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The Asian Tsunami's Havoc and Death Toll: Nature's Wrath or Human Shortsightedness?

Zvy Dubinsky[1], Osnat Chomsky[2] and Steve Brenner[3]
[1]*The Mina & Everard Goodman Faculty of Life Sciences Bar-Ilan University, Ramat-Gan 52900*
[2]*National Institute of Oceanography, Israel Oceanographic and Limnological Research, Tel Shikmona, P.O. Box 8030, Haifa 31080*
[3]*Department of Geography and Environment, Bar-Ilan University Ramat-Gan 52900*
Israel

1. Introduction

The unprecedented devastation caused by the December 2004 tsunami (Reuters, 2005) was followed by environmentalists' claims that the human toll and overall impact were aggravated by disregard for conservation of coral reefs and mangrove forests (Channel News Asia, 2005; Cripps, 2005; Mangrove Action Project, 2005). Corals surround tropical shorelines (Spalding et al., 2001) and beyond them, on land, grow, in most cases, dense belts of mangroves (Chapman, 1977). These twin barriers are thought to protect shorelines from waves and may be capable of mitigating tsunami impact (Fig. 1). According to reports in the mass media, reefs and mangroves sheltered people from the tsunami's impact, whereas in the hardest hit areas in terms of human casualties, coral reefs and mangroves had been removed in order to make room for shrimp and fish mariculture (Kaban, 2005). Here we present an attempt to evaluate the potential of the combination of coral reefs and mangroves to attenuate tsunamis, and validate the claims regarding the protective function of reefs and mangroves. Special attention will be given to the extent of the recent destruction of reef and coral ecosystems in the region afflicted by the tsunami, and the importance of their conservation and of remediation and rehabilitation efforts (Kaban, 2005).
Tsunamis have ravaged coastal communities since the earliest extant myths and written records (Table 1). The most prominent among these was the one generated by the volcanic eruption of Thera (Santorini), thought to have wiped out the Minoan civilization (Galanopoulos, 1960; Pararas-Carayannis, 1973), and sending survivors as far east as Canaan, where they settled as the biblical "Sea people" or Philistines, who competed with the Hebrews for what was to become the "Holy Land". There are historical records of tsunamis with death tolls ranging from no victims to estimates of over 300,000 in the last one (Table 1).
The Sumatra tsunami of December 2004 was the first to be witnessed via television in virtually every home, bringing the destructive potential of oceanic waves to unprecedented public awareness. In the wake of this tsunami, there have been several reports in the mass media regarding the reduction in the human death toll and overall destruction in areas that

