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Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles

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Abstract

In the granitic Seychelles, many shores and beaches are fringed by coral reef flats which provide protection to shores from erosion by waves. The surfaces of these reef flats support a complex ecology. About 10 years ago their seaward zones were extensively covered by a rich coral growth, which reached approximately to mean low water level, but in 1998 this was largely killed by seawater warming. The resulting large expanses of dead coral skeletons in these locations are now disintegrating, and much of the subsequent modest recovery by new coral recruitment was set back by further mortalities. A mathematical model of wave energy reaching shorelines protected by coral reef flats has been applied to 14 Seychelles reefs. It is derived from equations which predict: (1) the raised water level, or wave set-up, on reef flats resulting from wave breaking, which depends upon offshore wave height and period, depth of still water over the reef flat and the reef crest profile, and (2) the decay of energy from reef edge to shoreline that is affected by width of reef flat, surface roughness, sea level rise and 'pseudo-sea level rise' created by increased depth resulting from disintegration of coral colonies. The model treats each reef as one entity, but because biota and zonation on reef flats are not homogenous, all reefs are divided into four zones. In each, cover by both living and dead biota was estimated for calculation of parameters, and then averaged to obtain input data for the model. All possible biological factors were taken into account, such as the ability of seagrass beds to grow upwards to match expected sea level rise, reduction in height of the reef flat in relation to sea level as zones of dead corals decay, and the observed 'rounding' of reef crests as erosion removes corals from those areas.

Estimates were also made of all these factors for a time approximately a decade ago, representing a time before the mass coral mortality, and for approximately a decade in the future when the observed rapid state of dead coral colony disintegration is assumed to have reached an end point. Results of increased energy over the past decade explain observations of erosion in some sites in the Seychelles. Most importantly, it is estimated that the rise in energy reaching shores protected by fringing reefs will now accelerate more rapidly, such that the increase expected over the next decade will be approximately double than that seen over the past decade.

Keywords: shores; coral reefs; sea level rise; coral mortality; erosion; wave energy; Seychelles

1. Introduction

Erosion has increased markedly in recent years on many tropical shores, caused by a number of climatic changes and anthropogenic activities (CORDIO, 2002; Wilkinson, 2004). During the same period, reef corals have suffered heavy mortality due to seawater warming and, because mortality was especially severe in shallow water, the coral mortality included most of the populations on fringing reefs which protect shores from waves. A fringing reef typically consists of a broad,

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horizontal reef flat extending seaward from the shore, at an elevation at approximately mean low tide level. These reef flats and the reef crest at its seaward edge provide the main break to oncoming waves in many tropical islands and mainland shores. To seaward of each flat and crest there is usually a reef slope which dips steeply into deep water. Most fringing reef crests and reef slopes in the Seychelles, as well as the seaward portions of reef flats, are (or were) covered by growing corals but, following widespread mortality caused by warmed seawater in 1998, these huge expanses of corals now are largely dead and their limestone skeletons are eroding. Here the question is asked: are shores behind such fringing reefs less protected now that these corals have died and their limestone skeletons have partly disintegrated? Fourteen fringing reefs were examined in the granitic Seychelles (Figs. 1 and 2), each of which is several hundred metres to several kilometres in length. The wave energy reaching shores under three scenarios was then estimated: the recent past (i.e. a time immediately before the mass mortality), the present, and changes that might be expected to occur in the near future given a continuation of coral skeleton disintegration. The relative magnitude of the changes between these three scenarios is also estimated as this is crucial to management of the changes that are predicted.

1.1. Changes occurring to reef flats

In 1998, corals around the world died in large numbers; as much as 95% mortality was seen in many parts of the Indian Ocean, including the Seychelles. This mortality occurred to 10 m depth in some cases, but to > 30 m depth in many Indian Ocean atolls and fringing reefs (Linden et al., 2002; Sheppard and Obura, 2005). In shallow water and on reef flats, coral mortality was near total, resulting in reefs becoming largely denuded of live corals. The substrate that these occupied is progressively being occupied by mixtures of dead coral rubble from branching corals, and by increasingly eroded and hollowed-out colony remnants from massive and boulder forms (Sheppard et al., 2002). The ecological consequences are profound (Lindahl et al., 2001; McClanahan et al., 2002; Riegl, 2002; Spalding and Jarvis, 2002). Further, it has been calculated from climate model data (Cubasch et al., 2001; McAvaney et al., 2001) that repeat warming events will recur with increasing frequency over the coming decades, so that significant recovery of these shallow corals is unlikely to take place (Hoegh-Guldberg, 1999; Hughes et al., 2003; Sheppard, 2003). Social and economic consequences are likely to be substantial (Wilkinson et al., 1999; Cesar, 2000).

Reef flats are known to dissipate much offshore wave energy (Wolanski, 1994). Before 1998, many of the reef flats examined here were covered with 0.5 m high thickets of stagshorn corals of the genus *Acropora* and by massive or boulder forms of nearly equal height from the coral genus *Porites* in particular, and others from the Family Faviidae. With these corals killed, several variables visibly changed. Firstly, removal of the coral skeletons increased the depth of water over the reef flat, in still-water conditions, by approximately the same amount as the height of the previously existing coral stands, in locations where these existed. Fig. 2d and e shows the edges of extensive patches of coral, now dead and gradually disintegrating. The crumbling of these expanses is increasing the gap between their tops and sea level, creating a localised 'pseudo-sea level rise' on the reef flats. It is known from examples in several countries that removal of reef flat corals and rock for other reasons (building materials, for example) has led to decreased shoreline protection and increased problems of erosion (Edwards, 1995). Secondly, when the reef flat corals eroded away or became rubble, the three-dimensional structure of the reef flat surface reduced from a state of rough, mixed, irregular coral thickets and boulders to a much smoother surface of rubble or even to flat limestone, both of which present much less friction to waves and hence have a further reduced ability to attenuate wave energy. Thirdly, and this applies even to reefs which never had much coral on the reef flat, the reef crest corals also die (Figs. 2f), which slightly changes the shape of the wave breaking zone seaward of the reef crest.

