Response to comments of Referee 3: "The role of the reef-dune system in coastal protection in Puerto Morelos (Mexico)"

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Referee #3:

The manuscript presents a numerical study on the role that a reef-dune system plays in protecting a given coast from storms. The case study of Puerto Morelos, Mexico has been selected to this end. The study illustrates the importance of a holistic management of the coast (considering the reef and dunes as part of a single system) in order to maximise the protective service obtained from ecosystems, which is very relevant in the context of coastal developments, climate change and other factors that compromise the stability of such habitats. Therefore, the paper may potentially be very useful to policy makers, engineers and scientists concerned with a sustainable management of the coast. However, the study also presents some significant weaknesses that should be amended before publication of the manuscript is advised. Please find below a list of points –in decreasing order of importance- that should be addressed by the authors before I can recommend publication of the present paper in NHESS.

RESPONSE: We thank the referee for his/her comments, which have helped us improve the manuscript. A detailed point-by-point response to the referee's concerns is provided below. Furthermore, following the main referees' comments we have: (i) conducted a more thorough analysis of runup dynamics and (ii) incorporated an analysis of the role of storm surge in the hindcast modelling as follows:

(i) Analysis of runup dynamics

Incident and infragravity swash height have been analysed using the parameterisations proposed by Stockdon et al., (2006). For beaches, these authors found incident swash height (S_{inc}) to be best parameterised by a dimensional version of an Iribarren–type relationship (S_{inc}=0.75β$(H_0L_0)^{1/2}$, where β is the beach face slope, H_0 and L_0 incident wave height and length respectively. Fig. 1Ra shows the incident swash height for the present study (high and low water contributions are presented in green and red respectively). The 15% exceedance value of water level according to the astronomical tide *Z* was used for high ($Z \geq Z15\%=0.1636$ m) and low water level ($Z \leq Z15\%=-0.1636$ m). As shown in the figure, Stockdon's parameterisation works fairly well for S_{inc}, particularly for high water levels, although it slightly over predicts the numerical results. Figure 1Rb shows the results of using the same parameterisation for infragravity swash height (S_{ig}), as well as the effect of replacing the beach slope parameter (β) with the reef face slope (β_{reef}) (blue vs. cyan line), which results in an improved fit. Stockdon et al. (2006) found that by excluding beach slope in the parameterisation resulted in the best fit for S_{ig} (Fig 1Rc), which also works fairly well for the high water level S_{ig} values for the present study, although less applicable for more energetic waves. A notable difference between the runup contributions on reef-protected beaches with respect to sandy beaches is that S_{ig} contributions were considerably larger. In order to look at this further, S_{inc} vs. S_{ig} variance was plotted against the Iribarren number (Fig. 2R), showing a clear dominance of S_{ig} contributions under practically all wave conditions. This demonstrates a key difference in the swash contributions on beaches compared to reef environments, where infragravity dominates.

With regards to wave setup $\langle\eta\rangle$, the parameterisations presented by Stockdon et al. (2006), with (a) and without (b) beach face slope, underestimate wave setup for a reef environment (Fig. 3R). The effects of the relative contributions of high and low water to wave setup are less obvious for this profile than for sandy beaches (e.g. Medellin et al., 2016). When the slope of the reef face is used instead of the beach face slope, the parameterisation improves (cyan versus blue line Fig. 3Ra), although it still underestimates the setup values. In the case of the reef environment, there are two setup contributions, one where waves break over the reef and a second at the beach. When both slopes are included in the parameterisation, the fit improves further (not shown).

Finally, when analysing $R_{2\%}$ and comparing it to the complete parameterisation by Stockdon et al. (2006) for beaches, the fit improves considerably when the reef face slope is used instead of the beach face (Fig. 4R). However, the runup parameterisations fail to predict the runup during extreme wave conditions. This is mainly ascribed to the underestimation of wave setup. Ongoing work is devoted to improving such parameterizations by incorporating the reef geometry characteristics.