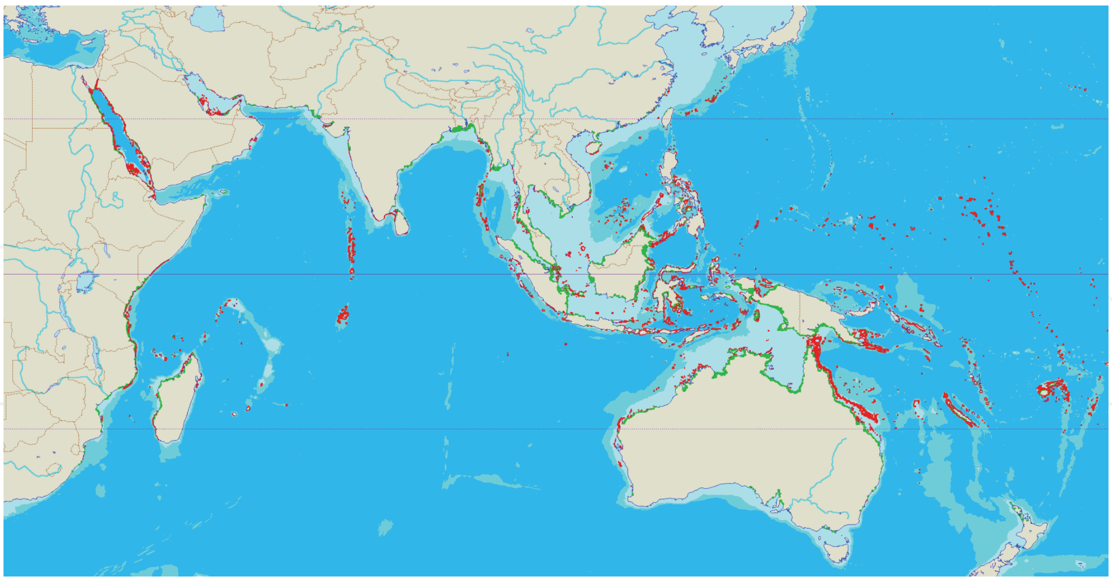

Fig. 1. World distribution of coral reefs and mangroves. Key: Coral = red, Mangrove = green
After www.unep-wcmc.org/marine/data/coral_mangrove/marine_maps_main.html

Principal areas	Magnitude	Year	Fatalities
Crete-Santorini, Ancient Greece	?	1600 ± 50 BC	~100,000
Tokaido-Nankaido, Japan	8.4	1707	30,000
Portugal, Morocco	8.5	1755	60,000
Ryukyu Trench, Japan	7.4	1771	13,486
South China Sea	7.0	1782	40,000
Kyushu Island, Japan	6.4	1792	15,030
Sumatra region	8.7	1833	36,000
Sumatra region	8.5	1861	Thousands
Northern Chile	8.5	1868	25,674
Krakatau, Indonesia	?	1883	36,500
Sanriku, Japan	7.6	1896	26,360
Tokyo	8.3	1923	140,000
Northeastern coast, Japan	8.9	1933	3,064
Japan	?	1944	1,251
Shikoku, Japan	8.0	1946	1,330
Fukui, western Japan	7.1	1948	3,769
Hokkaido	8.2	1952	8,233
Kamchatka Peninsula, Russia	8.2	1952	Considerable loss of life
Chile, Hawaii, Japan, and the Philippines	9.5	1960	500-2,300
Philippines		1976	5,000
Kobe, Western Japan	7.2	1995	1,800
Papua New Guinea	7.1	1998	3,000
Indian Ocean	9.0	December 26, 2004	305,276

Table 1. Historical records of major tsunamis

were sheltered from the wave by intact reefs and mangrove belts (Chapman, 1977; Spalding et al., 2001; Channel News Asia, 2005; Cripps, 2005; Mangrove Action Project, 2005). These reports were eventually substantiated by a field survey of Sri Lankan mangrove sites, whose destruction increased tsunami damage (Dahdouh-Guebas et al., 2005).

The global distributions of coral reefs and mangroves are almost identical: they skirt shorelines between 30 degrees north and south of the equator. These ecosystems are linked by complementary environmental requirements, and also by interactions among physical, chemical, and biological processes. Furthermore, the destruction of one endangers and eventually destroys the other (Kuhlman, 1998).

Coral reefs are biogenic, calcium carbonate, marine structures, based on the symbiosis between corals and unicellular microalgae, the zooxanthellae (Brandt, 1883). The algae contribute high-energy photosynthate whereas the host animal, an avid predator on zooplankton, provides the symbionts with metabolic wastes rich in nitrogen and phosphorus. It is this association that allows corals to outcompete seaweeds in the warm, transparent, nutrient-poor "blue deserts" of the tropics. Coral reefs extend over thousands of kilometers from the surface down to 100 m, usually decreasing in vigor below 30 m. This depth distribution is dictated by the exponential decrease in underwater light, upon which the algae depend (Achituv & Dubinsky, 1990). In recent decades, rising ocean temperatures have been implicated in bleaching events in which corals lose their symbionts and die (Hoegh-Guldberg, 2004). In addition, terrigenous nutrients and sediments disrupt the host–symbiont association, leading to the replacement of corals by other benthic communities. Over 70% of the world's reefs have been destroyed or are in great danger (Wilkinson, 2002), (Fig. 2). In the areas worst hit by the recent tsunami, the overriding cause of reef destruction (Fig. 3) was the spread of shrimp ponds and other mariculture enterprises, as well as tourist recreational facilities.

