Author's Response

Overall we greatly acknowledge the constructive and very helpful reviews given by the editor and all referees. All comments have been carefully addressed in the revised manuscript. In the following letter, each comment by Editor and all Referees are followed by our replies in red with lines based on the revised manuscript. The track-changes version of the manuscript can be found at the end of this document.

Response to Editor Heidi Kreibich

Dear authors,

According to the comments of the reviewers, your manuscript needs substantial revisions before it can be reconsidered for publication. An important aspect is the validation of your modelling results and comparisons with current and historical events. This is an important aspect. Modelling studies can only be of scientific value, if their reliability and accuracy is clearly proven. I ask you to revise your manuscript in accordance with all comments and recommendations of all reviewers. When you have completed your revision, please submit your revised manuscript with the changes undertaken visible, and a detailed item-by-item response to each of the reviewer's comments.

Best regards

Heidi Kreibich

We are grateful to you that you review. All comments and recommendations by referees have been carefully addressed in the revised manuscript. We understood your comments of validation of our simulation results. According to the historical records of TCs (please see new Table 1), prior to Typhoon Bopha that passed south of Palau in December 2 2012, it is suspected that no major typhoons had caused significant damage to coral reefs and coastal areas of Palau for over 60 years. In this study, we focused on impacts of Typhoon Bopha and an expected impact in year 2050 and 2100. However, we could not conduct the field survey just after Typhoon Bopha. Moreover, we could not found any *in situ* observation data for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems in Palau Islands. Therefore, we mainly attempted data of wave height and water level based on a wave simulation by CASMAS-SURF. In order to validate, we conducted local interviews to obtain reliable information of water level at the study site. We believe that our simulation data seems to match with the observation by the local peoples (please see new Fig. 4), although the data is qualitative. Furthermore, we discuss that to precisely evaluate the impact of hydrodynamic forces at coastal areas in Palau Islands, establishment of *in situ* observation systems of wave height, wave period, and water level should be considered. For example, establishment of ultrasonic-wave-based wave gauges, observation buoys, and radar-based wave meters are recommended to predict accurately the ocean wave heights and periods to alert peoples for disasters such as flooding during tropical cyclones.

We note that CADMAS-SURF model is probably not one of popular wave simulation models, but the model has been successfully applied to wave characteristics at coral reefs under TC conditions (Yamashita et al. 2008; Hongo et al. 2012; Nakamura et al. 2014; Watanabe et al. 2016). Actually, the model can reproduce highly non-linear wave profiles against various structures, e.g., impact of a wave breaking sea walls (Isobe et al., 1999) and it can apply to wave deformation (e.g., wave shoaling, wave breaking, wave overtopping, and wave run-up) at coral reefs. For a validation of the model, the computed results have been compared with observed data and laboratory experiments on wave deformation over coral reefs under TC conditions (e.g., Nagai and Shiraishi, 2004; Kawasaki et al., 2007; 2008).

Response to SC (Prof. Lucien Montaggioni)

Reef workers know from empirically supported data that the decrease in coral calcification and reef accretion in the next future might result in a decrease in the ability of reef-crest and reef flat zones to reduce wave energy and to maintain coastal protection. The present paper by Hongo and associates has the merit of quantifying the responses of a given reef (Melekeok reef, Palau Islands) to the expected rise in sea level and intensification of typhoon activity during the next decades, according to three RCP scenarios. I agree with the authors regarding the remarkable building power of corymbose acroporids that make up upper fore-reef, reef-crest and outer-reef flats in most high-energy reef environments. The fact that that *Acropora* forms belonging to robusta group are amongst the most robust branching corals and corals with the highest vertical growth rates in the considered domain suggests that the relevant reefs would be able to compensate for significant changes in sea level and typhoon strength.

We are grateful to you that you review. We are happy to know that you agree with our statement of an importance of corymbose *Acropora* as a reef builder at a high wave energy condition.

By contrast, I am skeptical about the capacity of arborescent acroporids typified by gracile branching colonies to resist higher water energy; I guess the relevant reef-crest zones will suffer from storm surges of increasing strength. I particularly appreciate the section dealing with an estimation of future reef production rate; the presented data provide a robust estimate of the growth potentiality of the acroporid facies.

Thank you for giving the comment. This was not fully explained in the original manuscript. We also believe that arborescent *Acropora* will less contribute to reef formation by 2100 because of the corals are overturned and broken under the high wave energy conditions (a few meter of water depth). Thus, we estimate a reef production rate for corymbose *Acropora* by 2100, based on the analysis of reef drillcore and future sea-level rise. Consequently, we clearly describe in discussion, as follows.

Page 12 Lines 14–24:

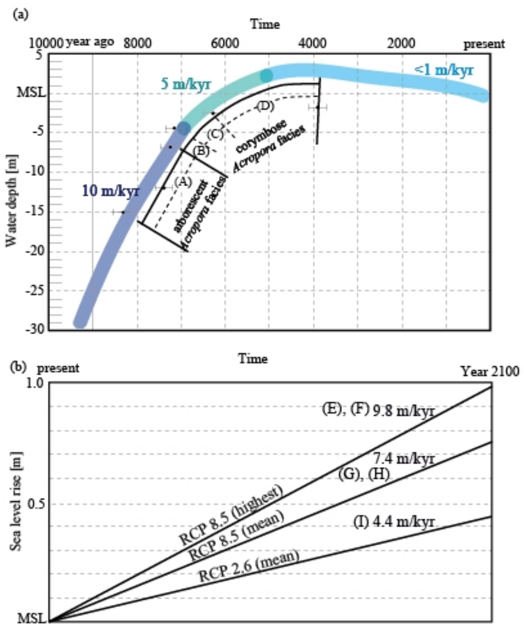
[According to the analysis of drillcore in this study, a corymbose *Acropora* facies at a high-wave energy condition in water depths less than 7 m and an arborescent *Acropora* facies at a low- to moderate- wave conditions in water depths less than 20 m contributed to the Holocene reef in the Palau Islands (Kayanne et al., 2002; Hongo and Kayanne, 2011). The maximum future SLR is predicted to +0.98 m by 2100 (Church et al., 2013). This implies that arborescent *Acropora* corals 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. In contrast, corymbose corals at the study site will contribute to reef formation by 2100, in response to future SLR. 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*, *Acropora 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 this context, we add the detail information about cormybose *Acropora* facies and arboresent *Acropora* facies into Method.

Page 6 Lines 25–32:

[The corymbose *Acropora* facies is characterized by corals by corymbose and tabular *Acropora* (e.g., *Acropora digitifera*). These corals are found on distinct reef crests and upper reef slopes in Palau Islands (Kayanne et al., 2002; Yukihira et al., 2007). The zone is generally characterized by high-energy waves in water depths less than 7 m (Hongo and Kayanne, 2011). The arborescent *Acropora* facies is characterized by corals by arborescent *Acropora* (e.g., *Acropora muricata/ intermedia* complex). These corals occupy the inner reef slope and leeward reef slope at water depths of less than 20 m in Palau Islands and other reefs in the present-day Pacific Ocean (Montaggioni, 2005; Yukihira et al., 2007). These corals are interpreted to inhabit a low- to moderate- energy wave conditions (Hongo and Kayanne, 2011).]

In this context, to well understand, we revised Figure 7 because of the graph was very small.



(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

Revised Figure 7

However, I am surprised to see that there would have no significant upward reef growth in response to changes (increase) in the water level (WLs) (page 9, lines15-16). And I do not see how porous framework with high permeability degree could prevent upward accretion. Examples from the literature reveal that the highest vertical reef growth rates relate to porous branching corals, especially robust branching ones. It would be interesting to assess the role of massid coral forms (e.g.poritids, faviids) in reef resistance to increasing wave energy, since a number of reef fronts in the Indo-Pacific province are dominantly composed of such builders.

Thank you for giving the comment. Our original manuscript was unclear. If the reef has no porosity, sea water will not permeate through the reef. But we know that a reef framework has a wide range of porosities from low (where internal cavities have been infilled with marine cements) to high (e.g., a reef framework is mainly composed of branching corals) (Hopley, 2011 Encyclopedia of Modern Coral Reefs). In this study, we assumed 10 % of porosity of reef structure for our wave/water level simulation. This means that a reef framework contributes to reducing wave height due to a 3D structure, but sea water permeates through the reef framework due to porosity. Consequently, our result indicates that upward reef growth reduces incoming wave heights, but there is no significant change of water level at reef between a degraded reef and a healthy reef by 2100. Moreover, the reviewer is interested in a role of reef framework by massive corals in reducing wave heights and water level. We are also interested in the question, but we assume that the study reef will be composed of corymbose *Acropora* corals. Therefore, the estimation is beyond our research in this manuscript. In a revised manuscript, we clearly describe as follows:

Page 4 Lines 4–9:

[Our results indicate that there is no significant change in WL_s between a degraded reef and a healthy reef. This can be explained by the nature of coral reefs, which are porous structures characterized by a high degree of water permeability. A reef framework has a wide range of porosities from low (where internal cavities have been infilled with marine cements) to high (e.g., a reef framework is mainly composed of branching corals) (Hopley, 2011). In this study, mean porosity of reef framework is estimated as 10 %. This means that sea water permeates through the reef due to porosity, even if the reef is characterized by three dimensional structures.]

Additionally, we add the following into the Method:

Page 6 Lines 9–10:

[We used 10 % of porosity for predicting vertical reef growth.]

Response to RC1 (Referee #1)

This paper proposes an assessment of the risk of coastal flooding and submersion by waves in one of the Palau islands surrounded by a coral reef in 2100, in a context of climate change. The study is certainly of interest, the study is rather comprehensive, well conducted and the paper is concise, clear and well written. The objectives of the paper are clearly exposed and the conclusions correspond to these objectives.

We are grateful to you that you review.

I have however two main concerns, that in my opinion prevent the acceptance of the paper in its present state: 1- The authors state that their first objective is to assess the present-day efficiency of the Palau coral reef as wave breaker and natural barrier against water level rise during a tropical cyclone (TC). They give (from what I understand) the corresponding figures obtained from a numerical hydrodynamic modeling, using as forgings the outer wave significant height (SWHo), the outer significant wave period, and the outer water level. These forcings are taken from a GFS simulation and observations of SWH in similar conditions. The percent of reduction of wave height due to the reef is 85.7% (87.9%) with (without) storm surge. As these values are used as a reference in the projective part of the paper, it would be relevant to confirm them (at least at first order) using observations. Recent TCs (Bopha and Haiyan) hit Palau, and it is may be possible to find even crude observations of (outer) SWHo and (reef) SWHr to check either the value of SWHr or the percentage of reduction (Table1). The same applies to the flooding risk (Table2). Especially, the authors mention in the discussion that some of the values obtained in 2100 would result in a flooding of the coastal road: did such flooding occur in the recent years? in the historical period? Has the value of 2.10m for the present-day coastal flooding with storm surge already been observed? The authors did a rather good job in estimating the various contributions (even if it is first order) and their uncertainties but it would be more convincing if the accuracy (and not only uncertainty) was estimated (by comparing with observations).

We are glad to receive your constructive comments. Firstly, we attempted to find a recorded data of ocean wave and water level in Palau Islands. However, we could not found any *in situ* observation data for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems in Palau Islands. Therefore, we conducted the wave simulation using the wave height and wave period obtained by the Global Forecast System (GFS) model at the study site.

Secondly, we attempted to find a record of past typhoon around the study site, using Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en) based on the Japan Meteorological Agency (JMA) best track data. According to the record, 19 typhoons have passed within 150 km of Melekeok reef since 1951. Only 1 severe typhoon passed near the study reef in 1990 (Typhoon Mike), but the impact on Palau's reef was limited to the northern reef (Maragos and Cook, 1995 *Coral Reefs*). Consequently, prior to Typhoon Bopha in 2012, it is supposed that no major typhoons had caused significant damage to coral reefs and coastal areas for over 60 years. We also talked with local peoples and confirm this expectation. These evidences imply that Typhoon Bopha in 2012 was the most severe typhoon around the study site for over 60 years.

Thirdly, since we could not found any record of wave height at the study site during Typhoon Bopha, we conducted interviews to the local peoples about the state of flooding at the study reef during Typhoon Bopha. As a result, local people mentioned that the road (+2.86 m above MSL) along the shore at the study site was flooded during the Typhoon Bopha and that this was never seen for a past ca. 70 years. Unfortunately, we could not obtain quantitative data, however, our simulation data (please see the following new Fig. 4) seems to match with the observation by the local peoples.

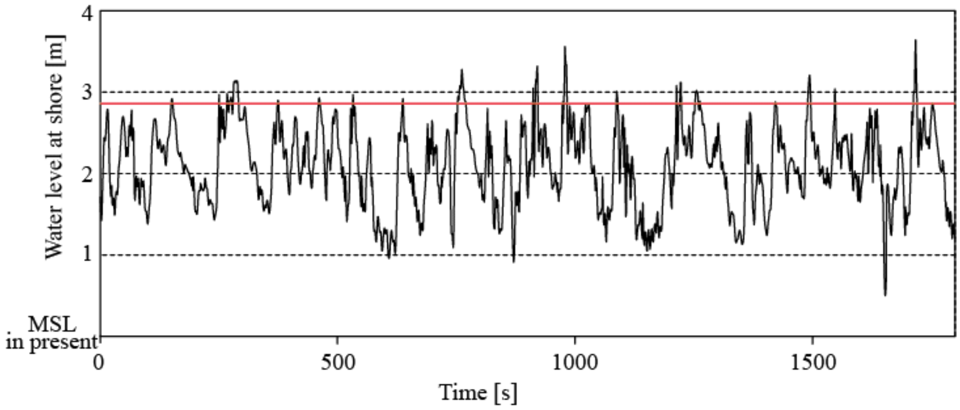


Figure 4: Calculated water level at the study site under the present-Day TC (Typhoon Bopha). The assumed SWHo and SWPo values were 8.70 m and 13.0 s, respectively. The assumed WLo was +1.80m above MSL (i.e., high tide and storm surge). The horizontal solid line in red shows the elevation of the road (+2.86 m above MSL) at the study site. The road was frequently flooded.

As pointed by the reviewer, taking into account that the lack of field observation system for ocean wave and water level around Palau limit accurate predictions for the wave and water level at coastal areas during TCs, we also added in the discussion awareness for the importance of establishing field observation system to predict potential coastal disaster in Palau.

To clarify these points, we added the following sentences into the revised manuscript:

Page 4 Lines 4–15:

[2.2 Impacts of historical TCs and Typhoon Bopha

Since 1951, 19 typhoons passed within 150 km of Melekeok reef in Palau, provided by the Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en) based on the Japan Meteorological Agency (JMA) best track data (Table 1). Only 1 severe typhoon passed near this study reef in 1990 (Typhoon Mike), and the impact was limited to the northern reef of Palau (Maragos and Cook, 1995). Prior to Typhoon Bopha that passed south of Palau in December 2 2012, it is suspected that no major typhoons had caused significant damage to coral reefs and coastal areas of Palau for over 60 years.

The minimum pressure of Typhoon Bopha center was 935 hPa and the maximum wind speed was 50 m/s (data obtained by Digital Typhoon: http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en). The average wind speed was 27 m/s around the study site, provided by Windguru (see http://www.windguru.cz) in December 2 2012 because the study site is 121 km distance from the pass of Typhoon Bopha. In order to understand the impacts of Typhoon Bopha, we attempted to find *in situ* recorded data of ocean wave and water level at the study site. However, we could not found any *in situ* observation data for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems. Because observed evidence was not clear, we conducted local interviews to obtain reliable information of the impacts.]

In this context, we draw new Table 1 for a historical record of TCs in Palau Islands.

Table 1 Tropical cyclone passing within 150 km of Melekeok reef from 1951 to 2015.

