Response to comments of Referee 2:
"The role of the reef-dune system in coastal protection in Puerto Morelos (Mexico)"

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Referee #2:

The paper presents numerical modeling and analysis of wave runup on a reef-dune fronted coastline. The material presented is interesting and scientifically relevant. However, the description of methods and analysis of the data are lacking. Variables need to be defined more clearly and the notation (including italics) needs to be consistent throughout the text and figures; wave setup and 2% exceedance runup are two examples of inconsistent notation. The model validation with laboratory data is cursory and doesn't add much to the paper as it is written. The two model validation figures (Figures 2 and 3) do not state what runs are shown and whether it is a monochromatic or irregular wave case. This is extremely important as infragravity waves likely dominate the runup spectra in the field case. I would use the laboratory results and model comparison to highlight some of the important wave and wave setup dynamics, before going into the field modeling results. Of particular interest would be using the flume/ model results to explain the trends in Figure 8 and 10, which show less difference between reef degradation scenarios under large wave conditions. Not including storm surge is very problematic to the legitimacy of the hind-cast modeling. I think the authors should either include storm surge or reorganize the paper as more of a theoretical investigation rather than an applied hind-cast analysis. Major revisions are recommended before publication.

RESPONSE: We thank the referee for his/her comments, which have helped improve the manuscript. The paper has been revised to be a more theoretical study. Furthermore, following the 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 ($S_{inc}=0.75\beta(H_0L_0)^{1/2}$, 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 overpredicts 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 <η>, the parameterisations presented by Stockdon et al. (2006), (a) with and (b) without 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. 4Ra), 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).

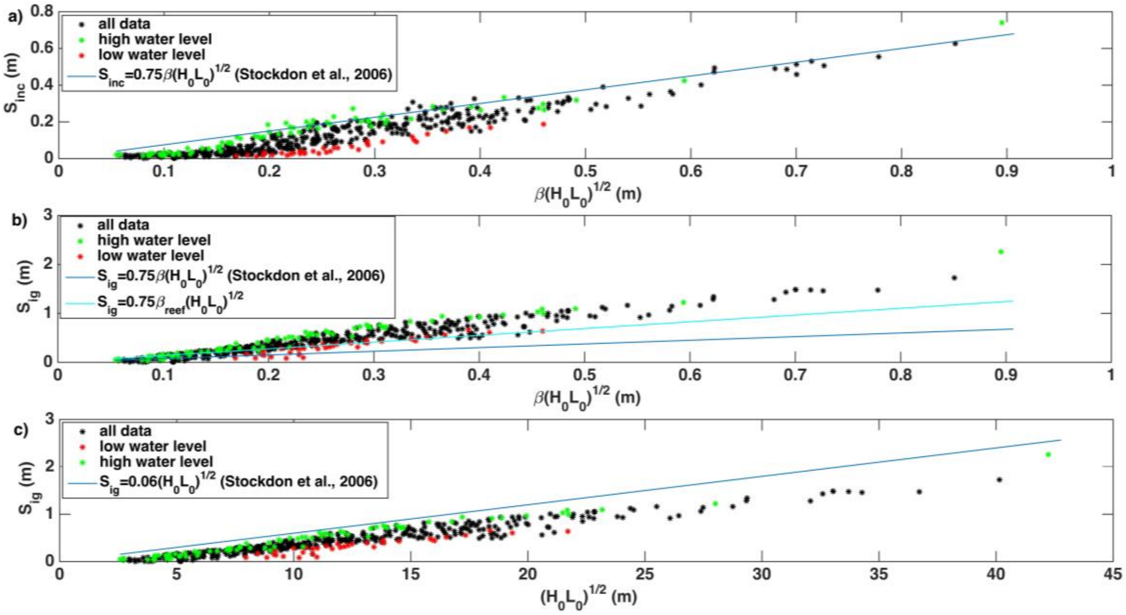


Fig. 1R a) Incident and b) infragravity swash parameterised in a dimensional form of the Iribarren equation and in comparison to Stockdon et al. (2006) (blue line) and a modified form, which includes the reef face slope (cyan line), and c) the parameterisation of S_{ig} excluding the beach slope as suggested 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).