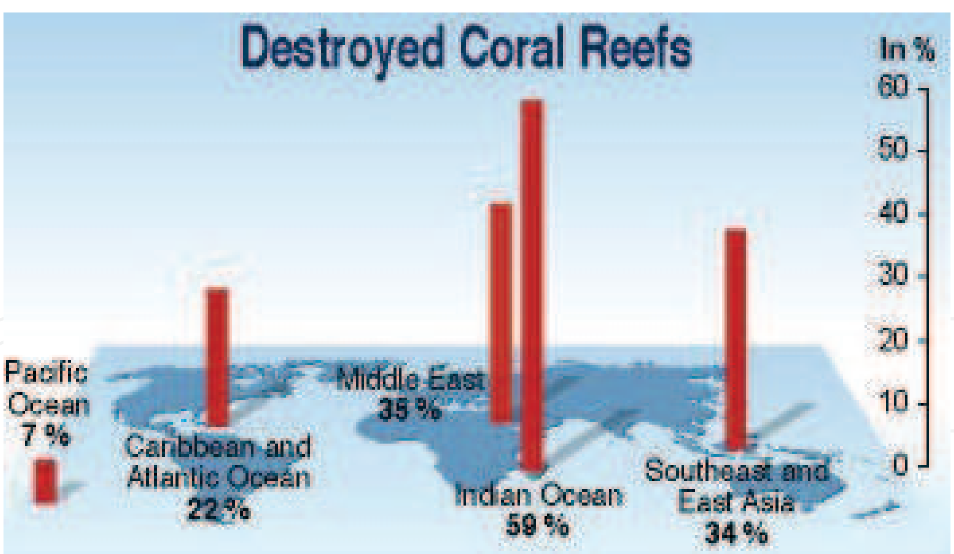

Fig. 2. Global distribution of coral reef destruction
www.unep.org/ vitalwater/marine.htm

Mangroves dominate 75% of tropical coastlines between 25° N and 25° S (Duke et al., 2002). These coastal forests are made up of some forty species of trees and shrubs adapted to life in high-salinity waters, where they are rooted in anaerobic mud. They depend on aerial roots, or pneumatophores, supplying their roots with oxygen (Hanagata et al., 1999). The

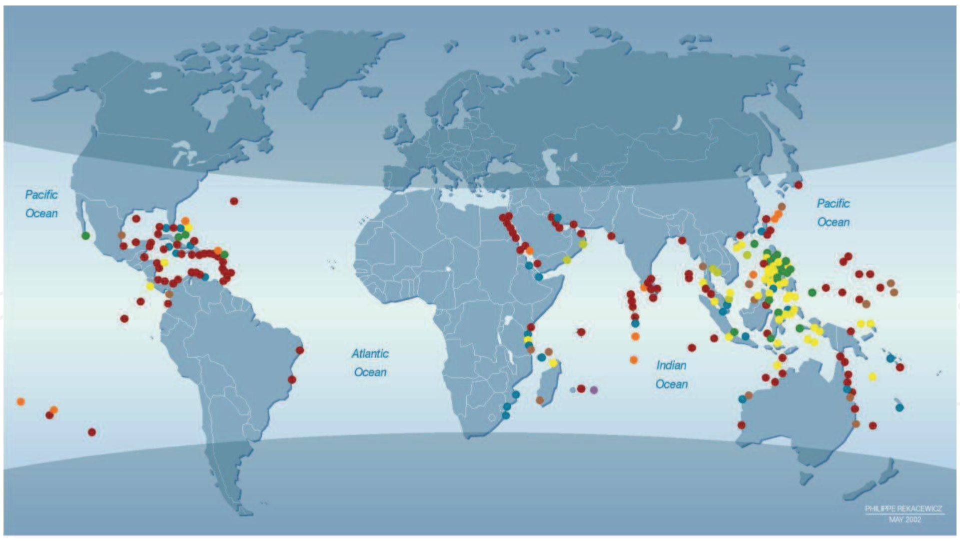

Fig. 3. Main causes for reef destruction: tourism; poison fishing; overexploitation; sedimentation; coral harvesting; dynamite fishing; pollution
After Bryant et al., Reefs at Risk; a Map-Based Indicator tom the World's Coral Reefs, World Resources Institute (WRI), Washington DC, 1998