Testing of each of these parameters (see later) shows that all are important in affecting the amount of energy

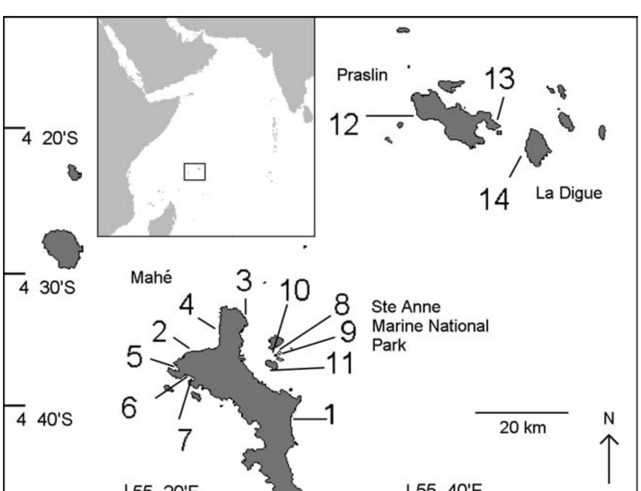

Fig. 1. Sketch map of the granitic Seychelles islands, showing locations of each reef surveyed. Within the Ste Anne Marine National Park are the islands of Moyenne (sites 8, 9), St Anne (10) and Cerf and Cachee (11).

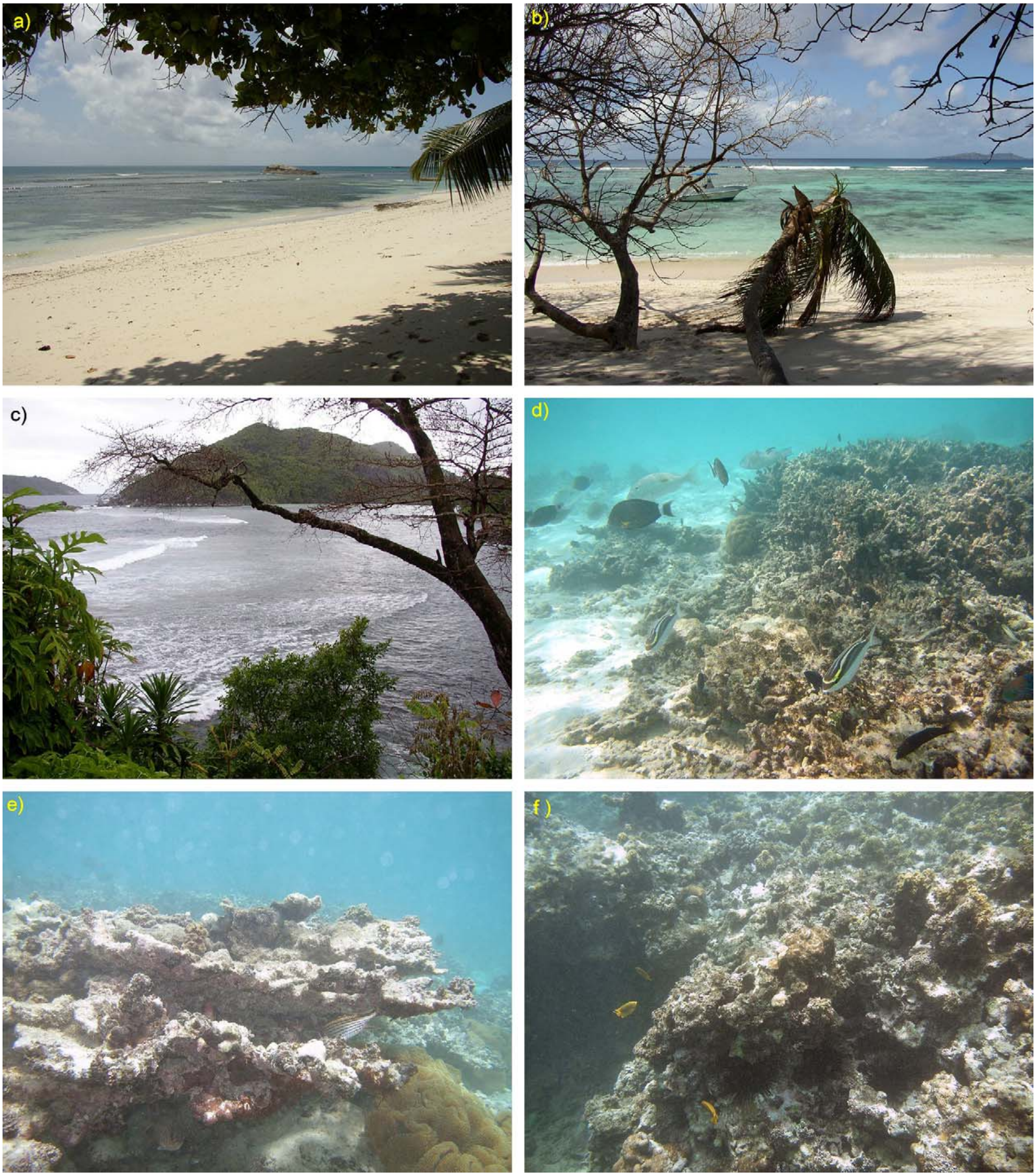

Fig. 2. (a–c) Typical reef flats in the Seychelles: (a) Beau Vallon, Mahé island, site 4, reef flat 135 m wide, at low tide, and (b) Praslin island, site 13, reef flat 205 m wide. Both on calm days with small waves breaking at the edge of the reef flat. Dark patches underwater are seagrasses to shoreward, and dead coral further seaward. (c) Site 6, Ternay-Laurnay, showing propagation of wavelets towards the shore. (d–f) Underwater views: (d) edge of expanse of dead 'staghorn' coral. The packed but dead branches extend about 0.6 m above the sand covered platform. (e) Dead *Acropora palifera*, commonly packing the seaward edges of Seychelles reef flats. These grow 0.5–0.8 m above the substrate, approximately to low sea level. They are robust, and disintegrate more slowly than the finely branched forms shown in (d). (f) Reef crest, showing lack of live coral and an eroding, more rounded edge. Prior to the coral mortality, reef crests supported live coral which grew approximately to the low water level where they formed a steep slope and sharp angle.