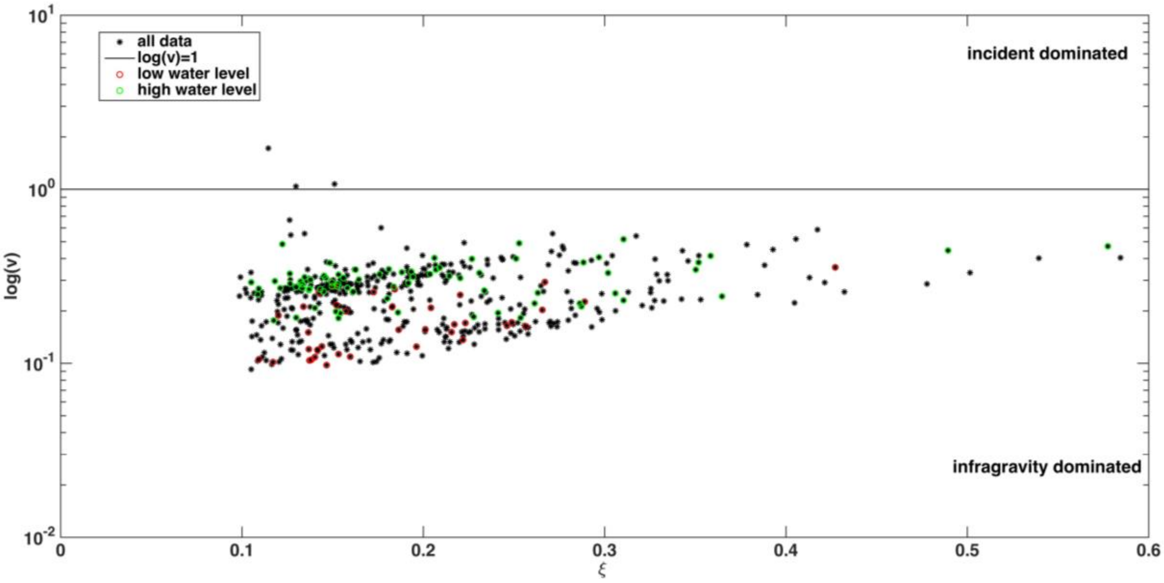


Fig. 2R Ratio of incident to infragravity swash variance (v) against the Iribarren number. The solid line at log(v)=1 divides incident (above) from infragravity (below) dominated values. Black dots represent all data, green the values associated with high water levels (Z ≥ Z15%=0.1636 m) and red those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