mechanisms allowing them to retain water against the osmotic gradient posed by seawater still elude full understanding (Zimmermann et al., 2002). To increase chances of survival, in many mangrove species, fruits germinate while still connected to the mother plant, and when they fall off, they become planted in the soft soil (Hogarth, 1999). Mangrove forests may reach a width of several hundred meters and a height of up to 40 m.
Mangroves act as a filter, preventing sediment from reaching the reef and abrading the delicate coral tissues. They also absorb dissolved nutrients in runoff, forming a biofilter protecting reefs from eutrophication. Indeed, the destruction of mangroves has led to the death of adjacent reefs (Dubinsky & Stambler, 1996; Dahdouh-Guebas et al., 2005). In yet another recent study (Danielsen *et al.*, 2005) of the Cuddalore District in southeastern India based on satellite images validated by surveys on the ground, the authors also confirm the role of mangroves in attenuating tsunami waves and mitigating their destructive potential. Their data are in agreement with experiments, which have shown that 30 trees per 100 square meters suffice to dissipate most of a tsunami's energy (Hiraishi & Harada, 2003). More recently, Yanagisawa et al. (2009) used satellite images and field measurements to assess the damage of the mangrove forests caused by the 2004 Asian tsunami along a stretch of the coast of Thailand. They also used a numerical model to simulate the effects of the tsunami on the mangroves and the role of the mangroves in reducing the inundation depth and concluded that in addition to the density of the tree coverage, the tree stem diameter and the initial inundation depth are crucial parameters in determining the survival rate of the trees as well as the mangroves ability to reduce the inundation depth. The mangrove roots serve as the reef's nurseries, where juveniles of myriad reef creatures find shelter from predators. Coral reefs weaken surf, reducing the removal of soil and the uprooting of mangroves and their seedlings.
The human need for land, firewood, and material for construction has acerbated the global climate change-driven decline of corals (Buddemeier et al., 2004) and mangroves (Table 2). However, our burgeoning appetite for seafood, and human greed have probably been the driving force in recent decades behind the clearcutting of mangroves and their replacement,

as well as that of reefs, by various mariculture enterprises and recreational villages. In Southeast Asia, this destruction has led to losses of 70-90% of the reefs and mangroves (Wilkinson, 2002).

It is of great interest to explore the potential of the twin barriers, mangrove forests and coral reefs, to attenuate destructive waves and prevent disaster. We present here an initial attempt of physically modeling and evaluating the attenuation of tsunami waves by reefs and their further weakening by mangrove belts.

While it is clear that both the coral reefs and the mangroves play a role in reducing the devastating effects of tsunami run-up and inundation of the coastal area, most of the evidence has been anecdotal and taken from the mass media or from eyewitness reports. Furthermore, the primary measure of tsunami damage is the number of casualties, which may be more a function of land use and demographics than the force of the tsunami itself. Therefore, in order to quantitatively assess the potential mitigating effects of coral reefs and mangroves, we have conducted a series of simulations with an established wave model (Chen et al., 2000; Kennedy et al., 2000), which has been tested for a wide variety of surface wave types including tsunamis. The goal of our experiments is to demonstrate the role of the bulk properties of the combined coral reef – mangrove system as a barrier that can mitigate the potential damage of the tsunami by reducing the inundation depth. We do not consider or focus on the small scale details of the structure of the reef or the mangrove forest as was done in other studies (e.g., Yanagisawa et al., 2009).