transmitted across the reef from the offshore wave regime to the shoreline. Most of the variables act in non-linear manner. An additional factor is the small but now significant amount of global sea level rise over one and two decades which also must be factored in and, finally, of great importance, is the width of the reef flats themselves which varied from tens to hundreds of metres wide.

1.2. The Seychelles reefs

Fringing reefs occur along the coasts of most of the inner granitic islands in the Seychelles (see Fig. 2a–c). Along the west coasts, they are generally confined to sheltered bays, whereas on eastern coasts fringing reefs are more extensive and well developed. Numerous older studies described those reefs as diverse (e.g. Lewis, 1968, 1969). However, as much as 95% of coral species were killed in 1998, and recent observations indicate that while some recovery took place (Engelhardt, 2004), many young colonies died again in early 2004 (personal observations). Reefs in a variety of coastal environments were selected for this study, from extensive fringing reefs of over 500 m width to narrow reefs less than 100 m width.

1.3. Basis of the model

Wave energy and its propagation across a reef towards the shore is not a straightforward process. Waves breaking at the edge of the reef create an increase in water level – a wave set-up – over the reef flat. At the same time the longer offshore waves usually decompose after breaking into groups of shorter secondary waves which travel shoreward across the reef flat.

Earlier research concerning wave set-up and wave transformation on coral reefs has been reviewed by Gourlay (1994, 1996a, b) and Massel and Gourlay (2000). Gourlay's (1996b) semi-empirical model indicates that offshore wave height and period and reef-top water depth are important factors affecting the amount of wave energy reaching the shore. This model is based upon laboratory experiments from various sources, together with field measurements by Hardy et al. (1990) (see also Hardy and Young, 1996). The model assumes a two dimensional situation where the waves break parallel to the edge of the reef and propagate over the reef flat without refraction to finally break parallel to the shoreline behind the reef. No water escapes laterally or at the shoreward end of the reef flat. Hence there is no wave-induced flow. The model recently has been extended to the case where the breaking waves also generate a flow across the reef (Gourlay and Colleter, in press). This last paper also includes a review of the theoretical approaches of other researchers.

The practical application of the basic model is given in Gourlay (1997) which presents the equations required to determine the wave set-up generated by waves breaking at the seaward edge of the reef, and the subsequent propagation of the residual wave energy towards the shore (see Section 2 and Appendix A). A spreadsheet model was constructed which incorporated these equations to compute the wave energy reaching a shore behind any reef flat. With it, all the physical variables and empirical constants can be changed to represent the conditions on any observed reef, and any of these parameters can be 'standardised' to observe the changes caused by other factors. This simplified model is applied consistently to the three scenarios (the past, present and the future) which were developed for 14 Seychelles fringing reefs. In both the past and future scenarios, the use of the term 'decade' is not meant to denote a precise date.

2. Methods

2.1. Spreadsheet model

Using an Excel model based on Gourlay's (1996a, b, 1997) equations for a single reef, all parameters were tested for their sensitivity in influencing changes to final energy reaching the shore. The model 'WaveEnergy.xls' is available from the 'Research' tab in http://www.bio.warwick.ac.uk/res/frame.asp?ID=42. Appendix A summarises the equations used. Any or all parameters can be changed as desired to reflect any reef, and results are displayed interactively. Values of each parameter used here may be debated, but other values can easily be substituted, and indeed substitutions with some extreme values are illuminating. In addition to the measured parameters, all variables connected with graphing the results are also changeable, and a macro permits parameter testing of any variable for any range of selected values of the others.

Throughout, the significant offshore wave height (H_o) used was 1.25 m and zero up-crossing period (T) was 5.2 s, which are annual means as provided from the Voluntary Observing Ship (VOS) program and South African Data Centre for Oceanography (SADCO), for the Seychelles region. For parameter testing, one other variable at a time was changed, with others held constant: all reef flats were standardised at 100 m wide with a steep seaward reef profile ($K_p = 0.78$), and with an intermediate roughness, represented by a friction factor of $f_w = 0.15$. The standard still water depth (h_r) over the reef flat used was 0.85 m, which is the mean tidal range in the Seychelles (Seychelles tide tables, 2004); reef flats generally grow upwards to approximately mean low water level, and a high tide situation was selected.

Fig. 3 shows the effect of changing four variables (others remaining fixed). Width of reef flat, steepness of the wave breaking zone, depth of still water (without setup) over the reef flat and the mean roughness on the reef flat all have marked influence on the final energy. All these variables are retained in the final model, despite the difficulties of estimating some of them.

