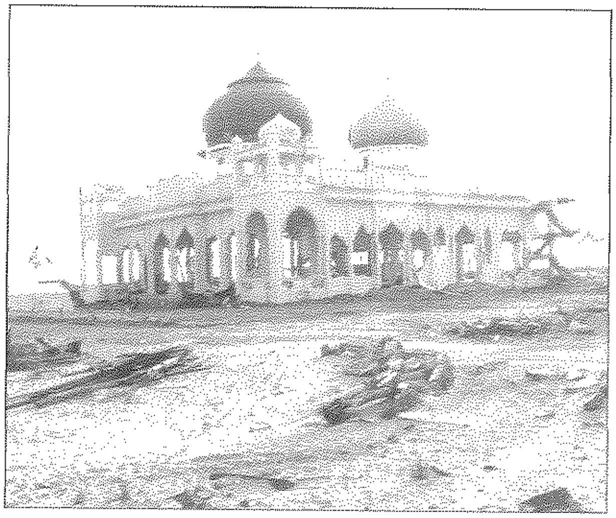

FIGURE 10 Photograph of a mosque in Banda Aceh showing that well engineered buildings survived the devastation.

The absence of official emergency responses had disastrous consequences. For example, neither India's storm-warning experience nor its sophisticated seismic networks led to warnings being issued on December 26, even after the tsunami had struck the Andaman and Nicobar Islands about two hours before hitting the Indian mainland and Sri Lanka (Synolakis, 2005). Allegedly, communications links had survived in Port Blair in the Andaman Islands, not to mention nearby air force and navy bases. Some have argued that as many as 40,000 people might have been saved if they had been warned.

The first tsunami forecast based on real-time computation was made in November 2003.

Contrast the lack of response to the real-time tsunami forecast by NOAA-PMEL during the tsunami on November 17, 2003. Based on a single reading off a NOAA tsunameter in the north Pacific, Titov et al. (2005) scaled their pre-computed scenario event that most closely matched the parent earthquake to evaluate the height of the leading wave off Hilo, Hawaii, and proceeded with a real-time computation that resulted in the first tsunami forecast.

There were some glimmers of hope last December. In the Maldives, after Malle had been hit, the Ministry of Atolls warned the outer islands of a "freak" wave approaching about 15 minutes before the tsunami arrived. As a result, some villagers were able to evacuate towards the centers of the small islands and were not exposed to the full fury of the advancing wave at the shoreline. In the yacht harbor in Langawi, Malaysia, once reports of a big wave hitting Aceh began arriving on short-wave radio, some mariners instinctively sailed their yachts to deeper water outside the marina. Anecdotal reports—too numerous to dismiss—suggest that some upscale hotels in Phuket evacuated guests to upper floors once the earthquake had been felt. In Sri Lanka, the ITST heard at least one report that a hotel in the south, warned by its sister hotel in Tricomalle in the east of a freak wave approaching, followed its standard evacuation plan for storm waves. Another hotel in the vicinity evacuated guests to the second floor after the first wave hit, again following pre-existing storm evacuation plans. Even though the second wave was catastrophic, some lives were spared. If one believes the hotel reports, no guests died in either hotel. Even in Aceh, some who ran from the beach when the first wave hit were spared, but we may never know how many who ran died. The very topography of Banda Aceh made it very difficult to escape the tsunami, which penetrated almost unhindered up to 3 kilometers inland.

Everyone now realizes the urgent need for a worldwide educational effort on tsunami hazards. By some accounts, about 1,000 Swedes died in Thailand, as well as many other tourists visiting from areas where tsunamis are unknown. Thus, educating local populations at risk will not be enough. In an era of global citizenship, people visit remote locales, often without reading up on the geological history of their destinations. It is important that everyone be able to identify the precursors of a tsunami and know they should head for high ground or inland as quickly as possible. If this is not possible, they should know to go to the upper floor of a well built structure that has survived the earthquake.

The Indian Ocean Today

Clearly, it is too soon to know if Indian Ocean populations are better prepared today than they were last December. Some signs are encouraging, but others are less so. The Pacific Tsunami Warning Center covers only the Pacific Ocean and has no tsunameters to verify tsunamigenesis in the Indian Ocean. NOAA plans to expand its network of tsunameters around the Pacific and to transfer NOAA-PMEL real-time capabilities for tsunami forecasting to the warning centers. In the United States and several other nations on the Pacific Rim, inundation maps have been developed for planning evacuations, standards and guidelines for tsunami-resilient communities have been established, and standards for the construction of structures are under development.

UNESCO's Intergovernmental Oceanographic Commission (IOC) has held several meetings, culminating in a meeting in Paris in March 2005, with the objective of setting up an Indian Ocean tsunami warning center (IOTWC). One welcome conclusion of the meeting was an acknowledgement of the need for global educational efforts, even before specific mitigation technologies are implemented and an IOTWC is in place.

