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Coral reef ecosystems protect shore from high-energy waves under climate change scenarios

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Abstract Coral reefs and other coastal ecosystems such as seagrasses and mangroves are widely recognized to provide protection against the devastating effects of strong waves associated with tsunamis and storms. The predicted warming climate brings to fore the role of these ecosystems in providing protection against stronger typhoons that can result in more devastating waves of greater amplitude. We performed a model simulation of storm generated waves on a Philippine reef, which is located along the path of tropical storms, i.e., at least 10 typhoons on the average pass through the study site yearly. A model to simulate wave propagation was developed using Simulating Waves Nearshore (SWAN) and DELFT3D-WAVE computer simulation software. Scenarios involving local monsoonal wind forcing and storm conditions were simulated. In addition, as climate change may also result to increased relative sea level, a 0.3 m and 1 m rise in sea level scenarios were also used in the wave model simulations. Results showed that the extensive reef system in the site helped dissipate wave energy that in turn reduced wave run-up on land. A significant reduction in wave energy was observed in both climate change, i.e., stronger wind and higher sea level, and non-climate change scenarios. This present study was conducted in a reef whose coral cover is in excellent condition (i.e., 50 to 80% coral cover). Estimates of coral reef growth are in the same order of magnitude as estimates of relative sea level rise based on tide gauge and satellite altimeter data, thus it is possible that the role of reefs in attenuating wave energy may be maintained if coral reef growth can keep up with the change in sea level. Nonetheless, to maintain reef growth, it is imperative to manage coral reef ecosystems sustainably and to eliminate the stressors that are within human control. Minimizing activities such as illegal and destructive blast and poison fishing methods, pollution and siltation, is crucial to minimize the impacts of high-energy waves that may increase with climate change.

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1 Introduction

Present consensus among the experts on climate change suggests the inevitability of intense typhoons and sea level rise. Site-level determination of impacts and their magnitude however, remain to be elucidated (Burke and Maidens 2004; WRI 2009). This is a necessary step in order to formulate adaptation measures tailored to a given locality.

Because of its archipelagic nature, the Philippines is particularly vulnerable to increased sea level rise. Moreover, considering the location of the Philippines within the typhoon belt, the synergistic effects of sea level rise and waves that strong typhoons will bring, can generate wave run-up invading farther into the coast.

The typical response is to protect coastal communities by building defenses like seawalls. Seawalls may not sufficiently protect coastal inhabitants from strong typhoons but it will help minimize the damage. However, the cost of building these structures and maintaining them can be prohibitive. Seawalls are expensive to build; a kilometer will cost between USD 3.3 and 18.0 M (University of Liverpool 2009). Its lifespan will also depend on several factors including the geological characteristics of the shore, the degree of exposure, design and construction materials. In addition, attendant environment impacts must be considered before embarking on such measures.

Coral reefs, seagrass meadows, and mangrove forests are widely accepted to provide natural protection from typhoons and storm-generated wave surge. There is limited literature however, on the actual quantitative measure of the wave energy dissipation provided by coral reefs and associated coastal ecosystems (WRI 2009).

This study carried out wave simulation modeling taking into consideration the existence of reefs and other coastal features. The premise is that reefs provide protection to the coast from strong waves and that a rising sea level will diminish this protective function unless growth of the corals are ensured so that reef growth can catch up with increasing sea level. Different climate change scenarios wherein sea level and wave heights were increased to simulate the role of reefs in coastal wave energy dissipation during sea level rise and storm events, respectively. The sea level rise scenarios used were based on satellite altimetry data which show a linear trend east of the Philippine of about 9 mm yr^{-1} for the period October 1992 to July 2009 (http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/). Hulme and Sheard (1999) also projected an increase in sea level in the Philippines of 0.19–1.04 m by 2080 relative to mean sea level during 1961–1990. Such estimates do not take into account land subsidence or rise which, in some coastal areas (e.g. Manila), may dominate relative sea level rise (Rodolfo and Siringan 2006). Rahmsorf (2007) have shown that sea level rise projected by models may have underestimated the actual sea level rise since the 1990 by about 1 mm year^{-1}. based on reconstructions using tide gauge and satellite data

2 Methods

2.1 Wave energy

The focus of the study is the two barangays of Bagacay and Rizal of the Municipality of Sorsogon, Philippines (Fig. 1). The two sites both face the Pacific Ocean but with different orientation: Bagacay faces southeast and Rizal northeast. Like the other areas of eastern Sorsogon, there are prominent reef and mangrove areas surrounding the two barangays but both have channel systems where reefs are absent and the coast is exposed.