Following parameter testing, these values were changed according to measurements made on the 14 Seychelles reefs. For each reef, values for each input

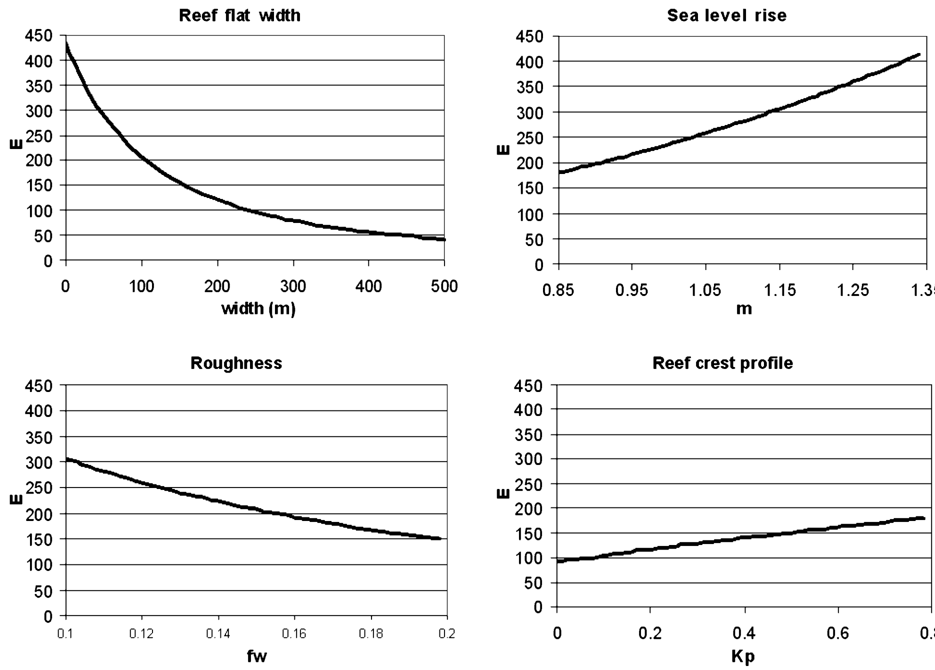

Fig. 3. Parameter testing with four main variables. The y-axes are all to same scale, for comparison of magnitude of effects, where E is in J m^{-2}. The x-axes of bottom pair span the valid range. The x-axes of top pair: reef flat width encompasses most Seychelles reefs; sea level rise is from the 'starting point' of high tide above reef flat to high tide plus sea level rise of 0.5 m.

variable were calculated. At the same time, estimates of each were made for a decade previously when coral growth was known to be vigorous, rich and healthy, when dense coral colonies reached low tide level, and for approximately a decade in the future when the decay of the coral structure is assumed to have progressed to a more degraded stage than is the case at present. Fig. 4 is a sketch of the measurements needed for the three time periods, showing the changes measured. The present time is represented by the middle section.

In this comparison across about 20 years, sea level rise is also incorporated. The Permanent Service for Mean Sea Level (http://www.pol.ac.uk/psmsl/) shows that there is only poor data for the Seychelles, none of which has been corrected to a 'Revised Local Reference' or RLR that is needed to determine trends. Therefore, a rounded and somewhat arbitrary sea level rise value of 5 mm y^{-1} is used. While this is higher than the global mean, it is similar to, or slightly less than, values for other island sites in the central Indian Ocean for which there are better data, such as the Maldives, Chagos and Madagascar, where values range from 5 to about 8 mm y^{-1}.

Most effort was required for the determination of values for the parameters still water depth and roughness on the reef flat. These real reefs were not as simple as the initial model requires, and in particular neither water depth nor roughness were uniform over any of them. A typical Seychelles reef, like most others, may be divided into zones from shore to reef crest, and in the granitic Seychelles four zones were found to be appropriate. All reefs were different, but typically might consist of a sandy zone near the beach, with no living coral, followed by one or two zones of seagrasses, followed by one or two zones of hard substrate which previously were packed with live corals but which today are covered by dead coral skeletons which are eroding, and by coral skeletal rubble. Therefore each reef flat was

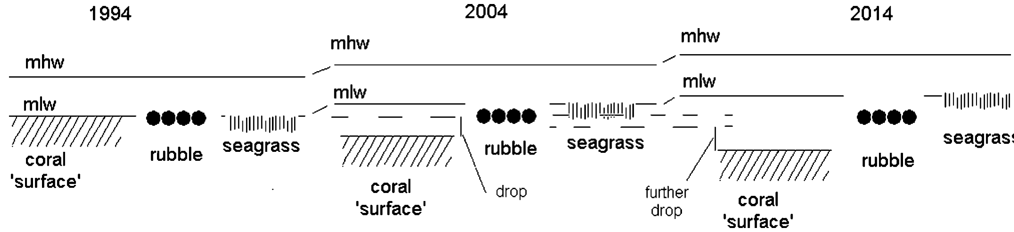

Fig. 4. Sketch of measured parameters at the three stages, from left to right: a decade ago, today and a decade in the future. Note that coral surface drops each decade, while seagrass keeps pace with sea level rise. Bare rock (not shown) remains unchanged in elevation throughout.

divided into four zones of equal width, each treated separately, and the average depth and roughness values for the reef flat as a whole were calculated from these for use as model input values. Where one zone itself had, say, 50% seagrass and 50% sand, or 25% coral and 75% rubble, then the zone was similarly averaged according to the proportions of each habitat it supported.

Treatment of each zone, or portion of each zone, depended on known ecological or biological behaviour of its present and previous biota, where this was clear. For dead coral, the height of the species (still identifiable) was determined, along with coral cover, and accuracy was augmented by both local knowledge and previous survey reports (Van der Land, 1994; Engelhardt, 2004). Where rich coral stands had died and disintegrated, the drop in heights of each zone of each reef flats' upper surfaces was estimated, this equalling an increase in still water depth (the pseudo-sea level rise). Ultimately the magnitude of this will equal the average height of the reef flat coral species in cases where that species is assumed or known both to have provided dense cover and to have reached approximately to the low tide level.

Roughness likewise was assumed to vary over the range, $f_w = 0.1$ to 0.2, measured by Nelson (1996), where 0.1 is smooth and 0.2 is rough, healthy coral. The exceptions were values of 0.08 for sand, following Gourlay (1997). Table 1 shows values of the roughness factor definitions used for each individual zone on each reef.