TC no.	TC name	Approaching date	Minimum pressure of center (hPa)[a]	Nearest distance from Melekeok reef (km)[a]	Maximum wind speed at nearest distance from Melekeok reef (m/s)[a]
T5501	VIOLET	January 02 1955	995	81	NA
T5701	NO-NAME	January 04 1957	995	93	NA
T5703	SHIRLEY	April 11 1957	975	76	NA
T5901	RUBY	February 28 1959	998	127	NA
T5902	SALLY	March 11 1959	990	101	NA
T5922	GILDA	December 15 1959	925	121	NA
T6431	LOUISE	November 16 1964	915	105	NA
T6702	SALLY	March 03 1967	980	51	NA
T6903	SUSAN	April 20 1969	940	22	NA
T7230	THERESE	December 02 1972	945	32	NA
T7501	LOLA	January 22 1975	975	21	NA
T7603	MARIE	April 07 1976	930	99	NA
T7903	CECIL	April 13 1979	965	9	23
T8201	MAMIE	March 18 1982	990	71	23
T8601	JUDY	February 02 1986	970	139	20
T9025	MIKE	November 10 1990	915	44	45–50
T9101	SHARON	March 11 1991	985	66	25
T1224	BOPHA	December 02 2012	930	121	50
T1330	HAIYAN	November 07 2013	895	72	55–60

NA: Not available

[a] Estimated by Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/) and based on Japan Meteorological Agency best track data.

Page 5 Lines 11–15:

[(1) SWH_o: Since there is no *in situ* observation systems for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems in Palau Islands, the present-day SWH_o value was simulated by using the Global Forecast System (GFS) model at 27 km resolution, provided by Windguru (see http://www.windguru.cz). In Palau Islands, the values for 4 sites (Melekeok, Koror, North beaches, and West Passage) are provided by the model. The largest SWH_o value at Melekeok during Typhoon Bopha was 8.70 m.]

Page 7 Lines 18–21:

[During the Typhoon Bopha, local people mentioned that beach erosion and destruction of structure (e.g., the pier and a pavilion, ~3 m above MSL) occurred along the shore at the study site (Figure 2). Moreover, the road and the ground of elementary school (+2.86 m above MSL) along the shore were flooded and that this was never seen for a past ca. 70 years.]

In this context, we draw a new figure (Figure 2).

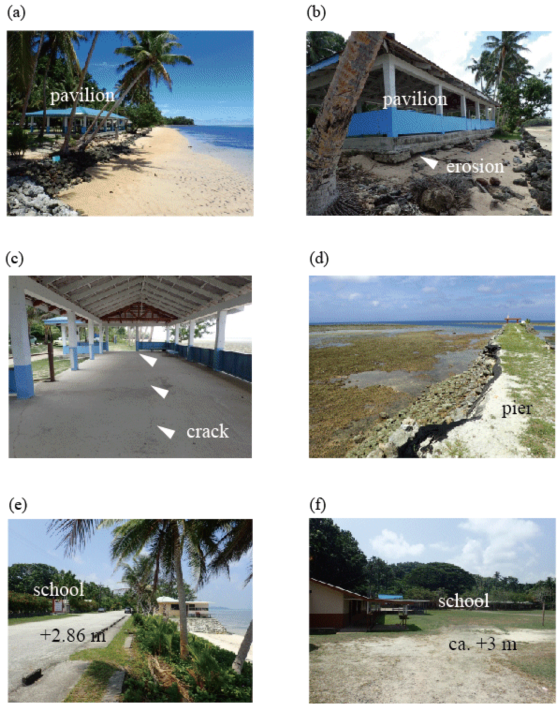


Figure 2: Photograph of the coast at the study site. (a) A pavilion located in the coast. The elevation of the pavilion is less than 3 m above present mean sea level (MSL). (b) Damage of the foundation of pavilion due to the erosion during Typhoon Bopha. (c) Many cracks of the floor of the pavilion. (d) Photograph of the collapsed pier at Melekeok reef. (e) Photograph of the road and Melekeok elementary school along the coast. The elevation of the road is +2.86 m above present MSL. (f) Photograph of the ground of the school. The elevation of the ground is ca. 3 m above present MSL. The road and the ground were flooded during Typhoon Bopha.

Page 7 Lines 27–29:

[The WL_s was 0.86 m for present-day TCs (case 30, Table 3) and the WL_s increased to 2.10 m under storm surge conditions (case 44, Table 3). Moreover, the water level at the shore under present-day TCs (i.e., Typhoon Bopha) reached the elevation of road (+2.86 m above MSL) at the study site (Figure 4).]

Page 10 Lines 20–22:

[Our result of WL_s shows that the road along the shore at the study site was flooded during an assumed present TC (i.e., Typhoon Bopha). Our simulation data seems to correspond with the observation by the local peoples, although we could not obtain quantitative data.]

Page 13 Lines 27–31:

[Furthermore, to evaluate the impact of hydrodynamic forces at coastal areas in the islands, establishment of *in situ* observation systems of wave height, wave period, and water level should be considered. For example, establishment of ultrasonic-wave-based wave gauges, observation buoys, and radar-based wave meters are recommended to predict accurately the ocean wave heights and periods to alert peoples for disasters such as flooding during TCs.]

2-The conclusion of the projective part of the study is twofold. Firstly, the healthy of the reef does not impact significantly the risk of flooding – in some cases, an healthy reef will result in higher water level at the shoreline than a damaged reef. Secondly, there is an impact of the state of the reef on SWHr, which varies according to the climatic scenarios (sea level rise), to the wave conditions, and to the presence of storm surge. Its maximum value (SWHr at degraded reef – SWHr at healthy reef) is 0.30m (0.44m with storm surge), corresponding to a change of the percentage of reduction from 88.2 to 85.2% (85.5 to 81.3%). I wonder whether this 3-4% change is significant and whether the corresponding change in SWHr will really have an impact at the shoreline. Providing such estimates is certainly interesting per se, but their significance justify the discussion about the use of coral reef to mitigate the future coastal risk (4.2,4.3). So, even though this study actually proves that an healthy reef slightly reduces the SWH at the shoreline with respect to a damaged reef, this reduction is may be not enough to provide an efficient protection against high waves at the shore. Is there any (observed) difference between a SWHr of 1.24m and 1.05m (present-day values with/without surge)? This point is not answered This could help to assess whether a 0.30m change in the 2100 scenarios would have an impact or not and justify the recommendation of using of coral reef as an efficient barrier.
Thank you for giving the comments. The original manuscript has insufficient explanations. If the future WL_s value shows below the road (+2.86 m above present MSL), the difference in SWH_r between healthy and degraded reefs (max. 0.44 m) will have not a significant impact on the coastal area. However, our results indicated that the WL_s will increase from max 2.10 m at present to max 3.45–3.51 m by 2100. This means that by year 2100, the WL_s will often reach the road (+2.86 m above present MSL) and then an increase in SWH_r of only 0.1 m will lead an increasing of coastal risks such as flooding, destruction of constructions, saltwater intrusion into groundwater and coastal erosion. Consequently, we add the following point in a revised manuscript:

Page 12 Lines 3–13:
[If the future WL_s value shows below the road (+2.86 m above present MSL), the difference in SWH_r between healthy and degraded reefs (max. 0.44 m) will have not a significant impact on the coastal area. However, our results indicate that the future WL_s will almost reach the elevation of the road at the study site. The above result implies that an increase in wave height of only 0.1 m leads to an increase in risks of substantial coastal damages such as flooding, destructions of constructions (houses and buildings), saltwater intrusion into groundwater, and coastal erosion. Detail quantity of the damages was beyond the scope of the present study, but the difference in SWH_r by a maximum of 0.44 m will probably cause a significant coastal damages. For example, flooding mostly occurs within a 1-km wide coastal zone along the shoreline, and a 0.33 m of water level rise has little effect on

inundation, but 0.66 m of water level rise, reveals widespread groundwater inundation of the land surface at Oahu Island in Hawaii (Rotzoll and Fletcher, 2013), although it is difficult to directly compare a coastal area between the Melekeok reef and the result of Oahu Island. Consequently, upward reef growth will be required for the reduction of risks of coastal damages.]

In this context, we clearly changes of wave height and water level between degraded reef and healthy reefs for new Figures 5 and 6.

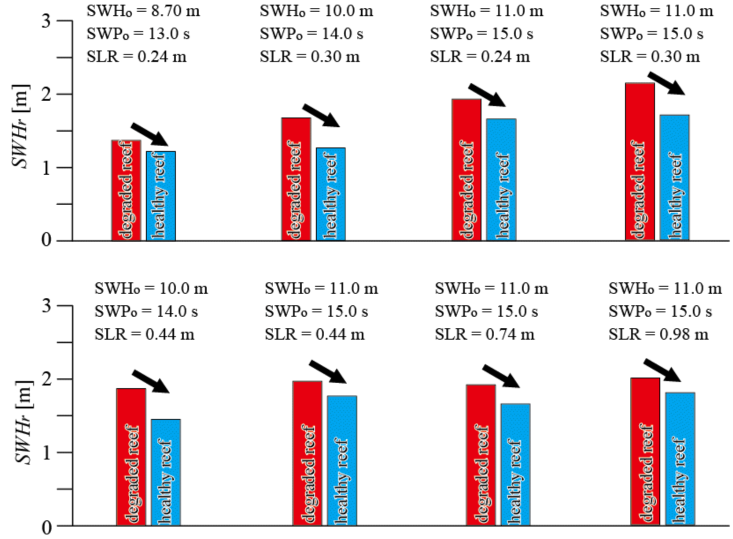


Figure 5: Effect of reef growth on change in the significant wave height at the reef flat for the TCs by 2100. Assumptions: 8.70–11.0 m SWH_o; 13.0–15.0 s SWP_o; SLR 0.24–0.98 m; 1.8 m above present MSL WL_o (i.e., high tide and storm surge). The SLR values are based on the values for the RCP scenario in 2100 (Church et al., 2013). The examples show that healthy reefs will reduce wave height.

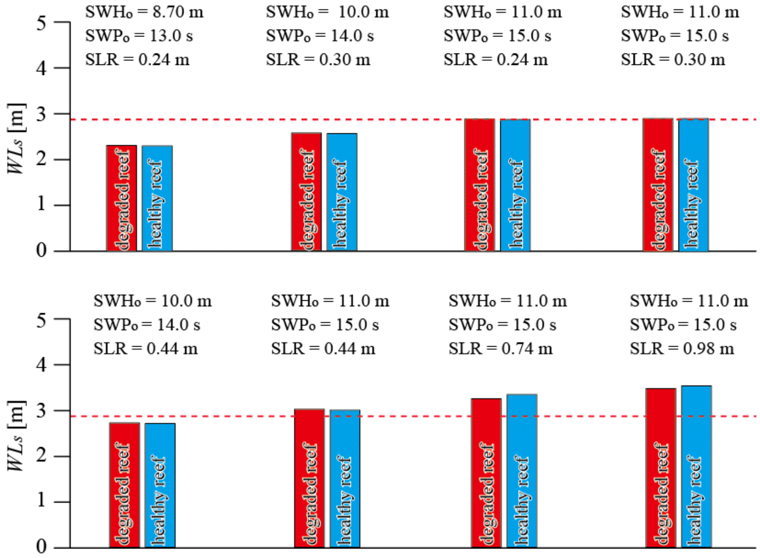


Figure 6: Effect of reef growth on change in the water level at the shore for the TCs by 2100. Assumptions: 8.70–11.0 m SWH_o; 13.0–15.0 s SWP_o; SLR 0.24–0.98 m; 1.8 m above present MSL WL_o (i.e., high tide and storm surge). The SLR values are based on the values for the RCP scenario in 2100 (Church et al., 2013). The horizontal dashed line shows the elevation of the road (+2.86 m above present MSL) at the study site. The road will be frequently flooded even if the reef is healthy.

As pointed by the reviewer, we recognize the lack of evacuation information in the Palau Islands. We added an importance of evacuation information into discussion, as follows.

Page 13 Lines 25–27:
[Additionally, we recognize that a ground elevation of construction varies from house to building. To evacuate the people from the flooding area, an investigation of ground elevation each construction and the signboard of elevation will be required.]

Minor comments:
p.1, l.21-24: the role of the reef crest/entire reef in reducing the wave height is not clear here (much clearer in part 3.1), please improve.
We clearly revised.
Page 1 Lines 21–25:
[The present reef is currently highly effective in dissipating incoming waves. The SWH_o was found to rapidly decrease from the upper reef slope to the reef crest. 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. 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.]

p.4, l.8 to 31: the values and uncertainties of the forcings given here correspond to order of magnitude rather than precise values. This is not an issue, as the impact on the final results (SWHr and water level) is probably very weak, but this should be specified more clearly.
We clearly explained in a revised manuscript.
Page 5 Lines 7–9:
[The four input parameters are given as double figures below decimal point because the future SLR is given as double figures below decimal point (e.g., +0.24 m: Church et al., 2013). Therefore, the calculated values of SWH_r and WL_s are given as rounding at triple figures below decimal point.]

p.4, l.10: the values of SWHo and wind speed are model outputs? 27m/s seems rather "low" for cyclonic wind. I wonder whether this is due to the rather crude resolution of the (global) atmospheric model. Are the corresponding wind observations (possibly satellite products) available?
Yes, the values of SWH_o and wind speed are provided by by the Global Forecast System (GFS) model at a 27 km resolution. We attempted to find the values based on more high resolution model, but we could not find it. Typhoon Bopha passed south Palau in December 2 2012. The maximum wind speed of 50 m/s, provided by Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en) based on JMA best track data. But the study site is 121 km distance from the pass in December 2. Therefore, the wind speed was 27 m/s at the study site. Consequently, we clearly explained in a revised

manuscript.

Page 4 Lines 10–12:

[The average wind speed was 27 m/s around the study site, provided by Windguru (see http://www.windguru.cz) in December 2 2012 because the study site is 121 km distance from the pass of Typhoon Bopha.]

Page5 Lines 11–13:

[Since there is no *in situ* observation systems for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems in Palau Islands, the present-day SWH_o value was simulated by using the Global Forecast System (GFS) model at 27 km resolution, provided by Windguru (see http://www.windguru.cz).]

p.4, l.27: about the SLR, if the level of precision of the discussion is 0.1m or below, you should also take into account a possible effect of ElNino/LaNina. This could result regionally (tropical Pacific in 0.3m difference or more.

Thank you for the comment. We know that the sea level around the Palau Islands is not constant due to effects of El Niño/La Niña. During the El Niño of early 1998, mean sea level was ca. 0.20 m lower than normal in Palau Islands (Colin 2009 *Marine Environments of Palau*). This was quickly followed by the La Niña of late 1998, during which period the mean sea level was 0.35 m above normal (Colin 2009). In this study, we focused on predictable effects of sea level change such as long-term global sea-level rise and tropical cyclones. But, it is difficult to predict the timing and magnitude of El Niño/La Niña around the study site, thus the effect of El Niño/La Niña was beyond our research. However, to better understand the coastal risks by wave and water movements, we will take into account the effects of El Niño/La Niña. Consequently, we described the importance as one of further researches in Conclusion.

Page 14 Lines 26–31:

[The present study emphasizes that further research is required regarding a short-term variation in sea level. During the El Niño of early 1998, mean sea level was ca. 0.20 m lower than normal in Palau Islands (Colin, 2009). This was quickly followed by the La Niña of late 1998, during which period the mean sea level was 0.35 m above normal (Colin, 2009). This was a half-meter change in mean sea level over just a few months. Such information will allow us to better understand changes in wave height and water level in the Palau Islands by 2100.]

p.6, l.30-31: how comes that these cases show a decrease of SWHr with a degraded reef? In cases5, 11, 18, the reduction is comparable to the opposite reductions obtained with an healthy reef. Please elaborate.

The original manuscript is lacking in the explanation. Our results showed that 6 cases (cases 3, 6, 14, 17, 23, and 26) the SWH_r was increased to 0.02 m–0.18 m by upward reef growth by 2100. We think that the difference was explained by an effect of infragravity waves although its overall effect remains unclear. In the original manuscript, we have discussed a reduction of wave height for upward reef growth, affected by 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. (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. (3) With upward reef growth the wave breaking zone will probably migrate from its present location towards the ocean. Moreover, we discuss infragravity waves in a revised manuscript.