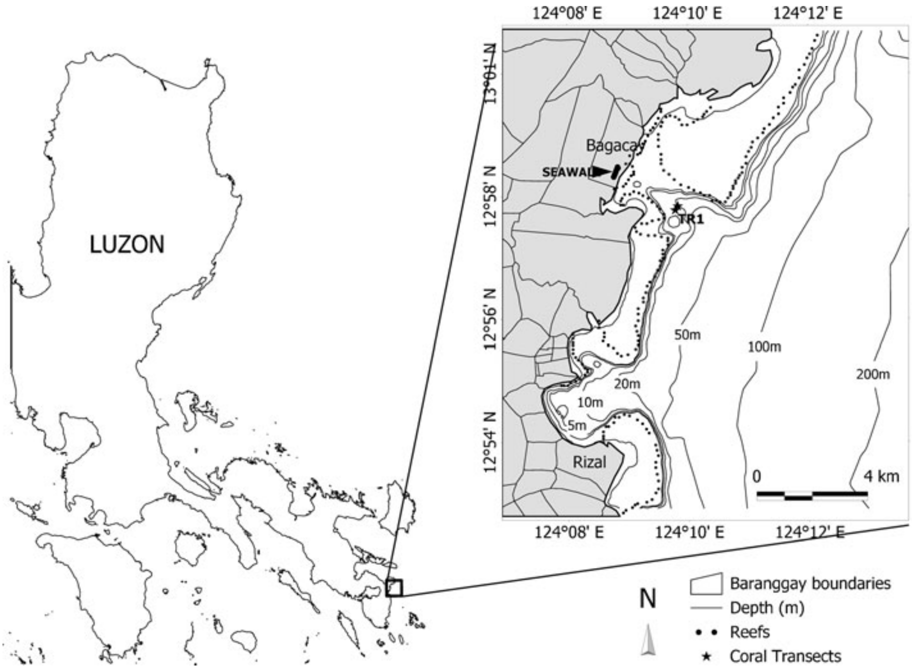

Fig. 1 Map of the study area with inset map showing the Barangay boundaries and bathymetry of boxed area. Take note of the location of Barangay Rizal and Bagacay and the seawall in Bagacay

2.2 Model parameters

Measurements of wave properties in the Sorsogon area have not yet been empirically assessed. For this paper, a model to simulate wave propagation was employed. The DELFT3D-WAVE is a computer simulation software that computes wave propagation, wave generation by wind, non-linear wave-wave interactions, refractions, and dissipation for a given bay geometry and bottom topography, wind field, water level, and remote wave forcings. The WAVE module is based on the SWAN model (Simulating WAves Nearshore model, Booij et al. 1999) and incorporates high resolution coastline and bathymetry from digitized maps. Several model runs were done to simulate waves generated from wind data and hypothetical wave period, height and incident angles at open boundaries. The objective of this modeling exercise was to map out wave energy along the coast and to simulate conditions for different climate change scenarios.

Modeling coastal areas in the level of barangays necessitate high resolution domains. Therefore, a three-way nesting was used to propagate the waves from a large, coarse resolution grid encompassing almost the whole southeast Pacific coast of Luzon to be focused in Sorsogon and resolved to high resolution grids encompassing just Bagacay and Rizal. Model bathymetry was digitized from available navigational charts and topographic maps. The maps indicate the edges of coral reef areas but does not contain depth information, thus some assumptions were made about the depth distribution within the reef. Since part of the reef crest are exposed during spring low tide and the tidal range at this location is about 1.5 m, we prescribed a mean depth of 2 m for the reef.

Based on historical wind data from the QuickSCAT satellite, the prominent wind pattern in Sorsogon is a very strong and prolonged northeasterly winds and weaker southwesterly winds (Fig. 2). Storms, on the other hand, usually approach from the east.

At the open eastern boundary, incident wave conditions are prescribed with varying wave height, period, and direction to simulate storm-generated waves coming from the Pacific. Several runs were made to simulate different wave and wind conditions and also when bottom depth increased uniformly simulating an increase in sea level. A summary of the simulated scenarios are shown in Table 1. The simulations are meant to determine changes in wave characteristics expressed as either wave energy dissipation rates or wave bottom orbital velocities as a result of local wind forcing (Run A and B), storm conditions (Run C and D), absence of reef (Run E) and changes in relative sea level (Run F and G).

2.3 Coral cover measurement

A rapid coral cover survey was conducted to assess the condition of the reef. Two techniques were used, namely, the manta tow and the line intercept transect (LIT) (English et al. 1997). The manta tow is normally used for quick reconnaissance surveys and involves towing a diver holding on to a board at a speed of 2 knots. Estimates of the proportion of live, soft and dead corals are done at 2-min intervals. The line intercept transect method uses transect lines made of 50 or 100 m long measuring tapes. The transect line is deployed on the reef bottom at uniform depth usually oriented parallel to the coast. Benthic cover is measured by divers recording the transitions on the measuring tape occupied by each coral colony (or individuals in the case of solitary species) which is used to calculate the percent cover of each benthic category.

3 Results

3.1 Wave simulations

Results of the wave model highlight the importance of the coral reef areas in dissipating wave energy as highest dissipation clearly outlines the reef edges resulting in a significant

