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Projecting the risk of damage to reef-lined coasts due to intensified tropical cyclones and sea level rise in Palau to 2100

Chuki Hongo[1,2], Haruko Kurihara[1,2], Yimnang Golbuu[3]

[1]Department of Chemistry, Biology, and Marine Science, Faculty of Science, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan
[2]JST (Japan Science and Technology Agency)/JICA (Japan International Cooperation Agency)/SATREPS (Science and Technology Research Partnership for Sustainable Development)
[3]Palau International Coral Reef Center, 1 M-Dock Road, PO Box 7086, Koror 96940, Republic of Palau

Correspondence to: Chuki Hongo (g123001@sci.u-ryukyu.ac.jp)

Abstract. Tropical cyclones (TCs), sea level rise (SLR), and storm surges cause major problems including beach erosion, saltwater intrusion into groundwater, and damage to infrastructure in coastal areas. The magnitude and extent of damage is predicted to increase as a consequence of future climate change and local factors. Upward reef growth has attracted attention for its role as a natural breakwater able to reduce the risks of natural disasters to coastal communities. However, projections of change in the risk to coastal reefs under conditions of intensified TCs, SLR, and storm surges are poorly quantified. In this study we assessed the current status of natural breakwaters on Melekeok reef in the Palau Islands. Based on wave simulations we predicted the potential effects on the reef by 2100 of intensified TCs (significant wave height at the outer ocean = 8.7–11.0 m; significant wave period at the outer ocean = 13–15 s), SLR (0.24–0.98 m), and storm surge. The simulation was conducted for two reef condition scenarios: a degraded reef and a healthy reef. Analyses of reef growth based on drillcores enabled an assessment of the coral community and rate of reef production that are necessary to reduce the risk to the coast of TCs, SLR, and storm surges. The reef is currently highly effective in dissipating incoming waves, with the reef crest to the upper reef slope reducing wave height by 75%, and the entire reef dissipating waves by 88% of the incident wave height. However, our calculations show that under intensified TCs, SLR, and storm surges, by 2100 significant wave heights at the reef flat will increase from 1.05–1.24 m at present to 2.14 m if reefs are degraded. Similarly, by 2100 the sea level at the shoreline will increase from 0.86–2.10 m at present to 1.19–3.45 m if reefs are degraded. These predicted changes will probably cause beach erosion, saltwater intrusion into groundwater, and damage to infrastructure. However, our simulation indicates that reef growth reduces the wave height by a maximum of 0.44 m at the reef flat by 2100. These findings emphasize the need for future reef formation to reduce the damaging effects of waves on the coastline. Corymbose *Acropora* corals will be key to reducing such effects, and 2.6–5.8 kg $CaCO_3/m^2/y$ will be required to build the reef by 2100. If the RCP 8.5 scenario is realized by 2100, an increase in coral cover of >8% will be needed to reduce the impact of waves on the coastline. The use of coral reef growth to reduce disaster risk will be more cost-effective than building artificial

barriers. Benefits in addition to reducing disaster risk include the ecological services provided by reefs, and marine products and tourism. Research of the type described here will be required to advise policy development directed at disaster prevention for small island nations, and for developing and developed countries.

1 Introduction

Approximately 90 tropical cyclones (TCs; also referred to as hurricanes and typhoons) occur globally every year (Frank and Young, 2007; Seneviratne et al., 2012). TCs cause large waves, storm surges, and torrential rainfall, and can lead to coastal erosion, salinization of coastal soils, and damage to infrastructure (Gourlay, 2011a). These negative impacts have major economic costs. For example, the economic cost of TC Pam (category 5 on the Saffir–Simpson scale), which affected Vanuatu in March 2015, exceeded US$449 million, equivalent to ~64% of the GDP of Vanuatu (GFDRR, 2016).

Numerical projections indicate that climate change will increase the mean maximum wind speed of TCs (Christensen et al., 2013). Towards the end of the 21st century, the wind speed and minimum central pressure of the most intense super typhoons in the northwest Pacific Ocean are estimated to attain 85–90 m/s and 860 hPa, respectively (Tsuboki et al., 2015). Additionally, sea level rise (SLR) caused by global warming will probably increase the risk of coastal erosion, flooding, and saltwater intrusion of surface water (Woodruff et al., 2013). Economic development and population growth are also expected to increase the baseline damages (World Bank and UN, 2010). Therefore, the development of policies for adaptation to TCs and SLR is essential if their projected negative impacts in the near future are to be adequately addressed.

There are been several approaches to reducing the effects of TCs and SLR, including the construction of sea walls and shelters, developing accurate weather forecasts, and developing TC and SLR warning systems (GFDRR, 2016). However, small island nations and developing countries will need to develop cost-effective strategies to address the problems associated with these phenomena, including the use of ecosystem services provided by mangroves and coral reefs. For example, mangrove restoration has been demonstrated to attenuate wave height, and reduce wave damage and erosion (Wong et al., 2014). It has also been suggested that coral reefs are highly effective as natural breakwaters. More than 150,000 km of the shoreline in 100 countries and territories is thought to receive some protection from reefs (Burke et al., 2011). Meta analysis has demonstrated that the entire reef system, from reef slope to reef flat, reduces wave height by an average of 84% (Ferrario et al., 2014). Coral reefs are also habitats for diverse marine organisms and provide various services (e.g., tourism and marine product) that benefit human populations. Additionally, it has been suggested that reefs can be considered to represent self-adapting “green infrastructure” (Benedict and McMahon, 2002) in ocean that protects against SLR and TCs. The growth of Holocene reefs has been reported to have kept pace with the SLR that occurred in the period 19–6 ka (Montaggioni and Braithwaite, 2009). This suggests that reef growth, as a form of green infrastructure, may be able to respond to SLR and contribute to reducing the impacts of TCs and SLR in the future.

Approximately 75% of the world’s coral reefs are subject to local threats such as coastal development, watershed pollution, and overfishing (Burke et al., 2011). Additionally, global climate change, including global warming and ocean acidification, is expected to have major impacts on coral reefs. Sheppard et al. (2005) indicated that the effectiveness of reefs in coastal protection decreased under calm ocean conditions (significant offshore wave heights of 1.25 m) because of coral mortality that occurred in 2004 and 2014. Ocean acidification reduces the $CaCO_3$ saturation rate, reduces the calcification rate of corals, slows coral growth, and can lead to the dissolution of the reef frameworks (Anthony et al., 2007). This suggests that the effectiveness of reefs as natural breakwaters will change in the future. However, few studies have considered how the effectiveness of reefs as natural breakwaters may change as healthy reefs become degraded under future climate conditions.