The UNESCO meeting provided an opportunity to launch an IOTWC, and UNESCO worked hard to present existing warning and mitigation technologies. Surprisingly, however, countries with no experience in long-wave modeling or tsunami hazard mitigation announced that they intend to build expensive end-to-end systems from the ground up. The lack of experience with tsunamis even led some in the earth-science disciplines to present an unbalanced assessment of the value of their tools for tsunami hazards mitigation, leading one country to suggest it would "protect" communities of more than 10,000 people with broadband seismometers. The tidal-gauge community suggested that an expanded tide-gauge network could provide reliable warnings, even though tidal gauges are most often located in protected areas inside harbors and bays. Once a tsunami hits, tide gauges measure the response in the harbor or bay, but the amplitudes they record, although they confirm that a tsunami has been generated, provide little usable information for forecasting wave height in other locations.

The limitations of some of these approaches were evident during the March 28, 2005, event, the eighth largest earthquake ever reported. The earthquake was located and the magnitude determined within 15 minutes using the worldwide seismic network, and a nondestructive tsunami was detected by tide gauges. Based on those readings, most nations issued evacuation warnings, and emergency managers everywhere waited for several hours to be sure there was no tsunami before they issued the all-clear signal. Most experts agree that seismic observations and tidal gauges are not enough for predicting tsunamis. Reliable prediction will require a network of real-time accurate tsunami sensors in the deep ocean. Combined with public education, these are still our best tools for averting the next Indian Ocean tsunami disaster.

References

Borrero, J.C. 2005. GIS measurements of the inundation in Banda Aceh. Nature, in press.

Eisner, R., J.B. Borrero, and C.E. Synolakis. 2001. Inundation Maps for the State of California. In Proceedings of the International Tsunami Symposium, Seattle, Washington. Available online at: *http://www.pmel.noaa.gov/its2001*.

Gelfenbaum, G., and B. Jaffe. 2003. Erosion and sedimentation from the July 17, 1998, Papua New Guinea tsunami. Pure and Applied Geophysics 160(10-11): 1969–1999.

Kanoglu, U., and C.E. Synolakis. 1998. Long wave runup on piecewise linear topographies. Journal of Fluid Mechanics 374(November): 1–28.

Kerr, R.A. 2005. Model shows islands muted tsunami after latest Indonesian quake. Science 308(5720): 341.

Liu, P.L.-F., C.E. Synolakis, and H. Yeh. 1991. Impressions from the First International Workshop on Long-Wave Runup. Journal of Fluid Mechanics 229: 675–688.

Liu, P.L-F., P. Lynett, J. Fernando, B. Jaffe, H. Fritz, B. Higman, C.E. Synolakis, R. Morton, and J. Goff. 2005a. Observations by the International Tsunami Survey Team in Sri Lanka. Science, in press.

Liu, P.L-F., T.R. Wu, F. Raichlen, J. Borrero, and C.E. Synolakis. 2005b. Runup and rundown from a three dimensional sliding mass. Journal of Fluid Mechanics, in press.

Okal, E.A., and C.E. Synolakis. 2004. Source discriminants for near-field tsunamis. Geophysical Journal International 158(3): 899–912.

Okal, E.A., L. Dengler, S. Araya, J.C. Borrero, B.M. Gomer, S.-i. Koshimura, G. Laos, D. Olcese, F.M. Ortiz, and M. Swensson. 2002. A field survey of the Camana, Peru, tsunami of June 23, 2001. Seismological Research Letters 73(6): 907–920.

Plafker, G. 1997. Catastrophic tsunami generated by submarine slides and backarc thrusting during the 1992 earthquake on eastern Flores I., Indonesia. Geological Society of America, Cordilleran Section, 93rd Annual Meeting 29(5): 57.

Stein S., and E.O. Okal. 2005. Speed and size of Sumatran Earthquake. Nature 434: 581–582.

Synolakis, C.E. 2004. Why There Was No Warning? Editorial. *Wall Street Journal*, December 29, 2004.

Synolakis, C.E., J.-P. Bardet, J.C. Borrero, H.L. Davies, E.A. Okal, E.A. Silver, S. Sweet, and D.R. Tappin. 2002. The slump origin of the 1998 Papua New Guinea tsunami. Proceedings of the Royal Society of London A 458(APR): 763–790.

Synolakis, C.E. 2004. Tsunami and Seiche. Pp. 9-1 to 9-90 in Earthquake Engineering Handbook, edited by W.F. Chen and C. Scawthorn. Washington, D.C.: CRC Press.

Synolakis, C.E. 2005. India must cooperate on a tsunami warning system. Nature 434: 17–18.

Tadepalli, S., and C.E. Synolakis. 1996. Model for the leading waves of tsunamis. Physical Review Letters 77(10): 2141–2145.

Titov, V.V., and C.E. Synalokis. 1998. Numerical modeling of tidal wave runup. Journal of Waterways, Port, Coastal and Ocean Engineering 124(4): 157–171.

Titov, V.V., F.I. González, E.M. Bernard, M.C. Eble, H.O. Mofjeld, J.C. Newman, and A.J. Venturato. 2005. Real-time tsunami forecasting: challenges and solutions. Natural Hazards 35(1): 45–58.