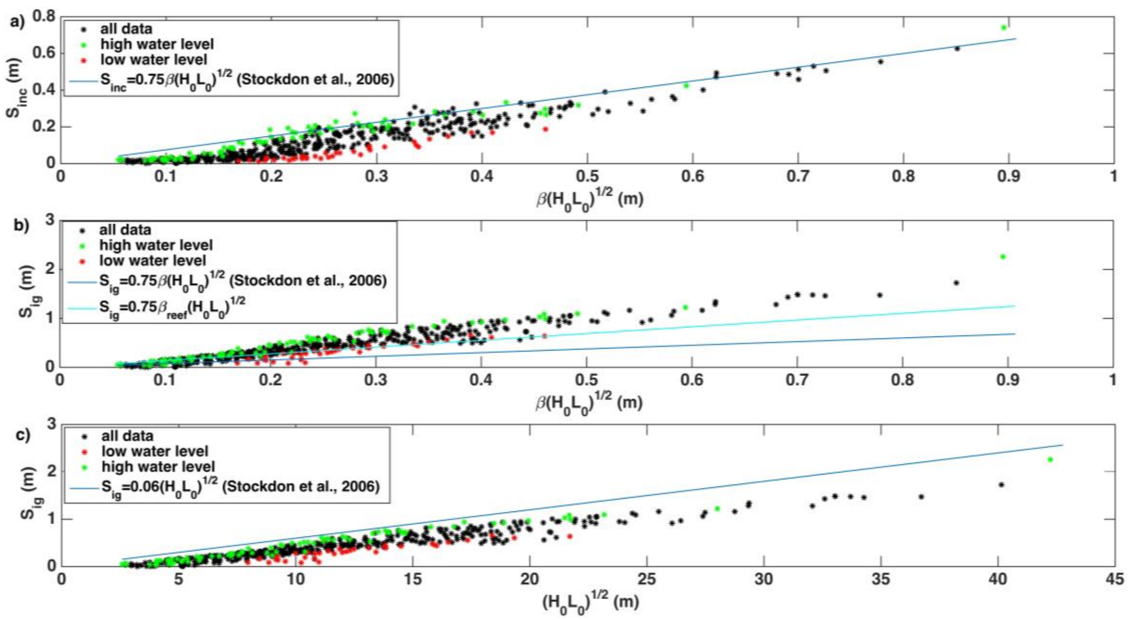


Fig. 1R a) Incident and b) infragravity swash parameterised in a dimensional form of the Iribarren equation and in comparison, to Stockdon et al. (2006) (blue line) and a modified form, which includes the reef face slope (cyan line), and c) the parameterisation of S_{ig} excluding the beach slope as suggested by Stockdon et al. (2006). Black dots represent all data, green the values associated with high water levels ($Z \geq Z15\%=0.1636$ m) and red those associated with low water levels ($Z \leq Z15\%=-0.1636$ m).