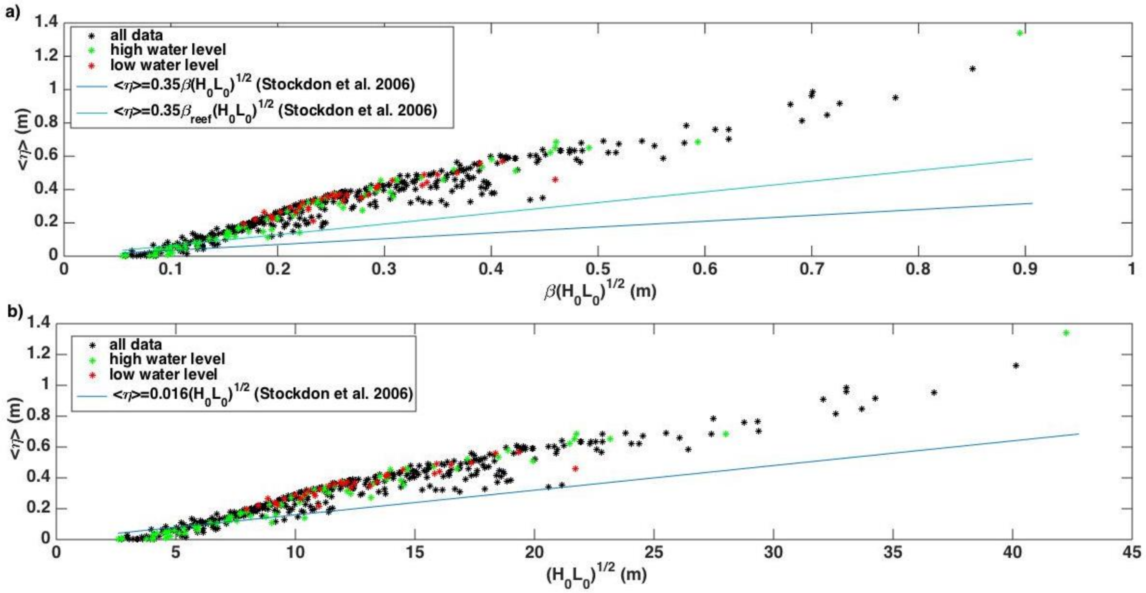


Fig. 3R a) wave setup parameterised in a dimensional form of the Iribarren equation and in comparison to Stockdon et al. (2006) (blue line) and a modified form, which includes the reef face slope (cyan line), and b) the parameterisation excluding the beach slope as suggested by Stockdon et al. (2006).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

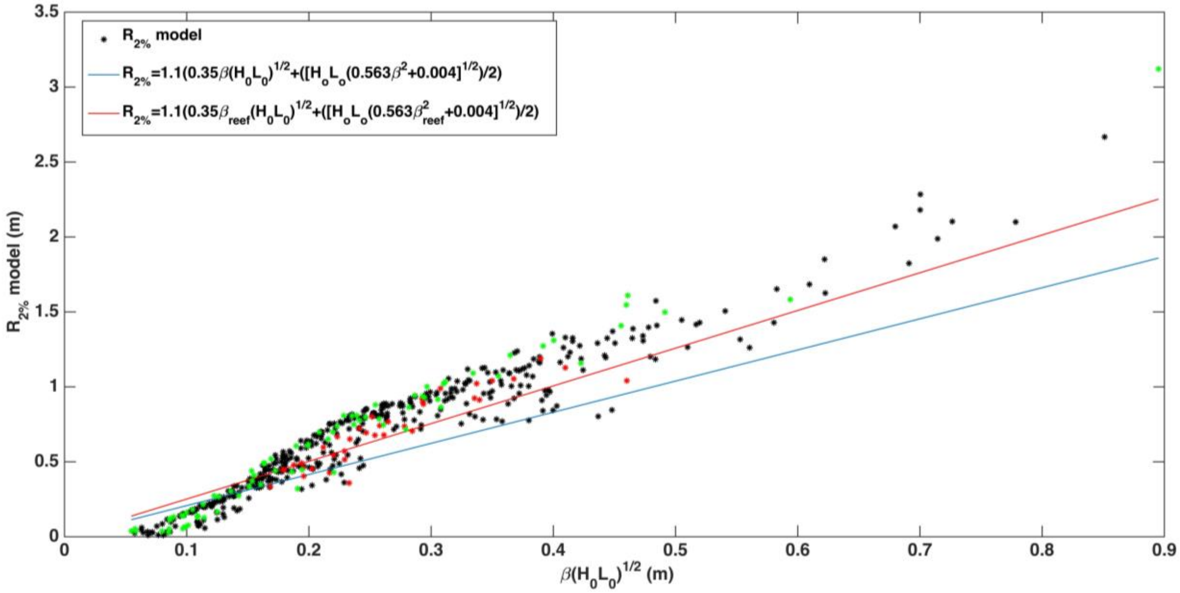
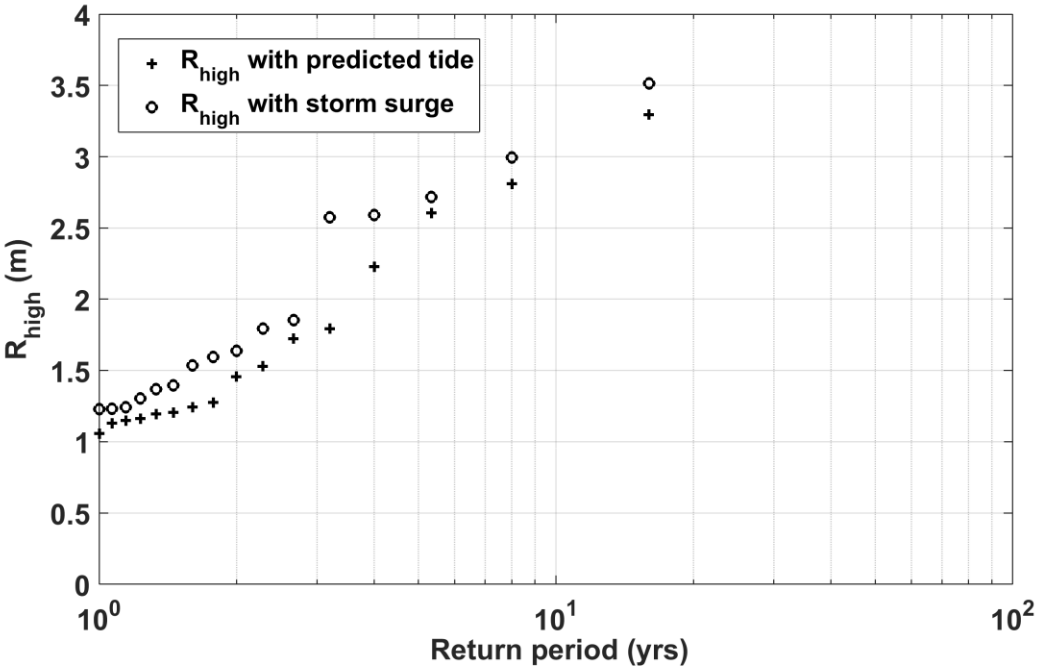