This study had three main aims. Firstly, we evaluate the effectiveness of coral reefs in Palau as a natural breakwater for waves and water level change under present TC and sea level conditions. The Palau Islands are rarely affected by TCs, although two severe TCs (Typhoon Bopha in 2012 and Typhoon Haiyan in 2013) recently impacted the islands. These storms caused 56%–83% loss of coral cover on the shallow slopes of the eastern reefs (Gouezo et al., 2015), and this had a significant impact on the country. Secondly, we provide a quantitative projection of wave heights and water level change for the reef under intensified TC and SLR conditions, projected for the 21st century. Thirdly, we estimate the reef production rate necessary to reduce the risk under the predicted reef degradation.

2 Methods

2.1 Study site

Melekeok reef (7.501°N, 134.640°E) is located on the eastern coast of Babeldaob Island (Figure 1a). There is no artificial breakwater for ocean waves along the reef. The reef was devastated by Typhoon Bopha in December 2012, and the coastal area was damaged (destruction of piers, erosion, flooding) (Figure 1b). Most communities on the coast are at an altitude of ~3 m above the present mean sea level (MSL) (Figure 1c).

2.2 Estimation of wave height and water level

We first quantitatively assessed the effectiveness of Melekeok reef in attenuating waves and reducing flooding. We then calculated the effectiveness of the reef in terms of disaster reduction under conditions expected to occur by 2050 and 2100. We focused on two parameters: (1) the significant wave height (SWH) at the reef flat (SWH_r); and (2) the water level at the shore (WL_s). SWH was defined as the mean wave height of the highest 33% of waves.

To estimate the wave parameters we used the CADMAS-SURF (Super Roller Flume for Computer Aided Design of Marine Structure) wave simulation model (CDIT, 2001). This is a specialized numerical wave tank model used for assessing the threshold of destruction for structures (e.g., sea walls); its use also contributes to coastal management decisions. The governing equation in the model is based on the extended Navier–Stokes equations for a two-dimensional wave field in

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porous media. The time resolution was 0.01 s and the calculation time was 3600 s. We used data for 1801–3600 s. The model has been successfully applied to waves breaking at coral reefs under TC conditions (Kawasaki et al. 2007; Hongo et al. 2012; Nakamura et al. 2014; Watanabe et al. 2016). The model calculates wave characteristics (wave velocity and water level) using four input parameters: (1) incident significant wave height at the outer ocean (SWH_o); (2) incident significant wave period at the outer ocean (SWP_o); (3) incident water level at the outer ocean (WL_o); and (4) topography. The model output is given as arbitrary grid data. Data for SWH_r were calculated using the output from the zero-up crossing method. The four parameters are discussed below.

(1) SWH_o: The present-day SWH_o value for Melekeok reef was obtained at 27 km resolution using the Global Forecast System (GFS) model, provided by Windguru (see http://www.windguru.cz). When Typhoon Bopha crossed Palau, the SWH_o was 8.70 m and the average wind speed was 27 m/s at Melekeok reef. Numerical experiments have shown that the maximum wind speeds of TCs in the northwest Pacific will increase by 19% by the late 21st century as a consequence of global warming (Tsuboki et al., 2015). This implies that SWH_o will increase in the future, but will probably vary among study sites as a function of wind speed and the path of TCs. Projecting wind speed depends on future greenhouse gas emission pathways. Therefore, we assumed that TCs are characterized by a minimum central pressure of 900 hPa. We also assumed that the future maximum SWH_o at Palau reef will be comparable to the TCs that typically affect the Ryukyu Islands (northwest Pacific). These include Typhoons Shanshan (0613) and Talim (0513), which the Japan Meteorological Agency (JMA) reported had wind speeds and SWH_o of 26–34 m/s and 10.6–11.3 m, respectively (JMA, 2012; see http://www.data.jma.go.jp/gmd/kaiyou/db/wave/chart/daily/coastwave.html). Consequently, we assumed that by 2100 the SWH_o will range from 8.70 to 11.0 m.

(2) SWP_o: The SWP_o during Typhoon Bopha was 13.0 s (based on the GFS Windguru model: see http://www.windguru.cz) and was recorded as a peak period (P_{peak}). The empirical P_{peak}:SWP ratio is approximately 1 (≈ 0.95); consequently, we assumed the value of P_{peak} equated to SWP_o. As an analogy, the SWP_o during the severe typhoons Shanshan and Talim in the Ryukyu Islands was 13.0–15.0 s (see JMA: http://www.data.jma.go.jp/gmd/kaiyou/db/wave/chart/daily/coastwave.html). Therefore, we assumed that the future SWP_o at Palau reef will range from 13.0 to 15.0 s.

(3) WL_o: We assumed that the WL_o ranges from 0 to 2.78 m above the present MSL, based on future SLR, tidal ranges, and storm surges. The future SLR is predicted to range from +0.24 m to +0.30 m by 2050, and from +0.44 m to +0.98 m by 2100, based on the Intergovernmental Panel on Climate Change (IPCC) scenarios RCP 2.6 and RCP 8.5, respectively (Church et al., 2013). At the Palau Islands the tidal range is ~1.60 m during spring tides, and the high tide is ~0.80 m above MSL. Storm surges lead to extreme SLR when TCs make landfall. We assume that the WL will increase to 1.00 m above MSL as a result of the suction effect of TCs.

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(4) Topography: We established a transect of 2000 m width that extended from 21 m above MSL at the shore to 269 m water depth in the outer ocean. The topography along the transect was determined using a topographic map (USGS, 1983) on land, and was measured using an automatic level (NIKON-TRIMBLE, AE-7) and an aluminum staff from the shore to the reef crest, and a single beam echo sounder (Honda Electronics, PS-7) on the reef slope at water depths of 0–75 m. At water depths of 75–269 m the topography was assumed to increase with depth at an angle of 23°. The field survey was conducted in July and September 2015. We used two reef condition scenarios for predicting vertical reef growth from the reef crest to the upper reef slope to 2100. The first was that reefs are healthy and have a growth rate equal to the SLR, and the second was that the reef is degraded and no growth occurs (Figure 1d).