Due to the complex reef bathymetry and wave dynamics characters of reef conditions, waves propagating onto shallow reefs steepen and break, and while some of the breaking wave energy propagates shoreward as reformed high-frequency waves, the spectral wave energy shifts into lower frequencies and long-period (infragravity) waves often dominate (Cheriton et al., 2016). In extreme wave conditions such as tropical cyclones, infragravity waves cause increasing of wave height and water level (e.g., Nakaza et al., 1994; Shimozono et al., 2015). In the present study, the upward reef growth affects a reduction in water depth in the reef crest–upper reef slope zone and it probably enhances a resonant oscillation of water by infragravity waves. The process probably causes increase of SWH_r at the degraded reefs. However, the infragravity waves are known to be generated across the coral reef through nonlinear wave interactions and its overall effect remains unclear. Consequently, we add a detail explanation in a revised manuscript, as follows:

Page 11 Line 21—Page 12 Line 2:
[However, our results showed that 6 cases (cases 3, 6, 14, 17, 23, and 26) the SWH_r was increased to 0.02 m–0.18 m by upward reef growth by 2100. An increase in SWH_r is likely to be explained by a difference in magnitude of infragravity waves between the degraded reef and the healthy reef. Waves propagating onto shallow reefs steepen and break, and while some of the breaking wave energy propagates shoreward as reformed high-frequency waves, the spectral wave energy shifts into lower frequencies and long-period (infragravity) waves often dominate (Cheriton et al., 2016). Infragravity waves over shallow reef flats have established relationships between the offshore conditions and resulting reef flat characteristics (e.g., complex bathymetry). Increased of wave height and water level due to the infragravity waves have been observed for various coral reefs (Nakaza et al., 1994; Cheriton et al., 2016) and have also been demonstrated in laboratory and modelling studies (Nakaza et al., 1994; Roeber and Bricker, 2015; Shimozono et al., 2015). Under normal wave conditions, the effect is not remarkable phenomenon. In contrast, in extreme wave conditions such as tropical cyclones, extreme waves enhance the effect on coral reefs. For above 6 cases, the upward reef growth affects a reduction in water depth in the reef crest–upper reef slope zone and it probably enhances a resonant oscillation of water by infragravity waves. However, the infragravity waves are known to be generated across the coral reef through nonlinear wave interactions and its overall effect remains

unclear.]

p.7, l.30-31: the cases leading to the road flooding give similar results with a degraded and healthy reef.
We clearly describe your comment in a revised manuscript.
Page 9 Lines 19–20:
[We found that the road (+2.86 m above MSL) adjacent to the study site would be flooded both degraded and healthy reefs in 7 cases (cases 49, 50, 53, 55, 56, 57, and 58, Table 3) of intensified TCs, SLR, and storm surge.]

p.9, 4.2: I really appreciate the discussion on the effects of the reef growth on the wave dissipation.
Thank you for giving the comments. We believe that Figure 8 enhances an understanding of wave deformation by readers.

p.9,15: this sentence is not clear. You mean that there is no significant WLs change in response to upward reef growth? Please rephrase.
Thank you for giving the comments. We clearly describe it in a revised manuscript.
Page 11 Line 4:
[Our results indicate that there is no significant change in WL_s between a degraded reef and a healthy reef.]

Table1, also table2: the readability of the results would be improved if the forecasts were more clearly related to the present-day values. For instance, present-day value without storm surge and projected (2050 and 2100) values without storm surge and different scenarios, then present-day value with storm surge, and projected values with storm surge.
Thank you for giving the suggestions. We modify it, as follows:

Table 2 Significant wave heights at the study site.

Case	Year	SWH_o (m)	SWP_o (s)	SLR (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
Without storm surge								
1	Present	8.70	13.0	0.00	-	-	1.05	87.9%
2	Year 2050	8.70	13.0	0.24	1.11	87.2%	0.88	89.9%
3	Year 2050	8.70	13.0	0.30	0.97	88.9%	1.09	87.5%
4	Year 2050	10.0	14.0	0.24	1.45	85.5%	1.21	87.9%
5	Year 2050	10.0	14.0	0.30	1.51	84.9%	1.46	85.4%
6	Year 2050	11.0	15.0	0.24	1.31	88.1%	1.49	86.5%
7	Year 2050	11.0	15.0	0.30	1.53	86.1%	1.50	86.4%
8	Year 2100	8.70	13.0	0.44	1.07	87.7%	1.06	87.8%
9	Year 2100	8.70	13.0	0.74	1.34	84.6%	1.11	87.2%
10	Year 2100	8.70	13.0	0.98	1.28	85.3%	1.12	87.1%
11	Year 2100	10.0	14.0	0.44	1.54	84.6%	1.33	86.7%
12	Year 2100	10.0	14.0	0.74	1.48	85.2%	1.18	88.2%
13	Year 2100	11.0	15.0	0.44	1.63	85.2%	1.40	87.3%
14	Year 2100	11.0	15.0	0.74	1.68	84.7%	1.77	83.9%
With storm surge of 1.00 m								
15	Present	8.70	13.0	0.00	-	-	1.24	85.7%
16	Year 2050	8.70	13.0	0.24	1.37	84.3%	1.22	86.0%
17	Year 2050	8.70	13.0	0.30	1.33	84.7%	1.35	84.5%
18	Year 2050	10.0	14.0	0.24	1.57	84.3%	1.52	84.8%
19	Year 2050	10.0	14.0	0.30	1.67	83.3%	1.26	87.4%
20	Year 2050	11.0	15.0	0.24	1.93	82.5%	1.66	84.9%
21	Year 2050	11.0	15.0	0.30	2.14	80.5%	1.70	84.5%
22	Year 2100	8.70	13.0	0.44	1.32	84.8%	1.21	86.1%
23	Year 2100	8.70	13.0	0.74	1.24	85.7%	1.40	83.9%
24	Year 2100	8.70	13.0	0.98	1.47	83.1%	1.30	85.1%
25	Year 2100	10.0	14.0	0.44	1.87	81.3%	1.45	85.5%
26	Year 2100	10.0	14.0	0.74	1.59	84.1%	1.64	83.6%
27	Year 2100	11.0	15.0	0.44	1.97	82.1%	1.77	83.9%
28	Year 2100	11.0	15.0	0.74	1.92	82.5%	1.66	84.9%
29	Year 2100	11.0	15.0	0.98	2.00	81.8%	1.80	83.6%

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).
SWH_r: significant wave height at reef flat
The tide is 0.80 m above present mean sea level (i.e., high tide).

Table 3 Flooding risk at the study site.

Case	Year	SWH_o (m)	SWP_o (s)	SLR (m)	WL_s at degraded reef (m)	WL_s at healthy reef (m)	Change in WL_s from degraded reef to healthy reef (m)
Without storm surge							
30	Present	8.70	13.0	0.00	-	0.86	
31	Year 2050	8.70	13.0	0.24	1.19	1.24	-0.05
32	Year 2050	8.70	13.0	0.30	1.30	1.41	-0.11
33	Year 2050	10.0	14.0	0.24	1.58	1.55	0.03
34	Year 2050	10.0	14.0	0.30	1.54	1.64	-0.10
35	Year 2050	11.0	15.0	0.24	1.87	1.90	-0.03
36	Year 2050	11.0	15.0	0.30	1.97	1.99	-0.02
37	Year 2100	8.70	13.0	0.44	1.50	1.52	-0.02
38	Year 2100	8.70	13.0	0.74	1.82	1.90	-0.08
39	Year 2100	8.70	13.0	0.98	2.06	2.12	-0.06
40	Year 2100	10.0	14.0	0.44	1.82	1.81	0.01
41	Year 2100	10.0	14.0	0.74	2.09	2.07	0.02
42	Year 2100	11.0	15.0	0.44	2.07	2.12	-0.05
43	Year 2100	11.0	15.0	0.74	2.41	2.45	-0.04
With storm surge of 1.00 m							
44	Present	8.70	13.0	0.00	-	2.10	
45	Year 2050	8.70	13.0	0.24	2.30	2.29	0.01
46	Year 2050	8.70	13.0	0.30	2.42	2.35	0.07
47	Year 2050	10.0	14.0	0.24	2.44	2.53	-0.09
48	Year 2050	10.0	14.0	0.30	2.55	2.54	0.01
49	Year 2050	11.0	15.0	0.24	2.87	2.86	0.01
50	Year 2050	11.0	15.0	0.30	2.89	2.89	0.00
51	Year 2100	8.70	13.0	0.44	2.49	2.50	-0.01
52	Year 2100	8.70	13.0	0.74	2.81	2.83	-0.02
53	Year 2100	8.70	13.0	0.98	3.00	3.01	-0.01
54	Year 2100	10.0	14.0	0.44	2.70	2.69	0.01
55	Year 2100	10.0	14.0	0.74	2.97	2.96	0.01
56	Year 2100	11.0	15.0	0.44	3.00	2.98	0.02
57	Year 2100	11.0	15.0	0.74	3.23	3.32	-0.09
58	Year 2100	11.0	15.0	0.98	3.45	3.51	-0.06

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).

WL_s: water level at shore

Under line: over of risk level of flooding (2.86 m above present mean sea level)

The tide is 0.80 m above present mean sea level (i.e., high tide).

In this context, we change all case number in the original manuscript into new one.

Response to RC2 (Referee #2: Dr. Alberto. Armigliato)

The paper by Hongo and co-authors addresses the problem of projecting toward the end of the present century the impact of increased tropical cyclones (TC), sea level rise (SLR) and storm surges on the reef-lined coasts of Palau (western Pacific Ocean), with special focus on the coasts of the Melekeok state (Babeldaob island). The paper has three main objectives: 1) evaluating the effectiveness of coral reefs as a natural breakwater in the present conditions, 2) assessing quantitatively the impact, on the reef and at the shore, of waves forced by increased meteo-hydro-ocean extreme phenomena in the conditions forecasted for the end of the 21th century; 3) estimating the reef production rate necessary to cope with the increased hazard and to maintain the effectiveness of the reef itself in attenuating the wave impact at the shore. The effects of the above-mentioned meteo-hydro-ocean increased forcing terms are investigated numerically by means of the numerical code CADMAS-SURF. The effects of increased TC, SLR and storm surges are treated separately by means of several different scenarios, in each of which a set of values for the significant wave height offshore, for the significant wave period offshore, for the SLR value and the storm surge "height" are provided as input. The outputs are the significant wave height at the reef flat and the water level at the shore, calculated in conditions both of healthy and degraded reef. The most hazardous scenarios are those for which the water level at the shore is larger than the minimum topographic height at which the local communities are found (local road presently at 2.86 m above MSL). The authors find two of these scenarios in their projection to 2050 and four in the projection to 2100. Another important conclusion regards the coral growth rate needed to cope with the increased hazard. A Corymbose Acropora growth rate of <1% will be needed for RCP 2.6, a growth rate >8 % will be needed for RCP8.5. Although the topic and conclusions are important and relevant, I see a number of issues that need to be solved before the paper can be considered for publication.

We are grateful to you that you review.

1) A first issue regards the title, which contains the terms "risk" and "damage". Neither "risk" nor "damage" are assessed in this paper. Rather, only hazard is assessed in terms of significant wave height at the reef flat and of water level at the shore. Risk and damage make sense only if some kind of vulnerability is assessed and if this vulnerability is combined with the hazard. This operation is not part of the study, so it is important that no mention to damage and risk is made in the paper.

Thank you for giving the comments. We changed the title into "Projecting of wave height and water level on reef-lined coasts due to intensified tropical cyclones and sea level rise in Palau to 2100".

2) A clear statement of the reasons motivating the choice of Melekeok as test site is missing. Section 2.1 "Study site" is too short and no sufficient justification is given for the choice. The only obvious one is that a reef is present. But what about the history of Palau? What about its demographics, what about its cultural/historical/environmental/...assets?

Thank you for giving the comments. We focused on Melekeok site because of four reasons: (1) The present capital of Palau is located at Melekeok. (2) Melekeok as well as Koror was traditionally powerful village for the history of Palau (Rechebei and McPhetres, 1997 *History of Palau*). (3) The village is located at coastal area and most houses are located a few meters above the present mean sea level. (4) We use a forecasting wave data by the Global Forecast System (GFS) model for Melekeok. To clarify the reasons motivating the choice of Melekeok as test site we added the following sentences:

Page 3 Line 20–Page 4 Line 2:
[The present study site is located in Melekeok state, at the east central coast of Babeldaob, the biggest island in Palau (Figure 1a). Melekeok is an important state because it is the national capital of Palau, housing the national government including the executive, legislative and judiciary branch of the government. Melekeok is an ideal site for this study because it is representative of the east coast of Palau in terms of its closeness to the sea and the threats it faces. Understanding what happen in Melekeok can be applied to other states on the east coast and can help with the other states in preparation for the future impacts of climate change. The state consists of reefs, long beaches, mangroves, hills, steep ridges, and rivers. Prior to the contact with foreigners, some of the villages started to increase their influence and power by forming alliances through warfare (Rechebei and McPhetres, 1997), and Melekeok and Koror village became the most powerful villages in the islands. During the Japanese administration (1919–1945), the settlement of the state had moved to the coastal area from inland. In the present-day, most of the communities are settled at altitude of ~3 m above the present mean sea level (MSL). The Melekeok elementally school and Melekeok state office are also located in the coast. Melekeok reef (7.501°N, 134.640°E) is located on the eastern coast of the state. There is no artificial breakwater for ocean waves along the reef. Our one survey transect is located near the elementary school (Figure 1b), because the school will be probably one of potential evacuation places during assumed intensified TCs.]

Page 5 Lines 11–15:
[Since there is no *in situ* observation systems for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems in Palau Islands, the present-day SWH_o value was simulated by using the Global Forecast System (GFS) model at 27 km resolution, provided by Windguru (see http://www.windguru.cz). In Palau Islands, the values for 4 sites (Melekeok, Koror, North beaches, and West Passage) are provided by the model. The largest SWH_o value at Melekeok during Typhoon Bopha was 8.70 m.]

3) Is there any evidence regarding the maximum inundation liner elative to Typhoon Bopha in 2012 and Typhoon Haiyan in 2013? Were these two events simulated with CADMAS-SURF? They would represent a good benchmark for all the scenarios provided in this paper.
Thank you for giving the comments. Another Referee is also wondering. Firstly, we attempted to find

a recorded data of water level in the study site. However, we could not found any *in situ* observation data for water level at offshore and onshore using underwater loggers and/or radar observational systems. However, we conducted interviews to the local peoples about the state of flooding at the study reef during Typhoon Bopha. As a result, local people mentioned that the road (+2.86 m above MSL) along the shore at the study site was flooded during the Typhoon Bopha and that this was never seen for a past ca. 70 years. We believe that our simulation data seems to match with the observation by the local people, although we could not obtain quantitative data. To clarify these points, we added the following sentences into the revised manuscript:

Page 4 Lines 3–15:
[2.2 Impacts of historical TCs and Typhoon Bopha
Since 1951, 19 typhoons passed within 150 km of Melekeok reef in Palau, provided by the Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en) based on the Japan Meteorological Agency (JMA) best track data (Table 1). Only 1 severe typhoon passed near this study reef in 1990 (Typhoon Mike), and the impact was limited to the northern reef of Palau (Maragos and Cook, 1995). Prior to Typhoon Bopha that passed south of Palau in December 2 2012, it is suspected that no major typhoons had caused significant damage to coral reefs and coastal areas of Palau for over 60 years.

The minimum pressure of Typhoon Bopha center was 935 hPa and the maximum wind speed was 50 m/s (data obtained by Digital Typhoon: http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en). The average wind speed was 27 m/s around the study site, provided by Windguru (see http://www.windguru.cz) in December 2 2012 because the study site is 121 km distance from the pass of Typhoon Bopha. In order to understand the impacts of Typhoon Bopha, we attempted to find *in situ* recorded data of ocean wave and water level at the study site. However, we could not found any *in situ* observation data for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems. Because observed evidence was not clear, we conducted local interviews to obtain reliable information of the impacts.]