Fig. 4R Extreme runup values for the 30 year hindcast data and the complete parameterisation suggested by Stockdon et al. (2006) with the beach face slope (blue line) and reef face slope (blue line). Black dots represent all data, green the values associated with high water levels (Z ≥ Z15%=0.1636 m)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

Furthermore, the paper was checked for consistency throughout the text and we removed the model validation section in accordance to the referees' suggestion. A detailed point-by-point response to all the referee's comments are provided below.

Specific comments

1. Figure 1: Label color bar.

RESPONSE: This figure's colour bar has been labelled in the new version of the manuscript. Furthermore, the site location was modified to broaden the geographical setting (see figure 6R below).

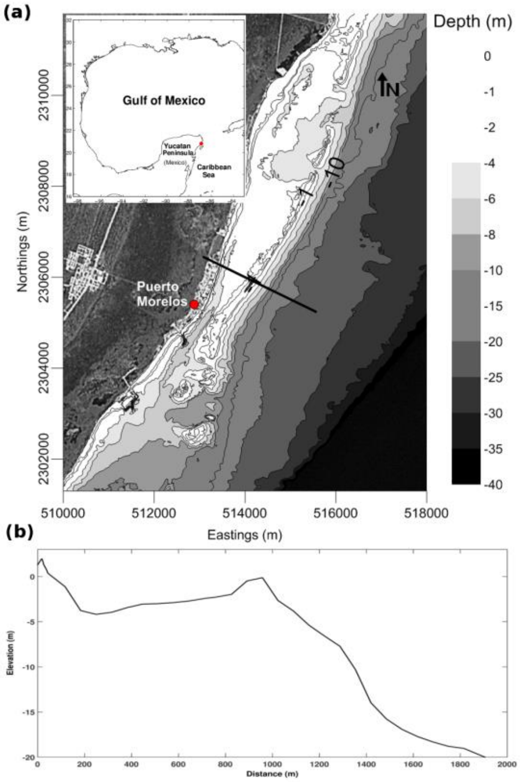


Figure 6R. (a) Map of the study area in the Gulf of Mexico. The solid black line indicates the location of the bathymetric transect used in the numerical model. (b) Bathymetry obtained from the transect indicated on the map (bathymetry courtesy of CONABIO), including a beach profile surveyed in March, 2014 (courtesy of CINVESTAV-Merida).

2. Figure 2: Need to state the wave forcing and still water level. Also, the measured wave setup is negative offshore due having a fixed volume of water in the flume (Figure 2b). The initial water levels in the model should be adjusted to this offshore water level and rerun with the correct offshore water level. I would include a low wave and a large wave example to highlight the dynamics seen in Figure 8 and 10.

RESPONSE: In accordance with comments made by referees 1 and 2, the section on laboratory validation of the model, including Figures 2 and 3, has been removed in the revised version of the manuscript. Therefore, we have made reference to previous studies where the numerical model has been validated for reef profiles. The following text has been included in the revised manuscript:

"The model is also capable of simulating wave-current interaction, wave breaking (Smit et al., 2013; de Bakker et al., 2015), and wave-runup (e.g., Brinkkemper et al., 2013; Ruju et al., 2014; Guimarao et al., 2015; Medellín et al., 2016). Furthermore, previous studies (Torres-Freyermuth et al., 2012; Zijlema et al., 2012; Buckley et al., 2014) have shown good agreement on simulating wave transformation on reef profiles."