2.3 Estimation of future reef production rate

We estimated the potential future rate of reef production (kg $CaCO_3/m^2/y$) using drillcore from the reef crest at Ngerdiluches reef in the Palau Islands (Figure 1a). One reef crest core (PL-I; 25 m long) was recovered from Ngerdiluches reef (Kayanne et al., 2002). The thickness of the Holocene sequence is 14.5 m long. The Holocene sequence comprised two facies: (1) corymbose *Acropora* facies; and (2) arborescent *Acropora* facies (Hongo and Kayanne, 2011). We weighed all samples and measured the density of each facies. Assuming that the reef crest has a homogenous structure, the production rate of the reef crest is given by following Eq. (1):

$$R = \frac{\rho H}{t} \quad (1)$$

where R (kg $CaCO_3/m^2/y$) is the production rate of the reef crest, ρ is the density (kg $CaCO_3/m^3$), H (m) is the thickness of the reef crest, and t (y) is the duration of vertical reef formation. We used two reported radiocarbon ages for arborescent *Acropora* facies (PL- I-79: 8.31 ka, –15.1 m below MSL; PL- I-67: 7.39 ka, –12.0 m below MSL) and four radiocarbon ages for corymbose *Acropora* facies (PL- I-43: 7.25 ka, –6.8 m below MSL; PL- I-26: 7.15 ka, –4.4 m below MSL; PL- I-8: 6.28 ka, –2.5 m below MSL; PL- I-3: 3.92 ka, –1.8 m below MSL) (Kayanne et al., 2002; Hongo and Kayanne, 2011). We assumed that the range of upward reef growth rate (i.e., H/t) was 3.4–37.1 m/kyr (between samples PL- I-79 and PL- I-67, and samples PL- I-67 and PL- I-43) for arborescent *Acropora* facies in response to 10 m/kyr of Holocene SLR, 24.0 m/kyr (between samples PL- I-43 and PL- I-26) for corymbose *Acropora* facies in response to 10 m/kyr of Holocene SLR, 2.2 m/kyr (between samples PL- I-26 and PL- I-8) for the facies in response to 5 m/kyr of Holocene SLR, and 0.3 m/kyr (between samples PL- I-8 and PL- I-3) for the facies in response to <5 m/kyr of Holocene SLR.

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3 Results

3.1 Present-day reef

Melekeok reef has distinctly zoned landforms, comprising the reef flat and reef slope (Figure 1d). The reef flat is ~1000 m wide and consists of a shallow lagoon (900 m wide) and a reef crest (100 m wide). The shallow lagoon (~1 m deep) is situated between the shore and the reef crest. The elevation of the road is 2.86 m above MSL (Figure 1d).

The SWH_o was found to rapidly decrease from the upper reef slope to the reef crest (Figure 2). Under present-day TCs (8.70 m SWH_o, 13.0 s SWP_o), the SWH at the reef crest was 2.15 m and the SWH_r was 1.05 m (case 1, Table 1). The reef crest dissipated 75.3% of the SWH_o. The shallow lagoon dissipated 51% of the remaining wave height at the reef crest. The entire reef dissipated 87.9% of the SWH_o. The WL_s was 0.86 m for present-day TCs (case 30, Table2) and the WL_s increased to 2.10 m under storm surge conditions (case 31, Table 2).

3.2 Future wave height at the reef flat

The SWH_r was found to increase to a maximum of 2.14 m for degraded reefs and to 1.80 m for healthy reefs under intensified TCs, SLR, and storm surges by 2100 (Table 1). An increase in the intensity of TCs will cause an increase in the SWH_r. For example, an SWH_r value of 1.22 m for a healthy reef under present TC conditions (8.70 m SWH_o, 13.0 s SWP_o) (case 4) will increase to 1.52 m (+24.6%) in 2050 with more intense TCs (10.0 m SWH_o, 14.0 s SWP_o) (case 8), and increase to 1.66 m (+36.1%) with the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o) (case 12). Overall, the increase in TC intensity will increase the SWH_r by 38.0 ± 16.0% (mean ± SD, n = 17) for degraded reefs and by 30.7 ± 18.2% (mean ± SD, n = 17) for healthy reefs (Table S1).

Moreover, the SLR will cause a slight increase in the SWH_r. For example, 1.66 m in SWH_r at a healthy reef under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o) and 0.24 m in SLR (case 12) will increase by 0.30 m in SLR to 1.70 m (+2.4%, 0.30 m in SLR; case 14) and to 1.77 m (+6.6%, 0.44 m in SLR; case 26). Consequently, the effect of SLR will increase the SWH_r by 6.5 ± 11.0% (mean ± SD, 21) at degraded reefs and by 3.0 ± 9.2% (mean ± SD, n = 23) at healthy reefs (Table S1).

Furthermore, storm surges (1.00 m) will also increase the SWH_r. For example, storm surges will cause an increase in the SWH_r from 1.09 m to 1.35 m (+23.9%) at healthy reefs subject to a TC (8.70 m SWH_o, 13.0 s SWP_o; between cases 5 and 6). As another example, under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o; between cases 11 and 12), storm surges will cause an increase in the SWH_r at healthy reefs from 1.49 m to 1.66 m (+11.4%). Consequently, storm surges will increase the SWH_r by 20.1 ± 14.9% (mean ± SD, n = 13) at degraded reefs, and by 17.3 ± 14.8% (mean ± SD, n = 14) at healthy reefs (Table S1).

The modeling showed that in all but 6 cases (cases 5, 6, 11, 18, 24, and 27) the SWH_r was reduced to 0.01–0.44 m by upward reef growth by 2100 (Table 1). For example, 0.24 m in upward reef growth caused a 0.24 m reduction in the

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SWH_r (from 1.45 m for degraded reef to 1.21 m for healthy reef) under more intense TCs (10.0 m SWH_o, 14.0 s SWP_o) (case 7). This indicates that reef growth enhanced the reduction in wave height from 85.5% at degraded reefs to 87.9% at healthy reef (case 7, Table S1). Similarly, under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o), SLR (0.98 m), and storm surge (1.00 m) in 2100 (case 29), 0.98 m in reef growth caused a 0.20 m reduction in the SWH_r (from 2.00 m for the degraded reef to 1.80 m for the healthy reef; Figure 3a); thus, the role of the reef as a natural breakwater increased from 81.8% for the degraded reef to 83.6% for the healthy reef (Table S1). Overall, as a result of reef growth, the wave reduction rate increased from 84.6% at degraded reefs to 86.0% at healthy reefs (Table S1).