The reef profile factor, K_p, varies with the slope of the edge of the reef where waves break. There are two variants of this parameter, K_p and K_p^1, choice of which depends on whether waves break on a reef edge or reef rim, as defined and sketched in Gourlay (1997, Fig. 1). Both vary as a tangent function of the angle of the slope, and for all steep slopes between about 45° and 90° (typical of healthy reefs), both parameters are the same,

Table 1
Friction factor selected for each reef flat zone

Criteria	f_w (friction factor)
75%–100% sand	0.08
75%–100% smooth rock or coral pavement. 75%–100% seagrass or algal turf	0.10
Smooth rock or coral pavement with 50%–100% coral rubble	0.12
10%–25% live coral or dead uneroded coral or tall (>30 cm) boulders	0.14
25%–50% live coral or dead uneroded coral or tall (>30 cm) boulders	0.16
50%–75% live coral or dead uneroded coral or tall (>30 cm) boulders	0.18
75%–100% live coral or dead uneroded coral or tall (>30 cm) boulders	0.20

Where greater than 50% macroalgae occur on a boulder substrate the next highest factor was selected.

Table 2
Relationship between angle of slope of the reef face and rim where waves break, approximate gradient, corresponding K_p and K_p^1 values (Gourlay 1997, Fig. 2), and the average value used

Angle of slope (degrees)	Gradient as ratio	K_p value	K_p^1 value	Value of K_p used in this paper
5	1:10	0.34	0.6	0.47
10	1:6	0.42	0.62	0.52
15	1:5	0.45	0.65	0.55
20	1:3	0.5	0.7	0.6
30	1:2	0.58	0.75	0.67
40	1:1.2	0.75	0.78	0.77
45–90	1:1	0.78	0.78	0.78

with maximum value of 0.78. This maximum value creates maximum wave setup. For more gently sloping slopes, the reef profile parameter is less. In the Seychelles, most reefs are not simply either one or other category, but vary over a distance of a few metres from one profile type to the other, and back again. Thus a mean value of K_p was used, interpolated from the two variants (Table 2). All reef slopes prior to the mortality of 1998 are assumed to have had a sharp reef crest, $K_p = 0.78$. These now have noticeably become more rounded as well as deeper, so the values of this reef profile factor have declined to values calculated for 2004. In the future, while it is likely that erosion will continue to 'round off' the reef crest, it is clear that in this turbulent area most such rounding has already taken place as most coral skeletons from here have already been completely removed (Fig. 2f). Because any change over the next decade is both likely to be small and not easily estimated in any case, it is conservatively assumed that no further change to K_p will take place.

With respect to still water depth, beds of rubble, sand and the underlying limestone platform were assumed here not to have changed in height themselves, though the absolute depth from Indian Ocean sea level rise was applied to these habitats. Seagrasses are an important component of reef flats in the Seychelles (Engelhardt, 2004) and these form beds which may adjust to sea level (Phillips and Durako, 2000). Therefore, sections of reef flats dominated by seagrasses were here assumed to rise with the gradual rise in sea level such that there was no increase in still water depth where seagrasses covered 100% of a zone.

Van der Land (1994) and references therein provide useful local information of pre-mortality conditions, which have also been monitored by one of us (RP). Where local knowledge or previous reports are missing, estimates were always conservative. Values were assumed not to change if there was no clear evidence or justification for doing so. Values for each zone of each reef were entered onto another excel sheet, which computed the averages used for input into the model 'WaveEnergy.xls'.

3. Results and discussion

3.1. Present condition of the reefs

Table 3 shows the values used for model input. In the Seychelles, most of the previously rich coral fauna, and thus most mortality, was located in the seaward one or two zones of each reef flat. The mortality also affected deeper areas on the reef slope to seaward of the reef flat, but this area is not an important factor in this model. Over 99% of all corals in these reef flat zones was dead in 2004 (see Fig. 2d–f). Most skeletons were disintegrating, though many central stumps of stout branching forms such as *Acropora palifera* still remained (Fig. 2e). Very few skeletons of other species were now taxonomically identifiable in situ, being heavily eroded, although it was still fairly clear whether they had been massive forms, stumps of table corals, or encrusting etc. Identification of any sort will not remain clear for much longer, given the observed rate of reduction. Much rubble has resulted from the mortality and this tended to complicate the present measurements, since it was never possible to be sure of the origin of the rubble and it was never assumed that their origin was where the rubble beds presently lay. This means that many previously existing rich stands of branching coral almost certainly had to be excluded from our measurements, and so our predicted 10 and 20 year changes of pseudo-sea level rise are underestimates in these cases.

The alarming extent of coral reduction was manifested both in terms of reduced roughness and greater depth on the reef flats, and was reflected in the values obtained for energy at the shore (Table 3, bottom rows). The measure tabulated is the energy of the non-breaking reformed waves propagating from the reef rim surf zone shoreward across the reef flat. Mitigating against the rise in energy over time to some degree was the slight rounding-off of the reef crest as the corals of this area were removed. In some cases erosion of the upper reef slope and reef crest has been sufficient to blend them smoothly into the outer zone of the reef flat over a near-indistinguishable boundary. This process reduces the reef profile parameter K_p and, fortuitously, reduces wave setup and consequently the energy reaching the shorelines.

Substantial seagrass beds grow on the shoreward zones of almost all of these reef flats. The assumption was made that they are able to accrete at least at the rate of present sea level rise of 5 mm y^{-1}. Little is known about the capacity of seagrasses to match current sea level rise; a recent review (Short and Neckles, 1999) had little to say on this aspect. That seagrasses offer some resistance to waves is clear (Fonseca and Calahan, 1992) so the assumption is made here that they can accumulate sediments and build vertically to the necessary degree. If this proves over-optimistic then the resistance they offer will likewise be less than modelled here.

The fate of extensive rubble beds is not speculated upon in terms of changes of depth or roughness factor. It is likely of course that they will move, or be reduced further to sand. This was observed but not quantified in some sites in this study, but as the extent of this could not be measured, the conservative assumption was made that their elevation on their zones of reef flats did not change, and that only the modest amount of ‘real’ sea level rise affected those parts of the reef flats.