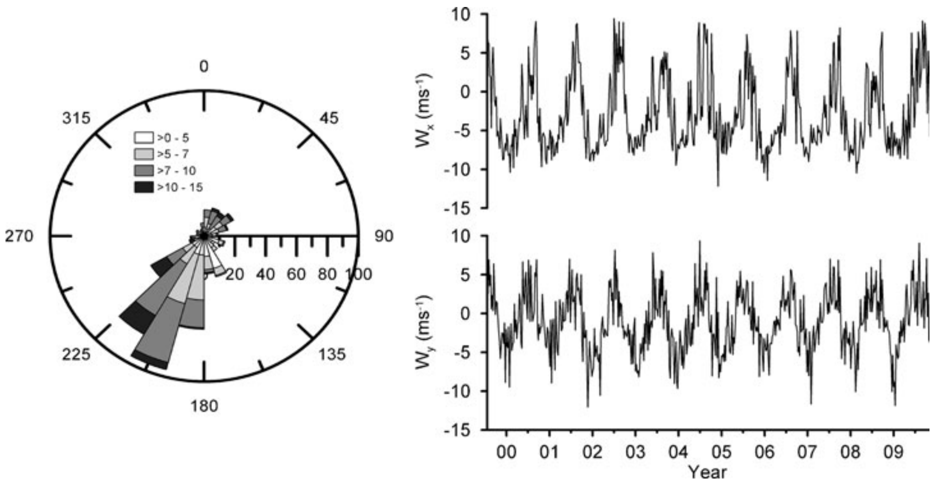

Fig. 2 Wind rose and time series in the area off Sorsogon from QUIKSCAT satellite data

Table 1 Wave simulation scenarios (H_s is significant wave height and P is wave period, z_0 is sea surface elevation)

Run	Model forcing and initial conditions			
	Wind forcing	Wave forcing at open boundaries	Sea level	Presence of reef
A	10 ms^{-1} NE	None (local wind-generatedWaves)	$z_0=0$	Yes
B	None	2 m H_s, 8 sec P from E	$z_0=0$	Yes
C	None	4 m H_s, 8 sec P from E	$z_0=0$	Yes
D	None	4 m H_s, 8 sec P from SE	$z_0=0$	Yes
E	None	2 m H_s, 8 sec P from E	$z_0=0$	No
F	None	4 m H_s, 8 sec P from E	$z_0=0.3$	Yes
G	None	4 m H_s, 8 sec P from E	$z_0=1.0$	Yes

reduction of the height of incoming waves across the reef edge (Fig. 3). In contrast, parts of the coastline which are not fringed by coral reefs are exposed to relatively bigger waves (lower energy dissipation).

To determine the energy available at the bottom for sediment transport and reworking, wave orbital velocity near the bottom was also mapped for the two barangays for the different wave simulations. During the northeast monsoon, 10 ms^{-1} winds coming from 40° were prescribed. The difference in orientation of the two bays caused different patterns in orbital velocity near the bottom, with Bagacay shown to be more sheltered than Rizal during northeast monsoon (Fig. 4).

The bottom orbital velocities during storm events are shown in Fig. 5. The storms are introduced by prescribing incoming 2 m and 4 m high waves at the open eastern boundary of Bagacay and Rizal. It is interesting to note that in Bagacay, the high orbital velocity near the bottom along the channel matches exactly the site of the seawall (Fig. 5, left panel). Increasing the wave height at the open boundary from 2 m to 4 m to simulate extreme events also increased the bottom orbital velocity (Fig. 5, middle panel). The increase is even more significant when the direction of wave propagation was changed from east to southeast (Fig. 5, right panel).

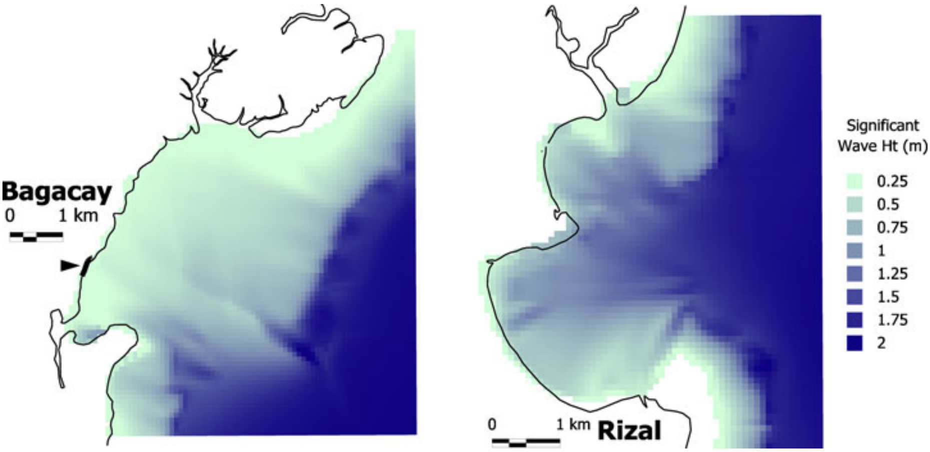

Fig. 3 Significant wave height (m) along the coast of Bagacay and Rizal for model A run with corals

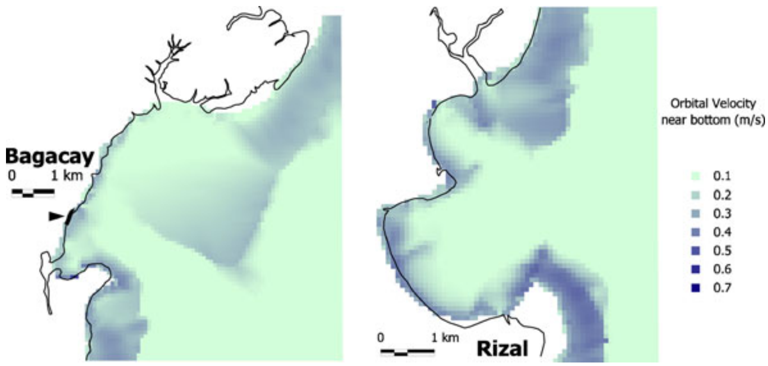

Fig. 4 Orbital velocity near bottom along the coast of Bagacay and Rizal for model run simulating northeast monsoon season