3.3 Future water level at the shore

The modeling showed that the WL_s will increase from 0.86–2.10 m at present to 1.19–3.45 m at degraded reefs and to 1.24–3.51 m at healthy reefs under intensified TCs, SLR, and storm surges by 2100 (Table 2). An increase in the intensity of TCs will cause an increase in the WL_s. For example, a 1.24 m WL_s at a healthy reef under a current modeled TC (8.70 m SWH_o, 13.0 s SWP_o) (case 32) will in 2050 increase to 1.55 m (+25.0%) under more intense TCs (10.0 m SWH_o, 14.0 s SWP_o) (case 36), and increase to 1.90 m (+53.2%) under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o) (case 40). Overall, the increase in intensity of TCs resulted in an increase in the WL_s by 22.7 ± 15.3% (mean ± SD, n = 17) for the degraded reef and by 21.4 ± 13.3% (mean ± SD, n = 17) for the healthy reef (Table S2).

The WL_s will also be increased by SLR. For example, the WL_s at a degraded reef subjected to a present modeled TC (8.70 m SWH_o, 13.0 s SWP_o) increased from 1.19 m with 0.24 m SLR (case 32) to 1.50 m (+26.1%) with 0.44 m SLR (case 44), and to 1.82 m (+52.9%) with 0.74 m SLR (case 46). Overall, SLR increased the WL_s by 8.7 ± 18.1% (mean ± SD, n = 21) for the degraded reef and by 32.2 ± 37.8% (mean ± SD, n = 23) for the healthy reef (Table S2).

Storm surge also directly increased WL_s. For example, by 2050 this effect caused an increase in WL_s from 1.87 m to 2.87 m (+1.00 m, +53.5%) for the degraded reef and from 1.90 m to 2.86 m (+0.96 m, +50.5%) for the healthy reef under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o) and SLR (0.24 m) (cases 40–41, Table S2). Overall, storm surge significantly increased the SWH_r by 56.5 ± 17.2% (mean ± SD, n = 13) for the degraded reef and by 59.5 ± 27.7% (mean ± SD, n = 14) for the healthy reef (Table S2).

The difference in WL_s between degraded and healthy reefs was found to range from only –0.11 to 0.07 m by 2100. For example, by 2050 no difference in WL_s was found between the degraded and healthy reefs under intense TCs (11.0 m SWH_o, 15.0 s SWP_o) and SLR of 0.30 m (case 43). Similarly, a difference of only 0.01 m in WL_s was found between degraded and healthy reefs under more intense TCs (10.0 m SWH_o, 14.0 s SWP_o) (case 53), even with a difference of 0.74 m in upward reef growth.

We found that a road (+2.86 m above MSL) adjacent to the study site would be flooded in 6 cases (cases 41, 43, 53, 55, 57, and 58, Table 2) of intensified TCs, SLR, and storm surge. In the worst scenario, in 2100 under the most intense TCs

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(11.0 m SWH_o, 15.0 s SWP_o), 0.98 m SLR, and a storm surge of 1.00 m, the WL_s was found to increase to 3.45 m for the degraded reef and to 3.51 m for the healthy reef (case 58, Figure 3b).

3.4 Potential reef production in mitigating wave risk

The Holocene reef density (ρ), determined from the PL-I core, was 720 kg $CaCO_3/m^3$ for arborescent *Acropora* facies and 590 kg $CaCO_3/m^3$ for corymbose *Acropora* facies. The estimated reef production rate (R) ranged from 2.4 to 26.7 kg $CaCO_3/m^2/y$ for arborescent *Acropora* facies, and from 0.3 to 14.2 kg $CaCO_3/m^2/y$ for corymbose *Acropora* facies, depending on the upward reef growth rate and the Holocene SLR (Figure 4). The lower part of the reef was composed of both arborescent and corymbose *Acropora* facies when SLR was 10 m/kyr, whereas the upper part of the reef comprised only corymbose *Acropora* facies when SRL was <5 m/kyr.

The value of R needed for growth of the Melekeok reef to keep pace with future SLR to 2100 was calculated to be 5.3 to 7.1 kg $CaCO_3/m^2/y$ for arborescent *Acropora* facies and 2.6 to 5.8 kg $CaCO_3/m^2/y$ for corymbose *Acropora* facies, based on the assumption that the future $CaCO_3$ density and reef growth rate will be equivalent to those of the Holocene reef (Figure 4).

4 Discussion

4.1 Coastal risks increase in the future

Our results show that Melekeok reef is highly effective in dissipating waves, with the reef crest alone reducing the SWH_o by 75% and the entire reef able to reduce the wave height by 88%. Other reefs (e.g., US Virgin Island, Hawaii, Australia, and Guam) have been reported to reduce wave height by an average 64% (n = 10, 51%–71%) at the reef crest, and by an average of 84% (n = 13, 76%–89%) for the entire reef (Ferrario et al., 2014). Generally, greater wave dissipation efficiency is associated with steep topography from the upper reef slope to the reef crest, because of the rapid decrease in water depth (i.e., shoaling of waves), and wider reef flats are reported to have greater dissipation efficiency (Sheppard et al., 2005). The reef in the present study is characterized by a steep reef topography and a wide reef flat (~1000 m wide).

However, our wave calculations show that increasing TC intensity, SLR, and storm surges will causes an increase in SWH_r by 2100, even under healthy reef conditions. An increasing wind speed because of climate change (Christensen et al., 2013) will directly cause increasing SWH_o. Water tank experiments have shown a positive relationship between SLR and increasing wave height (Takayama et al., 1977). Sheppard et al. (2005) reported a positive relationship between SLR and wave energy density (an increase in SLR of ~0.2 m increased the density by ~100 J/m^2) at the Seychelles, with the density being proportional to the wave height squared. These studies suggest that the shoreline at Melekeok reef will be at greater risk of damage from waves in the future because of climate change. TCs generating large waves typically cause significant beach erosion, as occurred in Tuvalu (Connell, 1999; Sato et al., 2010).

