Response to comments of Referee 1:
"The role of the reef-dune system in coastal protection in Puerto Morelos (Mexico)"

(nhess-2017-304)

by Gemma L. Franklin, Alec Torres-Freyermuth, Gabriela Medellin, María Eugenia Allende-Arandia, Christian M. Appendini

Referee #1:
Review of "The role of reef-dune systems in coastal protection in Puerto Morelos (Mexico)" by Franklin et al. This paper presents an analysis of the combined impact of reef and dune degradation on determining storm impact. In general I found the paper interesting and conclusions primarily supported (and very timely given recent events), but the analysis a bit lacking. See my detailed comments below, but my general recommendation is that this paper needs a major revision prior to publication. The numerical simulations conducted by the authors can provide much more information about what is causing the observed runup extremes and it would be good to delve a bit deeper into what is going on.

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 comments is provided below. Following the referee's suggestion the revised manuscript includes: (i) a more thorough analysis on the role that storm surge has in the storm impact, and (ii) a detailed study of runup dynamics.

Specific comments

1. **Pg 3, lines 5-15. A majority of this information is not relevant, e.g. annual temperature and rainfall do not impact the runup.**

RESPONSE: We agree with the referee and hence most of this information has been removed from this section in the revised manuscript. The following text has been removed from the 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during the summer, with a mean annual rainfall of 1,041 mm (Caribbean Coastal Marine Productivity Program: CARICOMP, unpublished data for the period 1993-1998).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)."

"The lagoon bed is characterised by calcareous sand covered by patches of seagrass with occasional coral colonies."

"The mean grain size of the sediment is 0.3 mm, and the mean lower beach slope is 0.05 (Ruiz de Alegría-Arazaburu et al., 2013)."

2. **Pg. 4, line 10. Please specify which model.**

RESPONSE: The name of the model and reference have been included (page 4, lines 19-20 in the revised manuscript). The text has been changed to:

"These data were estimated using the third-generation spectral wave model MIKE 21 SW (Sørensen et al. 2004) forced with wind data from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006)."

3. Pg. 4, line 13. A high r2 does not indicate model performance unless coupled with the regression slope. The r2 only tells you how well a model reproduces the variance.

RESPONSE: Further information on the model performance has been included (page 4, lines 22-24 in the revised manuscript).

"The mean observed wave height (H_s) and peak period (T_p) were 1.22 m and 6.70 s respectively, compared to the mean reanalysis/hindcast values of 1.31 m and 7.27 s (Rms of 0.33 H_s and 1.59 for T_p with correlation coefficients of 0.90 and 0.51)."

4. Section 3. I do not see the point in including the flume experiments in this paper. You are essentially calibrating the model on an unrelated data set for a reef/beach profile that was not made to replicate your field site. Essentially you are just showing that SWASH works on reef profiles which has already been shown (Zijlema, 2012, Buckley et al., 2014). Additionally, and while it is unfortunately the case, showing that the model is calibrated at one site does not mean it is calibrated at all other sites. As a result, my preference would be to entirely remove the discussion and comparison with the flume results and use the extra space to further develop the results as they result to the field site. Also I found the discussion of the runs with and without the reef crest confusing.

RESPONSE: The referee's comment is consistent with those from the other two referees in the sense that there is no added value by including the flume experiments in this paper. Therefore, the section on the model validation employing laboratory data has been removed. One of the co-authors has been removed from the list of authors since his contribution was related to the laboratory experiments. In the revised manuscript we have made reference to previous studies where the model has been validated for reef profiles. The following text has been included in the revised manuscript (page 4, line 31-page 5, line 4 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), wave transformation on reefs (e.g. Torres-Freyermuth et al., 2012; Zijlema et al., 2012; Buckley et al., 2014), and wave-runup (e.g., Brinkkemper et al., 2013; Ruju et al., 2014; Guimarao et al., 2015; Medellín et al., 2016). Therefore this numerical model is suitable for conducting a numerical study on wave transformation and wave runup in the Puerto Morelos reef lagoon. For further model details, including model equations see Zijlema et al. (2011)."

5. Figure 1. Can the inset be made a higher resolution and zoomed out a bit to provide more geographic context?

RESPONSE: Following the referee's suggestions Figure 1 has been modified to provide a better geographical context and improve its quality.

6. How long is each simulation run for? This is important in determining the validity of the statistics which include long waves.

RESPONSE: The SWASH simulations were run for 3200 s which were sampled for 2700 s (see page 7, line 31) after accounting for model spin-up time (500 s), considering a constant water level. The simulation time is sufficient to account for long wave statistics.

7. Page 6 line 26. Extreme runup is defined inconsistently.

RESPONSE: We thank the referee for pointing out this inconsistency. Extreme value statistics of runup, often defined as the elevation exceeded by only 2% of runup, is denoted by $R_{2\%}$ (Holman, 1986).

8. Page 6. Line 30. I am confused about the definition of Rlow. The setup is the average runup so why is this no Ravg? Also it would be helpful to remind the reader that here Z is the tidal level.

RESPONSE: Here, R_{low} is adopted from a previous study (i.e., Sallenger, 2000) where the storm impact scale was introduced for the first time. The term R_{low} consists of the average runup (setup) plus the tidal level and, where applicable, the storm surge. Thus, it represents the low extreme sea level resulting from the aforementioned contributions, which is then compared with morphological features in the beach profile. Therefore, we have maintained this terminology for consistency with previous work (e.g., Stockdon et al., 2007; Medellín et al., 2016; among many others). The revised manuscript includes the following text for further clarification (page 8, lines 8-9):

"R_{low} represents the low extreme sea level resulting from the setup, tidal level and storm surge contributions consistent with Sallenger (2000)."

9. Page 6 line 32. As is sort of acknowledged in the discussion, not including surge is a huge limitation of the approach. As the depth of reef submergence directly effects the short wave transmission across the reef the surge is critical in determining the runup (in addition to the fact that the surge adds to the water level from which waves runup). Could you not include this for the simulations suing the hycom model? I find this a major limitation of the current study. High surge also acts as a proxy for the reef degradation, and thus neglecting surge probably causes your results to underestimate the occurrence of over toping.

RESPONSE: We agree with the referee on the importance of including the storm surge. The reason for not including the storm surge contribution in the previous version of the manuscript is the lack of long tidal records in the study area and that the Hycom data only encompasses 16 years of the 30 years of data corresponding to the wave hindcast information. However, we recognise the importance of studying the role of the storm surge 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: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) and (ii) the astronomical tide (see Section 5.4 in the revised manuscript - page 11, line 23 to page 12, line 18). The numerical results made it possible compare the effect of including this contribution on the extreme water levels and the storm impact.

The following text has been included in the revised manuscript (page 11, line 23-page 12, line 18):

5.4 Role of Storm surge

To investigate the storm surge contribution, sea level data were obtained from the HYbrid Coordinate Ocean Model (HYCOM; Halliwell et al., 1998; Bleck, 2001) for the Gulf of Mexico (GoM) (https://hycom.org/data/goml0pt04) for the dates that coincided with the available wave hindcast information (1993-2008). For the GoM, HYCOM has a 1/25° or 0.04° equatorial and latitudinal resolution (~3.5 km) for each variable at mid-latitudes. The version of HYCOM used is 2.2.77. Both H_s and T_p from the Hindcast data were interpolated to the same time vector as that of the GoM sea level data. A total of 300 representative cases were simulated for the 16-year period (using the same methodology as for the 30-year hindcast), using: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) or (ii) the astronomical tide. Figure 7 shows R_{high} as a function of the return period while considering the two different scenarios. An increase in R_{high} is observed when storm surge is included. This increase is important since it acts as a proxy for reef degradation. Neglecting the storm surge contribution results in an underestimate of the effects of reef degradation on runup and hence coastal flooding. However, 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 (Fig. 7).

In order to study the effects of the storm surge on extreme water levels for the specific case of a hurricane event, wave parameters were selected from the hindcast data between the 19th and the 25th of October (Fig. 8a and b), corresponding to Hurricane Wilma, a Category 5 hurricane, which reached the

Yucatan Peninsula on the 20^{th}-21^{st} of October, 2005. The maximum values are higher and the minimum values are lower owing to the storm surge contribution during the hurricane passage. In terms of reef degradation and the effects of the storm surge during the hurricane, the R_{high} values are generally greater for the degraded profiles throughout the five days presented, except around the peak of the hurricane (results not shown). This might be ascribed to waves breaking further offshore of the reef crest. Therefore, the storm impact during more extreme conditions appears to be less sensitive to reef crest degradation than during moderate storm conditions, further supporting the reef degradation results presented in Section 5.2. 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. Furthermore, it is likely that by treating the dune as a non-erodible feature, overtopping is underestimated.

10. I think the results section could be considerably beefed up. By using a phase resolving model you allow for a lot of information on the runup dynamics to be gleaned. As has been demonstrated in the available literature reef/lagoon systems can often act as open basins and thus have the potential to enhance/trap IG energy.

RESPONSE: By removing the section on the laboratory validation, there is more room to look into the results in greater detail. Thus, runup was separated into the incident (S_{inc} = fp*0.5<S<fp*2) and infragravity (S_{ig} = fp*0.1<S<fp*0.5) swash frequencies (Figs. 6b and c) and setup (Fig. 6a). Furthermore, setup, swash and runup data were analysed in further detail (Section 5.2, page 10, line 24-33):

*In order to explain the observed differences in Rhigh at larger wave heights, the runup was separated into the incident (S_{inc} = fp*0.5<S<fp*2) and infragravity (S_{ig} = fp*0.1<S<fp*0.5) swash frequencies (Figs. 6b and c) and setup (Fig. 6a). Furthermore, setup, swash and runup data were analysed in further detail. The change in the importance of the reef crest in the wave breaking process seems to take place for H_0L_0^1/2 >30 m (Fig. 6). 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. 6a) seems to be slightly greater for the non-degraded 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.6c). The clear increase in $R_{2\%}$ for the degraded scenario demonstrated by Figure 6d reiterates the importance of the reef in protecting the coast from flooding.*

In addition a discussion on the applicability of current runup parameterisations to a reef environment is presented in Section 6 (page 12, line 19 – page 14, line 14):

The calculation of extreme runup is necessary to estimate the storm impact in coastal areas. Runup parameterisations provide a rapid assessment of coastal vulnerability and hence deserve further investigation. Under certain combinations of energetic wave conditions on fringing reefs, the steep reef face has been shown to facilitate the liberation of fluctuations with infragravity periods, which can pass into the lagoon with little energy loss and exacerbate the effect of the storm (Roeber et al., 2015). The importance of these long-wave motions inside the lagoon has been previously demonstrated by Van Dongeren et al. (2013). The above phenomenon can be intensified if the reef lagoon resonates with the wave period, amplifying the peak energy of the surf beat (Torres-Freyermuth et al., 2012; Roeber et al., 2015). Therefore, runup dynamics and the validity of applying parameterisations used for beaches in reef environments are investigated here.