For Rizal, high bottom orbital velocity was found near the town center of Gubat while significantly lower bottom orbital velocity was found near Rizal Beach (Fig. 6, left panel). Such a pattern was consistent with ocular observations of an eroded beach and exposed tree roots seen in the Dangkalan Beach Resort near the town center and the relatively stable beach seen in Veramariz Resort in Rizal Beach. Increasing the wave height at the open boundary from 2 m to 4 m increased the bottom orbital velocity (Fig. 6, middle panel) but still with similar wave exposure patterns. However unlike in Bagacay, the patterns changed in Rizal when direction of wave propagation was shifted from east to southeast (Fig. 6, right panel), with the Rizal beach becoming more sheltered or experiencing lower bottom orbital velocities. Even during storm events, wave height was found to be significantly reduced behind the reefs.

Increasing wave height by 1–2 m will have enormous consequence to wave energy reaching the coastline of Bagacay and Rizal. Areas that will be hit by stronger, and hence more abrasive, waves will be more extensive compared to normal conditions. In Bagacay, the length of coastline that will be battered by strong waves will be larger than the existing seawall. In addition, the present height of the seawall will not be sufficient to stop water from reaching the fishing community behind it. It is important to point out, however, that reefs continue to afford protection to Bagacay even under this scenario and strong waves

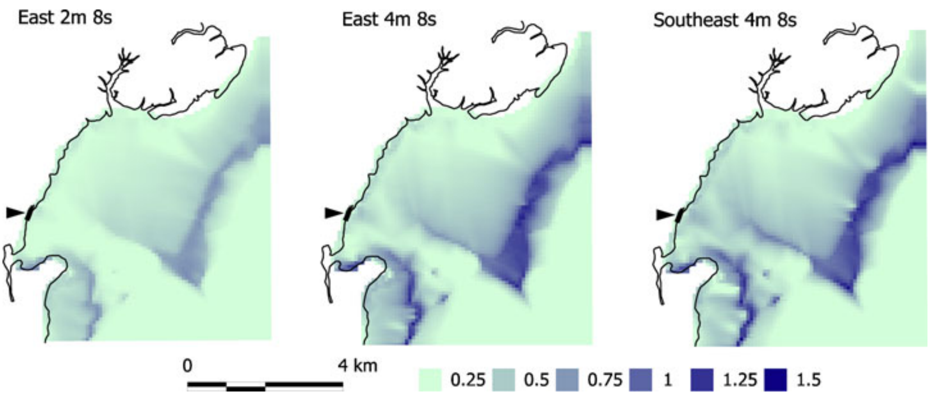

Fig. 5 Orbital velocity near bottom along the coast of Bagacay for model runs with varying wave height and directions. *Left* panel is for 2 m wave coming from the east, *middle* panel is for 4 m wave coming from east, and *right* panel is for 4 m wave coming from southeast

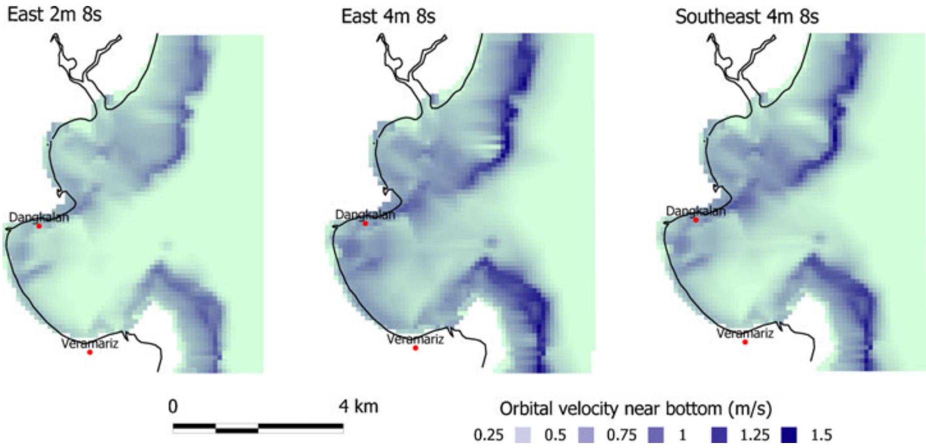

Fig. 6 Orbital velocity near bottom along the coast of Rizal for model runs with varying wave height and directions. *Left* panel is for 2 m wave coming from the east, *middle* panel is for 4 m wave coming from east, and *right* panel is for 4 m wave coming from southeast

would reach the coast only through the channels. In Rizal, high wave exposure was found near Barangay Gubat while significantly lower exposure was found near Rizal Beach. Increasing the wave height increased the overall exposure although with still similar patterns.