2. Model description and setup

The model we have chosen is the fully nonlinear, Boussinesq surface wave model FUNWAVE (Chen et al., 2000; Kennedy et al., 2000) based on the work of Wei et al. (1995). FUNWAVE is capable of simulating waves in the open sea as well as in the nearshore zone, and has been tested extensively for a wide range of surface wave types, including tsunamis (Chen et al., 2000; Watts et al., 2003). The model is based on the shallow water equations which consist of equations for the conservation of mass (i.e., the free surface height) and the horizontal momentum with parameterizations added to account for frictional dissipation and wave breaking. Further details can be found in the references mentioned above. For this study we use the two dimensional version of the model.

Since our goal is to assess the potential role of coral reefs and mangroves in reducing the impact of tsunamis in general, rather than trying to simulate the specific details of the 2004 Asian tsunami, we focus on simulations of an idealized case, with bathymetry typical of an ocean basin, and initial conditions typical of a tsunami that might be induced by an earthquake of a magnitude 8-9 or more. The model domain consists of a 400-km-long by 200-km-wide channel. The bathymetry includes a 300-km-long abyssal plain with a constant depth of 4000 m, a 40-km-wide continental slope over which the seafloor rises to 200 m, followed by a continental shelf also 40 km wide. The beach above the mean water level continues with the same slope as the shelf until reaching an elevation of 25 m, remaining flat until the end of the domain. The bathymetry is uniform in the cross-channel direction, and a sponge zone is imposed along all four boundaries. The grid spacing is 250 m.

For all experiments, the initial free surface is level and at rest, except in the area of the earthquake. Here we assume that displacement takes the form of a 100-km-wide delta function in which half of the zone is lifted and half is depressed. The magnitude is similar to that estimated for the recent Sumatra tsunami, with instantaneous, initial upward and downward displacements of +7.2 m and –3.5 m, respectively (Yalciner et al., 2004).

Period covered	Loss, %	Region and country
	Africa	
To 1980s[a]	50	Angola
To 1980s	60	Ivory Coast
To 1980s	50	Gabon
To 1980s	70	Guinea-Bissau
1971-88	4	Kenya
To 1980s	60	Tanzania
	Latin America	
1983-90	-6 (gain)	Costa Rica
1983-90	8	El Salvador
1983-90	72	Guatemala
1970s to 1992	65	Mexico
1983-90	67	Panama
1982-92	25	Peru
	Asia	
To 1986	20	Brunei
To 1980s	55	Indonesia
To 1992-93	74	Malaysia
To 1992-93	75	Myanmar
To 1980s	78	Pakistan
1918 to 87-88	67	Philippines
To 1993	84	Thailand
To 1993	37	Vietnam
	Oceania	
To 1992-93	8	Papua New Guinea

[a] Unless otherwise stated, the decline is relative to the earliest pre-destruction records

Table 2. Mangrove loss in selected countries with available data from the World Resources Institute 1991, 2001 (Adeel & Pomeroy, 2002)

A coral reef can affect wave propagation and development by presenting an abrupt change in bathymetry and through increased bottom roughness. To model the former effect, at any grid point where a reef is present, the bottom depth is replaced by a step that rises to 1 m below the surface. This was done for the three grid lines between the 11 and 14 m isobaths. In FUNWAVE, wave energy dissipation is simulated by friction with the sea floor which is represented by a quadratic bottom drag formulation (i.e., a drag coefficient multiplied by the velocity magnitude and the relevant velocity component). The default value of the dimensionless, bottom drag coefficient is 0.001. To model the roughness effect, we arbitrarily assumed that the bottom drag coefficient at the reef grid points is the default value multiplied by a constant factor. A range of multiplicative factors between two and twenty was tested. The changes in the wave height over and beyond the reef were not overly sensitive to the values tested and, thus, we chose a factor of ten as representative.