3. Figure 4: Need to state the wave forcing and still water level. Are Z and Z_m the same? Include definition of Z and R_high in the caption.

RESPONSE: We thank the referee for pointing out these issues. This was a typing mistake and has been corrected to Z in the text. The revised Figure's caption is as follows:

“Figure 4. Reconstructed time series, including R_{high}, for the current reef profile using the 30-year hindcast wave conditions (wave height and period; H_s and T_p) and predicted tidal level (Z). (a)–(c) Black lines indicate available hindcast data and red stars indicate the selected cases used to represent the complete time series. (d) Blue line represents time series reconstructed from the results of the simulated results. Red stars indicate the cases used for reconstruction. $R_{high} = R_{2\%} + Z$.”

4. Figure 6: Is this data repeated in Figure 8? Remove this figure if it is.

RESPONSE: We agree with the referee’s comment and hence this figure has been removed from the manuscript since the data is also presented in Figure 8.

5. Figure 8: This figure is extremely interesting. I would reorganize the paper to focus on explaining the trends seen here.

RESPONSE: We thank the referee for bringing attention to this plot. One of the ecosystem services provided by the reef crest consists in the coastal protection via wave dissipation by breaking. The numerical results show that this becomes more important in the short to medium term storm events (*Tr*<10 years). On the other hand, above certain threshold conditions (*Tr*>10 years at this site) the reef-crest for the non-degraded condition no longer provided significant dissipation with respect to the degraded condition. The latter can be ascribed to the fact that the wave breaking point moves further offshore and that is why the degraded and non-degraded conditions present similar storm impact. This information is very important for insurance risk analysis. Therefore, following the referee’s suggestion the structure, conclusions, and abstract will be re-organized to emphasize such trends.

6. Page 2 Line 10: This paragraph needs revision. “The degradation of coral reefs affects the incident wave climate.” Are you referring to the offshore wave climate? If so how does coral reef degradation affect offshore conditions?

RESPONSE: This sentence refers to the conditions reaching the coast. Reef degradation affects wave transformation over the reef and hence the conditions that reach the shore. This sentence has been rewritten as:

“The degradation of coral reefs affects the wave runup due to modifications in the spatial gradient of wave dissipation controlling both the incident wave energy and the wave-induced setup.”

7. Page 3 Line 5-15: Most of this site description isn’t needed.

RESPONSE: We agree with the referee, hence most of this information has been removed in the revised manuscript. The following text was removed from the revised manuscript:

“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).”

8. Page 4 Line 30: I would not include monochromatic waves in the model analysis and statistics as infragravity waves will be important for runup in the field.

RESPONSE: The section on the laboratory experiment has been removed in accordance with suggestions made by Referees 1 and 2.

9. Page 5 Line 5: I don't understand this discussion of bottom friction coefficients. Coefficients used in flume studies are discussed as if they are applicable to field cases? Are you using these values for your hind-cast analysis?

RESPONSE: The friction coefficient was chosen based on reported values for numerical models used for coral reefs, for model validation. Friction in the field is likely to be much larger and, while important, the present study is not focused on this aspect. The focus of the present study is on the effects of vertical erosion of the reef and dune morphology more than on 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)."

10. Page 5 Line 10: I would either remove the rˆ2 statistics or expand on how these values were calculated and which runs were used with table of runs, etc. I would probably remove and just focus on detailed analysis of two representative wave cases.

RESPONSE: The section on the laboratory experiment has been removed in accordance with suggestions made by Referees 1 and 2.

11. Page 5 Line 20: Did the flume have active reflection compensation? Were outgoing waves removed from the time series used to force the model? Generally need more details.

RESPONSE: The wave flume is equipped with an active wave generation and absorption system developed by Aalborg University and VTI. However, the section on the laboratory experiment has been removed in accordance with suggestions made by Referees 1 and 2.