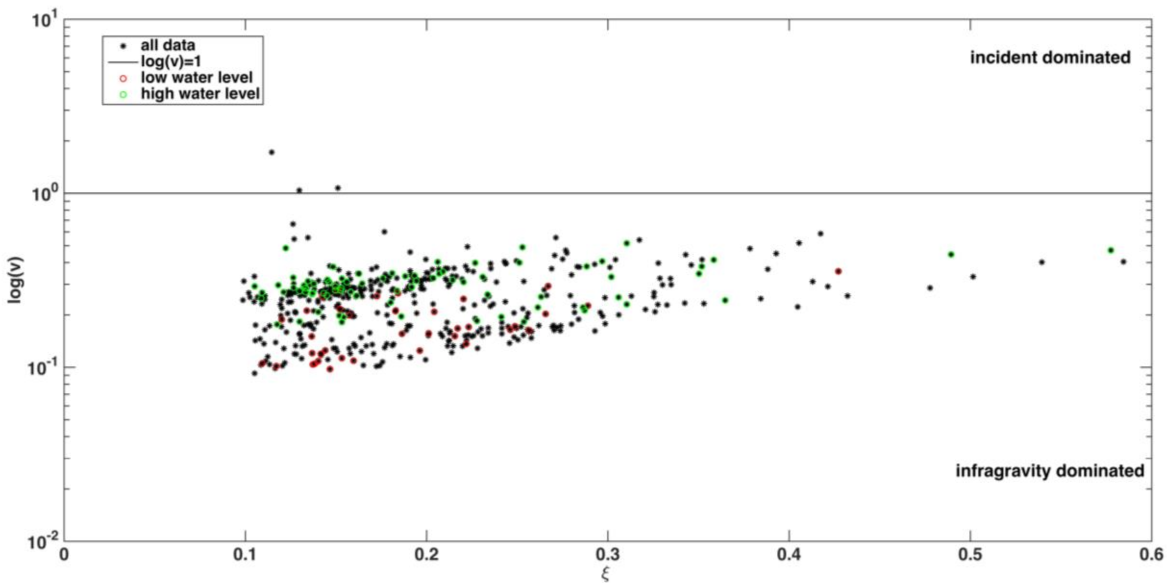


Fig. 2R Ratio of incident to infragravity swash variance (v) against the Iribarren number. The solid line at log(v)=1 divides incident (above) from infragravity (below) dominated values. Black dots represent all data, green the values associated with high water levels ($Z \geq Z15\%=0.1636$ m) and red those associated with low water levels ($Z \leq Z15\%=-0.1636$ m).

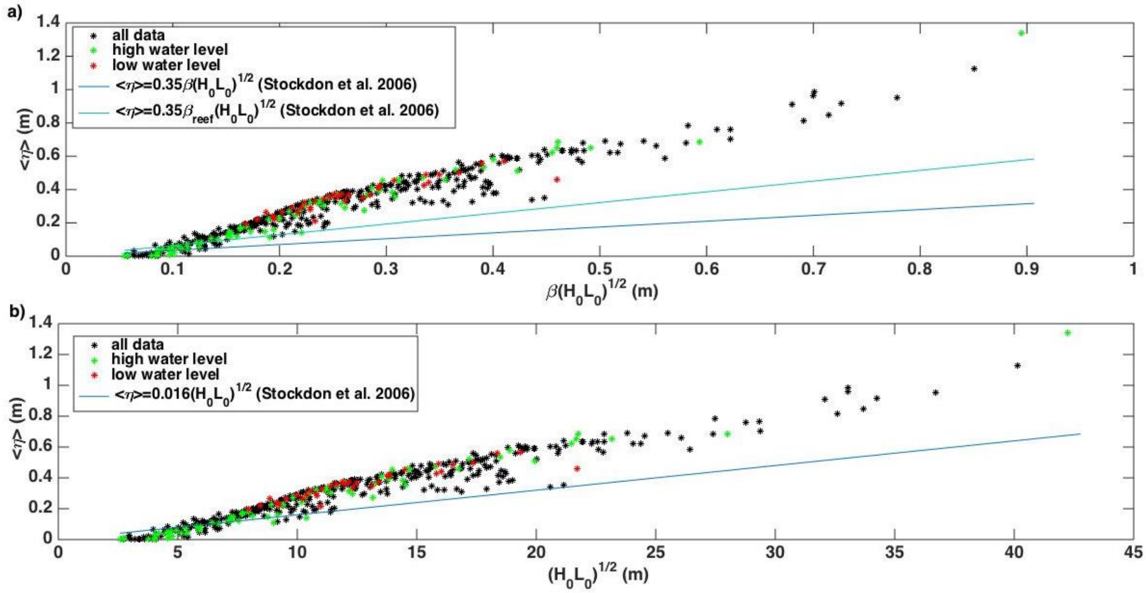


Fig. 3R a) wave setup parameterised in a dimensional form of the Iribarren equation and in comparison to Stockdon et al. (2006) (blue line) and a modified form, which includes the reef face slope (cyan line), and b) the parameterisation excluding the beach slope as suggested by Stockdon et al. (2006). Black dots represent all data, green the values associated with high water levels ($Z \geq Z15\%=0.1636$ m) and red those associated with low water levels ($Z \leq Z15\%=-0.1636$ m).