Incident and infragravity swash height have been analysed for the conserved scenario using the parameterisations proposed by Stockdon et al., (2006) where the swash height was calculated as follows:

$$S = \sqrt{(S_{inc})^2 + (S_{ig})^2}$$

where S_{inc} and S_{ig} are significant swash height in the incident and infragravity frequencies respectively. For *beaches, Stockdon et al. (2006) 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. Figure 9a shows the incident swash height for the 600 cases simulated in the present study (high and low water contributions are presented in green and red respectively). As shown in the figure, Stockdon's parameterisation (blue solid line) works fairly well for S_{inc}, particularly for high water levels, although it slightly overpredicts the numerical results. Figure 8b shows the parameterisation for infragravity swash height (S_{ig}), excluding beach slope in the parameterisation, which also works satisfactorily for the high-water level, although is 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 (not shown), 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 irrespective of the beach slope conditions.*

With regards to wave setup $<\eta>$, the parameterisations presented by Stockdon et al. (2006) significantly underestimate wave setup in the study area (Fig. 9c). 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 (red versus blue line Fig. 9c), although it still underestimates the setup values.

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. 10). However, the runup parameterisations fail to predict the runup during extreme wave conditions. This is mainly attributed to the underestimation of wave setup. However it is worth noticing that the good fit of the $R_{2\%}$ parameterisation is ascribed to a combination of the over prediction of S and under prediction of setup. Therefore, future work should be devoted to improving such parameterisations by incorporating the reef geometry characteristics in the formulations.

11. I like the inclusion of the dune height in the analysis but wonder if treating the dune as an un-erodible feature underestimates the overtopping.

RESPONSE: The current model does not have the option for treating the dune nor the beach as erodible features, and this approach is beyond the scope of the current study. However, a discussion on such limitations is now included in the manuscript (page 14 line 32-page 15, line 4):

However, the main drawback in the present study is that it does not consider the dune or the beach as erodible features. Both play an important role in energy dissipation and hence further research is warranted to investigate its effects on increasing/decreasing the storm impact during extreme events. Furthermore, the role of reef roughness and two-dimensional horizontal processes need to be addressed for a more comprehensive study on the implication of reef degradation in such environments

Response to comments of Referee 2:
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(nhess-2017-304)

by Gemma L. Franklin, Alec Torres-Freyermuth, Gabriela Medellin, María Eugenia Allende-Arandia, Christian M. Appendini

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. We have also included additional information in the methods and analysis (see Section 4.1, page 6, line 29 - page 7, line 12 and Section 4.2 page 8, line 15-20). Much of this information was omitted in the previous version of the manuscript since it is available in the cited literature.

Furthermore, following the referees' comments the revised manuscript contains (i) a more thorough analysis on the role that storm surge has in the storm impact, and (ii) a detailed study of runup dynamics. The reason for not including the storm surge contribution in the previous version of the manuscript is the lack of long tidal records in the study area and that the Hycom data only encompasses 16 years of the 30 years of data corresponding to the wave hindcast information. However, we recognise the importance of studying the role of the storm surge 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: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) and (ii) the astronomical tide (see Section 5.4 in the revised manuscript - page 11, line 23 to page 12, line 18). The numerical results made it possible compare the effect of including this contribution on the extreme water levels and the storm impact.

The following text has been included in the revised manuscript (page 11, line 23-page 12, line 18):

5.4 Role of Storm surge

To investigate the storm surge contribution, sea level data were obtained from the HYbrid Coordinate Ocean Model (HYCOM; Halliwell et al., 1998; Bleck, 2001) for the Gulf of Mexico (GoM) (https://hycom.org/data/goml0pt04) for the dates that coincided with the available wave hindcast information

(1993-2008). For the GoM, HYCOM has a 1/25° or 0.04° equatorial and latitudinal resolution (~3.5 km) for each variable at mid-latitudes. The version of HYCOM used is 2.2.77. Both H_s and T_p from the Hindcast data were interpolated to the same time vector as that of the GoM sea level data. A total of 300 representative cases were simulated for the 16-year period (using the same methodology as for the 30-year hindcast), using: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) or (ii) the astronomical tide. Figure 6 shows R_{high} as a function of the return period while considering the two different scenarios. An increase in R_{high} is observed when storm surge is included. This increase is important since it acts as a proxy for reef degradation. Neglecting the storm surge contribution results in an underestimate of the effects of reef degradation on runup and hence coastal flooding. However, 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 (Fig. 7).

In order to study the effects of the storm surge on extreme water levels for the specific case of a hurricane event, wave parameters were selected from the hindcast data between the 19^{th} and the 25^{th} of October (Fig.8a and b), corresponding to Hurricane Wilma, a Category 5 hurricane, which reached the Yucatan Peninsula on the 20^{th}-21^{st} of October, 2005. The maximum values are higher and the minimum values are lower owing to the storm surge contribution during the hurricane passage. In terms of reef degradation and the effects of the storm surge during the hurricane, the R_{high} values are generally greater for the degraded profiles throughout the five days presented, except around the peak of the hurricane (results not shown). This might be ascribed to waves breaking further offshore of the reef crest. Therefore, the storm impact during more extreme conditions appears to be less sensitive to reef crest degradation than during moderate storm conditions, further supporting the reef degradation results presented in Section 5.2. 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. Furthermore, it is likely that by treating the dune as a non-erodible feature, overtopping is underestimated.

Regarding runup dynamics, a discussion on the applicability of current runup parameterisations to a reef environment is presented in Section 6 (page 12, line 19 – page 14, line 14):

The calculation of extreme runup is necessary to estimate the storm impact in coastal areas. Runup parameterisations provide a rapid assessment of coastal vulnerability and hence deserve further investigation. Under certain combinations of energetic wave conditions on fringing reefs, the steep reef face has been shown to facilitate the liberation of fluctuations with infragravity periods, which can pass into the lagoon with little energy loss and exacerbate the effect of the storm (Roeber et al., 2015). The importance of these long-wave motions inside the lagoon has been previously demonstrated by Van Dongeren et al. (2013). The above phenomenon can be intensified if the reef lagoon resonates with the wave period, amplifying the peak energy of the surf beat (Torres-Freyermuth et al., 2012; Roeber et al., 2015). Therefore, runup dynamics and the validity of applying parameterisations used for beaches in reef environments are investigated here.

Incident and infragravity swash height have been analysed for the conserved scenario using the parameterisations proposed by Stockdon et al., (2006) where the swash height was calculated as follows:

$$S = \sqrt{(S_{inc})^2 + (S_{ig})^2}$$

where S_{inc} and S_{ig} are significant swash height in the incident and infragravity frequencies respectively. For beaches, Stockdon et al. (2006) 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. Figure 9a shows the incident swash height for the 600 cases simulated in the present study (high and low water contributions are presented in green and red respectively). As shown in the figure, Stockdon's parameterisation (blue solid line) works fairly well for S_{inc}, particularly for high water levels, although it slightly overpredicts the numerical results. Figure 9b shows the parameterisation for infragravity swash height (S_{ig}), excluding beach slope in the parameterisation, which also works satisfactorily for the high-water level, although is 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 (not shown), 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 irrespective of the beach slope conditions.*

With regards to wave setup $<\eta>$, the parameterisations presented by Stockdon et al. (2006) significantly underestimate wave setup in the study area (Fig. 9c). 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 (red versus blue line Fig. 9c), although it still underestimates the setup values.

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. 10). However, the runup parameterisations fail to predict the runup during extreme wave conditions. This is mainly attributed to the underestimation of wave setup. However it is worth noticing that the good fit of the $R_{2\%}$ parameterisation is ascribed to a combination of the over prediction of S and under prediction of setup. Therefore, future work should be devoted to improving such parameterisations by incorporating the reef geometry characteristics in the formulations.

Furthermore, the paper was checked for consistency throughout the text and we have 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.

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, the author responsible for these contributions has also been removed from the list of authors. In the revised manuscript we have made reference to previous studies where the model has been validated for reef profiles. The following text has been included in the revised manuscript (page 4, line 31-page 5, line 4 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), wave transformation on reefs (e.g. Torres-Freyermuth et al., 2012; Zijlema et al., 2012; Buckley et al., 2014), and wave-runup (e.g., Brinkkemper et al., 2013; Ruju et al., 2014; Guimarao et al., 2015; Medellín et al., 2016). Therefore this numerical model is suitable for conducting a numerical study on wave transformation and wave runup in the Puerto Morelos reef lagoon. For further model details, including model equations see Zijlema et al. (2011)."

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 (now Figure 2) is as follows:

"Figure 2. Reconstructed time series, including the extreme water level R_{high}, for the current reef profile using the 30-year hindcast wave conditions (wave height and period; H_s and T_p) and astronomical tide (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 was also presented in Figure 8 (now Figure 5 in the revised manuscript).

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 (now Figure 5 in the revised manuscript). 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 have been 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 (page 2, line 17-18) as:

"The degradation of coral reefs affects the wave runup due to modifications in the spatial gradient of wave dissipation, controlling both the incident swash and 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)."

"The lagoon bed is characterised by calcareous sand covered by patches of seagrass with occasional coral colonies."

"The mean grain size of the sediment is 0.3 mm, and the mean lower beach slope is 0.05 (Ruiz de Alegría-Arazaburu et al., 2013)."

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 (page 5, line 20-25) justifying the assumption:

"Although likely to be lower than values obtained in field studies, in the absence of measured values for the study site, this coefficient was used in the numerical simulations. This study focuses on the degradation of the reef-dune morphology. Reef roughness changes also play an important role in wave transformation (Franklin et al., 2013; Buckley et al., 2016) but 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). Therefore the study of these effects is beyond the scope of the present work"

10. Page 5 Line 10: I would either remove the r^2 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 whole 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 manuscript. 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. The following text and Figure 6 have been added to better explain these trends (page 10, line 18- line 33):

The behaviour of R_{high} for 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 than the location of the reef crest, hence the reef no longer plays such an important role. This seems to occur for return periods of approximately 10 years or greater. Furthermore, the larger the waves, the more the water depth will increase due to wave setup, making the differences in R_{high} due to reef degradation less noticeable

*In order to explain the observed differences in R_{high} at larger wave heights, the runup was separated into the incident (S_{inc} = fp*0.5<S<fp*2) and infragravity (S_{ig} = fp*0.1<S<fp*0.5) swash frequencies (Figs. 6b and c) and setup (Fig. 6a). Furthermore, setup, swash and runup data were analysed in further detail. The change in the importance of the reef crest in the wave breaking process seems to take place for $H_0L_0^{\wedge 1/2}$ >30 m (Fig. 6). 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. 6a) seems to be slightly greater for the non-degraded 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. 6c). The clear increase in $R_{2\%}$ for the degraded scenario demonstrated by Figure 6d reiterates the importance of the reef in protecting the coast from flooding.*

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.