The present results also show that increasing TC intensity, SLR, and storm surges will cause an increase in the water level at the shore (WL_s) of Melekeok reef, even under healthy reef conditions, with SLR and storm surges directly increasing the WL_s. Furthermore, an increase in wave height as a result of the increasing intensity of TCs will cause an increase in WL_s. An increase in WL_s is likely to be explained by the wave set-up and run-up at the shore. Wave set-up occurs if waves break in the reef crest–reef slope zone; the wave thrust decreases as the breaking surge travels shoreward, and consequently the water level rises (Gourlay, 2011b). Laboratory experiments and field observations have generally indicated that wave set-up increases with increasing incident wave height and wave period (Nakaza et al., 1994; Gourlay, 2011b). This implies that the occurrence of more intense TCs will cause an increase in wave set-up. Furthermore, water levels generally increase with decreasing water depth toward the shore (i.e., wave shoaling). If storm surges occur, the coastal area at Melekeok reef will be flooded (Table 2). This could lead to the destruction of infrastructure, because many buildings (including the elementary school) are located at ~3 m above the MSL. In addition, saltwater intrusion into groundwater could cause long-term problems for water management, including declining water quality for drinking and agriculture (Rotzoll and Fletcher, 2013).

4.2 Coastal risk reduction through future reef growth

Our results indicate no significant upward reef growth in response to changes in WL_s. This can be explained by the nature of coral reefs, which are porous structures characterized by a high degree of water permeability. The healthier a reef, the greater its effectiveness at reducing wave heights in the future. On average, reef growth resulted in an increase in the reduction rate from SWH_o to SWH_r of 84.6% to 86.0%, and it reduced SWH_r by a maximum of 0.44 m. The reduction is explained by the following three processes. (1) Future coral growth in the reef crest–upper reef slope zone will increase the dissipation of waves breaking as the water depth decreases (Figure 5). The breaking of waves will occur in shallow water when the ratio of wave height to water depth approaches 0.8 (Gourlay et al., 2011c). Based on many field observations at other reefs and the results of water tank experiments (Takayama et al., 1977; Nakajima et al., 2011), a rapid decrease in water depth at the zone results in an increase in wave height. (2) Upward reef growth will increase the reef angle in the wave breaking zone as a result of a rapid decrease in water depth in this zone. This process also results in an increase in wave breaking. (3) With upward reef growth the wave breaking zone will probably migrate from its present location towards the ocean. This process will expand the area of wave height reduction, and consequently wave heights will decrease on the reef flat. The above factors emphasize the need for future reef formation and growth to reduce the risk of damage by waves.

Corymbose corals at the study site will contribute to reef formation by 2100, in response to future SLR. The upper part of the Holocene reef at the reef crest on Ngerdiluches reef, in the Palau Islands, was composed of corymbose *Acropora* facies, mainly *A. digitifera*, *A. robusta*/ and *A. abrotanoides* (Hongo and Kayanne, 2011). Although the dominant corals at Melekeok reef have yet to be documented, the corymbose *Acropora* facies on reef crests in the Palau Islands is generally composed of *A. digitifera*, *A. hyacinthus*, and *Acropora humilis* (Kayanne et al., 2002; Yukihira et al., 2007). These coral types are highly resistant to wave action at water depths of 0–7 m, and their preferred habitat (good light penetration and high oxygen concentrations) enables vigorous upward growth. In contrast, arborescent *Acropora* corals (e.g., *A. muricata* and *A. intermedia*) will probably be overturned and broken by high wave energy in shallow water depths, and so will not contribute to upward reef formation at the reef crest by 2100.

Our results indicate that if the present MSL increases by 0.44 m (mean value for RCP 2.6) to 0.74 m (mean value for RCP 8.5) by 2100, maintaining reductions in the wave height at the study reef will require 2.6–4.4 kg $CaCO_3/m^2/y$ to support upward reef growth by the corymbose *Acropora* facies (Figure 4d). Similarly, 5.8 kg $CaCO_3/m^2/y$ will be required to maintain wave height reduction by the facies under 0.98 m SLR by 2100 (highest value for RCP 8.5). Field measurements of the reef crest community at the core site following the mass bleaching event in 1998 showed that the calcification rate decreased from 130 to 74 mmol C/m^2/day, equivalent to a rate of 4.7–2.7 kg $CaCO_3/m^2/y$ (Kayanne et al., 2005). Coinciding with the bleaching event, the coral cover decreased from 8.1% to 1.4% (Kayanne et al., 2005). Therefore, we assume that if the coral cover is ~1% in 2100 the corals will keep pace with 0.44 m SLR under RCP 2.6, but >8% coral cover will be needed under RCP 8.5 to reduce wave height and the risk of coastal damage at the study site.

However, if mortality of corymbose *Acropora* facies occurs at the study reef in the future because of global impacts (particularly elevated sea surface temperature and ocean acidification) and/or local stresses, the reef will not develop sufficiently. Coral calcification is considered to be highly sensitive to elevated sea surface temperature and ocean acidification. Although there is variability in calcification rates among coral species (Pandolfi et al., 2011), corymbose *Acropora* species (e.g., *A. digitifera*) are particularly vulnerable to thermal stresses (Loya et al., 2001; Golbuu et al., 2007). The growth of *Acropora* polyps at Okinawa Island in the Ryukyu Islands was significantly reduced by ocean acidification (Suwa et al., 2010). Local stresses, including sediment discharge, also have a negative impact on the species (Burke et al., 2011; Hongo and Yamano, 2013). A decrease in the rate of upward reef growth will probably cause a decline in reef effectiveness in reducing wave height. Our calculations for case 17 (TC: 8.70 m SWH_o, 13.0 s SWP_o; SLR 0.74 m) show that for a healthy reef, 0.74 m/kyr of upward growth produced a reduction of 0.23 m in SWH_r in 2100. If the reef growth rate decreases to 3.7 m/kyr, a reduction of 0.05 m in SWH_r would be expected (unpublished data). To reduce coastal risks, monitoring of global and local impacts on coral species and reef cover is needed.

4.3 Reduction of global disaster risk based on the health of coral reefs

More than 150,000 km of shoreline in 100 countries and territories is thought to receive protection from reefs, which reduce wave energy (Burke et al., 2011). More than 100 million people in Southeast Asia live in reef-associated areas (i.e., within 10 km of the coast and within 30 km of a reef), where fringing reefs predominate (Burke et al., 2011). By 2100 this area and its people are likely to be at risk from wave action because of the increasing intensity of TCs, and from SLR and storm surges, and this is likely to have negative economic and social effects. This study focused on Melekeok reef in the Palau Islands, but our results are applicable to other reefs in the Indo-Pacific and Caribbean regions, because the natural breakwater formed by reefs is more cost-effective in coastal protection than the construction of artificial defenses. Inexpensive but effective plans for coastal protection will be needed by small island nations and developing countries. Reef growth is self-adapting to long-term environmental change including SLR; it also provides a habitat for marine organisms and societal benefits including marine products, tourism, education, and recreation. Further research is needed to develop a policy of disaster risk reduction based on coral reef growth in the Indo-Pacific and Caribbean regions.