Page 7 Lines 18–21:
[During the Typhoon Bopha, local people mentioned that beach erosion and destruction of structure (e.g., the pier and a pavilion, ~3 m above MSL) occurred along the shore at the study site (Figure 2). Moreover, the road and the ground of elementary school (+2.86 m above MSL) along the shore were flooded and that this was never seen for a past ca. 70 years.]

Page 10 Lines 20–22:
[Our result of WL_s shows that the road along the shore at the study site was flooded during an assumed present TC (i.e., Typhoon Bopha). Our simulation data seems to correspond with the observation by the local peoples, although we could not obtain quantitative data.]

4) In my understanding, in the paper the term “degraded” is used to indicate a reef that is not going to grow, but that is anyway present. If my understanding is wrong, then ignore this point. But if it is correct, then since it is clearly stated that the 2012 and 2013 typhoons caused severe loss of coral cover, why a scenario in which a large portion of the reef is destroyed and hence the relative protection effect is missing, is not taken into account? Thank you for giving the constructive comment. Your understanding that the term of “degraded reef” means no reef growth is correct. If we had topographic and coral data for the study site before the attacking by severe typhoons in 2012 and 2013, we would evaluate an effect of corals to wave action. However, our field survey was conducted in July and September 2015 (Page 5 Line5─6 in original manuscript). Consequently, “Degraded reef” for our results means a state of no reef growth from our survey in 2015.

However, to better understand the present study and promote further researches, we added the present status of the study reef and importance for maintenance of reef environments into discussion.

Page 13 Lines 8─18:

[In Palau Islands, the loss of mature coral colonies on the eastern reef slopes may have decreased coral recruitments and led to the opening of space for turf algae around the islands after Typhoon Bopha in 2012 and Typhoon Haiyan in 2013 (Gouezo et al., 2015). Actually, there was a major decline in juvenile acroporidae corals at the reef slope on Melekeok and along the eastern reef slopes in Palau Islands (Gouezo et al., 2015). 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 9 (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). Although the decrease in juvenile acroporidae corals at Palau Islands, early successional corals, especially pocilloporidae, recruited 6 months after Typhoon Haiyan in 2013 (Gouezo et al., 2015). There is no information for upward reef growth by pocilloporidae facies in the islands. To understand the role in coastal risks, an estimation of reef production by pocilloporidae will be probably considered.]

5) Is there any historical evidence of tsunami impact/damage on the reef? If so, this should be another factor to be considered as possible responsible for degrading the reef.
Thank you for giving the interest comment. We are also interesting in impacts of tsunami to the reef. We attempted to find historical records of tsunamis around the study site, but the records around the Palau Islands are poor (Wolanski and Furukawa, 2007 *Coral Reefs of Palau*; International Strategy for Disaster Reduction, 2009). We attempted to reconstruct past tsunamis using geological evidences (e.g., deposited reef boulders) at the study site (we submitted our results to an international journal). According to our observations, even if some tsunamis have inundated the reef for past several thousand years, the hydraulic forces are assumed to have been lower than those associated with

Typhoon Bopha. Consequently, the impact of tsunami is beyond our research in this manuscript.

6) Why is a single cross-section considered? Can you make any estimate of how your results may change should other cross-sections be considered in the same area, or even if another coastal area along the island would be taken into account?

Thank you for giving the comment. For our research, we selected the most important site (as our viewpoint for "disaster risk reduction) in the study area where the Meleleok elementary school is located. We assumed that the school will be probably one of potential evacuation place during assumed intensified TCs. Therefore, we conducted the research for a single cross section. We explained the reason in method, as follow.

Page 3 Line 31–Page 4 Line 2:

[Our one survey transect is located near the elementary school (Figure 1b), because the school will be probably one of potential evacuation places during assumed intensified TCs.]

In this context, coastal area is often influenced by lateral flow such as diffracted waves due to topographic effect. In order to understand the complex behavior of waves, it is necessary to use 3D-wave analysis. Therefore, we described the necessary for 3D-wave analysis as a further research, as follows.

Page 14 Line 31–Page 15 Line 2:

[Moreover, the CADMAS-SURF wave simulation model can contribute to our projecting of wave height and water level due to intensified TCs and SLR by 2100. However, reef coasts are often influenced by lateral flows such as diffracted waves due to topographic effects. In order to understand the complex behavior of waves, 3D-wave analysis as well as 3D-topography measurement will be required.]

7) Regarding the modeling with CADMAS-SURF, if I understood correctly the forcing terms are impulsive, or maybe even steady-state. Can you clarify? Is this approximation well fit to TC? And to SLR? And to storm surges?

Thank you for the comment. Yes. We input the forcing (SWH_o and SWP_o) as a regular wave into CADMAS-SURF model because the value by the GFS model is restricted to single value. To input the values of SWH_o and SWP_o at Tyhoon Bopha (December 2 2012) into the CADMAS-SURF model, we extracted the values from the data set, provided by Windguru (see http://www.windguru.cz). Future forcing of SWH_o and SWP_o are discussed in the original manuscript. This is a limitation for the present study. Therefore, we clearly explained in Method and added an improvement of input forcing into Conclusion.

Page 5 Lines 24–25:

[We input the SWH_o as a regular wave into the model because the value of GFS model is restricted to single value.]

Page 15 Lines 2–7:
[The present study assumed a significant wave height and a significant wave period as a regular wave under TCs; however, coral reefs during TCs are affected by irregular waves. Consequently, it is necessary to set irregular waves for various TCs conditions using the CADMAS-SURF model and/or other 3D-wave model. Finally, the input parameters for the CADMAS-SURF model are obtained at 27 km resolution using the GFS model. To precisely estimate SWH_r and WL_s, *in situ* observed data of wave height, wave period, and water level should be collected.]

For the SLR and storm surge, we considered the global SLR separately from the tentative and local SLR (i.e., storm surge) during TCs. The future SLR is provided by Church et al. (2013) based on IPCC 5th assessment report. We cited the data. In contrast, an increased sea-level rise by storm surge varies with intensity of TCs. In this study, we assumed that future intensified TC will be characterized by a minimum central pressure of ca. 900 hPa and we assumed that the WL_o will increase to 1.00 m above MSL as a result of the "suction effect" of TC (i.e., storm surge). We clearly explained it at Method.
Page 6 Lines 9–11:
[We assume that intensified TC is characterized by a minimum central pressure of ca. 900 hPa, and thus WL_o will increase to 1.00 m above MSL as a result of the suction effect of TC.]

8) What are the uncertainties associated with the estimates in Tables1 and 2 (and S1 and S2 as well)?
Thank you for giving the comment. Our simulation results of SWHr and WLs (Tables 1 and 2) clearly varies with assumed forcing. It implies that a value between degraded reef and healthy reef each case is more important than a representative value (e.g., average). Therefore, we delete the average value in Tables 1 and 2. In contrast, we calculated mean value of each effect (increasing of intensity of tropical cyclone, sea level rise, and storm surge) in Tables S1 and S2, because the value is provided by a pool data. The value is use for a comparison between degraded reef and healthy reef.

In this context, as a result of our simulation, there are uncertainties for our output data of SWH_r and WL_s, depending on input data. To precisely estimate SWH_r and WL_s, we require the following improvements: (1) it is necessary to consider a short-term variation in sea level, influenced by El Niño/ La Niña. This was a half-meter change in mean sea level over just a few months. (2) The wave simulation model for the present study is limited to 2D model. In order to understand the complex behavior of waves, 3D-wave analysis as well as 3D-topography measurement will be required. (3) The present study assumed a significant wave height and a significant wave period as a regular wave under TCs; however, coral reefs during TCs are affected by irregular waves. It is necessary to set irregular waves for various TCs conditions using the CADMAS-SURF model and/or

3D-wave model. (4) In this study, input data are provided by using the Global Forecast System (GFS) model at 27 km resolution. To precisely estimate SWH_r and WL_s, *in situ* observed data of wave height, wave period, and water level should be collected. Consequently, we explained the uncertainties and improvements at Conclusion.

Page 14 Line 25–Page Line 7:

[Our research would be useful in predicting wave height and water level on coral reefs in the present climate and in a future climate. However, the research has uncertainties of the results and requires the following improvements. The present study emphasizes that further research is required regarding a short-term variation in sea level. During the El Niño of early 1998, mean sea level was ca. 0.20 m lower than normal in Palau Islands (Colin, 2009). This was quickly followed by the La Niña of late 1998, during which period the mean sea level was 0.35 m above normal (Colin, 2009). This was a half-meter change in mean sea level over just a few months. Such information will allow us to better understand changes in wave height and water level in the Palau Islands by 2100. Moreover, the CADMAS-SURF wave simulation model can contribute to our projecting of wave height and water level due to intensified TCs and SLR by 2100. However, reef coasts are often influenced by lateral flows such as diffracted waves due to topographic effects. In order to understand the complex behavior of waves, 3D-wave analysis as well as 3D-topography measurement will be required. The present study assumed a significant wave height and a significant wave period as a regular wave under TCs; however, coral reefs during TCs are affected by irregular waves. Consequently, it is necessary to set irregular waves for various TCs conditions using the CADMAS-SURF model and/or other 3D-wave model. Finally, the input parameters for the CADMAS-SURF model are obtained at 27 km resolution using the GFS model. To precisely estimate SWH_r and WL_s, *in situ* observed data of wave height, wave period, and water level should be collected.]

All measures are provided at the centimeter scale. Is this sound?

Thank you for giving the comment. We clearly explained in a revised manuscript.

Page 5 Lines 7–9:

[The four input parameters are given as double figures below decimal point because the future SLR is given as double figures below decimal point (e.g., +0.24 m: Church et al., 2013). Therefore, the calculated values of SWH_r and WL_s are given as rounding at triple figures below decimal point.]

I ask the authors to carefully take into account the above comments and requests and to address them in the revised version of the manuscript. I am also attaching an annotated version of the manuscript with some corrections and further minor comments.

Thank you for carefully checking. We modified all grammatical comments and we clearly modified for two important comments, as follows:

1. RCP: The original manuscript is lacking in the explanation. We added it into a revised manuscript: Page 6 Lines 2–8:

[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 Representative Concentration Pathway (RCP) 2.6 and RCP 8.5, respectively (Church et al., 2013). The RCP was used for the new climate model simulations carried out under the framework of the Coupled Model Intercomparison Project Phase 5 of the World Climate Research Programme. For RCP 2.6, the radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines (IPCC, 2013).For RCP 8.5, the radiative forcing reaches greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time (IPCC, 2013).]

2. Satellite image. To clearly show the location of survey transect, we added a satellite image for the study site into Figure 1b.

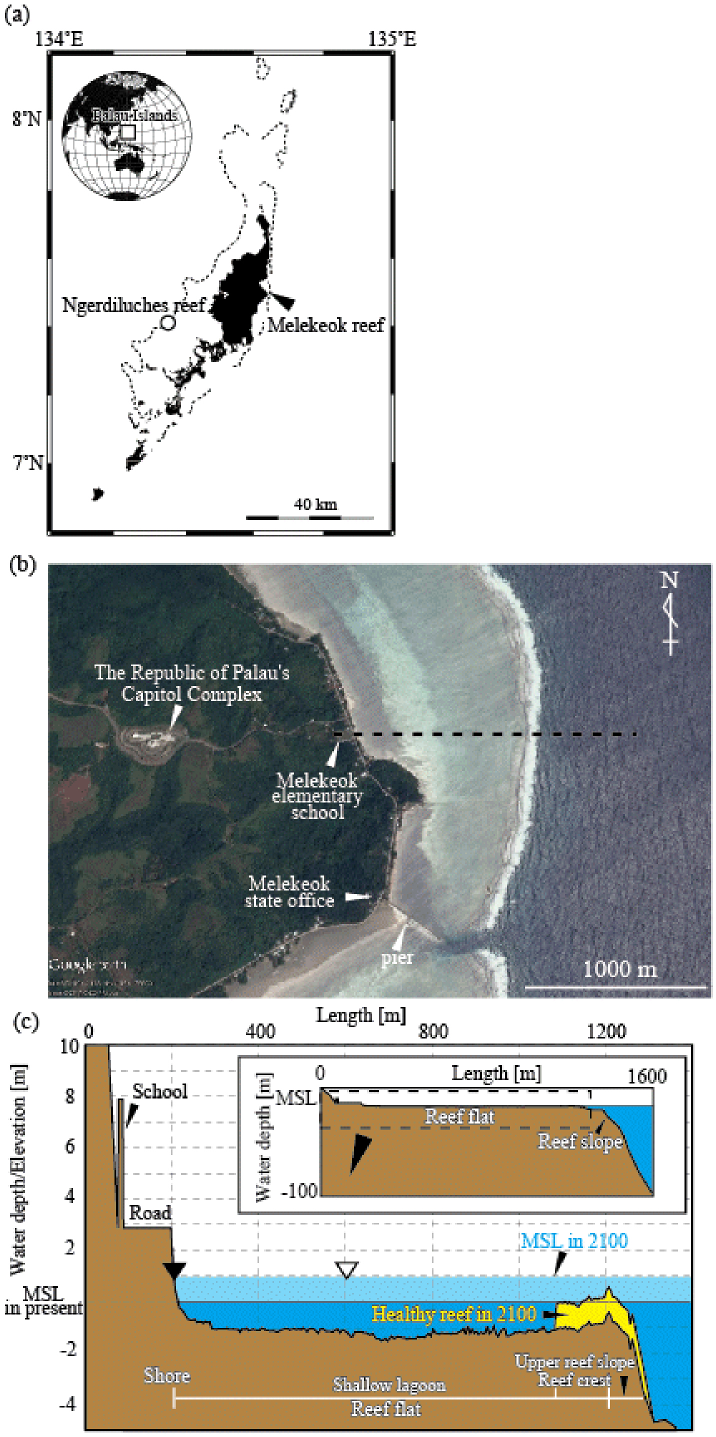


Figure 1: Location of Melekeok reef in the Palau Islands, and the reef topography used for wave calculations. (a) Location of Melekeok reef. The open circle indicates the drillcore site on Ngerdiluches reef (Kayanne et al., 2002). (b) Satellite image of the reefs, long beaches, the Republic of Palau's Capitol Complex, Melekeok elementary school, and Melekeok state office. The dashed line shows the location of the survey transect. (c) 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.

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

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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: SWH$_o$ = 8.7–11.0 m; significant wave period at the outer ocean: SWP$_o$ = 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 due toof TCs, SLR, and storm surges. The present reef is currently highly effective in dissipating incoming waves. The SWH$_o$ was found to rapidly decrease from the upper reef slope to the reef crest. 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. 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 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. But~~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 future SLR is predicted to 0.98 m by 2100 based on the Representative Concentration Pathway (RCP) 8.5~~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. For RCP 8.5, radiative forcing reaches greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time. 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 due to coral mortality 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., 20087). This process reduces the roughness of reef flat and consequently the wave energy reaching the shore. 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 has 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 countrycoastal areas (e.g., flooding, erosion, and destruction of buildings). 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 by 2100. Thirdly, we estimate the reef production rate necessary to reduce the risk under the predicted reef degradation.