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

(nhess-2017-304)

by Gemma L. Franklin, Alec Torres-Freyermuth, Gabriela Medellin, María Eugenia Allende-Arandia, Christian M. Appendini

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.

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 (page 5, line 20--21):

"…Although likely to be lower than values obtained in field studies, in the absence of measured values for the study site, 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 (page 5, line 21-25):

"This study focuses on the degradation of the reef-dune morphology. Reef roughness changes also play an important role in wave transformation (Franklin et al., 2013; Buckley et al., 2016) but 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). Therefore the study of these effects is beyond the scope of the present work."

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 (page 14, line 32-page 15, line 4):

"However, the main drawback in the present study is that it does not consider the dune or the beach as erodible features. Both play an important role in energy dissipation and hence further research is warranted to investigate its effects on increasing/decreasing the storm impact during extreme events. Furthermore, the role of reef roughness and two-dimensional horizontal processes need to be addressed for a more comprehensive study on the implication of reef degradation in such environments."

Furthermore, the text (page 12, line 13-18) has been modified in the revised 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. Furthermore, it is likely that by treating the dune as a non-erodible feature, overtopping is underestimated.

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)."

"The lagoon bed is characterised by calcareous sand covered by patches of seagrass with occasional coral colonies."

"The mean grain size of the sediment is 0.3 mm, and the mean lower beach slope is 0.05 (Ruiz de Alegría-Arazaburu et al., 2013)."

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

RESPONSE: This information has been included (page 9, line 12-20). The following text has been added in the manuscript:

These scenarios were selected based on 50-year projections of reported reef erosion values. For instance, the vertical loss of 6 mm yr^{-1} reported by Sheppard et al. (2005) was used for scenario (ii), whereas the value of 22 mm yr^{-1} reported by Eakin (1996) was used for scenario (iii).

The erosion values reported in prior studies 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). This is 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.

Furthermore, following the main referees' comments the revised manuscript contains (i) a more thorough analysis on the role that storm surge has in the storm impact, and (ii) a detailed study of runup dynamics.

The reason for not including the storm surge contribution in the previous version of the manuscript is the lack of long tidal records in the study area and that the Hycom data only encompasses 16 years of the 30 years of data corresponding to the wave hindcast information. However, we recognise the importance of studying the role of the storm surge 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: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) and (ii) the astronomical tide (see Section 5.4 in the revised manuscript - page 11, line 23 to page 12, line 18). The numerical results made it possible compare the effect of including this contribution on the extreme water levels and the storm impact.

The following text has been included in the revised manuscript (page 11, line 23-page 12, line 18):

5.4 Role of Storm surge

To investigate the storm surge contribution, sea level data were obtained from the HYbrid Coordinate Ocean Model (HYCOM; Halliwell et al., 1998; Bleck, 2001) for the Gulf of Mexico (GoM) (https://hycom.org/data/goml0pt04) for the dates that coincided with the available wave hindcast information (1993-2008). For the GoM, HYCOM has a 1/25° or 0.04° equatorial and latitudinal resolution (~3.5 km) for *each variable at mid-latitudes. The version of HYCOM used is 2.2.77. Both H_s and T_p from the Hindcast data were interpolated to the same time vector as that of the GoM sea level data. A total of 300 representative cases were simulated for the 16-year period (using the same methodology as for the 30-year hindcast), using: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) or (ii) the astronomical tide. Figure 6 shows R_{high} as a function of the return period while considering the two different scenarios. An increase in R_{high} is observed when storm surge is included. This increase is important since it acts as a proxy for reef degradation. Neglecting the storm surge contribution results in an underestimate of the effects of reef degradation on runup and hence coastal flooding. However, 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 (Fig. 7).*

In order to study the effects of the storm surge on extreme water levels for the specific case of a hurricane event, wave parameters were selected from the hindcast data between the 19th and the 25th of October (Fig. 8a and b), corresponding to Hurricane Wilma, a Category 5 hurricane, which reached the Yucatan Peninsula on the 20th-21st of October, 2005. The maximum values are higher and the minimum values are lower owing to the storm surge contribution during the hurricane passage. In terms of reef degradation and the effects of the storm surge during the hurricane, the R_{high} values are generally greater for the degraded profiles throughout the five days presented, except around the peak of the hurricane (results not shown). This might be ascribed to waves breaking further offshore of the reef crest. Therefore, the storm impact during more extreme conditions appears to be less sensitive to reef crest degradation than during moderate storm conditions, further supporting the reef degradation results presented in Section 5.2. 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. Furthermore, it is likely that by treating the dune as a non-erodible feature, overtopping is underestimated.

Regarding runup dynamics, a discussion on the applicability of current runup parameterisations to a reef environment is presented in Section 6 (page 9, line 24 – page 10, line 26):

The calculation of extreme runup is necessary to estimate the storm impact in coastal areas. Runup parameterisations provide a rapid assessment of coastal vulnerability and hence deserve further investigation. Under certain combinations of energetic wave conditions on fringing reefs, the steep reef face has been shown to facilitate the liberation of fluctuations with infragravity periods, which can pass into the lagoon with little energy loss and exacerbate the effect of the storm (Roeber et al., 2015). The importance of these long-wave motions inside the lagoon has been previously demonstrated by Van Dongeren et al. (2013). The above phenomenon can be intensified if the reef lagoon resonates with the wave period, amplifying the peak energy of the surf beat (Torres-Freyermuth et al., 2012; Roeber et al., 2015). Therefore, runup dynamics and the validity of applying parameterisations used for beaches in reef environments are investigated here.

Incident and infragravity swash height have been analysed for the conserved scenario using the parameterisations proposed by Stockdon et al., (2006) where the swash height was calculated as follows:

$$S = \sqrt{(S_{inc})^2 + (S_{ig})^2}$$

where S_{inc} and S_{ig} are significant swash height in the incident and infragravity frequencies respectively. For beaches, Stockdon et al. (2006) 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. Figure 9a shows the incident swash height for the 600 cases simulated in the present study (high and low water contributions are presented in green and red respectively). As shown in the figure, Stockdon's parameterisation (blue solid line) works fairly well for S_{inc}, particularly for high water levels, although it slightly overpredicts the numerical results. Figure 9b shows the parameterisation for infragravity swash height (S_{ig}), excluding beach slope in the parameterisation, which also works satisfactorily for the high-water level, although is 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 (not shown), 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 irrespective of the beach slope conditions.

With regards to wave setup $<\eta>$, the parameterisations presented by Stockdon et al. (2006) significantly underestimate wave setup in the study area (Fig. 9c). 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 (red versus blue line Fig. 9c), although it still underestimates the setup values.

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. 10). However, the runup parameterisations fail to predict the runup during extreme wave conditions. This is mainly attributed to the underestimation of wave setup. However it is worth noticing that the good fit of the $R_{2\%}$ parameterisation is ascribed to a combination of the over prediction of S and under prediction of setup. Therefore, future work should be devoted to improving such parameterisations by incorporating the reef geometry characteristics in the formulations.

Summary List of Manuscript Edits

Please find below a summary of the relevant changes made to the manuscript by the authors in response to the above reviews. A fully marked-up version of the manuscript can be found below this summary.

- Section 2 has been modified to remove unnecessary information following the suggestions of all three referees.
- Section 3 has been changed to remove the laboratory experiment from the manuscript in accordance with observations made by the referees. Furthermore this section now includes a justification on the use of the chosen roughness coefficient to address the comments made by Referee#2, and an explanation as to why changes in reef roughness have not been taken into account as suggested by Referee#3.
- Section 4 has been modified to include greater detail on the methodology and analysis used in the present study to address the general comment made by Referee#2. This section also includes references and information for the adopted reef erosion projections, following the observation made by Referee#3.
- Section 5 now includes a more detailed analysis on runup and the effects of reef degradation in order to address observations made by Referee#1 and Referee#2. Furthermore a new subsection (5.4 Role of storm surge) has been included to study the effects of the storm surge on extreme water levels in accordance with comments made by Referee#1 and Referee#2.
- Section 6 has been rewritten as a discussion on the applicability of current runup parameterisations to a reef environment.
- The conclusions have been rewritten to take into account the new results and analyses.
- Extreme runup and wave setup have been redefined as $R_{2\%}$ and <η> throughout the revised manuscript.
- Typos have been corrected throughout the text.
- References have been modified in accordance with changes made in the text.
- Figure 1 has been changed to address comments made by Referee#1.
- The original Figure 2 and Figure 3 have been removed along with the section on the laboratory experiment.
- Figure 4 in the original manuscript is now Figure 2.
- Figure 5 in the original manuscript is now Figure 3.
- Figure 4 is a new figure included to provide a better description of the methodology and analysis used in accordance with Referee#2's suggestions.
- Figure 6 has been removed, following the comment made by Referee#2.
- Figure 7 has been removed, following the comment made by Referee#3.
- Figure 8 in the original manuscript is now Figure 5.

- Figure 6 is a new figure which has been added to help explain trends identified in Figure 5 in order to address comments by Referee#2 and Referee#3.

- Figure 7 is a new figure showing the effects of the storm surge in response to observations made by Referee#2 and Referee#3.

- Figure 9 in the original manuscript is now Figure 8 and has been improved.

- Figure 10 in the original manuscript has been removed from the revised version since the effects of the storm surge are now incorporated in the new results and Figure 7.

- Figure 9 and Figure 10 are new figures to show the applicability of current runup parameterizations to a reef environment.