This study highlights the importance of maintaining coral cover in the future, to reduce the risk of coastal damage arising from wave action. Therefore, it is necessary to monitor the cover of reef-building corals, the recruitment of coral larvae, and the occurrence of various stressors. For example, the Palau Islands has a Protected Areas Network (PAN), which consists of marine and terrestrial areas established for the protection of important biological habitats. To reduce future risks, warnings derived from monitoring such areas can indicate the need to remove or reduce stressors, and to consider implementing reef restoration efforts (e.g., coral transplantation).

5 Conclusion

This study predicted the risk of coastal damage at Melekeok reef in the Palau Islands in the case of intensified TCs, and increased SLR and storm surges that are likely to occur during the 21st century. Our results, based on wave height and water level using the CADMAS-SURF wave simulation model, and past coral assemblage and reef growth rates estimated from a drillcore, indicate that the present-day reef is highly effective at dissipating incoming waves. However, more intense TCs and increased SLR and storm surges resulting from climate change will increase wave height at the study site reef flat and water level at the shore. This will increase the risk of beach erosion, saltwater intrusion into groundwater, and damage to infrastructure. However, our sedimentological analysis suggests that reef formation by key reef-building corals, including corymbose *Acropora* (e.g., *A. digitifera*), may respond to future SLR. The upward reef growth will decrease the wave height on the reef flat, and reduce the risk of coastal damage. The use of coral reefs for disaster risk reduction is a cost-effective approach and includes other benefits derived from the various ecological services provided by living reefs. Future research such as that described in this study will be required for designing ecosystem-based disaster risk reduction policies for small island nations and for developing and developed countries alike.

Supplement

Table S1 Effects of intensification of tropical cyclones, and increased sea level rise and storm surges on wave height on the reef flat at the study site.
Table S2 Effects of intensification of tropical cyclones, and increased sea level rise and storm surges on water level at the shore at the study site.

Author contribution

C. Hongo had the idea and C. Hongo and H. Kurihara designed this research. All authors conducted data analysis, and the writing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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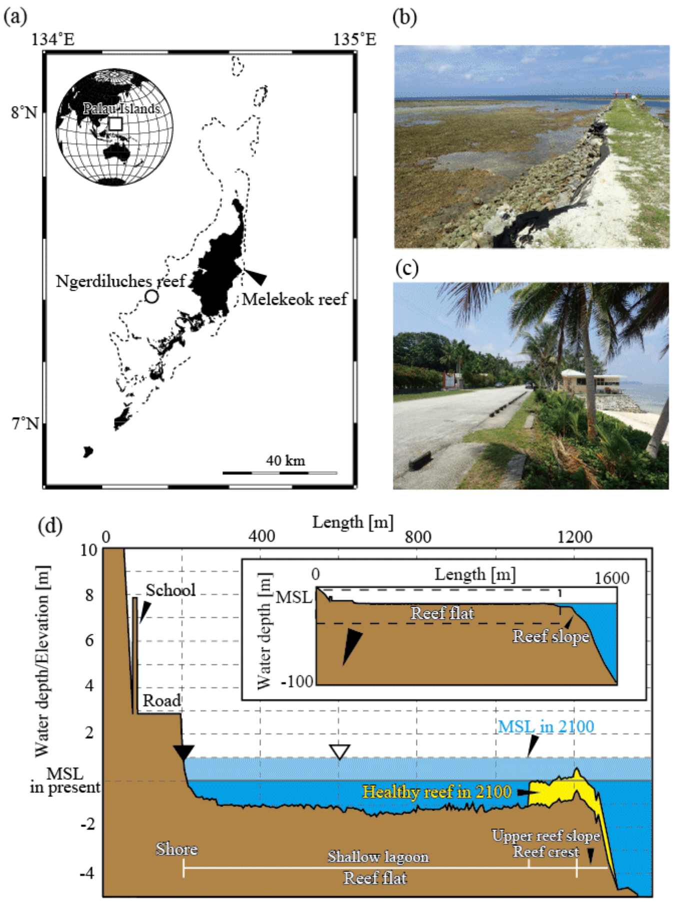

Figure 1: Location of Melekeok reef in the Palau Islands, and the reef topography used for wave calculations. (a) Location of Melekeok reef. The open circle indicates the drillcore site on Ngerdiluches reef (Kayanne et al., 2002). (b) Photograph of the collapsed pier at Melekeok reef. (c) Photograph of the coast at the study site. The elevation of the road is +2.86 m above present mean sea level (MSL). (d) The measured cross-section, showing the present day and the 2100 reef topography. The reef crest and upper reef slope will be characterized by upward reef growth or cessation of growth in response to sea level rise (SLR). This figure shows the example of upward reef growth for a healthy reef in response to +0.98 m SLR in 2100, based on the Representative Concentration Pathway (RCP) 8.5 scenario (Church et al., 2013). The open and solid triangles indicate the locations used for calculating the significant wave height at the reef flat (SWH_r) and the water level at the shore (WL_s), respectively.

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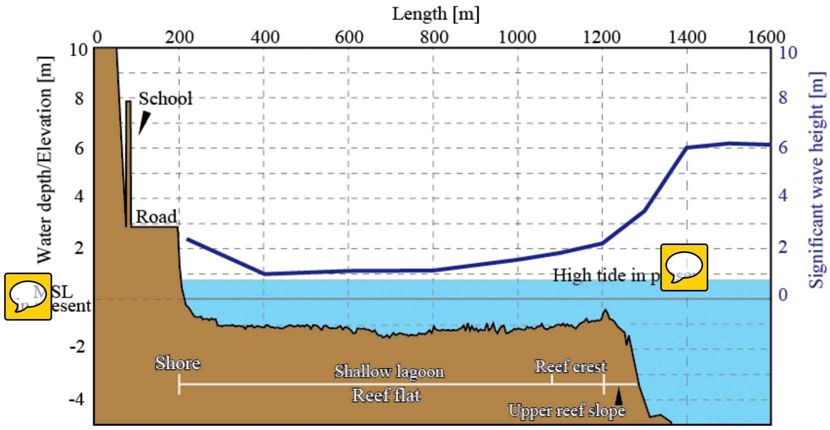


Figure 2: Calculated significant wave height (SWH) at the study site under present conditions. The assumed SWH_o and SWP_o values were 8.70 m and 13.0 s, respectively, for the present conditions model TC (i.e., Typhoon Bopha). The assumed WL_o was +0.80 m above MSL (i.e., high tide on spring tides). Rapid wave breaking occurs in the upper reef slope–reef crest zone, whereas the reef flat is characterized by relatively calm conditions. The SWH value at the shore increases as the water depth decreases.