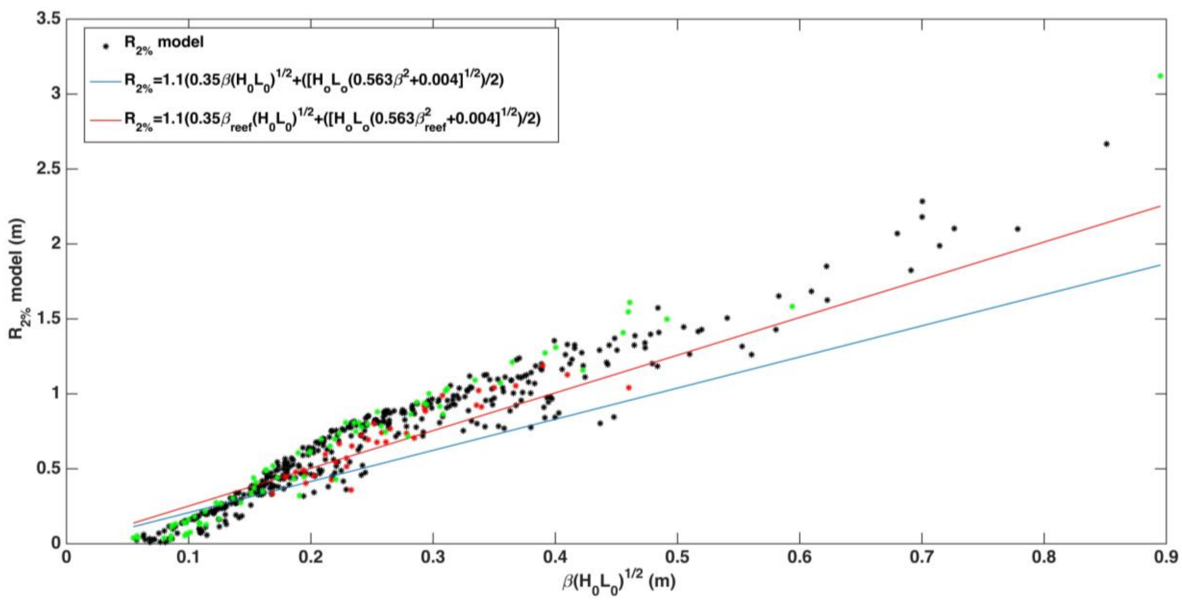
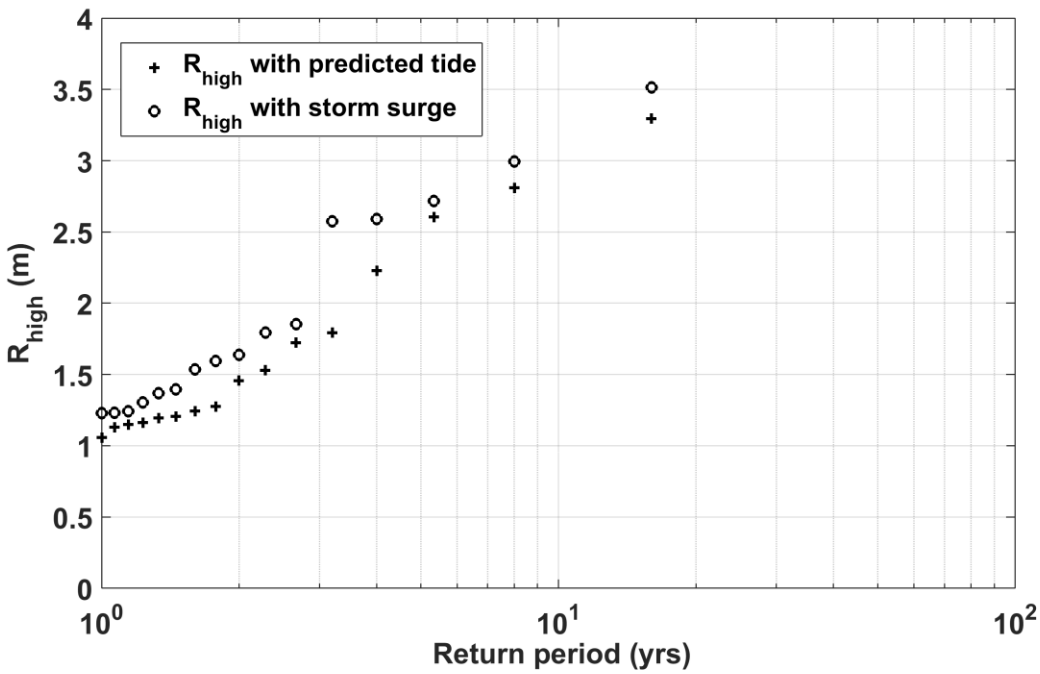


Fig. 4R Extreme runup values ($R_{2\%}$) for the 30 year hindcast data and the complete parameterisation suggested by Stockdon et al. (2006) with the beach face slope (blue line) and reef face slope (blue line). Black dots represent all data, green the values associated with high water levels ($Z \geq Z15\%=0.1636$ m) and red those associated with low water levels ($Z \leq Z15\%=-0.1636$ m).