The role of the reef-dune system in coastal protection in Puerto Morelos (Mexico)

Gemma L. Franklin[1,2], Alec Torres-Freyermuth[1,2], Gabriela Medellin~~1,~~[2,3], María Eugenia Allende-Arandia~~1,~~[2,3] and ~~Bernabé Gómez[1],~~ Christian M. Appendini[1,2]

[1]Laboratorio de Ingeniería y Procesos Costeros, Instituto de Ingeniería, Universidad Nacional Autónoma de México, Sisal, México
[2] Laboratorio Nacional de Resiliencia Costera, Laboratorios Nacionales CONACYT, México.
[3]CONACYT-Laboratorio de Ingeniería y Procesos Costeros, Instituto de Ingeniería, Universidad Nacional Autónoma de México, Sisal, México

Correspondence to: Gemma. L. Franklin (gfranklin@iingen.unam.mx)

Abstract. Reefs and sand dunes are critical morphological features providing natural coastal protection. Reefs dissipate around 90% of the incident wave energy through wave breaking, whereas sand dunes provide the final natural barrier against coastal flooding. The storm impact on coastal areas with these features depends on the relative elevation of the extreme water levels with respect to the sand dune morphology. However, despite the importance of ~~the~~ barrier reefs and dunes in coastal protection, poor management practices have degraded these ecosystems, increasing their vulnerability to coastal flooding. The present study aims to theoretically investigate the role of the reef-dune system in coastal protection under current climatic conditions at Puerto Morelos, located in the Mexican Caribbean Sea,~~. Firstly,~~ using a widely validated nonlinear non-hydrostatic numerical model (SWASH)~~ is validated with experimental data from a physical model of a fringing reef.~~. ~~The numerical model predicts both energy transformation and runup statistics as compared with experimental results for two different reef crest geometries conducted in a physical model. Thus, the numerical model is further used to investigate the role of the reef-dune degradation in coastal vulnerability.~~ Wave hindcast information, tidal level, and a measured beach profile of the reef-dune system in Puerto Morelos are employed to ~~predict~~ estimate extreme runup and ~~estimate~~ the storm impact scale for ~~different~~current and theoretical scenarios. The numerical results show the importance of including the storm surge when predicting extreme water levels and also show that ecosystem degradation has important implications for coastal protection against storms with return periods of less than 10 years. ~~This~~ The latter highlights the importance of conservation of the system as a mitigation measure to decrease coastal vulnerability and infrastructure losses in coastal areas in the short to medium term. Furthermore, the results are used to evaluate the applicability of runup parameterisations for beaches to reef environments. Numerical analysis of runup dynamics suggests that runup parameterisations for reef environments can be improved by including the fore reef slope. Therefore, future research to develop runup parameterisations incorporating reef geometry features (e.g. reef crest elevation, reef lagoon width, fore reef slope, etc.) is warranted.

1 Introduction

Coral reefs protect coastal regions against the natural hazards associated with storm wave events, thereby protecting beaches against processes of erosion. Energy dissipation at the coast is increased by the presence of irregular reef surfaces, which are important in wave transformation (Lowe et al., 2005). These natural barriers can dissipate up to 97% of the incoming wave energy, with the reef crest alone reducing wave height between 64-76% (Lugo-Fernandez et al., 1998; Ferrario et al., 2014). This property becomes particularly important considering that approximately 850 million people (one eighth of the world's population) reside within 100 km of a coral reef, with more than 275 million living less than 30 km from reefs, benefiting from the services they provide (Burke et al., 2011). While coral reefs protect the coasts from wave energy, wave-driven flooding along the coast can still occur under extreme events such as hurricanes.

~~While coral reefs protect the coasts from wave energy, wave-driven flooding along the coast can still occur under extreme events such as hurricanes.~~ C~~However, c~~oral reefs have been degrading over the last four decades (Alvarez-Filip et al., 2009), as a result of a combination of factors including overfishing, coastal development, contamination and an excess of nutrients, as well as degradation by coral bleaching events due to increased temperatures. Eakin (1996) reported erosion rates of 0.19 kg CaCO3 for a Panama reef, equivalent to a vertical loss of approximately 6 mm yr^{-1} (Sheppard et al., 2005). Considering that reef degradation reduces the protective characteristics of coral reefs, there is an increase in coastal vulnerability towards extreme events.

The degradation of coral reefs affects ~~the incident wave climate~~wave runup due to modifications in the spatial gradient of wave dissipation, controlling both the incident swash and wave-induced setup. Nevertheless, the impact of a storm depends not only on the bathymetry and forcing parameters of the storm but also on the geometry of the coast, particularly its elevation (Sallenger 2000). Sallenger (2000) proposed a scale that categorises storm-induced impacts and the magnitude of net erosion and accretion on barrier islands based on the elevation of extreme water levels relative to the elevation of geomorphic features. Thus, sand dunes ~~act~~ play an important role as natural barriers against coastal flooding by attenuating wave energy and slowing inland water transfer (USACE, 2013). After a storm, the height and recovery of the dune are critical for determining the coast's vulnerability to changes in sea level and storms (Durán and Moore, 2013). Although a storm may cause a dune to erode, it provides a source of sediment into the littoral cell (USACE, 2013). This is not the case when the dune is removed by increased coastal development and excessive exploitation of natural resources, which puts these regions at greater risk from extreme events.

According to a recent report on the importance of coral reefs and dunes (Secaira-Fajardo et al., 2017), the Caribbean is the region that presents the greatest loss of dune vegetation, reducing ~~the vertical extension of the beach~~dune stability (e.g. Silva et al., 2016) and hence its ability to provide natural coastal protection. For the case of Cancun, Quintana Roo (Mexico), since 1984 the beach has been receding by 2 m y~~ea~~r^{-1} as a result of the effects of hurricanes and coastal development (Silva et al., 2006). Construction on the dunes of the barrier island has restricted eolic transport, thereby preventing the natural regeneration of the dunes (Silva et al., 2006). On the other hand, heights of 3-4 m have been observed for sand dunes in

Puerto Morelos (Ruiz de Alegria-Arzaburu et al., 2013). Mariño-Tapia et al. (2014) pointed out that during the Category 5 hurricane~~,~~ Wilma, in 2005, the combined presence of dunes, a coral reef, and sand transported from Cancun during the event protected the coast of Puerto Morelos. This suggests that the coast is less vulnerable to extreme events where the reef-dune system is ~~maintained~~conserved. Unfortunately, coastal dunes in Mexico are at risk due to coastal or agricultural development (Jiménez-Orocio et al., 2014). Therefore, an assessment of~~n~~ the implications ~~for~~ of a reduction ~~of~~in natural coastal protection is required.

While there are a number of studies on the role of coral reef ~~geometry on coastal protection~~ (e.g., Quataert et al., 2015) and sand dune (e.g., Sallenger, 2000) geometry i~~o~~n coastal protection, fewer look at their combined effect ~~of reefs and sand dunes on coastal flooding~~. Therefore, this study aims to investigate the role of both reef and dune degradation on the storm impact in Puerto Morelos (Mexico). The outline of the paper is as follows. Section 2 describes the study area and the data employed in this work. The numerical model ~~validation~~ is described~~is presented~~ in Section 3. Then, methods used in this study are described in Section 4, followed by the results (Section 5). A discussion on ~~the coastal vulnerability during a hurricane event is presented in Section 6~~the applicability of current runup parameterisations to this environment is presented in Section 6. Finally, concluding remarks are provided in Section 7.

2 Site and Data description

The Puerto Morelos fringing reef lagoon is located in the western Caribbean, approximately 25 km south of Cancun, on the northeast coast of the Yucatan Peninsula, Mexico (Fig. 1a). ~~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).~~ This area is of particular interest for several reasons, notably its economic importance for tourism and fisheries (10 fishing cooperatives operate in the area), and its ecological significance, forming a natural protected area.

Puerto Morelos is characterised by a semi-diurnal microtidal regime with a tidal range of less than 0.4 m (Parra et al., 2015). There is also evidence of a low frequency, energetic oscillation (~ 0.4 m), associated with the Yucatan Current and atmospheric pressure which has a period of ~15 days (Coronado et al., 2007~~; Parra et al., 2014~~). The wave climate is dominated by wind waves from the Caribbean (South-southeast, SSE) generated by the trade winds. The waves have an average annual significant wave height, H_s, of 0.8 m and a dominant spectral peak period, T_p, between 6 and 8 s (Coronado et al., 2007; Parra et al., 2015). In this region, waves exceeding a height of 2 m are considered high-energy waves, which often occur during the northerlies season, locally known as “Nortes”, when anticyclonic cold fronts descend over the Gulf of

Mexico into the Caribbean Sea during the winter months (Coronado et al., 2007; Mariño-Tapia et al., 2011; Appendini et al., 2013). Between June and October, tropical cyclones can occasionally generate large waves ($H_s \approx$ 6–12 m; $T_m \approx$ 6–12 s) (Mariño-Tapia et al., 2008). One example of such a storm was Hurricane Wilma, which made landfall on the 23rd of August, 2005 with H_s>12 m and a T_p of 10-12 s (measured at a depth of 20 m) (Silva et al., 2012; Mariño-Tapia et al., 2008).

The coastline in the study area is protected by a fringing reef which forms a relatively shallow lagoon of 3-4 m depth and a width that varies from 550 m to 1,500 m (Coronado et al., 2007). ~~The lagoon bed is characterised by calcareous sand covered by patches of seagrass with occasional coral colonies.~~ The reef has a well-developed back-reef and crest consisting of relatively shallow, submerged coral banks, which play an important role in dissipating wave energy through an active surf zone, thereby protecting the coast. The gently sloping fore-reef descends to an extensive sand platform at a depth of 20-25 m. The shelf edge is located at a depth of 40-60 m, followed by a subsequent drop-off at approximately 10 km from the coast to depths exceeding 600 m (Ruíz-Rentería et al., 1998).

The width of the beach is relatively stable, ranging between 85-90 m, with a dune of approximately 4 m in elevation, which has been degraded in many areas as a result of coastal development. ~~The mean grain size of the sediment is 0.3 mm, and the mean lower beach slope is 0.05 (Ruiz de Alegría-Arazaburu et al., 2013).~~ The beach profile used in the present study for Puerto Morelos was measured using a Differential Global Positioning System (DGPS) and was provided by CINVESTAV-Mérida. From the beach profile to a depth of 20 m, the bathymetry obtained from CONABIO (http://www.conabio.gob.mx/informacion/gis/) was used (Fig. 1b). Wave information for a depth of approximately 20 m is available from a 30-year hindcast (1979-2008) for the Gulf of Mexico and the Western Caribbean Sea (Appendini et al., 2014). These data were estimated using the~~a~~ third-generation spectral wave model MIKE 21 SW (Sørensen et al., 2004) forced with wind data from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006). The numerical model was validated/calibrated in deep waters with wave buoys and altimeter information (Appendini et al., 2013, 2014). The model performance was found to be satisfactory for the Caribbean Sea with an r^2 of 0.87 (Appendini et al., 2014). The mean observed height (H_s) and peak period (T_p) were 1.22 m and 6.70 s respectively, compared to the mean reanalysis/hindcast values of 1.31 m and 7.27 s (Rms of 0.33 H_s and 1.59 for T_p with correlation coefficients of 0.90 and 0.51). Thus, this information is employed ~~for~~ as a forcing ~~the~~ boundary condition~~s~~ in the numerical model.