3.2. Changes over time

The change in energy reaching shores over the three time periods is clear (Fig. 5). From these, it is seen that, even accepting errors in the measured estimates of the various parameters, there is considerably greater change forecast for the future than has taken place over the last decade. On average, and for most of these reefs separately, there has been an appreciable change over the past decade, one which matches local concerns of greater wave energy on shores, greater erosion of beaches and greater incursions behind beaches. More important, perhaps, is the unavoidable conclusion from Fig. 5 that the changes to come in the next decade are likely to be double those seen in the recent past.

There are some interesting differences between reefs. One very narrow reef (3: NE Point) never had significant coral on its reef flat (RP, personal observation) and has a reef flat of smooth limestone covered with turf algae. In this model the reef experiences sea level rise but, with no reef flat corals, there was no degradation resulting from a loss of corals. Therefore it showed little change in reef profile parameter initially, resulting in the atypical pattern here.

The percent of offshore energy which reaches the shoreline from the offshore waves is shown in Fig. 6. Behind the two very broad reef flats with widths >500 m (numbers 1 and 5), absolute energy was lower than behind narrow reefs (<100 m) by up to an order of magnitude, though the pattern of change over time was similar. Across broad reefs, energy loss may be as much as 99%, though it is more commonly 80% in most of these reefs. This is similar in magnitude to the average energy loss measured across reefs in the Caribbean and Torres Strait (Lugo-Fernandez et al., 1998; Brander et al., 2004). It underlines the overall degree of protection provided by coral reefs, and the importance of water depth over them. It also illustrates the extent to which the proportion of energy passing across these reefs increases over the two-decade period studied here.

3.3. Beaches and sand production

Beach formation in the granitic Seychelles arises from the breakdown of corals and other carbonate-depositing

Table 3
Values of input parameters into the model for each reef and, last 4 rows, key output values

Site number and name	1 Anse aux Pins	2 Fisher-mans cove	3 NE Point	4 Beau Vallon	5 Baie Ternay	6 Ternay-Laurnay	7 Port Launay	8 Moyenne1	9 Moyenne2	10 St Anne	11 Cerf/Cachee	12 Praslin Airport	13 E Praslin	14 La Digue
Input values														
Slope angle (2004)	5	30	10	30	15	15	60	30	50	45	60	5	30	20
K_p (1994)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
K_p (2004)	0.47	0.67	0.52	0.67	0.55	0.55	0.78	0.67	0.78	0.78	0.78	0.47	0.67	0.6
K_p (2014)	0.47	0.67	0.52	0.67	0.55	0.55	0.78	0.67	0.78	0.78	0.78	0.47	0.67	0.6
Mean tidal range R (cm)	85	85	85	85	85	85	85	85	85	85	85	85	85	85
sl rise cm (1994)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sl rise cm (2004)	13.75	20	5	13.75	15.75	20	17.5	30	42.5	42.5	25	30	22.25	31.25
sl rise cm (2014)	27.5	40	10	27.5	35.5	23.75	35	85	72.5	63.75	38.75	42.5	29.5	50
Reef width (m)	690	65	105	135	690	55	105	115	100	225	160	250	205	225
f_w (1994)	0.115	0.185	0.1	0.135	0.14	0.145	0.2	0.155	0.15	0.18	0.15	0.15	0.115	0.155
f_w(2004)	0.11	0.165	0.1	0.105	0.13	0.125	0.185	0.155	0.15	0.17	0.15	0.125	0.095	0.12
f_w(2014)	0.09	0.145	0.1	0.1	0.095	0.105	0.165	0.105	0.1	0.1	0.1	0.095	0.09	0.095
Output values of energy at shore (J m^{-2})														
1994	25	213	239	157	18	269	137	159	183	68	122	75	125	82
2004	31	308	212	233	25	362	205	263	378	171	197	147	215	185
2014	58	453	244	307	67	412	304	757	712	398	343	246	256	318

Input values for each reef are averages of the 4 zones for that reef. Slope of breaking zone is not an input value but is used to determine the reef profile factor, K_p. The lines showing sl rise show the sum of sea level rise plus pseudo-sea level rise.

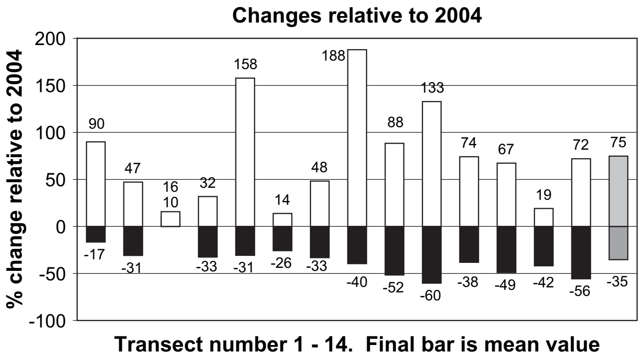

Fig. 5. Percent changes in energy on shores behind 14 reefs, compared to the present. Present time is the zero axis, black bars are the generally lower energy of a decade ago, white bars are the increased energy expected a decade in future. Right pair of bars with grey shading is the average of the 14 reefs. Sites 1–14 are ordered left to right, as shown in Table 3.

marine organisms; there are very few beaches where terrigeneous inputs are dominant. Consequently, loss of corals may be expected to be important. At present, the best-developed beaches are seen where the reefs are fairly narrow, while behind broader reef flats the beaches are narrower and coarse-grained. Beaches predominate on windward coasts (exposed to the dominant SE Trade winds), implying that wind generated wave action has an important role in the quality and type of beaches found. Because the granitic Seychelles lies outside the cyclone belt, reef and beach structure have evolved to withstand only the seasonal changes in wave conditions, rather than the violent conditions experienced by several other archipelagos. Partly as a consequence, the beaches in the Seychelles have been classified as some of the most attractive in the world, and have a corresponding importance to the national economy.