To simulate sea level increase that could be brought about by climate change, a simulation was ran with the same conditions as Run C (4-m wave at the eastern offshore boundary, direction from the southeast) but using bathymetry that is uniformly deeper by 0.3 and 1 m (i.e., relative sea level increase of 0.3 and 1 m representing a projected relative sea level rise for the next 30–100 years). Although near-bottom orbital velocity (also energy dissipation) was still high along the edges of the reefs, the wave dissipating effect of the reefs were decreased and a higher proportion of wave energy was able to propagate into the reef and onto the coast. This can be seen in the higher near-bottom orbital velocities observed behind the reefs compared to the model run with present sea-level or bathymetry (Fig. 7)

The wave model scenarios showed that in general, wave energy can reach the coast with small attenuation in areas where there are no reefs to block incoming waves. On-site survey of Bagacay and Rizal showed that indeed the erosional coasts are located in areas without any reefs or are in gaps between reefs. Simulations comparing the wave propagation to the coast in the absence of the reef (Run E) show that the areas with high energy dissipation rates are found much closer to the shore (Fig. 8). High energy dissipation right at the coast translates to strong wave breaking and high potential for erosion.

In order that the role of the reefs in protecting the coast is maintained in the advent of rising relative sea levels, it is imperative that the corals are alive so that vertical growth can catch up with rising sea level. Manta tow surveys revealed good to excellent coral cover for reefs in Gubat (Fig. 9). The preponderance of branching and table corals in Botog-botog sanctuary (location in Fig. 1) may indicate fewer disturbances either from blast fishing or other destructive fishing methods. Some portions of the sanctuary, however, showed some signs of damage with the predominance of dead corals but which are already overgrown with newly recruited corals. The young corals are dominated by the table acroporids that may be 8 to 10 years old. The estimate of age was based on the size of the corals; this estimate of age

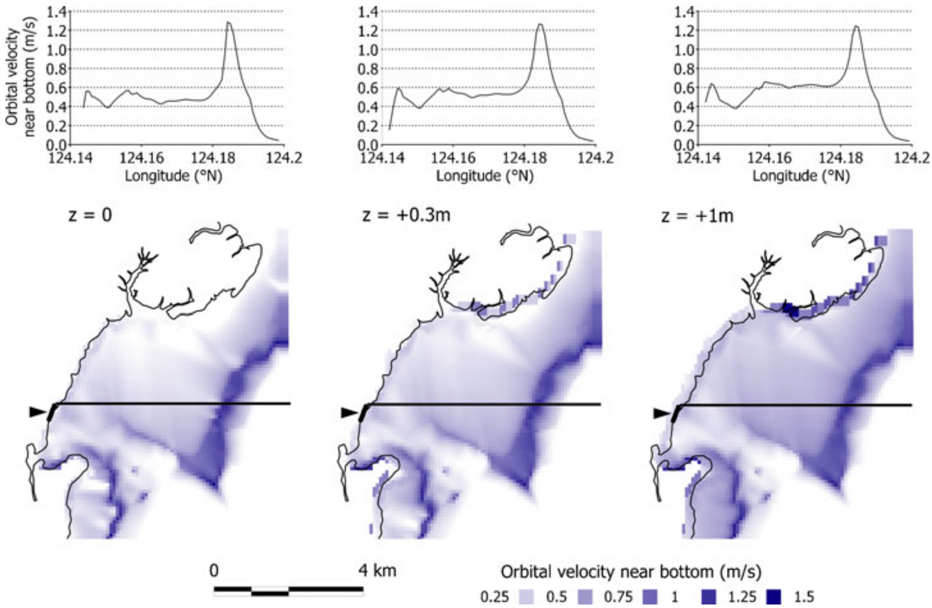

Fig. 7 Orbital velocity near bottom along the coast of Bagacay for model runs with varying sea level to account for projected sea level rise. Waves were propagated at the eastern offshore boundary with 4 m wave height and southeast direction of propagation, with bathymetry at present conditions (*left* panel) and with bathymetry uniformly increased by 0.3 m (*middle*) and by 1 m (*right*)

also corresponds with the length of time since Botog-botog reef was declared a marine protected area (MPA).

The reef formation and bottom topography at the Rizal area are spectacular. High-energy waves from the Pacific Ocean formed deep canals, caves and large crevices on the reef that

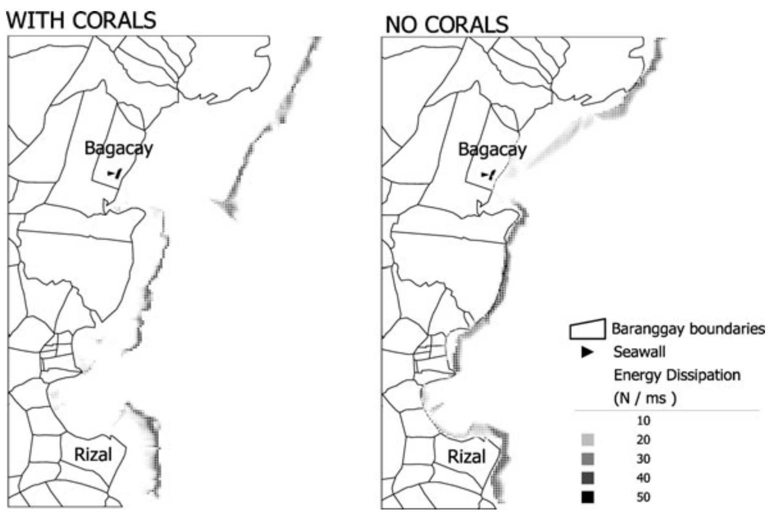

Fig. 8 Energy dissipation (Nm^{-1} s^{-1}) along the coast of the study area for model A run using bathymetry with corals and without corals