3 Numerical Model ~~Validation~~

The Simulating WAves till Shore (SWASH) model ~~is used~~, which is a phase-resolving nonlinear non-hydrostatic model (http://swash.sourceforge.net) developed at Delft University of Technology (Zijlema et al., 2011), is used in this study. This numerical model solves the nonlinear shallow water equations, including the terms for non-hydrostatic pressure, which make it suitable for simulating wave transformation as a result of nonlinear wave-wave interactions in the surf and swash regions. The model is also capable of simulating wave-current interaction, wave breaking (e.g. Smit et al., 2014~~3~~; de Bakker et al., 2015), wave transformation on reefs (e.g. Torres-Freyermuth et al., 2012; Zijlema et al., 2012; Buckley et al., 2014), and wave-runup (e.g., Brinkkemper et al., 2013; Ruju et al., 2014; Guimarao et al., 2015; Medellín et al., 2016). Therefore, this numerical model is suitable for conducting a numerical study on wave transformation and wave runup in the Puerto Morelos reef lagoon. For further model details, including model equations see (Zijlema et al., (2011).

Laboratory experiments with a physical model of a reef were carried out in the wave flume at the Engineering and Coastal Processes Laboratory of the Universidad Nacional Autónoma de México (UNAM), Sisal. The simplified reef profile (scale of 1:64) was based on that presented by Demirbilek et al. (2007) but with a reef flat of 2.5 m instead of 4.9 m (Fig. 2c). Therefore, the idealised model consisted of a beach with a 1:12 slope followed by a 2.5-m-wide reef flat and a composite slope reef face. Furthermore, a simplified reef crest (2 cm high, 50 cm wide) was added to the profile in the second set of the experiments to investigate the role of the reef crest on beach runup. Different wave conditions were modelled, including monochromatic waves and Jonswap spectra with various significant wave heights and periods (5-8 cm and 1.75-2.5 s, respectively). Eight sensors were installed at different cross-shore positions along the profile, and the data from these were used to validate the numerical model employed in the present study. In addition to these sensors, a runup sensor was also installed on the beach face (Fig. 2c). A more thorough description of the simulated cases can be found in Gómez-Pérez (2016).

Consistent with prior studies, a wave breaking parameter (α) of 0.6 was used for all simulations. The results of the physical model were used to validate the SWASH model, with a domain which was 12 m long with a regular grid resolution of $\Delta x = 0.01$. A bottom friction coefficient (*cf*) of 0.014 (Manning) was used, which is equal to that reported previously for a study involving a fringing reef (Peláez et al., 2017). This value and is also similar to that reported by Yao et al. (2014 and 2016) for a numerical study on a fringing reef (0.015). Although likely to be lower than values obtained in field studies, in the absence of measured values for the study site, this coefficient was used in the numerical simulations. This study focuses on the degradation of the reef-dune morphology. Reef roughness changes also play an important role in wave transformation (Franklin et al., 2013; Buckley et al., 2016). However, 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*). Therefore, the study of these effects is beyond the scope of the present work. The Manning coefficient was used since it best represents the dynamics of waves in the surf zone, compared to other coefficients (Zijlema et al., 2011). A wave breaking parameter (α) of 0.6 was used for all simulations. The numerical model was forced with the free-surface elevation time series measured at the offshore sensor for the profiles with and without the reef crest. Laboratory observations were employed to estimate the significant wave height, wave setup and swash excursion for the reef flat and the reef crest profiles. Figure 2 shows the cross-shore variations in H_s and wave setup (η) employed for the model validation corresponding to a JONSWAP spectrum with γ=3.3, H_s=8.0 cm and T_p=2.5 s. Model simulations show good agreement with respect to the laboratory data (r^2 of 0.87 and 0.85 for the reef flat H_s and η, respectively and r^2 of 0.85 and 0.82 for the reef crest H_s and η, respectively). This is particularly important, since previous studies have demonstrated the importance of accurately predicting wave setup in the prediction of coastal hazards, including erosion and inundation due to storms (Sheppard et al., 2005; Vetter et al., 2010; Storlazzi et al., 2011; Baldock et al., 2014; Buckley et al., 2015).

Overall the non-breaking wave height is marginally greater for the reef crest profile for both model and data. This is likely due to enhanced wave reflection from the reef face when the crest is included in the profile. There is a rapid decrease in H_s with both profiles at x=7-8 m, related to depth-induced wave breaking. At the same time, the presence of the reef crest increases the cross-shore radiation stress gradient and hence the maximum wave setup is larger compared to the reef flat, consistent with prior studies (e.g., Yao et al., 2012). Immediately after wave breaking (x=8 m), H_s is slightly greater for the reef flat than the reef crest, and wave height becomes depth-limited over the reef flat, as suggested by Storlazzi et al. (2011). Finally, the simulated swash height time series are compared against laboratory observations. A satisfactory agreement is observed for both cases (Fig. 3). Therefore, this numerical model is suitable for conducting a numerical study on wave transformation and wave runup in the Puerto Morelos reef lagoon.

4 Methods

The methodology used in this study is as follows. Firstly, a subset of wave conditions at a water depth of 20 m was selected from the 3-hourly 30-year wave hindcast. Selected wave conditions were propagated along different non-degraded and degraded beach profiles, with the corresponding tidal level, from a depth of 20 m to the shore using the SWASH model. Subsequently, the extreme runup $R_{u2\%}$ and maximum setup <η> were calculated from the simulated water elevation time series, corresponding to each simulated case, and were further employed to re-construct the 30-year extreme water level hindcast using an interpolation technique. Finally, the storm impact was obtained for different return periods and different scenarios of reef and dune degradation by coupling the extreme water level and dune elevationmorphology.

4.1 Simulated cases

A total of 87,664 sea states (H_s, T_p and θ)-, one every 3 h, comprise the available 30-year wave hindcast (Appendini et al., 2014). Due to the computational effort involved in simulating the entire data set, aA subset of 600 cases was selected, following the method presented by Camus et. al. (2011b) and applied in Medellin et al. (2016)., due to the computational effort involved in simulating the entire data set. This method employs the maximum dissimilarity algorithm (MDA) to obtain a subset of wave conditions representative of a variety of sea states (see references for further details). In the present study, the multivariate data included peak period (T_p), significant wave height (H_s) and mean sea level (Z_m). The wave parameters were obtained from the wave hindcast and the Z_m time series corresponds to the astronomical tide prediction for the same period and location (www.predmar.cicese.mx).- In accordance with Camus et al. (2011a) and Medellin et al. (2015), the deep-water multivariate data are defined as:

$$X_i^* = H_{s,i}, T_{p,i}, Z_{m,i}; i = 1 \dots, N.$$

where N refers to the ~~87,664~~total sea states obtained from the wave hindcast. ~~Following Medellin et al. (2015), t~~The vector components were normalised in order to assign them even weightings for the similarity criterion defined by the Euclidean distance~~. T~~ and hence the dimensionless vectors are defined as (e.g.~~,~~ Camus et al., 2011),

$$X_i = H_i, T_{i,}, Z_i; i = 1 \ldots, N$$

The MDA is used to select a subset of M vectors ($D_1 \ldots D_M$) from the sample data. First, one vector is transferred to the subset from the data sample. Subsequently the dissimilarity between each of the remaining elements in the data sample and those in the subset is calculated and the most dissimilar element is transferred to the subset. This is repeated iteratively until M elements have been selected. The dissimilarity between vector i of the data sample and vectors j of the subset R is determined by:

$$d_{ij} = \parallel X_i - D_j \parallel; i = 1, \ldots, N - R; j = 1, \ldots, R.$$

Subsequently, the dissimilarity between vector i and the subset R, is obtained using:

$$d_{i,\text{subset}} = \min \parallel X_i - D_j \parallel; i = 1, \ldots, N - R; j = 1, \ldots, R$$

Once the N-R dissimilarities have been calculated, the next data to be selected have the maximum $d_{i,\text{subset}}$. The Euclidean distance was calculated (Fasshauer, 2007; Medellin et al., 2016) as:

$$\parallel X_i - D_j \parallel = \sqrt{\left(H_i - H_j^D\right)^2 + \left(T_i - T_j^D\right)^2 + (Z_i - Z_j^D)^2}$$

Finally, the subset was denormalised using:

$$D_j^* = H_{s,j}^D, T_{s,j,}^D Z_{s,j}^D; j = 1, \ldots, M.$$

The 600 selected sea states were found to adequately represent the whole sample, and were well distributed throughout the time series of sea level and wave parameters (Fig. 2~~4~~a-c), ~~. This is~~ consistent with prior studies (e.g. Guanche et al., 2013; Medellín et al., 2016).

In the model runs the dune profile was extended beyond the crest, assuming a continuation of the slope measured in the profile, to complete the model domain and to enable ~~us to infer~~ the effect of reducing the dune crest values to be inferred (Fig. 3~~5~~). The model was run with the original profile, which included the back of the dune, and with the extended dune to test whether this affected the wave statistics and no significant differences were found.

4.2 Extreme water level calculation

Waves were propagated from a depth of 20 m using SWASH (Zijlema et al., 2011). The SWASH domain extends from a water depth of 20 m to the shoreline (a distance of 2 km) with a uniform mesh size of 0.1 m. The numerical model was forced using a JONSWAP spectrum at the offshore boundary ~~with~~ derived from the H_s and T_p corresponding to the 600 selected cases from the 30-year wave hindcast and the corresponding sea level according to the ~~tidal prediction~~astronomical tide. The initial time step was 0.025 s and simulations were sampled for 2,700 s, after 500 s of spin-up time.