Mangroves present a permeable obstacle through which the wave can continue to propagate, but the densely-packed roots and trees will lead to more rapid wave-energy dissipation. Here, too, we model this effect through an increase of the drag coefficient. Field studies of the impact of mangroves on short-period (wind) waves (Mazda et al., 1997) as well as wave tank models of tsunamis (Hiraishi & Harada, 2003) show that the increased rate of energy dissipation across mangrove or other tropical tree forests can be expressed as an equivalent drag coefficient that can be several orders of magnitude larger than usual. Other investigators studied the dependence of the drag coefficient as a function of the tree density for longer period waves. Thus for tidal scale flow Mazda et al. (2005) estimated the drag coefficient to be in the range of O(0.1) – O(10) while for a tsunami Teh et al. (2009) estimated values of O(1). Thus, in our simulations at grid points where mangroves are assumed to be present, we multiplied the default drag coefficient by a factor of 200, thus giving a value of 0.2 which is at the lower end of the values estimated by Mazda et al. (2005) and somewhat smaller than the values of Teh et al. (2009). The mangroves extend from a water depth of 2.5 m to a land elevation of 3.75 m, thereby covering a 6-grid-point, 1.5-km-wide coastal strip.

3. Model results

Here we present results from four simulations for our typical rectangular ocean basin with various combinations of fringing reefs and mangroves and an initial surface displacement representative of the recent Sumatra earthquake. The simulations are designated as: 1) NONE – a smooth, sandy bottom only; 2) REEF – with a 750 m wide reef in the form of a bathymetric step rising abruptly from 12 m to 1 m below the surface; 3) MANGROVE – with a 1.5 km wide mangrove forest centered on the still water coastline in which the bottom drag is significantly increased; and 4) BOTH – with a reef and a mangrove forest. The results are summarized in Figure 4, where we show the time records of virtual wave gauges located at four points along the centerline of our channel. The points are: (A) immediately seaward of the coral reef; (B) immediately behind the reef; (C) at the mean water level coastline, which is roughly midway through the mangrove; and (D) immediately landward of the mangrove.

At point A, there was a clear separation between the simulations with and without the reef as the primary wave approached and passed the station. Until minute 42, the NONE and MANGROVE curves were coincident as were the REEF and BOTH curves. In the two simulations with the reef, the shoaling effect of the reef led to a maximum wave height on the seaward side that was more than 40% larger than in the cases without the reef, i.e., 11.7 m and 8.3 m, respectively. As the secondary wave approached, the curves from the four simulations began to separate and fall into two new groups – with and without mangroves. The mangroves apparently reflected a certain amount of the wave energy back to the sea, thereby producing a higher secondary wave than in the no-mangrove cases. Behind the reef, at point B, the dissipating effect of the reef was evident. For the two simulations with the reef, the maximum primary wave height was reduced by 25%, reaching only 7.1 m as compared to 9.4 m for the two cases without the reef. Also, as at point A, the influence of wave energy reflection by the mangroves can be seen with the appearance of a significant secondary wave only in the two simulations that included the mangroves.

Point C is the mean still-water coastline. From here we began to see noticeable differences between the results of the simulations. Not surprisingly, the highest wave occurred in the NONE simulation. Based on additional simulations run without the reef and mangrove, we found that an important parameter that controls the extent of run up and inundation is the slope of the beach. However, since our interest here is to examine the role of the reef and the mangrove, we only present the results with the same bottom slope in all experiments. The

order of the maximum wave heights above-ground for the four simulations is 11.8 m, 9.8 m, 8.5 m, and 7.3 m for NONE, REEF, MANGROVE, and BOTH, respectively.
Finally, point D is located four grid points landward of the coast (one point past the mangrove). As at point C, the NONE simulation produced the highest wave, with a height of 8.4 m above-ground. The additional energy dissipation due to the reef reduced the wave height by 26%. In contrast, the mangrove forest was very effective in blocking most of the wave energy, leading to a 93% reduction in wave height. When both the reef and mangroves were included, the tsunami was completely attenuated and did not emerge from the forest. From our results, it is clear that while both coral reefs and mangroves contribute to mitigating the destruction caused by tsunamis, it is the latter that provide the most effective protection.