(ii) The role of storm surge in the hindcast modelling

The reason for not including the storm surge contribution is that the Hycom data only encompasses 16 years of the 30 years of data corresponding to the wave hindcast information. However, we also believe it is important to investigate its role using the available information. Therefore, the numerical model has been re-run selecting 300 representative cases, for the 16-year Hycom period (using the same methodology as for the 30 year hindcast), using both the sea surface height obtained from Hycom (including storm surge) and considering only the predicted tide. The numerical results made it possible to compare the effect of including this contribution on the storm impact scale. Figure 5R shows R_{high} as a function of the return period while considering the two different scenarios. A significant increase in R_{high} is observed when storm surge is included. This increase is important since it acts as a proxy for degradation, resulting in an underestimate of the effects of reef degradation on runup and hence coastal flooding when excluded. The effect of the storm surge (for the time period available) was smaller than the effect of the reef degrading by 1.1 m but slightly greater than the reef degrading by 0.3 m, particularly for return periods of less than 3 years. This will be incorporated in the discussion to highlight the fact that for the 30 year hindcast data, R_{high} is underestimated by using the predicted tidal level, although this was all that was available in order to study a longer time period.



Fig, 5R Return value of R_{high} for the model run with (open circles) and without (crosses) storm surge contribution for the time period of 1993-2008.

Specific comments

1. A good portion of the manuscript is devoted to the validation of the model (SWASH) against laboratory data, after which the authors conclude that such a validation justifies application of the model to the field case study. The problem with this line of reasoning should be evident and weakens the paper significantly. The numerical model SWASH has previously been validated (extensively) against laboratory experiments, so this section in itself does not add much to the present study. What one would expect instead is a calibration/validation of the model against field data from Puerto Morelos (the site selected for this research) before carrying out the rest of the study. If such data were not

available, the manuscript should probably be reformulated as a more theoretical study and all necessary assumptions (e.g. on bed friction coefficients) should be justified.

RESPONSE: The section on the laboratory experiments has been removed in accordance with suggestions made by the three referees. Field data for calibrating the model were not available. Therefore justifications of necessary assumptions, including bed friction have been included. The following text has been included in the revised version:

"…Although likely to be lower than values obtained in field studies, since the study is more a theoretical analysis of the effects of the vertical degradation of the reef than changes in its roughness, and in the absence of measured field values, this coefficient was used in the numerical simulations…"

2. The authors confess (e.g. page 9 line 30) that changes in reef roughness are important, but yet have not been considered in this study. Understandably, some assumptions need to be adopted (such as 1D approach, which may miss many important real 2D phenomena, but is a good first approximation), but variable reef roughness for degraded scenarios does not seem to be particularly cumbersome to include in the simulations. Hence, I would recommend that the authors either include variations in reef roughness for different degradations scenarios or justify why this has not been done.

RESPONSE: The focus of the present study is on the effects of vertical erosion of the reef and dune morphology more than the effects of changes in roughness, which although important, require different scales to be considered and are beyond the scope of this study. Thus, we include the following sentences justifying the assumption:

"This study focuses on the degradation of the reef-dune morphology and although reef roughness changes associated with degradation also play an important role in wave transformation (Franklin et al., 2013; Buckley et al., 2016) they are beyond the scope of the present work. In order to study its effects, high resolution Computational Fluid Dynamics (CFD) modelling is required to allow reef roughness to be taken into account explicitly (e.g., Osorio-Cano et al., sub judice)."