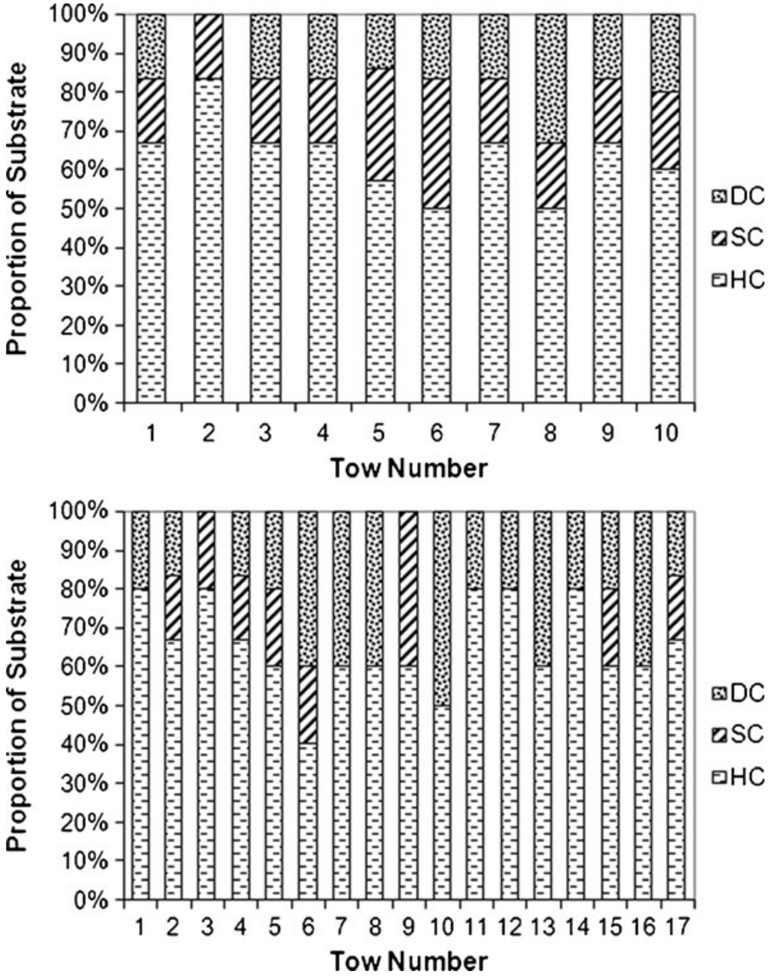

Fig. 9 Percent soft coral (SC), hard coral (HC) and dead coral (DC) cover from manta tow surveys in Bagacay (*top*) and Rizal (*bottom*)

oftentimes results to breaking of large chunks of the calcium carbonate structure. These outcrops provide recruitment space for corals; thus, large outcrops are oftentimes enveloped with diverse assemblages of corals. Due to wave action, encrusting, table and branching types characterized by compressed and stout branches (Licuanan and Gomez 1988) dominate the reef in Rizal and Bagacay (Fig. 10). Macroalgae, namely, *Caulerpa* and *Halimeda* were abundant especially in the deeper part of the reef. They thrived on rocks and dead coral substrate. The algae were teeming in deeper parts of the reefs and in sheltered areas such as the interior parts of coves or embayments, e.g., towards Rizal Beach.

The wide reef in Bagacay showed some interesting horizontal patterns of coral distribution. For example, the massive coral *Porites*, dominated the back reef. Siltation was evident in the site where poor visibility ensued after several hours of heavy downpour. Poritids are known to dominate highly silted areas, which might help explain their dominance in the back reef although the water may get very murky at times. In addition, its massive growth form would tend to withstand the impact of blast fishing. This would also account for the

Fig. 10 Coral reefs in Bagacay and Rizal showing dominant life forms

dominance of poritids in areas in Bagacay outside the protected zone which maintains a good coral cover despite the rampant blast fishing activities reported by community members in the vicinity.

One of the most common adaptation measure to protect the coasts from wave action are seawalls (University of Liverpool 2009). Bagacay is no exception with a seawall constructed in 1997 in an area unprotected by the reef. After a few years, the seawall showed signs of damage, part of it severely, leading to the collapse of a section of the seawall. The foundation is also visibly weakened by the erosion of sand that is probably caused by the wall itself, which had impeded natural movement of water and the transport of sand. Severe erosion was observed at the southern end of the wall where a number of damaged houses are found.

4 Discussion

The tsunami that hit Indonesia and other countries in the Indian Ocean in December 2004 provided a rare opportunity to assess the role of coral reefs in providing protection against strong waves. Wilkinson et al. (2005) reports "In most of these countries, the tsunami washed directly over coral reefs, which may have provided some limited protection to the land behind. There is anecdotal evidence that there was more damage on land behind coral reefs that had been extensively mined e.g., in Sri Lanka than in areas where reefs were intact". On the other hand, local communities recount their motivation for establishing MPA in mangroves and coral reefs, based on their experience in the 1976 tsunami where they felt that these ecosystems helped buffer their settlements. This sad experience places coral reefs and other marine ecosystems such as mangrove in the limelight as important and necessary line of defense against calamitous events like a tsunami. Although Wilkinson et al. (2005) also noted that there was no significant dissipation of wave energy that had happened even with the presence of reef where the waves were considerably big.