For each sea state propagated in SWASH, the height of the bottom profile at the wet-dry interface was used to extract the water elevation, η(t), relative to mean sea level (Medellin et~~.~~ al., 2016). To obtain a continuous time series, this location was tracked as the first grid point where water depth was less than 0.01 m. Extreme runup ($R_{2\%}$), corresponding to the 2% exceedance value in accordance with Stockdon et al. (2006), was calculated for each run (see Fig. 4). Furthermore, the maximum wave setup at the shoreline, which is the super-elevation of the mean water level due to waves (Longuet-Higgins and Stewart, 1964), was computed as the mean of the wave runup time series (<~~-~~η~~-~~>). ~~Therefore~~Subsequently, the extreme water levels R_{high}~~-~~=R~~u~~$_{2\%}$ + Z and R_{low}~~-~~=<η> + Z were calculated for each case in accordance with Sallenger (2000) and Stockdon et al. (2007). R_{low} represents the low extreme sea level resulting from the setup, tidal level and storm surge contributions (where applicable), consistent with Sallenger (2000).

The 30-year long time series was reconstructed ~~using~~ based on the extreme water levels from ~~each of~~ the 600 selected sea states.~~, where the storm surge was not included.~~ The time series of extreme water levels were reconstructed using an interpolation method based ~~on~~on a radial basis function~~s~~ (RBF). Previous studies have identified this method as one of the most suitable for interpolating multivariate scattered data (Franke, 1982) and it has been used to reconstruct time series of wave parameters in coastal waters (e.g.~~,~~ Camus et al., 2011a; Guanche et al., 2013; Medellin et al., 2016). The difference in the present study is that wave direction is not included. The interpolation function is:

$$RBF(X_i) = p(X_i) + \sum_{j=1}^{M} a_j\,\Phi(\|X_i - D_j\|),$$

where $X_i = \{H_{si}, T_{pi}, Z_i\}$; i=1, ..., N represents each of the sea states in the 30-year time series, ~~and~~ $D_j = \{H_{sj}^D, T_{pj}^D, Z_j^D\}$; j =1, ..., M represents each of the M = 600 cases selected, and $p(X_i) = b_0 + b_1 H_{si} + b_2 T_{pi} + b_3 Z_i$, $\|.\|$ indicates the Euclidean norm and Φ is the radial basis function (see Camus et al., 2011). The RBF interpolation was carried out as described in Medellin et al., (2016) using an algorithm developed by Fasshauer (2007). Therefore, the RBF was used to reconstruct the R_{high} and R_{low} 30-year time series for all bathymetric profiles studied. ~~The RBF interpolation was carried out using an algorithm developed by Fasshauer (2007), which incorporates an algorithm proposed by Rippa (1999) to obtain an optimal value for a shape parameter that minimizes the interpolation error and is therefore important for the accuracy of the RBF method. This method minimises the root mean square error (RMSE) of a data fit based on a radial interpolant where one of the centres is left out. The RBF was subsequently used to reconstruct the R_{high} time series for the 30 years for all bathymetric profiles studied (see blue line in Fig. 4d). The same method was used to reconstruct the time series of the wave-induced water level, R_{low}.~~

The 30-year reconstructed time series of R_{high} (see blue line in Fig. 2~~4~~d) and R_{low} (not shown) were used to assess beach vulnerability under current beach profile conditions (Fig. 3~~5~~). The return period for both the 30-year R_{high} and R_{low} time series was calculated as the inverse of the probability of a given R_{high} or R_{low} value using the annual maxima data from the re-constructed 30-year time series. Figure 5~~6~~ shows the return value for R_{high} for the simulations ~~under the current coastal ecosystem. On the other hand, additional simulations were~~ conducted with the current scenario and ~~beach profiles~~

considering reef degradation scenarios based on 50-~~-~~year projections of reef erosion values (see Section 4.3) reported in the literature (Fig. 3). ~~(Fig. 5).~~

4.3 Storm impact scale for different scenarios

The storm impact scale proposed by Sallenger (2000) for barrier islands was used to illustrate the implication of changes in either reef ~~and~~ or beach morphology (reef crest height and dune elevation) ~~on~~ with respect to storm-induced water levels. The scale includes four storm impact regimes (Table 1), which depend on the storm-induced water levels and dune elevation, defined as R_{low} (the astronomical tide, wave setup and storm surge, where included), R_{high} (the sum of the astronomical tide, $R_{2\%}$ and storm surge, where included), D_{high} (dune crest height), and D_{low} (dune toe height). These regimes were calculated for three different reef conditions: (i) present condition, (ii) degraded by 0.30 m, and (iii) degraded by 1.1 m (see Figure 3~~5~~). ~~). For scenario (ii) a vertical loss of 6 mm yr^{-1} was used (reported by Sheppard et al., 2005), while for scenario (iii) the value of 22 mm yr^{-1} was used (reported by Eakin 1996). The erosion values reported are a result of El Niño and bleaching events.~~ These scenarios were selected based on 50-year projections of reported reef erosion values. For instance, the vertical loss of 6 mm yr^{-1} reported by Sheppard et al. (2005) was used for scenario (ii), whereas the value of 22 mm yr^{-1} reported by Eakin (1996) was used for scenario (iii).

The erosion values reported in prior studies 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). This is 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.

5 Results

5.1 Present conditions

The R_{high} and R_{low} values associated with different~~a~~ (1-, 3-, 5-, 7.5-, 10-, 15- and 30-year) return periods were ~~then~~ used together with the beach morphology (D_{high} and D_{low}), to estimate the storm impact regimes proposed by Sallenger (2000) for the present conditions (Table 2). Based on the return values of R_{high} and R_{low}, the storm impact regime associated with a yearly return period was “swash” where the maximum runup is less than the height of the foot of the dune (R_{high}>D_{low}). For return periods of 3-5 years, the storm impact regime was “collision” where the maximum runup collides with the foot of the dune but falls below the dune crest (D_{high}>R_{high}>D_{low}). For a return period of 7.5 years, the storm impact increases to “overwash” where runup overtops the dune crest and the sand transported landward is lost form the system and does not return to the beach after the storm (R_{high}>D_{high}). For return periods of 10 years or greater, the storm impact is “inundation” where the sea level is sufficient that it completely submerges the dune.

5.2 Role of reef degradation

To investigate the role of reef degradation in the reduction of coastal protection we compared the current situation was compared with the scenarios of 0.3 and 1.1 m degradation of the reef crest (see Section 4.3)of the reef crest. It is important to note that in the present study, reef roughness is maintained constant in all three scenarios to study focus only on the effect of the vertical degradation of the reef, although in reality this would likely be accompanied by a loss of roughness. Figure 7 shows a section of the reconstructed $Ru_{2\%}$ time series for three different reef scenarios (conserved, degraded by 0.3 m and by 1.1 m). Numerical rResults show a slight increase in $Ru_{2\%}$ when the reef is degraded by 0.3 m, whereas there is a significant increase in $Ru_{2\%}$ when the reef is degraded by 1.1 m. The R_{high} results and the storm impact regimes for the different scenarios support these findings (see Fig. 58 and Table 3).

The effect of reef degradation varies depending on the intensity of the storm. For instance, for storms with return periods of approximately 1-2 years, the increase in R_{high} when the reef is degraded by 1.1 m is almost twofold, whereas the reef degradation of 0.3 m has no visible effect on R_{high} for such return periods (Fig. 58). However, for return periods of 2.5-7.5 years, there is a notable increase in R_{high} for the 0.3 m degraded reef (up to 30%) compared to the conserved scenario (current reef). This is particularly important since most people living on the coast are more likely to experience these storms several times in their lifetimes and relying on the protection provided by the reef will not suffice under a degraded scenario. For storms with a return period of >10 years the R_{high} values are similar for all threedegraded and non-degraded scenarios., The behaviour of R_{high} for 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 than the location of the reef crest, hence the reef no longer plays such an important role. This seems to occur for return periods of approximately 10 years or greater.this is likely due to the large wave height resulting in the waves breaking further offshore, with the effects of degradation exceeded by the extreme wave conditions. Furthermore, the larger the waves, the more the water depth will increase due to wave setup, making the differences in R_{high} due to reef degradation less noticeable

In order to explain the observed differences in R_{high} at larger wave heights, the runup was separated into the incident (S_{inc} = fp*0.5<S<fp*2) and infragravity (S_{ig} = fp*0.1<S<fp*0.5) swash frequencies (Figs. 6b and c) and setup (Fig. 6a). Furthermore, setup, swash and runup data were analysed in further detail. The change in the importance of the reef crest in the wave breaking process seems to take place for $H_0L_0^{1/2}$ >30 m (Fig. 6). 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. 6a) seems to be slightly greater for the non-degraded 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. 6c). The clear increase in $R_{2\%}$ for the degraded scenario demonstrated by Figure 6d reiterates the importance of the reef in protecting the coast from flooding.

~~because of reef degradation. Also, under certain combinations of energetic wave conditions on fringing reefs, the steep reef face has been shown to facilitate the liberation of fluctuations with infragravity periods, which can pass into the lagoon with little energy loss and exacerbate the effect of the storm (Roeber et al., 2015). The importance of these long-wave motions inside the lagoon has been previously demonstrated by Van Dongeren et al. (2013). The above phenomenon can be intensified if the reef lagoon resonates with the wave period, amplifying the peak energy of the surf beat (Torres-Freyermuth et al., 2012; Roeber et al., 2015).~~

Regarding the storm impact regime (Table 2), for a return period of 5 years, there is an increase from a collision regime to an overwash regime when the reef is degraded by 0.3 m. The importance of the reef in protecting the coast becomes more obvious in the scenario where the reef is degraded by 1.1 m, showing an increase in the storm impact ~~scenarios compared to the other scenarios (conserved and 0.3 m degraded)~~. Based on the results, the degraded 1.1 m scenario will result in the net erosion of the dune (i.e. collision regime) even for a storm with a yearly return period, whereas inundation will occur for a return period of 7.5 years.

5.3 Role of dune degradation

The dune crest elevation is a relevant parameter in coastal protection against extreme water levels. Therefore, the implications of dune degradation can be ~~studied~~ theoretically investigated by considering a smaller crest elevation (D_{high}<1.9 m) while estimating the storm impact scale. Model results show that for return periods of 3-10 years the dune degradation by 0.6 m (Table 3) plays a more important role in coastal protection than the reef crest when degraded 0.3 m (Table 2~~3~~). Moreover, moderate reef degradation and dune degradation together can be more important than the extreme reef degradation of 1.1 m (see Table 3). Therefore, results show the combined importance of conserving the reef-dune system in order to naturally protect the coast from storm conditions. This is ~~similar~~ consistent with ~~to~~ the results of Guannel et al. (2016), who found that the greatest nature-based coastal protection is offered when several habitats are considered.