3. In line with the previous point, study of the effect of a degraded sand dune, by means of a modified dune height, is an interesting aspect of this study. However, I wonder about the validity of the conclusions achieved regarding flooding (storm impact) when the sand dune has been reduced in height but considered non-erodible during the simulation. A discussion on how this assumption affects the conclusions would be valuable. Ideally, inclusion of morphological evolution of the dune/beach profile in the study of protective services provided by the reef-dune system would significantly strengthen the point made by this article (according to the authors themselves; page 9 line 28).

RESPONSE: We agree that treating the dune and beach as non-erodible features is a big assumption. Unfortunately, the current model does not have the option for treating the dune or the beach as erodible features. Conducting a hindcast study (1800 simulations) to assess the effects of reef-dune geomorphology and storm surge with a sediment transport model is computationally not feasible for us. Therefore, the following statement is now included in the conclusions of the manuscript:

"The present approach does not consider the dune or the beach as erodible features. Both play an important role on energy dissipation and hence further research is warranted to investigate its effects on increasing/decreasing the storm impact during extreme events."

Furthermore, the text (line 28, page 9) has been modified in the reviewed manuscript:

It is also important to note that during an extreme event, such as Hurricane Wilma, the reef can act as a barrier against sediment transport, further reducing the storm impact on the coast by retaining sand in the lagoon and on the beach. However, this is not taken into account in the present study, nor is the effect of changes in reef roughness associated with degradation, which have been shown to have important implications in wave transformation (Buckley et al., 2016) and wave runup (Osorio et al., 2017) but are not the focus of the present study. It is likely that by treating the dune as a non-erodible feature, overtopping is *underestimated, further demonstrating the importance of conserving the dune for it to provide natural protection of the coastal area.*

4. The paper could be written in a more concise manner by avoiding excess of uninformative or non-relevant details all throughout the manuscript (especially true for Section 2).

RESPONSE: We agree with the referee and hence most of this information has been removed from this section in the revised manuscript in accordance with suggestions made by all three referees. The following text has been removed:

"The climate in the region is hot and humid with a mean annual air temperature of 26.4°C, a maximum of 34.5°C in the summer and a minimum of 13°C in the winter (Merino and Otero, 1991). Rainfall is present all year round, although more intense during the summer, with a mean annual rainfall of 1,041 mm (Caribbean Coastal Marine Productivity Program: CARICOMP, unpublished data for the period 1993-1998). Evaporation varies from 102 mm in December to 178 mm in May (Merino and Otero 1983). The mean relative humidity is 84% (CONANP 2000). The water temperature at the bottom of the lagoon varies seasonally by around 5°C, from 31-32°C in August and September, to 24-25°C between December and March (Coronado et al., 2007)."

5. No reference is given for the adopted projections of reef erosion (page 7 line 15).

RESPONSE: This information has been included. The following text has been added in the manuscript:

These scenarios were selected based on 50 yr projections of reported reef erosion values. The vertical loss of 6 mm yr^{1} reported by Sheppard et al. (2005) was used for scenario (ii) and the value of 22 mm yr^{1} reported by Eakin (1996) was used for scenario (iii). The erosion values reported are a result of el Niño and bleaching events, which resulted in massive coral mortality and the subsequent erosion of the remaining limestone structure (Sheppard et al. 2005). In recent decades, mass coral bleaching has increased in intensity and frequency (Hoegh-Guldberg et al., 1999), preventing shallow corals from recovering and leading to their gradual disintegration (Sheppard et al. 2005), primarily associated with increased temperature, ocean acidification and sea level rise (Hoegh-Guldberg et al., 1999, 2005 and 2007; Pickering et al., 2017). Hence a projection of the above values was used assuming that reefs will continue to erode at similar rates.

6. I am not sure all figures are very useful or transmit their message in a clear way. For example, Fig 3 could be transformed into a statistical measure of the goodness of fit between model and experiments. Similarly, Fig 7 is not very informative – the y- axis could probably be presented as the percentage increase/decrease in Ru2% with respect to a reference case (e.g. current profile).

RESPONSE: We agree with the referee with respect to Fig. 7, and have removed this figure from the revised manuscript. Figure 3 has been removed along with the section on laboratory experiments.

7. In general, the manuscript is well structured and written, but is not completely free from typos and grammatically confusing sentences. A general revision of the writing is recommended.

RESPONSE: The manuscript has been reviewed for typos and grammatically confusing sentences.