This study presented a scenario where wave energy may not approximate that of a tsunami. The main forcing factor for storms even at Category 4 or 5 may not produce waves of similar amplitude to that generated by tsunamis. However, a compounding factor in the wave simulation was the increased sea level by 1 m. But even when coupled with stronger winds, the reef in the study area continued to provide protection from high-energy waves by effectively attenuating wave energy. It is, however, clear that the area inundated on land increased under such scenario.

One important thing to underscore in this paper is the argument made that coral reefs may not correspondingly grow with the sea level rise. In reality, the reefs can also be growing and increasing in height by accretion of more calcium carbonate deposits by hard corals. Assuming a growth rate of 2 cm y^{-1} (i.e., using lower range of Kuenen 1950 estimate), the reef is also capable of increasing its height by 1 m over a period of 50 years which is enough to cope with the increasing sea level that is rising at a similar rate. However, this assumption may not necessarily be accurate because coral growth may differ across the hard corals taxa. In this case, branching forms may be able to grow upwards but massive and encrusting forms may not.

A review of the literature on growth rates of corals reveals differences in the growth rates among coral species. Yap et al. (1992) compared the growth rates of three species of hard corals and found that *Acropora* grew faster than *Pavona* and *Porites*. *Acropora*'s ability to grow fast is widely recognized (Buddemeier and Kinzie 1976; Jinendadrasa and Ekaratne 2000; Yap and Gomez 1984; Veron 1986). In regard to reef growth, Roth (1979) documented .8 to 80 mm growth per year. Kuenen (1950) on the other hand, reported a wider range of 0.1 to 5 cm per year. Examining core samples, Slowey and Crowley (1995) found that corals could grow only 9 mm per year. Citing the study of Hudson and colleagues, they also noted significant variations in the growth rates which they posited to be dependent on the past environmental conditions that were either favorable for coral growth or not. For example, growth rate from 1907 to 1957 was significantly higher at 8.9 mm per year but declined to 7.2 mm per year from 1957 to 1979. Although the circumstances were not clearly elucidated, it is important to note that coral growth rate is not uniform but may fluctuate quite significantly over long periods and which renders long-term extrapolation of growth rate difficult to make.

Although it is not the subject of this study, we deduce that the vulnerability of corals to climate change will also depend in part on their life forms (branching, massive, foliose and encrusting). Some species have demonstrated plasticity in growth forms according to the location and condition they are exposed to, i.e., from branching to encrusting form, which might be an important determinant for surviving sea level rise. For species unable to keep pace with sea level rise because of lack of such adaption mechanism, they may be pushed to the limits of their survival.

4.1 Adaptation measures

The results of this study provide several important insights that are useful to policy. First, natural ecosystems, such as coral reefs, provide natural protection against storms and high-energy waves they generate. Coral reefs help dampen wave energy making them dissipate significantly before reaching the shore. The simulations revealed another important insight, that is, even when sea level was raised by 1 m, the coral reef system in the site can still help attenuate wave energy. Second, man-made structures such as seawalls are not enough to prevent wave surge effects. Relying on this structure alone would not guarantee protection in worst scenarios such as during high category typhoons. Authorities must consider moving coastal inhabitants to higher ground in such a situation. Third, construction of seawalls has attendant environmental cost. Seawalls could enhance coastal erosion by impeding natural transport of sand along the coast. Consequently, some portion of the coast may lose sand materials that may be deposited elsewhere. Unfortunately, this process is also responsible for the weakening of the seawall foundation that would slowly lead to the collapse of the wall itself.

4.2 Combined engineering and coastal resource management approach

Mere seawalls would not provide the long-term solution to stronger waves. As demonstrated in this study, coral reefs provide natural protection against strong waves. It is therefore imperative to continue and enhance efforts to manage and protect these coastal ecosystems. They have to be maintained at healthy conditions in order to enhance their self-maintaining attribute and thus resiliency to impacts. Dead corals will gradually erode so will the entire reef if this major contributor of calcium carbonate deposit will be gone. As has been shown, the coral reefs in the study site were in healthy condition (Fig. 9). This is in contrast with the general picture of coral cover in the Philippines with only 5% estimated to be in excellent condition (Nañola et al. 2006). In the simulation model, we did not factor in the growth of corals and the amount of additional calcium carbonate materials accreted to the reef during the length of time it took sea level to rise by 1 m. Simply put, the impact of 1 m in sea level might be an order of magnitude lower if corals are able to grow by a corresponding height of 1 m.

It might not be accurate to generalize that all corals may be able to survive sea level rise scenario. Some genera like acroporids which exhibit branching lifeform might be able to keep pace with increasing sea level compared to genera with other growth forms. Fortunately, the branching acroporids are the most dominant genus of corals in the study site albeit it might be more susceptible to other climate change situations such as coral bleaching associated to increased sea surface temperatures (SST) (Arceo et al. 2001; Pratchett et al. 2009). It is, thus, important to protect the coral reef from further damage. Branching forms are fragile and are most vulnerable to dynamite fishing. This necessitates a more comprehensive approach to coral protection. Integrated Coastal Management and the Coastal Resource Management (CRM) frameworks provide the platform for protecting and managing coastal ecosystems with sustainable use and preservation of biodiversity and ecosystem functions and processes at its core.