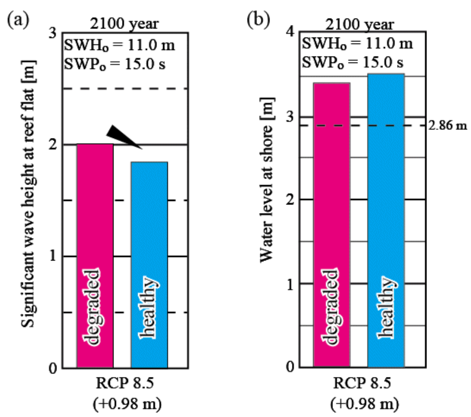
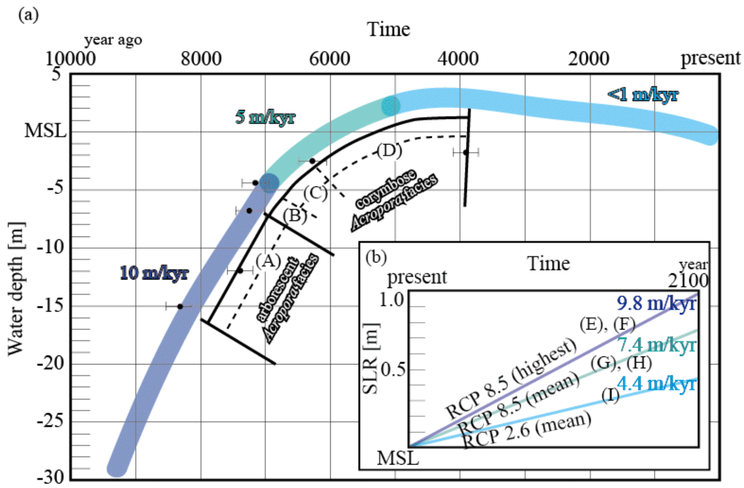


Figure 3: Effect of reef growth on change in the significant wave height at the reef flat, and risk assessment of flooding at the shore for the most intense TCs in 2100. (a) Reduction in wave height between degraded and healthy reefs for intensified TCs in 2100. Assumptions: 11.0 m SWH_o; 15.0 s SWP_o; SLR 0.98 m; storm surge 1.00 m above present MSL. The SLR value is based on the highest value for the RCP 8.5 scenario in 2100 (Church et al., 2013). Reef growth will result in a 0.20 m reduction in wave height. (b) Flooding risk assessment for degraded and healthy reefs under intensified TCs in 2100. The horizontal dashed line shows the elevation of the road (+2.86 m above present MSL) at the study site. The road will be flooded even if the reef is healthy.



(c)

Rate of Holocene SLR	Rate of reef prodcution (kg $CaCO_3/m^2/y$) arborescent *Acropora* facies	corymbose *Acropora* facies
10 m/kyr	(A) 2.4–26.7	(B) 14.2
5 m/kyr	——	(C) 1.3
<1 m/kyr	——	(D) 0.3

(d)

Rate of future SLR	Rate of potential reef prodcution (kg $CaCO_3/m^2/y$) arborescent *Acropora* facies	corymbose *Acropora* facies
9.8 m/kyr	(E) 7.1	(F) 5.8
7.4 m/kyr	(G) 5.3	(H) 4.4
4.4 m/kyr	——	(I) 2.6

Figure 4: Past and future reef production rates at the study site. (a) Sedimentary facies and Holocene sea level curve relative to present MSL at the study site. Solid circles represent ^{14}C ages obtained from the reef crest drillcore (PL-I: Kayanne et al., 2002). Radiometric counter errors are given in terms of two standard deviations (2σ). The reef growth curve is from Kayanne et al. (2002). The thick line shows two facies (arborescent *Acropora* facies and corymbose *Acropora* facies), from Hongo and Kayanne (2011). The dashed lines (A–D) indicate the period for estimation of the reef production rate for each facies in response to Holocene sea level change. The sea level curve around the study site is from Chappell and Polach (1991), Yokoyama et al. (1996, 2016), and Hongo and Kayanne (2010). (b) Sea level curve projected for 2100. The SLR ranges from +0.44 to +0.98 m until the end of the 21st century (RCP 2.6 and 8.5 scenarios; Church et al., 2013), equivalent to a SLR rate of 4.4–9.8 m/kyr. (E)–(I) Locations used for estimating reef production rates for each facies in response to future sea level change. (c) Holocene reef production rate based on drillcore. (D) Future potential reef production rate for each facies if the reef remains healthy.

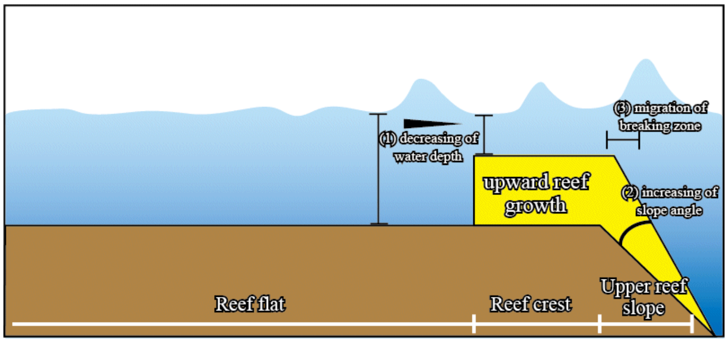


Figure 5: Effects of reef growth on reduction in wave height at the reef flat. In the reef crest to upper reef slope zone, upward reef growth will cause: (1) a decrease in water depth; (2) an increase in the reef slope angle; and (3) migration of the wave breaking zone towards the outer ocean. These processes will enhance wave breaking in the reef crest to upper reef slope zone relative to degraded reef. Consequently, wave height on the reef flat will be reduced.

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Table 1: Significant wave heights at the study site.