2 Methods

2.1 Study site

The present study site is located in Melekeok state, at the east central coast of Babeldaob, the biggest island in Palau (Figure 1a). Melekeok is an important state because it is the national capital of Palau, housing the national government including the executive, legislative and judiciary branch of the government. Melekeok is an ideal site for this study because it is representative of the east coast of Palau in terms of its closeness to the sea and the threats it faces. Understanding what happen in Melekeok can be applied to other states on the east coast and can help with the other states in preparation for the future impacts of climate change. ~~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 state consists of reefs, long beaches, mangroves, hills, steep ridges, and rivers. Prior to the contact with foreigners, some of the villages started to increase their influence and power by forming alliances through warfare (Rechebei and McPhetres, 1997), and Melekeok and Koror village became the most powerful villages in the islands. During the Japanese administration (1919–1945), the settlement of the state had moved to the coastal area from inland. In the present-day, most of the communities are settled at altitude of ~3 m above the present mean sea level (MSL). The Melekeok elementally school and Melekeok state office are also located in the coast. Melekeok reef (7.501°N, 134.640°E) is located on the eastern coast of the state. There is no artificial breakwater for ocean waves along the reef. Our one survey transect is located near the elementary school (Figure 1b), because the school will be probably one of potential evacuation places during assumed intensified TCs.

2.2 Impacts of historical TCs and Typhoon Bopha

Since 1951, 19 typhoons passed within 150 km of Melekeok reef in Palau, provided by the Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en) based on the Japan Meteorological Agency (JMA) best track data (Table 1). Only 1 severe typhoon passed near this study reef in 1990 (Typhoon Mike), and the impact was limited to the northern reef of Palau (Maragos and Cook, 1995). Prior to Typhoon Bopha that passed south of Palau in December 2 2012, it is suspected that no major typhoons had caused significant damage to coral reefs and coastal areas of Palau for over 60 years.

The minimum pressure of Typhoon Bopha center was 935 hPa and the maximum wind speed was 50 m/s (data obtained by Digital Typhoon: http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en). The average wind speed was 27 m/s around the study site, provided by Windguru (see http://www.windguru.cz) in December 2 2012 because the study site is 121 km distance from the pass of Typhoon Bopha. In order to understand the impacts of Typhoon Bopha, we attempted to find *in situ* recorded data of ocean wave and water level at the study site. However, we could not found any *in situ* observation data for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems. Because observed evidence was not clear, we conducted local interviews to obtain reliable information of the impacts.

~~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~~3 Estimation of wave height and water level

There was no *in situ* observation data for ocean wave and water level at the study site. We conducted an estimation of wave height and water level based on a numerical simulation. We first quantitatively assessed the ~~effectiveness~~ wave characters of Melekeok reef ~~in attenuating waves and reducing flooding.~~during Typhoon Bopha. 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 averaged 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 porous media. The model can reproduce highly non-linear wave profiles against various structures, e.g., impact of a wave breaking sea walls (Isobe et al., 1999). The model can apply to wave deformation (e.g., wave shoaling, wave breaking, wave overtopping, and wave run-up) at coral reefs. For a validation of the model, computed results have been compared with observed data and laboratory experiments on wave deformation over coral reefs under TC conditions (e.g., Nagai and Shiraishi, 2004; Kawasaki et al., 2007; 2008). Therefore, the model 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 breakingwave characteristics at coral reefs under TC conditions (Yamashita et al. 2008; 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. TThe data for SWH_r were calculated using the output from the zero-up crossing method. The time resolution was 0.01 s and the calculation time was 3600 s. We used outputs in the time interval for 1801–3600 s. The four input parameters are given as double figures below decimal point because the future SLR is given as double figures below decimal point (e.g., +0.24 m: Church et al., 2013). Therefore, the calculated values of SWH_r and WL_s are given as rounding at triple figures below decimal point. The four parameters are discussed below.

(1) SWH_o: Since there is no *in situ* observation systems for ocean wave and water level at offshore and onshore using underwater loggers and/or radar observational systems in Palau Islands, the present-day SWH_o value was simulated by using the Global Forecast System (GFS) model at 27 km resolution, provided by Windguru (see http://www.windguru.cz). In Palau Islands, the values for 4 sites (Melekeok, Koror, North beaches, and West Passage) are provided by the model. The largest SWH_o value at Melekeok during Typhoon Bopha was 8.70 m. 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). 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 ca. 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. We input the SWHo as a regular wave into the model because the value of GFS model is restricted to single value.

(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. We input the SWP_o as a regular wave into the model.

(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 Representative Concentration Pathway (RCP) 2.6 and RCP 8.5, respectively (Church et al., 2013). The RCP was used for the new climate model simulations carried out under the framework of the Coupled Model Intercomparison Project Phase 5 of the World Climate Research Programme. For RCP 2.6, the radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines (IPCC, 2013).For RCP 8.5, the radiative forcing reaches greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time (IPCC, 2013).~~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 intensified TC is characterized by a minimum central pressure of ca. 900 hPa, and thus WL_o will increase to 1.00 m above MSL as a result of the suction effect of TC.~~We assume that the WL will increase to 1.00 m above MSL as a result of the suction effect of TCs.~~

(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 (Figure 1b). 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~~1c). We used 10 % of porosity for predicting vertical reef growth.

2.~~3~~ 4 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). The corymbose *Acropora* facies is characterized by corals by corymbose and tabular *Acropora* (e.g., *Acropora digitifera*). These corals are found on distinct reef crests and upper reef slopes in Palau Islands (Kayanne et al., 2002; Yukihira et al., 2007). The zone is generally characterized by high-energy waves in water depths less than 7 m (Hongo and Kayanne, 2011). The arborescent *Acropora* facies is characterized by corals by arborescent *Acropora* (e.g., *Acropora muricata/ intermedia* complex). These corals occupy the inner reef slope and leeward reef slope at water depths of less than 20 m in Palau Islands and other reefs in the present-day Pacific Ocean (Montaggioni, 2005; Yukihira et al., 2007). These corals are interpreted to inhabit a low- to moderate- energy wave conditions (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):

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

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. Similarity, we assumed that the upward reef growth rates for the corymbose *Acropora* facies in response to 10 m/kyr, 5 m/kyr, and <5 m/kyr of Holocene SLR were ~~,~~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), respectively. ~~for the facies in response to <5 m/kyr of Holocene SLR.~~

3 Results

3.1 ~~Present-day reef~~Wave height and water level at Typhoon Bopha

Melekeok reef has distinctly zoned landforms, comprising the reef flat and reef slope (Figure ~~1d~~1c). 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).~~ During the Typhoon Bopha, local people mentioned that beach erosion and destruction of structure (e.g., the pier and a pavilion, ~3 m above MSL) occurred along the shore at the study site (Figure 2). Moreover, the road and the ground of elementary school (+2.86 m above MSL) along the shore were flooded and that this was never seen for a past ca. 70 years.

According to our wave simulation, ~~T~~the SWH$_o$ was found to rapidly decrease from the upper reef slope to the reef crest (Figure ~~2~~3). Under present-day TCs (8.7~~0~~0 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~~2). 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$_o$. Moreover, the SWH$_r$ was 1.24 m for storm surge under the present-day TCs (case 15, Table 2) and the entire reef dissipated 85.7% of the SWH$_o$.

The WL$_s$ was 0.86 m for present-day TCs (case 30, Table 3) and the WL$_s$ increased to 2.10 m under storm surge conditions (case 44, Table 3). Moreover, the water level at the shore under present-day TCs (i.e., Typhoon Bopha) reached the elevation of road (+2.86 m above MSL) at the study site (Figure 4).~~The WLs was 0.86 m for present-day TCs (case 30, Table2) and the WLs 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~~2). 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~~16) 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 18), 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~~20). 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~~20) will increase by 0.30 m in SLR to 1.70 m (+2.4%, 0.30 m in SLR; case ~~14~~21) and to 1.77 m (+6.6%, 0.44 m in SLR; case ~~26~~27). 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 3 and 617). As another example, under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o; between cases 11 6 and 1220), 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 53, 6, 14, 176, 11, 2318, and 264, and 27) the SWH_r was reduced to 0.01–0.44 m by upward reef growth by 2100 (Table 21, Figure 5). For example, 0.24 m in upward reef growth caused a 0.24 m reduction in the 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 74). This indicates that reef growth enhanced the reduction in wave height from 85.5% at degraded reefs to 87.9% at healthy reef (case 74, 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 wave water height level at the shoreat the reef flat

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 23, Figure 6). 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 3231) 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 3633), and increase to 1.90 m (+53.2%) under the most intense TCs (11.0 m SWH_o, 15.0 s SWP_o) (case 4035). 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 3231) to 1.50 m (+26.1%) with 0.44 m SLR (case 4437), and to 1.82 m (+52.9%) with 0.74 m SLR (case 4638). 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 4035 and –491, 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~~50). 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~~55), even with a difference of 0.74 m in upward reef growth.

We found that the road (+2.86 m above MSL) adjacent to the study site would be flooded both degraded and healthy reefs in 7 cases (cases 49, 50, 53, 55, 56, 57, and 58, Table 3) of intensified TCs, SLR, and storm surge.~~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 (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~~7). 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~~7).

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).

Our wave calculations show that increasing TC intensity, SLR, and storm surges will cause 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).

Our result of WL_s shows that the road along the shore at the study site was flooded during an assumed present TC (i.e., Typhoon Bopha). Our simulation data seems to correspond with the observation by the local peoples, although we could not obtain quantitative data.

The present results also show that increasing TC intensity, SLR, and storm surges will cause an increase in WL_s of Melekeok reef, even under healthy reef conditions, with SLR and storm surges directly increasing the WL_s. Furthermore, an increase in SWH_o 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 3). 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).

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 that there is no significant change in WL_s between a degraded reef and a healthy reef. This can be explained by the nature of coral reefs, which are porous structures characterized by a high degree of water permeability. A reef framework has a wide range of porosities from low (where internal cavities have been infilled with marine cements) to high (e.g., a reef framework is mainly composed of branching corals) (Hopley, 2011). In this study, mean porosity of reef framework is estimated as 10 %. This means that sea water permeates through the reef due to porosity, even if the reef is characterized by three dimensional structures.

T~~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. T~~he 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~~8). 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. However, our results showed that 6 cases (cases 3, 6, 14, 17, 23, and 26) the SWH_r was increased to 0.02 m–0.18 m by upward reef growth by 2100. An increase in SWH_r is likely to be explained by a difference in magnitude of infragravity waves between the degraded reef and the healthy reef. Waves propagating onto shallow reefs steepen and break, and while some of the breaking wave energy propagates shoreward as reformed high-frequency waves, the spectral wave energy shifts into lower frequencies and long-period (infragravity) waves often dominate (Cheriton et al., 2016). Infragravity waves over shallow reef flats have established relationships between the offshore conditions and resulting reef flat characteristics (e.g., complex bathymetry). Increased of wave height and water level due to the infragravity waves have been observed for various coral reefs (Nakaza et al., 1994; Cheriton et al., 2016) and have also been demonstrated in laboratory and modelling studies (Nakaza et al., 1994; Roeber and Bricker, 2015; Shimozono et al., 2015). Under normal wave conditions, the effect is not remarkable phenomenon. In contrast, in extreme wave conditions such as tropical cyclones, extreme waves enhance the effect on coral reefs. For above 6 cases, the upward reef growth affects a reduction in water depth in the reef crest–upper reef slope zone and it probably enhances a resonant oscillation of water by infragravity waves. However, the infragravity waves are known to be generated across the coral reef through nonlinear wave interactions and its overall effect remains unclear.

If the future WL_s value shows below the road (+2.86 m above present MSL), the difference in SWH_r between healthy and degraded reefs (max. 0.44 m) will have not a significant impact on the coastal area. However, our results indicate that the future WL_s will almost reach the elevation of the road at the study site. The above result implies that an increase in wave height of only 0.1 m leads to an increase in risks of substantial coastal damages such as flooding, destructions of constructions (houses and buildings), saltwater intrusion into groundwater, and coastal erosion. Detail quantity of the damages was beyond the scope of the present study, but the difference in SWH_r by a maximum of 0.44 m will probably cause a significant coastal damages. For example, flooding mostly occurs within a 1-km wide coastal zone along the shoreline, and a 0.33 m of water level rise has little effect on inundation, but 0.66 m of water level rise, reveals widespread groundwater inundation of the land surface at Oahu Island in Hawaii (Rotzoll and Fletcher, 2013), although it is difficult to directly compare a coastal area between the Melekeok reef and the result of Oahu Island. Consequently, upward reef growth will be required for the reduction of risks of coastal damages.

According to the analysis of drillcore in this study, a corymbose *Acropora* facies at a high-wave energy condition in water depths less than 7 m and an arborescent *Acropora* facies at a low- to moderate- wave conditions in water depths less than 20 m contributed to the Holocene reef in the Palau Islands (Kayanne et al., 2002; Hongo and Kayanne, 2011). The maximum future SLR is predicted to +0.98 m by 2100 (Church et al., 2013). This implies that arborescent *Acropora* corals 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. In contrast, ~~C~~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.cropora 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 4d8d). 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). In Palau Islands, the loss of mature coral colonies on the eastern reef slopes may have decreased coral recruitments and led to the opening of space for turf algae around the islands after Typhoon Bopha in 2012 and Typhoon Haiyan in 2013 (Gouezo et al., 2015). Actually, there was a major decline in juvenile acroporidae corals at the reef slope on Melekeok and along the eastern reef slopes in Palau Islands (Gouezo et al., 2015). 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 9 (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). Although the decrease in juvenile acroporidae corals at Palau Islands, early successional corals, especially pocilloporidae, recruited 6 months after Typhoon Haiyan in 2013 (Gouezo et al., 2015). There is no information for upward reef growth by pocilloporidae facies in the islands. To understand the role in coastal risks, an estimation of reef production by pocilloporidae will be probably considered. 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

This study highlights the importance of maintaining reef growth (as a function of 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). Additionally, we recognize that a ground elevation of construction varies from house to building. To evacuate the people from the flooding area, an investigation of ground elevation each construction and the signboard of elevation will be required. Furthermore, to evaluate the impact of hydrodynamic forces at coastal areas in the islands, establishment of *in situ* observation systems of wave height, wave period, and water level should be considered. For example, establishment of ultrasonic-wave-based wave gauges, observation buoys, and radar-based wave meters are recommended to predict accurately the ocean wave heights and periods to alert peoples for disasters such as flooding during TCs.

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~~defences. 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.

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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.

Our research would be useful in predicting wave height and water level on coral reefs in the present climate and in a future climate. However, the research has uncertainties of the results and requires the following improvements. The present study emphasizes that further research is required regarding a short-term variation in sea level. During the El Niño of early 1998, mean sea level was ca. 0.20 m lower than normal in Palau Islands (Colin, 2009). This was quickly followed by the La Niña of late 1998, during which period the mean sea level was 0.35 m above normal (Colin, 2009). This was a half-meter change in mean sea level over just a few months. Such information will allow us to better understand changes in wave height and water level in the Palau Islands by 2100. Moreover, the CADMAS-SURF wave simulation model can contribute to our projecting of wave height and water level due to intensified TCs and SLR by 2100. However, reef coasts are often influenced by lateral flows such as diffracted waves due to topographic effects. In order to understand the complex behavior of waves, 3D-wave analysis as well as 3D-topography measurement will be required. The present study assumed a significant wave height and a significant wave period as a regular wave under TCs; however, coral reefs during TCs are affected by irregular waves. Consequently, it is necessary to set irregular waves for various TCs conditions using the CADMAS-SURF model and/or other 3D-wave model. Finally, the input parameters for the CADMAS-SURF model are obtained at 27 km resolution using the GFS model. To precisely estimate SWH_r and WL_s, *in situ* observed data of wave height, wave period, and water level should be collected.

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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References

Anthony, K.R.N., Kline, D.I., Diaz-Pulido, G., Dove, S., and Hoegh-Guldberg, O.: Ocean acidification causes bleaching and productivity loss in coral reef builders, Proc. Natl. Acad. Sci. U.S.A., 105, 17442–17446, doi:10.1073/pnas.0804478105,2008.

Benedict, M.A. and McMahon, E.T.: Green infrastructure: smart conservation for the 21st century, Sprawl Watch Clearinghouse, Washington, D.C., 2002.

Burke, L., Reytar, K., Spalding, M., and Perry, A.: Reefs at Risk Revisited, World Resources Institute, Washington, D.C., 2011.