Several factors were not measured or measurable. It was clear that in one or two reefs there was a considerably increased production of sand and rubble as a result

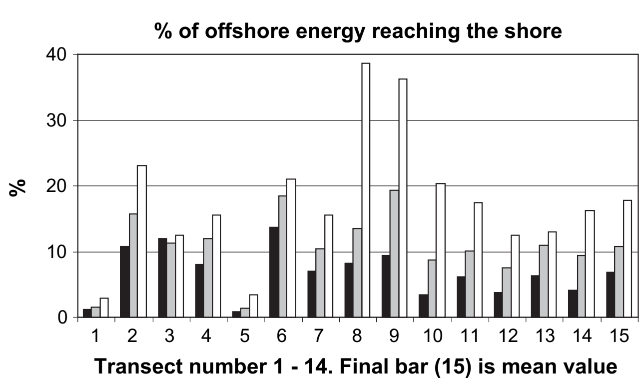

Fig. 6. Percent of offshore wave energy which reaches the shores behind each reef. Site labelled 15 at right is average of all reefs. Black bars = 1994; grey bars = 2004; white bars = 2014. Order of sites is 1–14, left to right, as for Table 3.

of disintegration of coral skeletons, especially of the 'staghorn' corals such as of the *Acropora formosa* group. Its fate and quantity was beyond the scope of the present investigations, but much currently may be being deposited on shore. Sandy deposits on some roads lying close to shores near present sea level suggest that this process may be occurring in such sites, and hence may be leading to complex patterns of increased deposition as well as erosion. Indeed, increased energy might be expected to lead to increased forcing of sand on shore (D. Hopley, pers. comm.). However, it should be noted that any present increased production of sand is not likely to persist beyond the point when the coral skeletons have eroded away completely, since the underlying more solid reef platform is much more dense than newly dead coral skeletons. Consequences to beaches therefore may be more serious in future than is indicated here, from this reason alone. In other parts of this ocean, substantially increased rubble and sand production resulted from the decay of vast, shallow staghorn coral beds (Sheppard et al., 2002; Sheppard and Loughland, 2002), though mostly this rubble and sand was swept off the reefs into deep water. Fringing reefs themselves exhibit a complex interplay between morphology, growth and behaviour of produced sediments (Kennedy and Woodroffe, 2002), such that mortality of corals and change in rate of sediment production can be expected to have marked consequences.

3.4. Acclimation and adaptation of corals

An important assumption here was that corals will not significantly recover. This gloomy prediction is supported by three factors. Firstly, there is the prediction that sea temperatures will continue to rise such that mortality events will not only recur but will do so with increasing frequency. Several analyses and models now suggest this is likely (Hoegh-Guldberg, 1999; Hughes et al., 2003; Sheppard, 2003), and from the last of these, Fig. 7 shows the predicted recurrence of the 1998 lethal sea surface temperatures in the granitic Seychelles. A value of $p = 0.2$, which will occur by about 2028, is likely to define the final extinction point for these reefs, given that the average age of corals at first reproduction is commonly 5 years. Secondly, it was clear from fieldwork in 2004 that much of the new recruitment of corals following 1998 has already been heavily set back from a repeat warming event in the very recent past; very few young corals are now seen on shallow Seychelles reefs, and indeed many dead juveniles were seen, including many examples which had recruited onto the skeletons of older, dead corals. Thirdly, the ability of corals to acclimate sufficiently rapidly to permit them to tolerate raised temperatures is far from certain (Gates and Edmunds, 1999; Pittock, 1999;

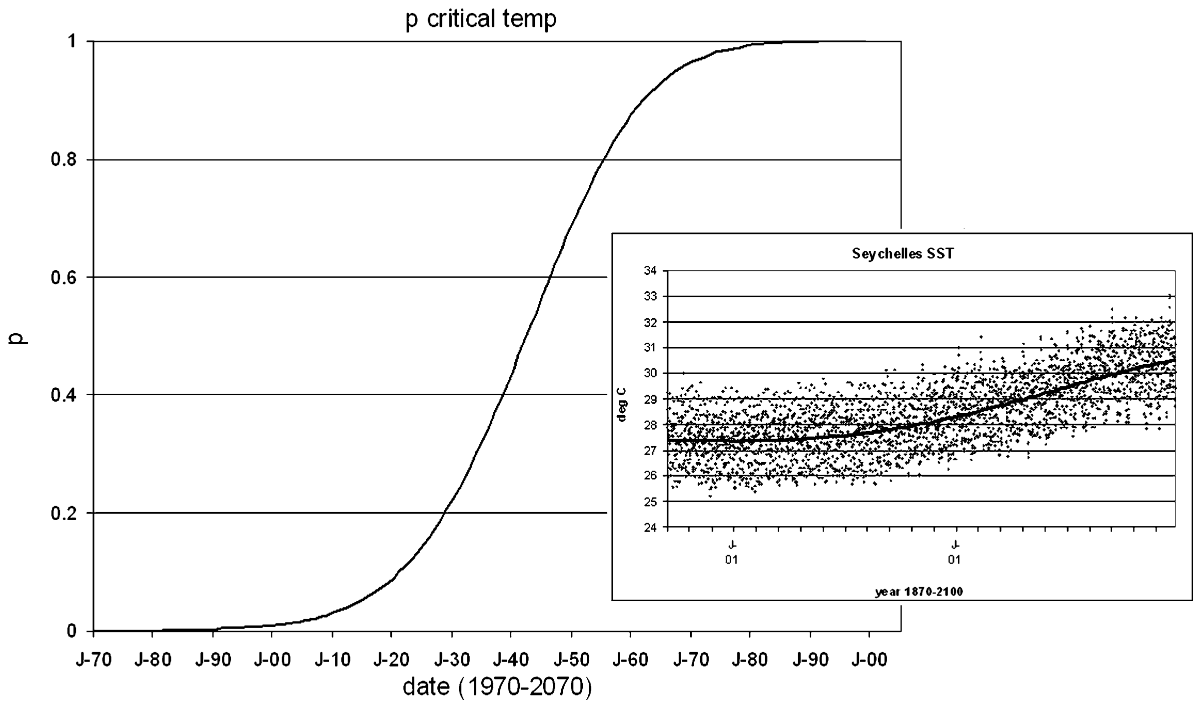

Fig. 7. Probability of recurrence of the lethal 1998 sea surface temperature in the granitic Seychelles. p = probability. Inset: the full SST curve for granitic Seychelles, 1870–2100 (from Sheppard 2003).

