**Detail response to Referee #2 (Dr. Alberto. Armigliato)**

In the following letter, each comment by Referee #2 (Dr. Alberto Armigliato) in black is followed by our replies in red.

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:

In Section 2.1:

[The present study site is located in Melekeok state, at the east central coast of Babeldaob, the biggest island in Palau. 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.

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. 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). Consequently, 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). The average wind speed was 27 m/s around the study site (see http://www.windguru.cz) in December 2 2012 because the study site is 121 km distance from the pass of Typhoon Bopha. Destruction of piers and erosions occurred at the coast of present study site by the Typhoon Bopha, (Figure 1c, d). 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. Our one survey transect is located near the elementary school, because the school will be probably one of potential evacuation places during assumed intensified TCs.]

In Section 2.2:

[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:

In Section 2.1:

[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. 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). Consequently, 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). The average wind speed was 27 m/s around the study site (see http://www.windguru.cz) in December 2 2012 because the study site is 121 km distance from the pass of Typhoon Bopha. Destruction of piers and erosions occurred at the coast of present study site by the Typhoon Bopha, (Figure 1c, d). 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.]

In Section 4.1:

[Our result of water level at the shore ($WL_s$) shows that the road (+2.86 m above MSL) 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.

In Section 4.2:

[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.

In Section 2.1:
[Our one survey transect is located near the elementary school, 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.

In Conclusion:
[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.

In Section 2.2:
[We input the $SWH_o$ as a regular wave into the model because the value of GFS model is restricted to single value.]

In Conclusion:
[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 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.
In Section 2.2:
[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. 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.

In Conclusion:

[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 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.]

In this context, 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 (section 3.2 Future wave height at the reef flat and 3.3 Future wave height at the reef flat).

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

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

In Section 2.2:

[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:
In Section 2.2:
[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.

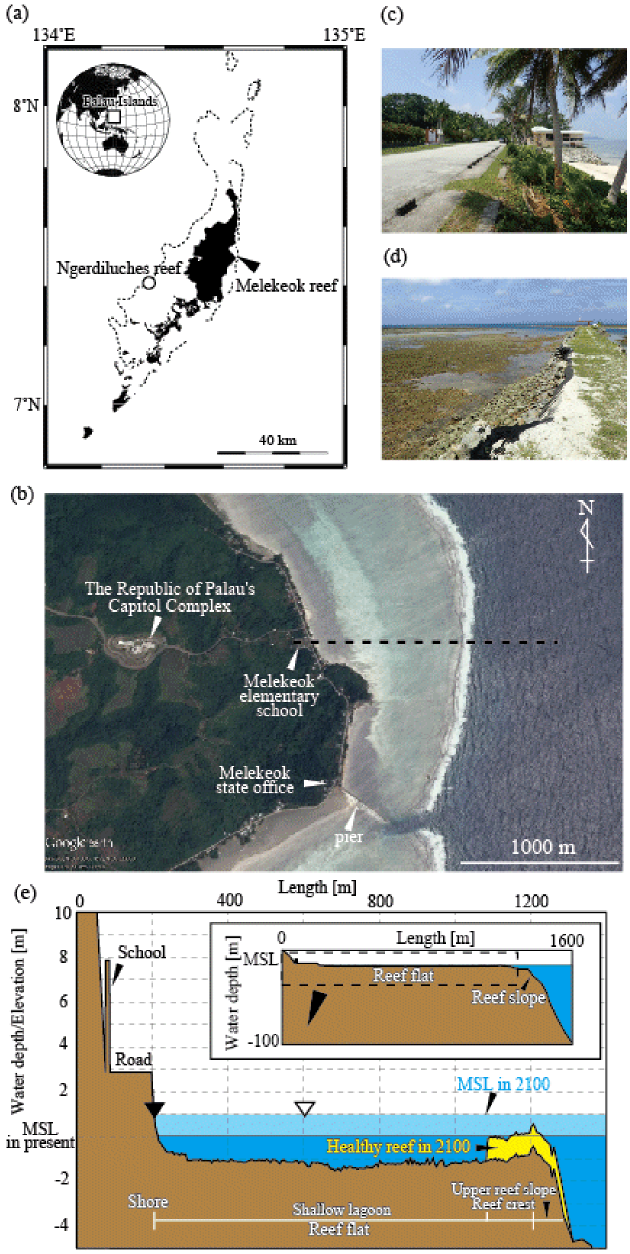


**Figure 1**: Location of Melekeok reef in the Palau Islands, and the reef topography used for wave calculations. (a) Location of Melekeok reef. The open circle indicates the drillcore site on Ngerdiluches reef (Kayanne et al., 2002). (b) Satellite image of the reefs, long beaches, the Republic of Palau's Capitol Complex, Melekeok elementary school, and Melekeok state office. The dashed line shows the location of the survey transect. (c) Photograph of the coast at the study site. The elevation of the road is +2.86 m above present mean sea level (MSL). (d) Photograph of the collapsed pier at Melekeok reef. (e) 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.