Chappell, J. and Polach, H.: Post glacial sea level rise from a coral record at Huon Peninsula, Papua New Guinea, Nature, 349, 147–149, doi:10.1038/349147a0, 1991.

Cheriton, O.M., Storlazzi, C.D., and Rosenberger, K.J.: Observations of wave transformation over a fringing coral reef and the importance of low-frequency waves and offshore water levels to runup, overwash, and coastal flooding, J. Geophys. Res., 121, 3121–3140, doi: 10.1002/2015JC011231, 2016.

Christensen, J.H., Krishna Kumar, K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., Xie, S.-P., and Zhou,T.: Climate phenomena and their relevance for future regional climate change, In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (Eds) Climate change 2013: The Physical Science Basis, Cambridge University Press, Cambridge and New York, pp. 1217–1308, 2013

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., and Unnikrishnan, A.S.: Sea level change, In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (Eds) Climate change 2013: The Physical Science Basis, Cambridge University Press, Cambridge and New York, pp. 1137–1216, 2013

Coastal Development Institute of Technology (CDIT): Research and Development of Numerical Wave Flume: CADMAS-SURF, Coastal Development Institute of Technology, Tokyo, 2001.

Colin, P.L.: Marine Environments of Palau, Mutual Publishing LLC, Honolulu, 2009.

Connell, J.: Environmental change, economic development, and emigration in Tuvalu, Pacific Studies, 22, 1–20, 1999.

Ferrario, F., Beck, M.B., Storlazzi, C.D., Micheli, F., Sheppard, C.C., and Airoldi, L.: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation, Nat. Commun., 5, 3794, doi:10.1038/ncomms4794, 2014.

Frank, W.M. and Young, G.S.: The Interannual Variability of Tropical Cyclones, Mon. Weather Rev., 135, 3587–3598, doi:http://dx.doi.org/10.1175/MWR3435.1, 2007.

Global Facility for Disaster Reduction and Recovery (GFDRR): GFDRR annual report 2015: Bringing resilience to scale. Global Facility for Disaster Reduction and Recovery, Washington, D.C., 2016.

Golbuu, Y., Fabricius, K., and Okaji, K.: Status of Palau's coral reefs in 2005, and their recovery from the 1998 bleaching event, In: Kayanne, H., Omori, M., Fabricius, K., Verheij, E., Colin, P., Golbuu, Y., Yukihira, H. (Eds.) Coral Reefs of Palau. Palau International Coral Reef Center, Palau, pp. 40–50, 2007.

Gouezo, M., Golbuu, Y., van Woesik, R., Rehm, L., Koshiba, S., and Doropoulos, C.: Impact on two sequential super typhoons on coral reef communities in Palau, Mar. Ecol.-Prog. Ser., 540, 73–85, doi:https://doi.org/10.3354/meps11518, 2015.

Gourlay, M.R.: Infrastructure and reef islands, In: Hopley, D. (Ed.), Encyclopedia of Modern Coral Reefs. Springer, Dordrecht, pp. 601–607, 2011a.

Gourlay, M.R.: Wave set-up, In: Hopley, D. (Ed.), Encyclopedia of Modern Coral Reefs. Springer, Dordrecht, pp. 1144–1149, 2011b.

Gourlay, M.R.: Wave shoaling and refraction, In: Hopley, D. (Ed.), Encyclopedia of Modern Coral Reefs. Springer, Dordrecht, pp. 1149–1154, 2011c.

Hongo, C., Kawamata, H., and Goto, K.: Catastrophic impact of typhoon waves on coral communities in the Ryukyu Islands under global warming, J. Geophys. Res., 117, G02029, doi:10.1029/2011JG001902, 2012.

Hongo, C. and Kayanne, H.: Holocene sea-level record from corals: Reliability of paleodepth indicators at Ishigaki Island, Ryukyu Islands, Japan, Paleogeogr. Paleoclimatol. Paleoecol., 287, 143–151, doi:10.1016/j.palaeo.2010.01.033, 2010.

Hongo, C. and Kayanne, H.: Key species of hermatypic coral for reef formation in the northwest Pacific during Holocene sea-level change, Mar. Geol., 279, 162–177, doi:10.1016/j.margeo.2010.10.023, 2011.

Hongo, C. and Yamano, H.: Species-specific responses of corals to bleaching events on anthropogenically turbid reefs on Okinawa Island, PLOS ONE 8, e60952, doi:10.1371/journal.pone.0060952, 2013.

Hopley, D.: Density and porosity: influence on reef accretion rates, In: Hopley, D. (Ed.), Encyclopedia of Modern Coral Reefs. Springer, Dordrecht, pp. 303–304, 2011.

IPCC, 2013: Annex III: Glossary [Planton S. (Ed)], In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (Eds) Climate change 2013: The Physical Science Basis, Cambridge University Press, Cambridge and New York, pp. 1447–1465, 2013.

Isobe, M., Takahashi, S., Yu, S.P., Sakakiyama, T., Fujima, K., Kawasaki, K., Jiang, Q., Akiyama, M., and Ohyama, H.: Interim development of a numerical wave flume for maritime structure design, Proceedings of Civil Engineering in the Ocean 15, 321–236, 1999.

Japan Meteorological Agency (JMA): Annual Report of Ocean wave in 2005. CD-ROM, 2012.

Kawasaki, K., Kiku, M., Maezato, K., Komesu, T., Shimada, H., Gomi, H., Shibata, T., and Itabashi, N.: Examination of countermeasures against wave overtopping around revetment using numerical wave flume, Proceedings of Coastal Engineering, Japan Society of Civil Engineers, 54, 951–955, 2007.Shimada, H., Shibata, T., Itabashi, N., and Mabuchi, Y.: Numerical analysis of wave deformation over the field reef and wave overtopping on revetment, Proceedings of Civil Engineering in the Ocean 23, 201–206, 2007.

Kawasaki, K., Kiku, M., Sasada, Y., Maezato, K., Uchima, Y., Shimada, H., Gomi, H., Miura, K., and Shibata, T.: Effects of bottom topography and revetment configuration on wave overtopping characteristics of coastal revetment in regular/ irregular wave field, Proceedings of Coastal Engineering, Japan Society of Civil Engineers, 55, 831–835, 2008.

Kayanne, H., Yamano, H., and Randall, R.H.: Holocene sea-level changes and barrier reef formation on an oceanic island, Palau Islands, western Pacific, Sediment. Geol., 150, 47–60, doi:10.1016/S0037-0738(01)00267-6, 2002.

Kayanne, H., Hata, H., Kudo, S., Yamano, H., Watanabe, A., Ikeda, Y., Nozaki, K, Kato, K, Negishi, A., and Saito, H.: Seasonal and bleaching‐induced changes in coral reef metabolism and CO_2 flux, Glob. Biogeochem. Cycle, 19, GB3015, doi:10.1029/2004GB002400, 2005.

Loya, Y., Sakai, K., Yamazato, K., Nakano, Y., Sambali, H., and Van Woesik, R.: Coral bleaching: the winners and the losers, Ecol. Lett., 4, 122–131, doi:10.1046/j.1461-0248.2001.00203.x, 2001.

Maragos, J.E., and Cook C.W.: The 1991–1992 rapid ecological assessment of Palau's coral reefs, Coral Reefs, 14, 237–252, doi: 10.1007/BF00334348, 1995.

Montaggioni, L.F.: History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors, Earth-Sci. Rev., 71, 1–75, doi:10.1016/j.earscirev.2005.01.002, 2005.

Montaggioni, L.F. and Braithwaite, C.J.R.: Quaternary coral reef systems: History, development, process and controlling factors. Elsevier, Amsterdam, 2009.

Nagai, H., and Shiraishi, S.: Study on stability of immersed tunnel against waves, Report of the Coastal Development Institute of Technology, 4, 41–44, 2004.

Nakajima, S., Sekimoto, T., Katayama, H., and Takahashi, K.: Experimental study on wave transformation on steep coral reef, Journal of Japan Society of Civil Engineers B3, 67, I_244–I_249, 2011.

Nakamura, M., Arashiro, Y., and Shiga, S.: Numerical simulations to account for boulder movements on Lanyu Island, Taiwan: tsunami or storm?, Earth, Planets and Space, 66,128, doi:10.1186/1880-5981-66-128, 2014.

Nakaza, E., Tsukayama, S., and Tanaka, S.: Waves and surf beats induced by wave group on coral reef flat, Proceedings of Coastal Engineering, Japan Society of Civil Engineers 41, 86–90, 1994.

Pandolfi, J.M., Connolly, S.R., Marshall, D.J., and Cohen, A.L.: Projecting coral reef futures under global warming and ocean acidification, Science, 333, 418–422, doi:10.1126/science.1204794, 2011.

Rechebei, E.D. and McPhetres, S.F.: History of Palau: Heritage of an emerging nation. The Ministry of Education, Republic of Palau, Koror, 1997.

Roeber, V. and Bricker, J.D.: Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan, Nat. Commun., 6, 7854, doi:10.1038/ncomms8854, 2015.

Rotzoll, K. and Fletcher, C.H.: Assessment of groundwater inundation as a consequence of sea-level rise, Nat. Clim. Chang., 3, 477–481, doi:10.1038/nclimate1725, 2013.

Sato, D., Yokoki, H., Sakurai, M., and Kuwahara, Y.: Lagoonal wave field on tropical cyclone condition in Funafuti atoll, Tuvalu, Journal of Japan Society of Civil Engineers B2, 66, 1236–1240, 2010.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., and Zhang, X.: Changes in climate extremes and their impacts on the natural physical environment, In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., and Midgley, P.M. (Eds.) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge and New York, pp. 109–230, 2012.

Sheppard, C., Dixon, D. J., Gourlay, M., Sheppard, A., and Payet, R.: Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles, Estuar. Coast. Shelf Sci., 64, 223–234, doi:10.1016/j.ecss.2005.02.016, 2005.

Shimozono, T., Tajima, T., Kennedy, A.B., Nobuoka, H., Sasaki, J., and Sato, S.: Combined infragravity wave and sea swell runup over fringing reefs by super typhoon Haiyan, J. Geophys. Res., 120, doi:10.1002/2015JC010760, 2015.

Suwa, R., Nakamura, M., Morita, M., Shimada, K., Iguchi, A., Sakai, K., and Suzuki, A.: Effects of acidified seawater on early life stages of scleractinian corals (Genus *Acropora*), Fish. Sci., 76, 93–99, doi:10.1007/s12562-009-0189-7, 2010.

Takayama, T., Kamiyama, Y., and Kikuchi, O.: Wave transformation on a reef, In: The Port and Harbour Research Institute, Ministry of Transport, Japan (Ed.) Technical note of the Port and Harbour Research Institute, Ministry of Transport, Japan. The Port and Harbour Research Institute, Ministry of Transport, 278, Yokosuka, pp. 1–32, 1977.

Tsuboki, K, Yoshioka, M.K., Shinoda, T, Kato, M., Kanada,S., and Kitoh, A.: Future increase of supertyphoon intensity associated with climate change, Geophys. Res. Lett., 42, 646–652, doi:10.1002/2014GL061793, 2015.

United States Geological Survey (USGS): Topographic map of Oreor, Republic of Palau, Caroline Islands. USGS, Denver, 1983.

Watanabe, M., Goto, K., Imamura, F., and Hongo, C.: Numerical identification of tsunami boulders and estimation of local tsunami size at Ibaruma reef of Ishigaki Island, Japan, Island Arc 25, 316–332, doi:10.1111/iar.12115, 2016.

Wong, P.P., Losada, I.J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y., and Sallenger, A.: Coastal systems and low-lying areas, In: Field, C.B., Barros, V.R., Dokken, D.J. Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L. (Eds.) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Chang, Cambridge University Press, Cambridge and New York, pp. 361–409, 2014.

Woodruffe, J.D., Irish, J.L., and Camargo, S.J.: Coastal flooding by tropical cyclones and sea-level rise, Nature, 504, 44–52, doi:10.1038/nature12855, 2013.

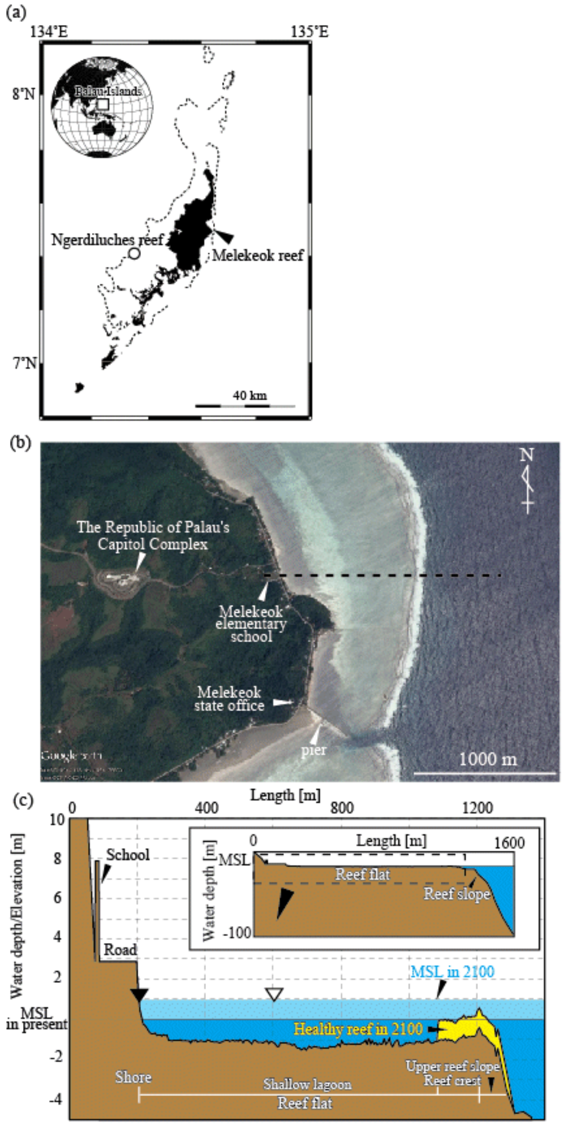
The World Bank, The United Nations (UN): Natural hazard, unnatural disasters: the economics of effective prevention, The World Bank, Washington, D.C. , 2010.

Yamashita, T., Nakamura, Y., Miyagi, E., Oka, H., Nishioka, Y., Takeuchi, H., Kyan, T., and Hoshi, M.: Evaluation of inundation and damage caused by tsunamis and storm surges on the coast of Okinawa Prefecture, Proceedings of Coastal Engineering, Japan Society of Civil Engineers, 55, 306–310, 2008.

Yokoyama, Y., Nakada, M., Maeda, Y., Nagaoka, S., Okuno, J., Matsumoto, E., Sato, H., and Matsushima, Y.: Holocene sea-level change and hydro-isostasy along the west coast of Kyusyu, Japan, Paleogeogr. Paleoclimatol. Paleoecol., 123, 29–47, doi:10.1016/0031-0182(95)00112-3, 1996.

Yokoyama, Y., Maeda, Y., Okuno, J., Miyairi, Y., and Kosuge, T.: Holocene Antarctic melting and lithospheric uplift history of the southern Okinawa trough inferred from mid- to late-Holocene sea level in Iriomote Island, Ryukyu, Japan, Quat. Int., 397, 342–348, doi:10.1016/j.quaint.2015.03.030, 2016.

Yukihira, H., Shimoike, K., Golbuu, Y., Kimura, T., Victor, S., and Ohba, H.: Coral reef communities and other marine biotopes in Palau, In: Kayanne, H., Omori, M., Fabricius, K., Verheij, E., Colin, P., Golbuu, Y., Yukihira, H. (Eds.) Coral Reefs of Palau. Palau International Coral Reef Center, Palau, pp. 10–29, 2007.