5.4 Role of Storm surge

To investigate the storm surge contribution, sea level data were obtained from the HYbrid Coordinate Ocean Model (HYCOM; Halliwell et al., 1998; Bleck, 2001) for the Gulf of Mexico (GoM) (https://hycom.org/data/goml0pt04) for the dates that coincide with the available wave hindcast information (1993-2008). For the GoM, HYCOM has a 1/25° or 0.04° equatorial and latitudinal resolution (~3.5 km) for each variable at mid-latitudes. The version of HYCOM used is 2.2.77. Both H_s and T_p from the Hindcast data were interpolated to the same time vector as that of the GoM sea level data. A total of 300 representative cases were simulated for the 16-year period (using the same methodology as for the 30-year hindcast), using: (i) the sea surface height obtained from Hycom (mean sea level including storm surge and astronomical tide) or (ii) the astronomical tide. Figure 7 shows R_{high} as a function of the return period while considering the two different scenarios. An increase in R_{high} is observed when storm surge is included. This increase is important since it acts as a proxy for reef degradation. Neglecting the storm surge contribution results in an underestimate of the effects of reef degradation on runup and hence coastal flooding. However, 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 (Fig. 7).

In order to study the effects of the storm surge on extreme water levels for the specific case of a hurricane event, wave parameters were selected from the hindcast data between the 19th and the 25th of October (Figure 8a and b), corresponding to Hurricane Wilma, a Category 5 hurricane, which reached the Yucatan Peninsula on the 20th-21st of October, 2005. The maximum R_{high} values are higher and the minimum values are lower owing to the storm surge contribution during the hurricane passage. In terms of reef degradation and the effects of the storm surge during the hurricane, the R_{high} values are generally greater for the degraded profiles throughout the five days presented, except around the peak of the hurricane (results not shown). This might be ascribed to waves breaking further offshore of the reef crest. Therefore, the storm impact during more extreme conditions appears to be less sensitive to reef crest degradation than during moderate storm conditions, further supporting the reef degradation results presented in Section 5.2. 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. Furthermore, it is likely that by treating the dune as a non-erodible feature, overtopping is underestimated.

6. Discussion:

The calculation of extreme runup is necessary to estimate the storm impact in coastal areas. Runup parameterisations provide a rapid assessment of coastal vulnerability and hence deserve further investigation. Under certain combinations of energetic wave conditions on fringing reefs, the steep reef face has been shown to facilitate the liberation of fluctuations with infragravity periods, which can pass into the lagoon with little energy loss and exacerbate the effect of the storm (Roeber et al., 2015). The importance of these long-wave motions inside the lagoon has been previously demonstrated by Van Dongeren et al. (2013). The above phenomenon can be intensified if the reef lagoon resonates with the wave period, amplifying the peak energy of the surf beat (Torres-Freyermuth et al., 2012; Roeber et al., 2015). Therefore, runup dynamics and the validity of applying parameterisations used for beaches in reef environments are investigated here.storm impact during hurricane events

Hurricane Wilma (2005) was used to investigate the effect of storm surge on extreme water levels. Thus, a set of runs during the hurricane event were simulated considering only the astronomical tide prediction and a second set including the contribution from the storm surge. We selected wave parameters from the hindcast data between the 19th and the 25th of October (Figure 9a and 9b), which correspond to Hurricane Wilma, a Category 5 hurricane, which reached the Yucatan

Peninsula on the 20th-21st of October, 2005. To investigate the storm surge contribution, sea level data were obtained from the HYbrid Coordinate Ocean Model (HYCOM; Halliwell et al., 1998; Bleck, 2001) for the Gulf of Mexico (GoM) (https://hycom.org/data/goml0pt04) for the same dates). For the GoM, HYCOM has a 1/25° or 0.04° equatorial and latitudinal resolution (~3.5 km) for each variable at mid-latitudes. The version of HYCOM used is 2.2.77. Both H_s and T_p from the Hindcast data were interpolated to the same time vector as that of the GoM sea level data (Figure 9).

Figure 9d shows a clear difference in R_{high} when the storm surge is included. The maximum values are higher and the minimum values are lower owing to the storm surge contribution during the hurricane passage. This has implications when calculating the storm regime. In terms of reef degradation and the effects of including the storm surge, the R_{high} values are generally greater for the degraded profiles throughout the five days presented, with the exception of an outlier around the peak of the hurricane, which was an interpolated value, and may therefore not be as accurate as the other values. This may be because during a hurricane the waves are significantly larger and therefore break further offshore than in non-storm conditions. Therefore, the storm impact during more extreme conditions appears to be less sensitive to reef crest degradation (see Figure 10) than during moderate storm conditions, as noticed previously. 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., 2015) and wave runup (Osorio et al., 2017). Therefore, the conservation of the dune during such conditions is fundamental for the natural protection of the coastal area.

Incident and infragravity swash height have been analysed for the conserved scenario using the parameterisations proposed by Stockdon et al., (2006) where the swash height was calculated as follows:

$$S = \sqrt{(S_{inc})^2 + (S_{ig})^2}$$

where S_{inc} and S_{ig} are significant swash height in the incident and infragravity frequencies respectively. For beaches, Stockdon et al. (2006) 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. Figure 9a shows the incident swash height for the 600 cases simulated in the present study (high and low water contributions are presented in green and red respectively). As shown in the figure, Stockdon's parameterisation (blue solid line) works fairly well for S_{inc}, particularly for high water levels, although it slightly overpredicts the numerical results. Figure 9b shows the parameterisation for infragravity swash height (S_{ig}), excluding beach slope in the parameterisation, which also works satisfactorily for the high-water level, although is 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 (not shown), 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 irrespective of the beach slope conditions.

With regards to wave setup <η>, the parameterisations presented by Stockdon et al. (2006) significantly underestimate wave setup in the study area (Fig. 9c). 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 (red versus blue line Fig. 9c), although it still underestimates the setup values.

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. 10). However, the runup parameterisations fail to predict the runup during extreme wave conditions. This is mainly attributed to the underestimation of wave setup. However it is worth noticing that the good fit of the $R_{2\%}$ parameterisation is ascribed to a combination of the over prediction of S and under prediction of setup. Therefore, future work should be devoted to improving such parameterisations by incorporating the reef geometry characteristics in the formulations.

7. Conclusions

A numerical model was employed to for the theoretical study of the role of the reef-dune system in coastal protection against extreme wave events in Puerto Morelos (Mexico). The numerical model was validated with laboratory data of wave transformation over a physical model of a reef system. The model-data comparison of free-surface elevation, wave setup, and swash height was satisfactory for simulations with and without a reef crest. Thus, the numerical model was employed to generate a 30-year hindcast of wave-induced extreme water levels for different scenarios of reef-dune degradation in Puerto Morelos (Mexico). The storm impact scale proposed by Sallenger (2000) shows that ecosystem degradation enhances beach vulnerability, particularly for storms with return periods smaller than 10 years. Results show the impact to be more sensitive to dune degradation than crest reduction by 0.3 m, while crest reduction by 1.1 m has a greater effect than degradation of the dune by 0.6 m. The combined degradation of both the dune and reef further increase the vulnerability, so that the conservation of the system as a whole is important for coastal protection. . This implies that the environmental service of coastal protection by coral reefs and dunes are is critical in the short term regarding infrastructure losses in coastal areas. This becomes particularly important as more people are exposed to sea level rise and coastal hazards (e.g. erosion, flooding, and hurricanes) due to coastal population growth (Neumann et al., 2015). Neglecting the storm surge contribution significantly underestimated the storm impact scale, particularly for return periods of less than 3 years. For the reef setting studied here, both the infragravity swash and the wave-induced setup play an important role when parameterising runup. The inclusion of the reef slope improves the model fit to numerical data, suggesting that the equations used for beach environments need to incorporate reef geometry characteristics. However, the main drawback in the present study is that it does not consider the dune or the beach as erodible features. Both play an important role in energy dissipation and hence further research is warranted to investigate their effect on increasing/decreasing the storm impact during extreme events. Furthermore, the role of reef roughness and two-dimensional horizontal processes need to be addressed for a more comprehensive study on the implication of reef degradation in such environments.~~ The role of reef roughness and two-dimensional processes need to be incorporated for a more comprehensive study.~~

Author contribution. Gemma Franklin carried out all the numerical simulations and data analysis and helped to design the numerical tests. Alec Torres-Freyermuth led and supervised this work and designed both the numerical and laboratory experiments. Gabriela Medellín developed the scripts for downscaling the wave hindcast data and reconstructing the runup time series. María Eugenia Allende-Arandia compiled and helped implement the numerical models in the cluster. ~~Bernabé Gómez carried out all the laboratory experiments. ~~Christian Appendini generated the wave hindcast information employed in this work. Gemma Franklin prepared the manuscript with contribution from all co-authors.

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Table 1. Storm impact scale according to Sallenger (2000).