Case	SWH_o (m)	SWP_o (s)	SLR (m)	Tide relative to present MSL (m)	Storm surge (m)	SWH_r at degraded reef (m)	Percent reduction of wave height from SWH_o to SWH_r at degraded reef	SWH_r at healthy reef (m)	Percent reduction of wave height from SWH_o to SWH_r at healthy reef
Present									
1	8.70	13.0	0.00	0.80	0.00	-	-	1.05	87.9%
2	8.70	13.0	0.00	0.80	1.00	-	-	1.24	85.7%
Year 2050									
3	8.70	13.0	0.24	0.80	0.00	1.11	87.2%	0.88	89.9%
4	8.70	13.0	0.24	0.80	1.00	1.37	84.3%	1.22	86.0%
5	8.70	13.0	0.30	0.80	0.00	0.97	88.9%	1.09	87.5%
6	8.70	13.0	0.30	0.80	1.00	1.33	84.7%	1.35	84.5%
7	10.0	14.0	0.24	0.80	0.00	1.45	85.5%	1.21	87.9%
8	10.0	14.0	0.24	0.80	1.00	1.57	84.3%	1.52	84.8%
9	10.0	14.0	0.30	0.80	0.00	1.51	84.9%	1.46	85.4%
10	10.0	14.0	0.30	0.80	1.00	1.67	83.3%	1.26	87.4%
11	11.0	15.0	0.24	0.80	0.00	1.31	88.1%	1.49	86.5%
12	11.0	15.0	0.24	0.80	1.00	1.93	82.5%	1.66	84.9%
13	11.0	15.0	0.30	0.80	0.00	1.53	86.1%	1.50	86.4%
14	11.0	15.0	0.30	0.80	1.00	2.14	80.5%	1.70	84.5%
Year 2100									
15	8.70	13.0	0.44	0.80	0.00	1.07	87.7%	1.06	87.8%
16	8.70	13.0	0.44	0.80	1.00	1.32	84.8%	1.21	86.1%
17	8.70	13.0	0.74	0.80	0.00	1.34	84.6%	1.11	87.2%
18	8.70	13.0	0.74	0.80	1.00	1.24	85.7%	1.40	83.9%
19	8.70	13.0	0.98	0.80	0.00	1.28	85.3%	1.12	87.1%
20	8.70	13.0	0.98	0.80	1.00	1.47	83.1%	1.30	85.1%
21	10.0	14.0	0.44	0.80	0.00	1.54	84.6%	1.33	86.7%
22	10.0	14.0	0.44	0.80	1.00	1.87	81.3%	1.45	85.5%
23	10.0	14.0	0.74	0.80	0.00	1.48	85.2%	1.18	88.2%
24	10.0	14.0	0.74	0.80	1.00	1.59	84.1%	1.64	83.6%
25	11.0	15.0	0.44	0.80	0.00	1.63	85.2%	1.40	87.3%
26	11.0	15.0	0.44	0.80	1.00	1.97	82.1%	1.77	83.9%
27	11.0	15.0	0.74	0.80	0.00	1.68	84.7%	1.77	83.9%
28	11.0	15.0	0.74	0.80	1.00	1.92	82.5%	1.66	84.9%
29	11.0	15.0	0.98	0.80	1.00	2.00	81.8%	1.80	83.6%
						Mean	84.6%	Mean	86.0%

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SWH_o: significant wave height at outer ocean
SWP_o: significant wave period at outer ocean
SLR: sea level rise, based on RCP scenarios 2.6 and 8.5 (Church et al., 2013).
MSL: mean sea level
SWH_r: significant wave height at reef flat

Table 2: Flooding risk at the study site.

Case	SWH_o (m)	SWP_o (s)	SLR (m)	Tide relative to present MSL (m)	Storm surge (m)	WLs at degraded reef (m)	WLs at healthy reef (m)	Chage in WL_s from degraded reef to healthy reef (m)
Present								
30	8.70	13.0	0.00	0.80	0.00	-	0.86	
31	8.70	13.0	0.00	0.80	1.00	-	2.10	
Year 2050								
32	8.70	13.0	0.24	0.80	0.00	1.19	1.24	-0.05
33	8.70	13.0	0.24	0.80	1.00	2.30	2.29	0.01
34	8.70	13.0	0.30	0.80	0.00	1.30	1.41	-0.11
35	8.70	13.0	0.30	0.80	1.00	2.42	2.35	0.07
36	10.0	14.0	0.24	0.80	0.00	1.58	1.55	0.03
37	10.0	14.0	0.24	0.80	1.00	2.44	2.53	-0.09
38	10.0	14.0	0.30	0.80	0.00	1.54	1.64	-0.10
39	10.0	14.0	0.30	0.80	1.00	2.55	2.54	0.01
40	11.0	15.0	0.24	0.80	0.00	1.87	1.90	-0.03
41	11.0	15.0	0.24	0.80	1.00	2.87	2.86	0.01
42	11.0	15.0	0.30	0.80	0.00	1.97	1.99	-0.02
43	11.0	15.0	0.30	0.80	1.00	2.89	2.89	0.00
Year 2100								
44	8.70	13.0	0.44	0.80	0.00	1.50	1.52	-0.02
45	8.70	13.0	0.44	0.80	1.00	2.49	2.50	-0.01
46	8.70	13.0	0.74	0.80	0.00	1.82	1.90	-0.08
47	8.70	13.0	0.74	0.80	1.00	2.81	2.83	-0.02
48	8.70	13.0	0.98	0.80	0.00	2.06	2.12	-0.06
49	8.70	13.0	0.98	0.80	1.00	3.00	3.01	-0.01
50	10.0	14.0	0.44	0.80	0.00	1.82	1.81	0.01
51	10.0	14.0	0.44	0.80	1.00	2.70	2.69	0.01
52	10.0	14.0	0.74	0.80	0.00	2.09	2.07	0.02
53	10.0	14.0	0.74	0.80	1.00	2.97	2.96	0.01
54	11.0	15.0	0.44	0.80	0.00	2.07	2.12	-0.05
55	11.0	15.0	0.44	0.80	1.00	3.00	2.98	0.02
56	11.0	15.0	0.74	0.80	0.00	2.41	2.45	-0.04
57	11.0	15.0	0.74	0.80	1.00	3.23	3.32	-0.09
58	11.0	15.0	0.98	0.80	1.00	3.45	3.51	-0.06
							Mean	-0.02

SWH_o: significant wave height at outer ocean
SWP_o: significant wave period at outer ocean

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SLR: sea level rise, based on RCP scenarios 2.6 and 8.5 (Church et al., 2013).
MSL: mean sea level
WL_s: water level at shore
Under line: over of risk level of flooding (2.86 m above present MSL)