A damaged reef will be more vulnerable to wave action. As observed during the 2004 Indian Ocean tsunami, the amount of damage on the carbonate reefs was determined by the degree of consolidation of the reef framework (Wilkinson et al. 2005). Damage was generally greater on degraded, carbonate reefs, where there was large amount of unconsolidated rubble substrates.

The importance to fisheries and other uses like tourism are the other compelling reasons why corals must be protected and managed sustainably. Climate change is believed to affect productivity, which may be enhanced or reduced in quantity depending on the area. Pelagic fisheries will be most vulnerable because fisheries production is closely linked with water circulation patterns and processes such as upwelling patterns which will not follow normal course when the sea gets warmer (Sudara 1993; Villanoy and Salamante 2000; Chavez et al. 2003).

In conclusion, because coral reefs help dampen wave energy and seawalls built on shorelines behind them can last longer than without them. Where resources allow, it is important to combine seawalls with reef protection and restoration as well as enhance enforcement effort under an implementable comprehensive framework such as CRM.

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This is University of the Philippines Marine Science Institute's contribution 408.

References

Arceo H, Quibilan M, Alino P, Lim G, Licuanan W (2001) Coral bleaching in Philippine reefs: coincident evidences with mesoscale thermal anomalies. Bull Mar Sci 69(2):573–593

Booij N, Ris RC, Holthuijsen LH (1999) A third-generation wave model for coastal regions: 1. Model description and validation. J Geophys Res 104:7649–7666

Buddemeier RW, Kinzie RA III (1976) Coral growth. Oceanogr Mar Biol Annu Rev 14:183–225

Burke L, Maidens J (2004) Reefs at risk in the Caribbean. World Resources Institute, Washington, DC

Chavez F, Ryan J, Lluch-Cota S, Niquen M (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science. Vol 299

English S, Wilkinson C, Baker V (eds) (1997) Survey manual for tropical marine resources – second edition. Australian Institute of Marine Science, ASEAN-Australia Marine Science Project. 390 pp

Hulme M, Sheard N (1999) Climate change scenarios for the Philippines. Climatic Research Unit, Norwich

Jinendradasa SS, Ekaratne SUK (2000) Linear extension of *Acropora formosa* (Dana) at selected reef locations in Sri Lanka. In: Proc. 9th Int. Coral Reef Symp. Bali, Indonesia. vol. 1

Kuenen H (1950) Marine geology. Wiley and Sons, New York

Licuanan W, Gomez E (1988) Coral reefs of the northwestern Philippines: a physiognomic-structural approach. In Proc. 6th Intl. Coral Reefs Symp., Australia 3:275–280

Nañola CL, Aliño PM, Arceo HO, Gomez ED, Quibilan MC, Uychiaoco AJ, Alcala AC, Campos W, Licuanan WL, White WT (2006) Status report on coral reefs of the Philippines-2004, pp. 1055–1061. Proceedings of the 10th Int'l Coral Reef Symposium, Okinawa, Japan, June 28 – July 2, 2004.

Pratchett MS, Wilson SK, Graham NAJ, Munday PL, Jones GP, Polunin NVC (2009) Coral bleaching and consequences for motile reef organisms: Past, present and uncertain future effects. In: van Oppen MJH, Lough JM (eds) Coral bleaching. Springer, Berlin Heidelberg, pp 139–158

Rahmsorf S (2007) A semi-empirical approach to projecting future sea-level rise. Science 315, 368-370

Rodolfo KS, Siringan FP (2006) Global sea-level rise is recognised, but flooding from anthropogenic land subsidence is ignored around northern Manila Bay, Philippines. Disasters 30(1): 118-139

Roth AA (1979) Coral reef growth. Origins 6(2):88–95

Slowey NC, Crowley TJ (1995) Coral cores from the Flower Gardens: a new tool for studying climate. Quarterdeck 3(3):4–7

Sudara S (1993) Implications of climate changes on marine productivity. In: Chou LM (ed) Implications of climate change in the East Asian Seas Region. 157 pp

University of Liverpool (2009) Curbing the cruel sea. http://www.liv.ac.uk/researchintelligence/issue24/seawalls.html. July 2009.

Veron JE N (1986) Corals of Australia and the Indo-Pacific.The University of Hawaii Press. 644 p.

Villanoy C, Salamante E (2000) Sea surface temperature variability in the seas surrounding the Philippines in relation to ENSO events Proceedings of the 21st Asian Conference on Remote Sensing II:P767–P771

Wilkinson C, Souter D, Goldberg J (eds) (2005) Status of coral reefs in Tsunami affected countries. Australian Institute of Marine Science

World Resources Institute (WRI) (2009). Coral reefs. http://wri.org/project/coral-reefs. July 2009

Yap HT, Gomez ED (1984) Growth of *Acropora pulchra* II Responses of natural and transplanted colonies to temperature and day length. Mar Biol 89:209–215

Yap HT, Aliño PM, Gomez ED (1992) Trends in growth and mortality of three coral species (Anthozoa: Scleractinia), including effects of transplantation. Mar Ecol Prog Ser 1992(83):91–101