Douglas, 2003). Predictions of non-recovery, in other words, are likely to be correct.

The potential for further reef reduction given continuing coral mortality is clear, but few quantitative numbers are available. In the present study, increased depth of the reef (pseudo-sea level rise) is restricted to the heights of the living corals. However, erosion of the reef flat platforms themselves is also possible. Vertical accretion of healthy reefs may be about 4 mm y^{-1} (Buddemeier and Smith, 1988) which, if sustained, would be generally or nearly sufficient to match sea level rise. However, heavy mortality of the shallow reef building corals changes this equation. An early example of what this can mean is described by Eakin (1996) who noted that a Panama reef, which had previously been depositing 0.34 kg $CaCO_3\,m^{-2}\,y^{-1}$, was eroding at about 0.19 kg $CaCO_3\,m^{-2}\,y^{-1}$. This is equivalent to a vertical loss of about 6 mm y^{-1}. This transformation came about from only a 50% coral mortality after the 1982 El Niño event. In the Seychelles, the mortality was more nearly 100%, though in this location the corals were mostly restricted to outer zones of reef flats.

Some of the major changes to shorelines are occurring from sea level rise (Leatherman et al., 2000; Woodroffe, 2003; Woodworth et al., in press). The equivalent of a localised sea level rise caused by a lowering of these reef flats in the Seychelles is greater than the global rate by an order of magnitude or greater. Even though this affects only the seaward zones of each reef flat in the Seychelles, its consequences appear to be significant. The fact that substantial expanses of reef flat are densely colonised by seagrasses is very important, and reaffirms the importance of their continued conservation.

The model may be changed as desired. Perhaps the most important finding from this study has been that, despite the substantial attention paid to the calamity of such massive coral mortality, most of the damaging effects in connection with shoreline protection may be still to come.

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Appendix A.

A1. Summary of equations used

The equation used to model the wave set-up on the reef flat is from eqs. (3) and (5) of Gourlay (1997):

$$\overline{\eta}_r = \frac{3}{64\pi} K_p \frac{g^{1/2} H_o^2 T}{(\overline{\eta}_r + h_r)^{3/2}} \left[1 - 0.16 S^2\right]$$

where S the relative submergence of the reef is expressed as:

$$S = \frac{\overline{\eta}_r + h_r}{H_o}$$

This is a simplified version of equation (8), developed by Gourlay (1996b) using a combination of energy flux and radiation stress theories.

The terms in square brackets are referred to as P_T the wave transmission parameter. If $S \geq 2.5$, complete transmission occurs and the wave does not break at the reef edge, $P_T = 0$ and there is no set-up at all. The transmission term P_T should be considered when $S < 2.5$. $P_T = 1$ when $S = 0$, since $\overline{\eta}_r = -h_r$ and all wave energy is dissipated on the reef-face without any over topping of the reef-crest.

A2. Reef top wave height decay due to friction/roughness

The decay of reef top wave heights due to reef top friction/roughness can be calculated from the following (Gourlay, 1996b):

$$\frac{dH_{rs}}{dx} = -\frac{f_w}{3\pi} \frac{H_{rs}^2}{(\overline{\eta}_r + h_r)^2}$$

Field data indicate that the maximum significant wave height on a horizontal reef-top is 0.4 times actual water depth, $H_{rs} = 0.4(\overline{\eta}_r + h_r)$, (Hardy et al., 1990; Gourlay, 1997). This is a more realistic value than previous estimates of 0.55 up to 0.8 discussed by Nelson (1994). The latter values apply to individual maximum wave heights.

A3. Wave energy density E

This is the combined kinetic and potential energy in a moving wave expressed as:

$$E = \frac{1}{8}\rho g H^2$$

where

E, energy per unit surface area ($J\,m^{-2}$)
f_w, wave bottom frictional factor
H_o, wave height offshore-deep water (m)
H_{rs}, wave height on reef flat – significant height (m)
h_r, water depth on reef flat (m)
$\overline{\eta}_r$, wave set-up on reef flat
K_p, reef profile gradient factor of the reef face slope
P_T, transmission factor of waves
S, relative submergence of reef $= (\overline{\eta}_r + h_r)/H_o$
T, wave period offshore in deep water (s)
x, distance along reef flat
g, gravitational acceleration 9.81 $m\,s^{-2}$
ρ, density of seawater 1025 $kg\,m^{-3}$.

Notes on application of the above equations

1. In applying the above equations to obtain absolute values for engineering design purposes etc., the offshore wave height should be the root mean square wave height H_{orms}, which is equal to $H_{os}/\sqrt{2}$, where H_{os} is the offshore significant wave height (Gourlay, 1996b, 1997). However, the validity of the comparative results presented in this paper is unaffected by neglect of this distinction.
2. The above equation for decay of reef top wave heights assumes that the reformed waves propagating across the quasi horizontal reef flat do not loose significant energy by breaking. If this were not the situation then it would be necessary to use a relationship which allowed for energy dissipation by both breaking and bottom friction, e.g. that proposed by Dally et al. (1985).

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