12. Page 6 Line 25: In Figure 2 and elsewhere eta is used for wave setup. Here eta is a function of time. Change wave setup to overbar eta or <eta>. Sometimes 2% runup exceedance is written as R sometime Ru2% sometime Ru_2% sometime italics sometimes not. Make this consistent

RESPONSE: We apologize for the inconsistencies in the variables definition. These terms have been corrected to ensure they are consistent throughout the paper. Ru2% is defined as $R_{2\%}$ and wave setup as $< \eta >$.

13. Page 8 Line 20: I would go more into explaining the R_high response at larger wave heights. You mention resonance, but you don't provide evidence or state if this is the cause of the R_high response.

RESPONSE: In the revised manuscript we include a more thorough discussion on the R_{high} trends obtained for larger wave heights. The main reason for the difference in R_{high} at larger wave heights is related to the role played by the reef in wave breaking. Under small wave heights, the reef plays an important role in this process, however as waves become larger, they break further offshore, and the reef no longer plays such an important role. When looking at the setup, swash and runup data, this change appears to take place for $H_oL_o^{\wedge 1/2}$ >30 m (Fig.7R). Prior to this point there is a clear dominance in S_{ig} and $R_{2\%}$ for the 1.1 m degraded scenario. For intermediate and large wave conditions, wave setup (Fig.7Ra) seems to be slightly greater for the conserved scenario as a result of the more intense wave breaking occurring over the reef crest and associated steeper gradient in radiation stress compared to the degraded scenario. However, for the degraded scenario the infragravity contribution is generally greater, where long waves enter the lagoon in the absence of reflection at the reef (Fig.7Rc). The clear increase in $R_{2\%}$ for the degraded scenario demonstrated by Fig. 7Rd reiterates the importance of the reef in protecting the coast from flooding. This explains why at larger wave heights R_{high} behaves as shown in Figure 8.

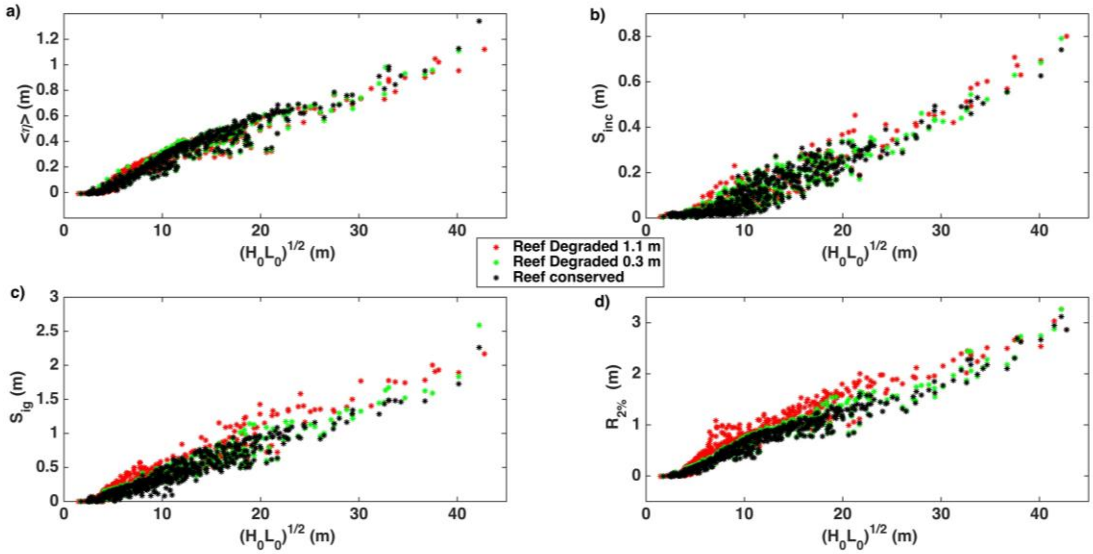


Figure 7R a) Wave setup, <η> b) incident swash (S_{inc}), c) infragravity swash (S_{ig}) and d) Extreme runup ($R_{2\%)}$ against incident wave conditions. Black dots represent the setup data for the conserved reef profile, green the values the reef degraded 0.3 m and red those associated with the reef degraded 1.0 m. The vertical arrow indicates the change in behaviour.

14. Page 10 Line 1: The Buckley et al. 2015 reference should be Buckley et al. 2016

RESPONSE: This reference has been corrected. The reference was changed to Buckley et al. 2016 and was included in the reference list.