(a)
134°E
135°E
8°N
7°N
Palau Islands
Ngerdiluches reef
Melekeok reef
40 km
(b)
N
The Republic of Palau's Capitol Complex
Melekeok elementary school
Melekeok state office
pier
1000 m
(c)
Length [m]
0
400
800
1200
10
8
6
4
2
-2
-4
Water depth/Elevation [m]
MSL in present
School
Road
MSL in 2100
Healthy reef in 2100
Shore
Shallow lagoon
Upper reef slope
Reef crest
Reef flat
Water depth [m]
MSL
-100
1600
Reef flat
Reef slope

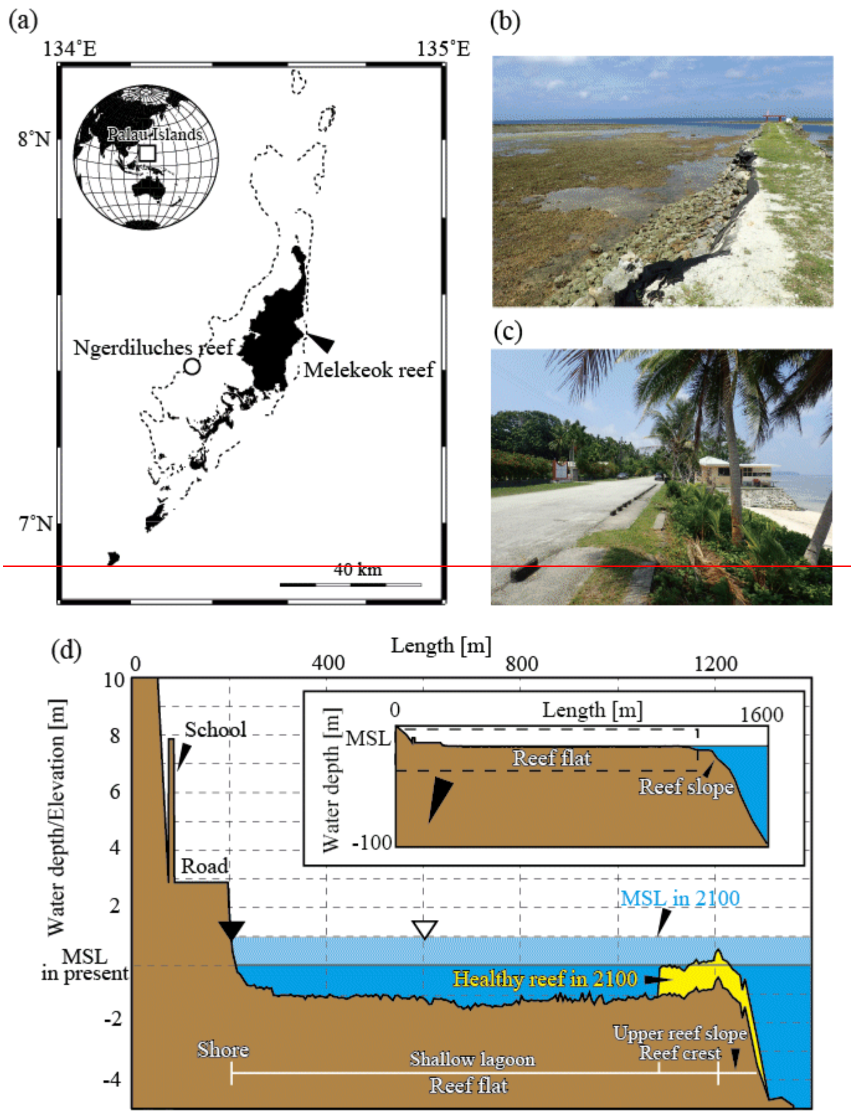


Figure 1: Location of Melekeok reef in the Palau Islands, and the reef topography used for wave calculations. (a) Location of Melekeok reef. The open circle indicates the drillcore site on Ngerdiluches reef (Kayanne et al., 2002). (b) Satellite image of the reefs, long beaches, the Republic of Palau's Capitol Complex, Melekeok elementary school, and Melekeok state office. The dashed line shows the location of the survey transect. (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). (dc) 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.

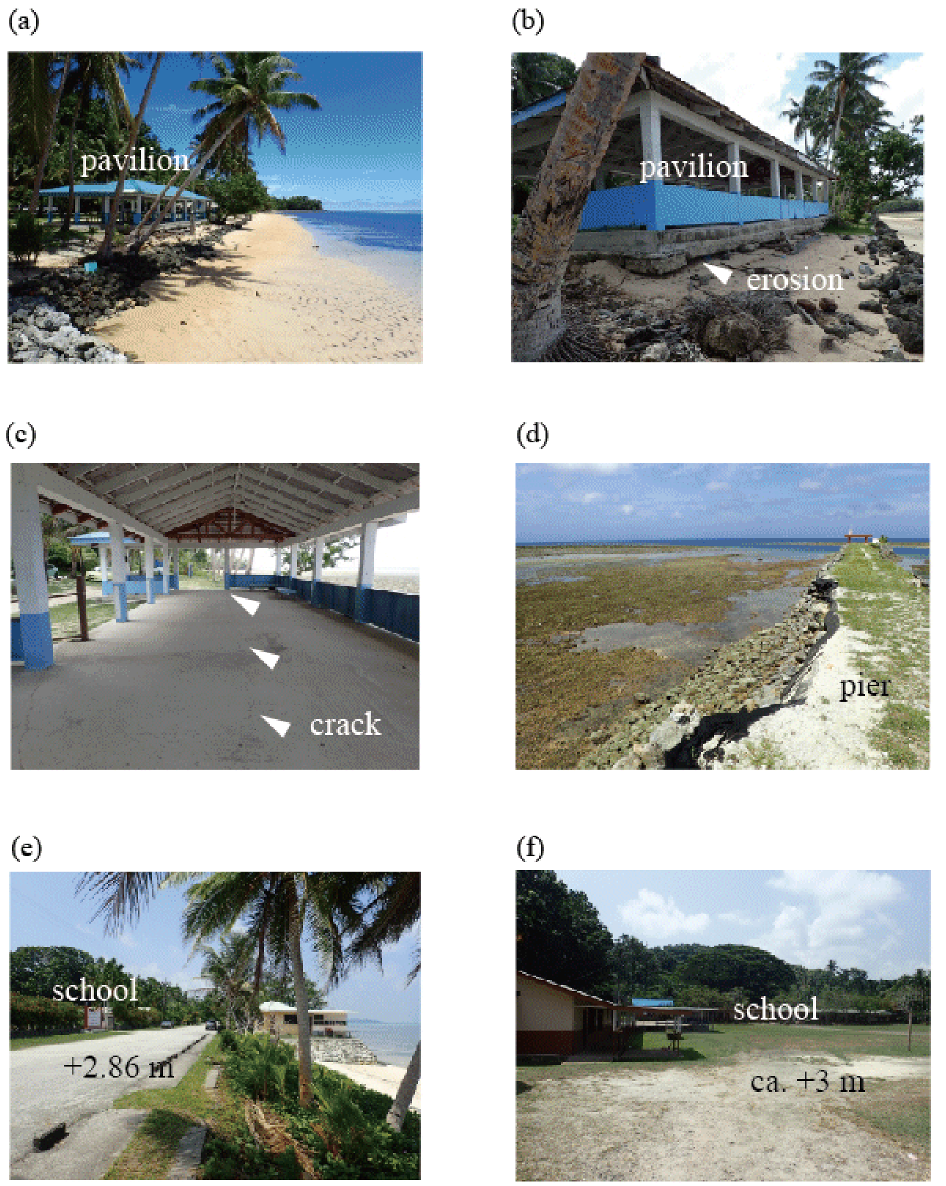


Figure 2: Photograph of the coast at the study site. (a) A pavilion located in the coast. The elevation of the pavilion is less than 3 m above present mean sea level (MSL). (b) Damage of the foundation of pavilion due to the erosion during Typhoon Bopha. (c) Many cracks of the floor of the pavilion. (d) Photograph of the collapsed pier at Melekeok reef. (e) Photograph of the road and Melekeok elementary school along the coast. The elevation of the road is +2.86 m above present MSL. (f) Photograph of the ground of the school. The elevation of the ground is ca. 3 m above present MSL. The road and the ground were flooded during Typhoon Bopha.

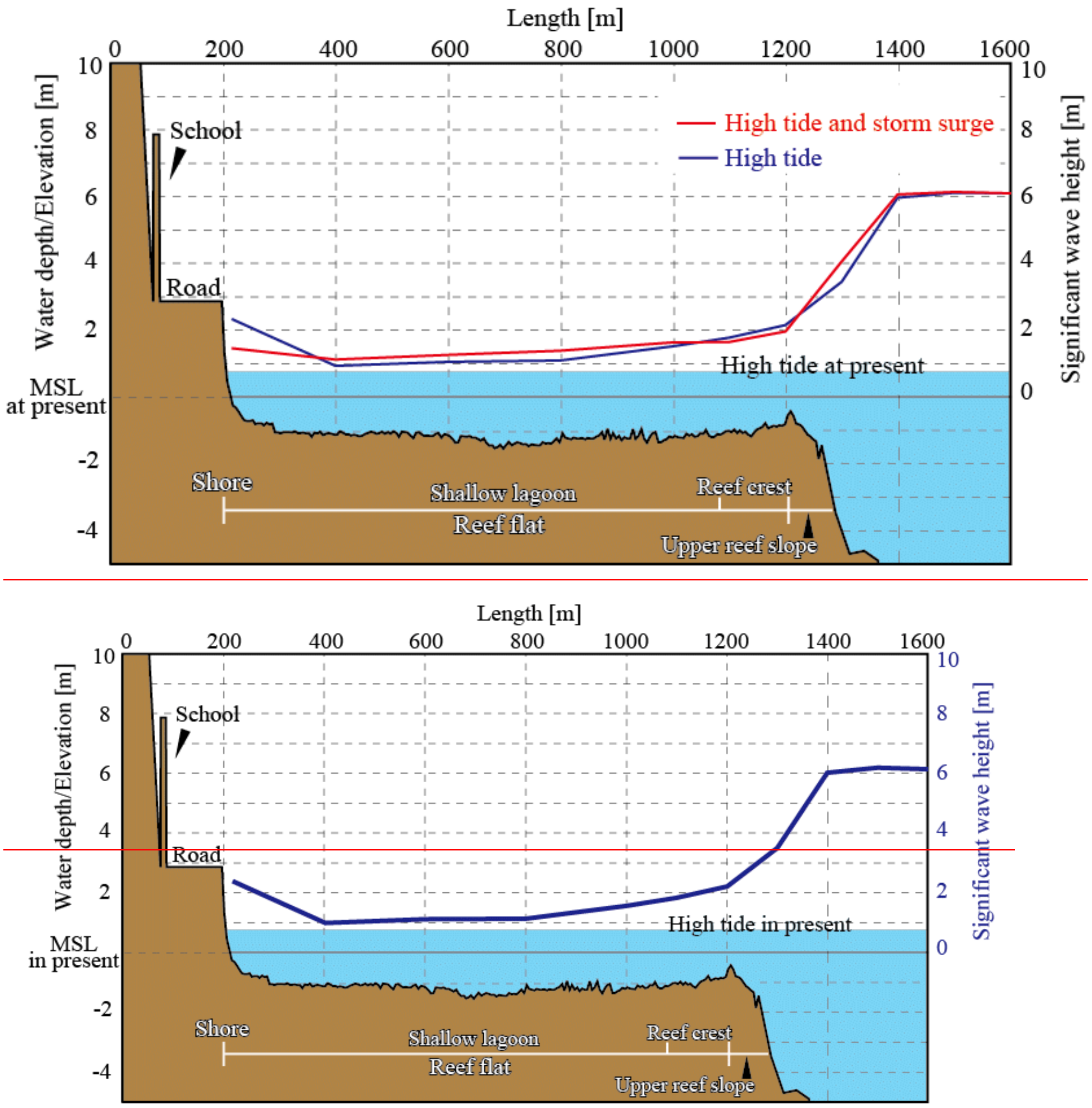


Figure ~~2~~3: Calculated significant wave height (SWH) at the study site under present conditions. The assumed SWH$_o$ and SWP$_o$ values were 8.70 m and 13.0 s, respectively, for the present conditions model TC (i.e., Typhoon Bopha). The assumed WL$_o$ was +0.80 m ~~above MSL~~ (i.e., high tide ~~on spring tides~~) and +1.80 m (i.e., high tide and storm surge) above the present-day MSL.~~.~~ 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.

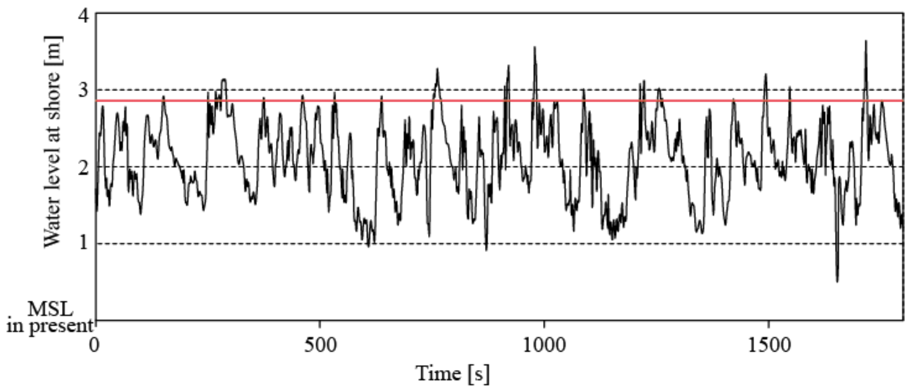
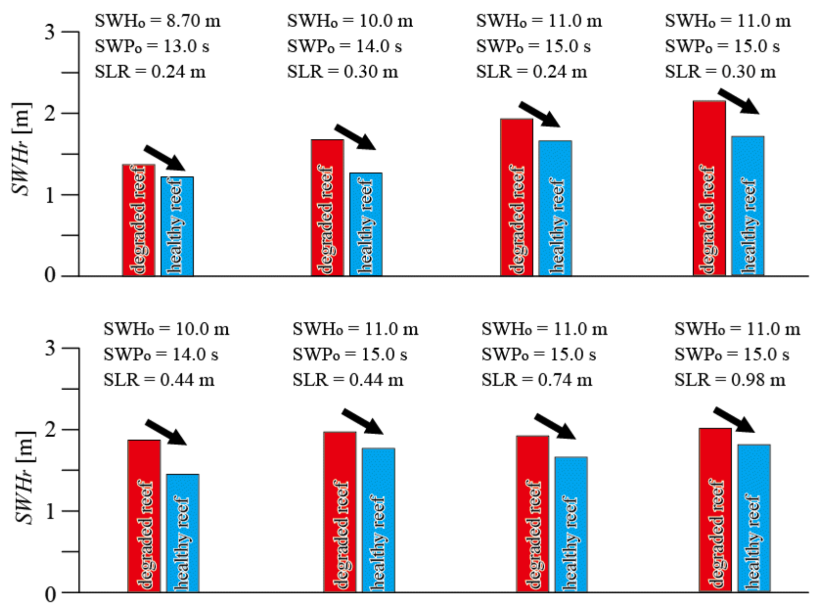


Figure 4: Calculated water level on the shore at the study site under the present-day TC (i.e., Typhoon Bopha). The assumed SWH_o and SWP_o values were 8.70 m and 13.0 s, respectively. The assumed WL_o was +1.80m above MSL (i.e., high tide and storm surge). The horizontal solid line in red shows the elevation of the road (+2.86 m above MSL) at the study site. The road was frequently flooded.