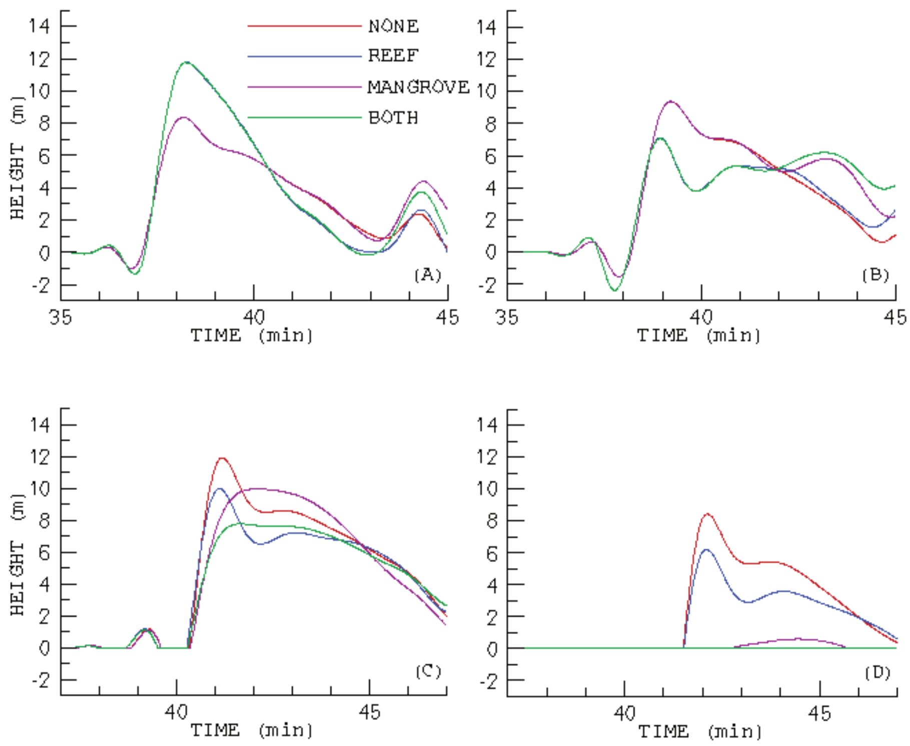

Fig. 4. Time series from wave gauges located at points (A) seaward of the reef, (B) immediately behind the reef, (C) still-water coastline, which is mid-way through the mangrove, and (D) immediately behind the mangrove. For the sea points (A) and (B), the values shown are the wave heights relative to the mean water level while for the land points (C) and (D), the values shown are the water levels relative to the land elevation. At point A, the curves for the primary wave for the NONE and MANGROVE cases are identical as are the curves for the REEF and BOTH cases. For the BOTH case the tsunami never reaches point D, beyond the mangrove, as indicated by the horizontal line

4. Conclusion

Based on our results and the results of other field and modeling studies, we can conclude with reasonable confidence that the numerous anecdotal media reports describing the protection afforded by intact coral reefs and mangrove belts from the 2004 Asian tsunami are most likely true. Indeed, the paired reef-mangrove belt can significantly reduce and, in some cases, totally dissipate tsunami-like wave energy, thereby reducing the destruction of property, and most importantly, greatly reducing the human death toll. In summary, the conservation of coral reefs and adjacent mangrove forests, the remediation of damaged ones, and the massive planting of new mangroves, will most likely contribute significantly to the reduction and, perhaps, prevention of destruction on the scale of the Sumatra tsunami, in addition to protecting shorelines and contributing to the preservation of our planet's vanishing biodiversity. The importance of preserving and planting mangrove forests is summarized in the post-tsunami document "The Tsunami and Coastal Wetlands – Recommendations for Action" (2005).

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Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.