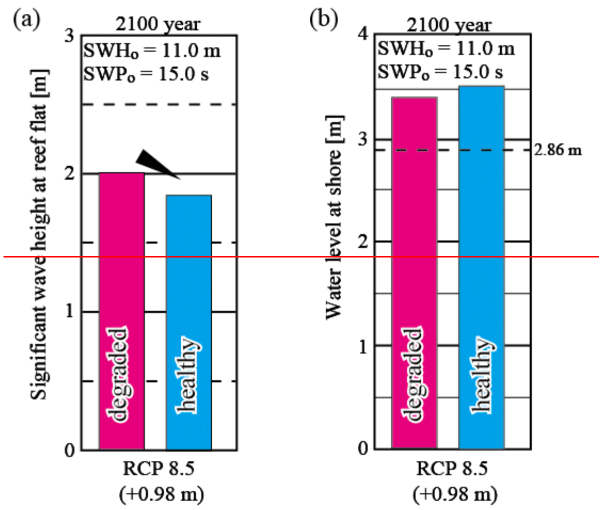


Figure 35: Effect of reef growth on change in the significant wave height at the reef flat for the TCs by 2100. Assumptions: 8.70–11.0 m SWH_o; 13.0–15.0 s SWP_o; SLR 0.24–0.98 m; 1.8 m above present MSL WL_o (i.e., high tide and storm surge). The SLR values are based on the values for the RCP scenario in 2100 (Church et al., 2013). The examples show that healthy reefs will reduce wave height.Effect of reef growth on change in the significant wave height at the reef flat

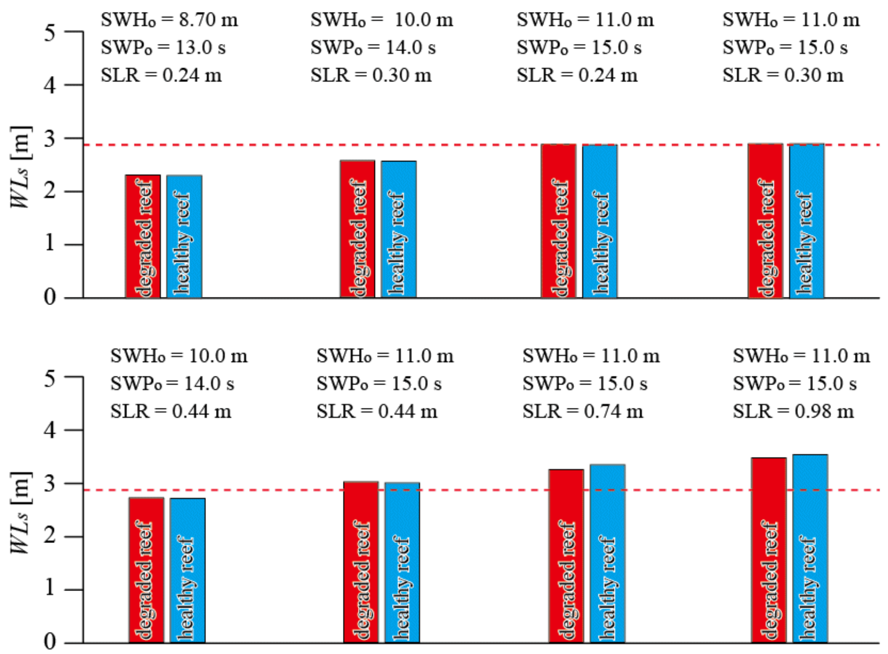
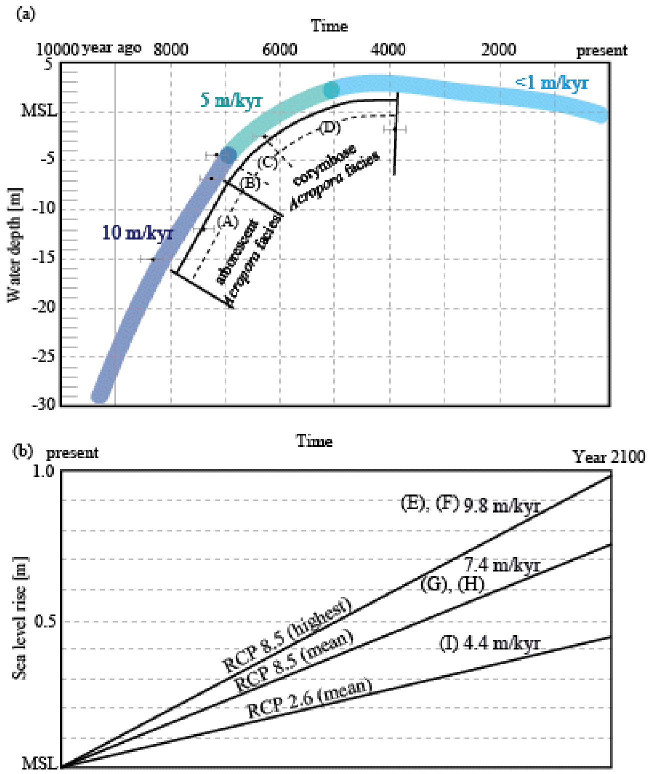


Figure 6: Effect of reef growth on change in the water level at the shore for the TCs by 2100. Assumptions: 8.70–11.0 m SWH_o; 13.0–15.0 s SWP_o; SLR 0.24–0.98 m; 1.8 m above present MSL WL_o (i.e., high tide and storm surge). The SLR values are based on the values

for the RCP scenario in 2100 (Church et al., 2013). The horizontal dashed line shows the elevation of the road (+2.86 m above present MSL) at the study site. The road will be frequently flooded even if the reef is healthy.



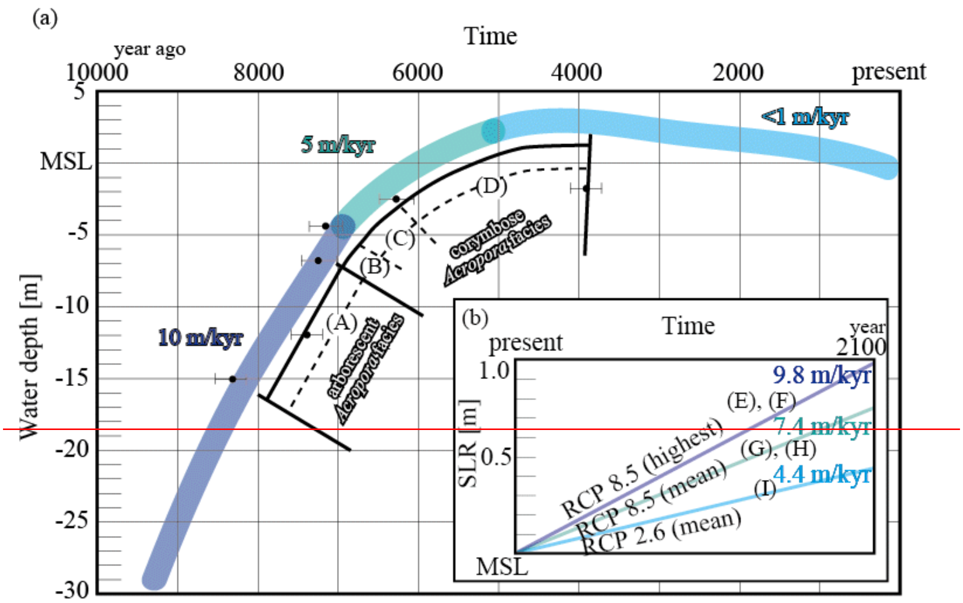
(c)

Rate of Holocene SLR	Rate of reef prodcution (kg $CaCO_3$/m²/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 $CaCO_3$/m²/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

~~, 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 74: 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.

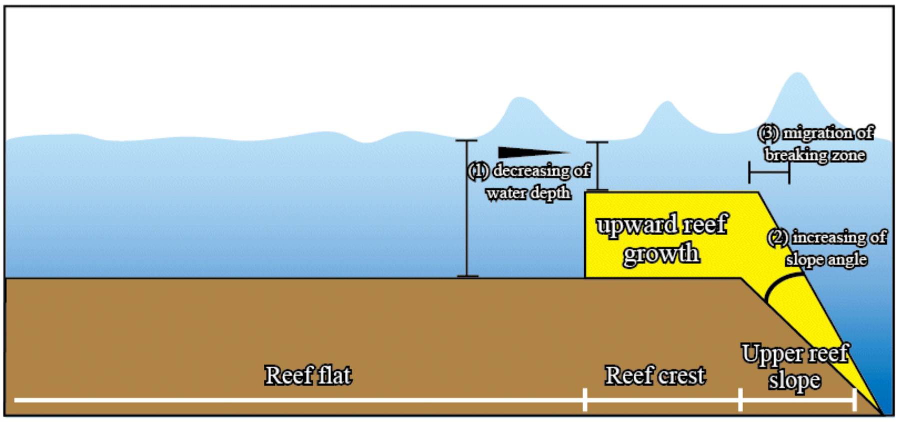


Figure ~~5~~8: Effects of reef growth on reduction in wave height at the reef flat. In the reef crest to upper reef slope zone, upward reef growth will cause: (1) a decrease in water depth; (2) an increase in the reef slope angle; and (3) migration of the wave breaking zone towards the outer ocean. These 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.

Table 1 Tropical cyclone passing within 150 km of Melekeok reef from 1951 to 2015.

TC ~~no.~~number	TC name	Approaching date	Minimum pressure of center (hPa)[a]	Nearest distance from Melekeok reef (km)[a]	Maximum wind speed at nearest distance from Melekeok reef (m/s)[a]
T5501	VIOLET	January 02 1955	995	81	NA
T5701	NO-NAME	January 04 1957	995	93	NA
T5703	SHIRLEY	April 11 1957	975	76	NA
T5901	RUBY	February 28 1959	998	127	NA
T5902	SALLY	March 11 1959	990	101	NA
T5922	GILDA	December 15 1959	925	121	NA
T6431	LOUISE	November 16 1964	915	105	NA
T6702	SALLY	March 03 1967	980	51	NA
T6903	SUSAN	April 20 1969	940	22	NA
T7230	THERESE	December 02 1972	945	32	NA
T7501	LOLA	January 22 1975	975	21	NA
T7603	MARIE	April 07 1976	930	99	NA
T7903	CECIL	April 13 1979	965	9	23
T8201	MAMIE	March 18 1982	990	71	23
T8601	JUDY	February 02 1986	970	139	20
T9025	MIKE	November 10 1990	915	44	45–50
T9101	SHARON	March 11 1991	985	66	25
T1224	BOPHA	December 02 2012	930	121	50
T1330	HAIYAN	November 07 2013	895	72	55–60

NA: Not available

[a] Estimated by Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/) and based on Japan Meteorological Agency best track data.

Table ~~1~~2: Significant wave heights at the study site.

Case	Year	SWH_o (m)	SWP_o (s)	SLR (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
Without storm surge								
1	Present	8.70	13.0	0.00	-	-	1.05	87.9%
2	Year 2050	8.70	13.0	0.24	1.11	87.2%	0.88	89.9%
3	Year 2050	8.70	13.0	0.30	0.97	88.9%	1.09	87.5%
4	Year 2050	10.0	14.0	0.24	1.45	85.5%	1.21	87.9%
5	Year 2050	10.0	14.0	0.30	1.51	84.9%	1.46	85.4%
6	Year 2050	11.0	15.0	0.24	1.31	88.1%	1.49	86.5%
7	Year 2050	11.0	15.0	0.30	1.53	86.1%	1.50	86.4%
8	Year 2100	8.70	13.0	0.44	1.07	87.7%	1.06	87.8%
9	Year 2100	8.70	13.0	0.74	1.34	84.6%	1.11	87.2%
10	Year 2100	8.70	13.0	0.98	1.28	85.3%	1.12	87.1%
11	Year 2100	10.0	14.0	0.44	1.54	84.6%	1.33	86.7%
12	Year 2100	10.0	14.0	0.74	1.48	85.2%	1.18	88.2%
13	Year 2100	11.0	15.0	0.44	1.63	85.2%	1.40	87.3%
14	Year 2100	11.0	15.0	0.74	1.68	84.7%	1.77	83.9%
With storm surge of 1.00 m								
15	Present	8.70	13.0	0.00	-	-	1.24	85.7%
16	Year 2050	8.70	13.0	0.24	1.37	84.3%	1.22	86.0%
17	Year 2050	8.70	13.0	0.30	1.33	84.7%	1.35	84.5%
18	Year 2050	10.0	14.0	0.24	1.57	84.3%	1.52	84.8%
19	Year 2050	10.0	14.0	0.30	1.67	83.3%	1.26	87.4%
20	Year 2050	11.0	15.0	0.24	1.93	82.5%	1.66	84.9%
21	Year 2050	11.0	15.0	0.30	2.14	80.5%	1.70	84.5%
22	Year 2100	8.70	13.0	0.44	1.32	84.8%	1.21	86.1%
23	Year 2100	8.70	13.0	0.74	1.24	85.7%	1.40	83.9%
24	Year 2100	8.70	13.0	0.98	1.47	83.1%	1.30	85.1%
25	Year 2100	10.0	14.0	0.44	1.87	81.3%	1.45	85.5%
26	Year 2100	10.0	14.0	0.74	1.59	84.1%	1.64	83.6%
27	Year 2100	11.0	15.0	0.44	1.97	82.1%	1.77	83.9%
28	Year 2100	11.0	15.0	0.74	1.92	82.5%	1.66	84.9%
29	Year 2100	11.0	15.0	0.98	2.00	81.8%	1.80	83.6%

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).

SWH_r: significant wave height at reef flat

The tide is 0.80 m above present mean sea level (i.e., high tide).

Table 3: Flooding risk 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%

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

Without storm surge

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

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)

Without storm surge

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

Under line: over of risk level of flooding (2.86 m above present MSL)

Case	Year	SWH_o (m)	SWP_o (s)	SLR (m)	WL_s at degraded reef (m)	WL_s at healthy reef (m)	Change in WL_s from degraded reef to healthy reef (m)
Without storm surge							
30	Present	8.70	13.0	0.00	-	0.86	
31	Year 2050	8.70	13.0	0.24	1.19	1.24	-0.05
32	Year 2050	8.70	13.0	0.30	1.30	1.41	-0.11
33	Year 2050	10.0	14.0	0.24	1.58	1.55	0.03
34	Year 2050	10.0	14.0	0.30	1.54	1.64	-0.10
35	Year 2050	11.0	15.0	0.24	1.87	1.90	-0.03
36	Year 2050	11.0	15.0	0.30	1.97	1.99	-0.02
37	Year 2100	8.70	13.0	0.44	1.50	1.52	-0.02
38	Year 2100	8.70	13.0	0.74	1.82	1.90	-0.08
39	Year 2100	8.70	13.0	0.98	2.06	2.12	-0.06
40	Year 2100	10.0	14.0	0.44	1.82	1.81	0.01
41	Year 2100	10.0	14.0	0.74	2.09	2.07	0.02

42	Year 2100	11.0	15.0	0.44	2.07	2.12	-0.05
43	Year 2100	11.0	15.0	0.74	2.41	2.45	-0.04
With storm surge of 1.00 m							
44	Present	8.70	13.0	0.00	-	2.10	
45	Year 2050	8.70	13.0	0.24	2.30	2.29	0.01
46	Year 2050	8.70	13.0	0.30	2.42	2.35	0.07
47	Year 2050	10.0	14.0	0.24	2.44	2.53	-0.09
48	Year 2050	10.0	14.0	0.30	2.55	2.54	0.01
49	Year 2050	11.0	15.0	0.24	2.87	2.86	0.01
50	Year 2050	11.0	15.0	0.30	2.89	2.89	0.00
51	Year 2100	8.70	13.0	0.44	2.49	2.50	-0.01
52	Year 2100	8.70	13.0	0.74	2.81	2.83	-0.02
53	Year 2100	8.70	13.0	0.98	3.00	3.01	-0.01
54	Year 2100	10.0	14.0	0.44	2.70	2.69	0.01
55	Year 2100	10.0	14.0	0.74	2.97	2.96	0.01
56	Year 2100	11.0	15.0	0.44	3.00	2.98	0.02
57	Year 2100	11.0	15.0	0.74	3.23	3.32	-0.09
58	Year 2100	11.0	15.0	0.98	3.45	3.51	-0.06

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).

WL_s: water level at shore

Under line: over of risk level of flooding (2.86 m above present mean sea level)

The tide is 0.80 m above present mean sea level (i.e., high tide).