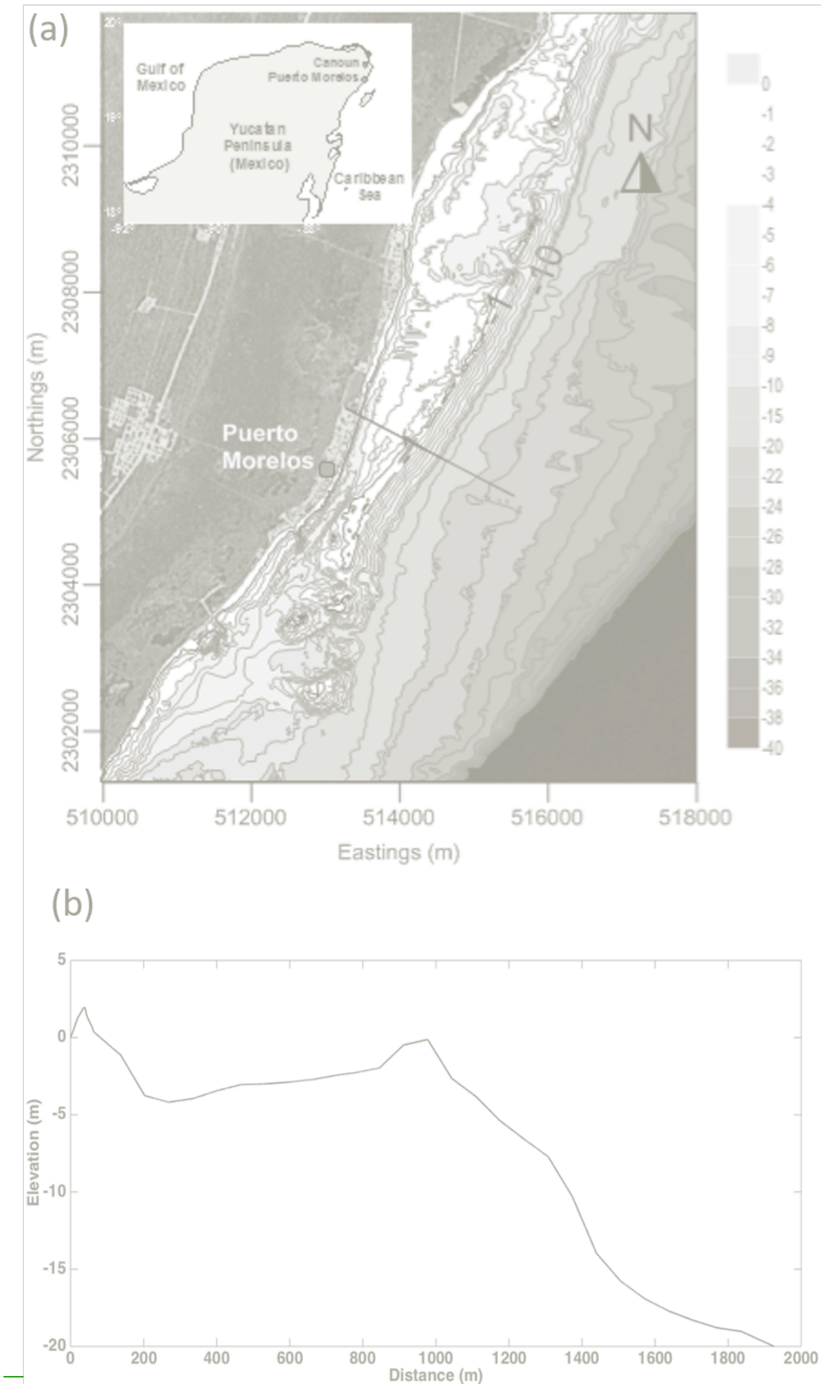
Regime	Description
Swash	$R_{high} < D_{low}$
Collision	$D_{high} > R_{high} > D_{low}$
Overwash	$R_{high} > D_{high}$
Indundation	$R_{low} > D_{high}$

Table 2. Storm impact regime for the 1-, 3-, 5-, 7.5-, 10-, 15- and 30-year return periods, considering a D_{high} and D_{low} of 1.9 and 1.3 m respectively, for different degrees of reef degradation (0.3 m and 1.1 m).

	Storm impact regime		
Return period	Conserved (D_{high}=1.9)	Reef degraded 0.3 m (D_{high}=1.9)	Reef degraded 1.1 m (D_{high}=1.9)
1	SWASH ($R_{high} < D_{low}$)	SWASH ($R_{high} < D_{low}$)	COLLISION ($D_{high} > R_{high} > D_{low}$)
3	COLLISION ($D_{high} > R_{high} > D_{low}$)	COLLISION ($D_{high} > R_{high} > D_{low}$)	OVERWASH ($R_{high} > D_{high}$)
5	COLLISION ($D_{high} > R_{high} > D_{low}$)	OVERWASH ($R_{high} > D_{high}$)	OVERWASH ($R_{high} > D_{high}$)
7.5	OVERWASH ($R_{high} > D_{high}$)	OVERWASH ($R_{high} > D_{high}$)	OVERWASH ($R_{high} > D_{high}$)
10	OVERWASH ($R_{low} > D_{low}$)	OVERWASH ($R_{high} > D_{high}$)	INUNDATION ($R_{low} > D_{low}$)
15	INUNDATION ($R_{low} > D_{low}$)	INUNDATION ($R_{low} > D_{low}$)	INUNDATION ($R_{low} > D_{low}$)
30	INUNDATION ($R_{low} > D_{low}$)	INUNDATION ($R_{low} > D_{low}$)	INUNDATION ($R_{low} > D_{Llow}$)

Table 3. Storm impact regime for the 1-, 3-, 5-, 7.5-, 10-, 15- and 30-year return periods, considering a D_{high} and D_{low} of 1.3 m, for different degrees of dune and reef degradation.

	Storm impact regime	
Return period	Dune degraded reef conserved (D_{high}=1.3)	Reef (1.1 m) and dune degraded (D_{high}=1.3)
1	SWASH (R_{high}< D_{low})	OVERWASH (R_{high}>D_{high})
3	OVERWASH (R_{high}>D_{high})	OVERWASH (R_{high}>D_{high})
5	OVERWASH (R_{high}>D_{high})	OVERWASH (R_{high}>D_{high})
7.5	OVERWASH (R_{high}>D_{high})	OVERWASH (R_{high}>D_{high})
10	OVERWASH (R_{high}>D_{high})	INUNDATION (R_{low}>D_{low})
15	INUNDATION (R_{low}>D_{low})	INUNDATION (R_{low}>D_{low})
30	INUNDATION (R_{low}>D_{low})	INUNDATION (R_{low}>D_{low})



(a)
Gulf of Mexico
Cancun
Puerto Morelos
Yucatan Peninsula (Mexico)
Caribbean Sea
Puerto Morelos
N
-1
-10
Northings (m)
Eastings (m)
(b)
Elevation (m)
Distance (m)

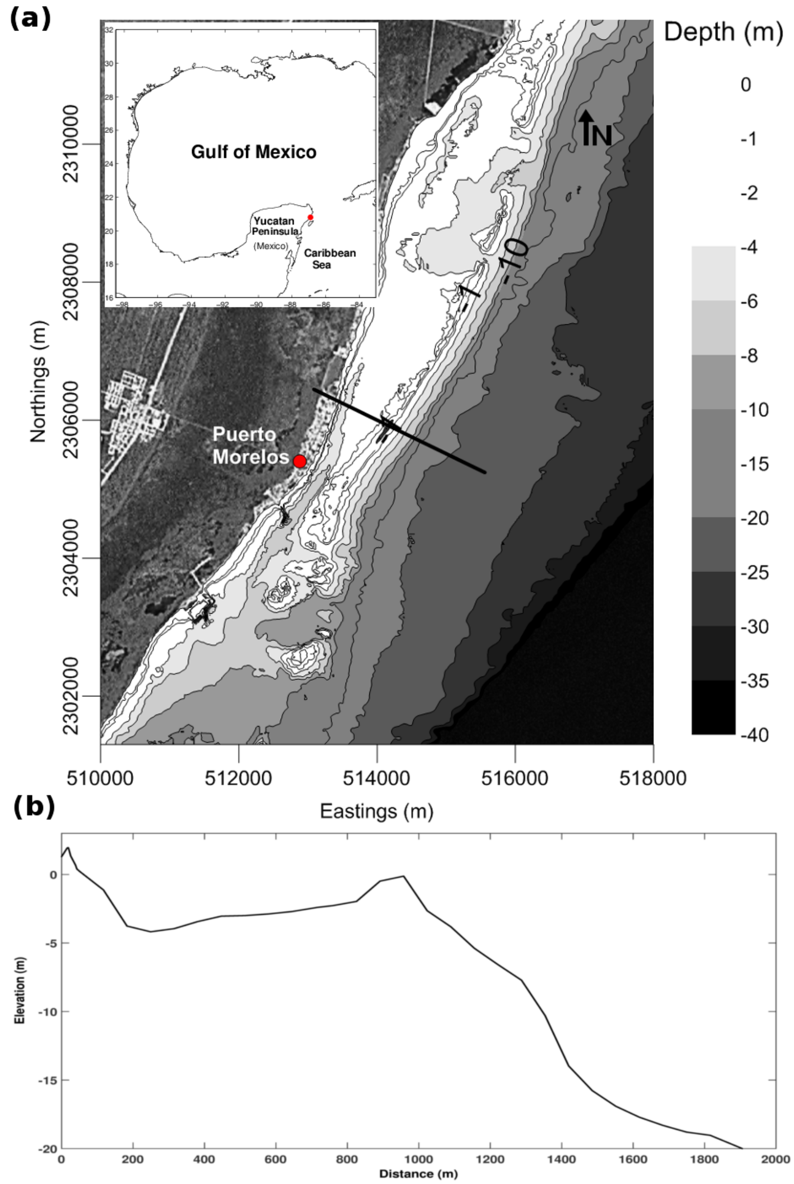
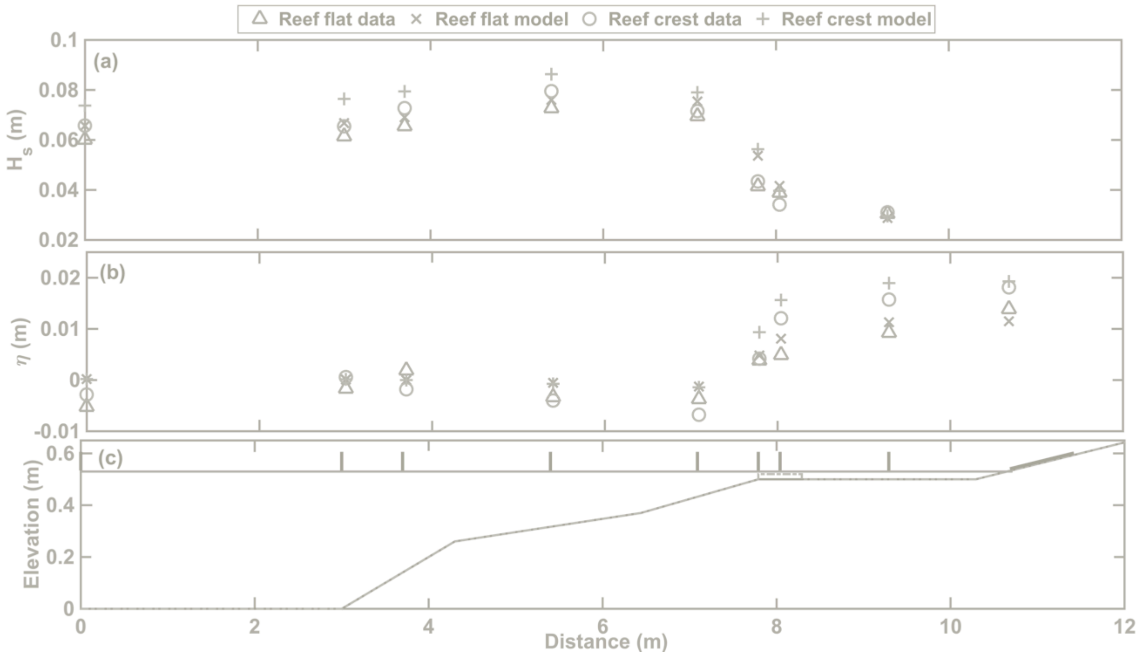
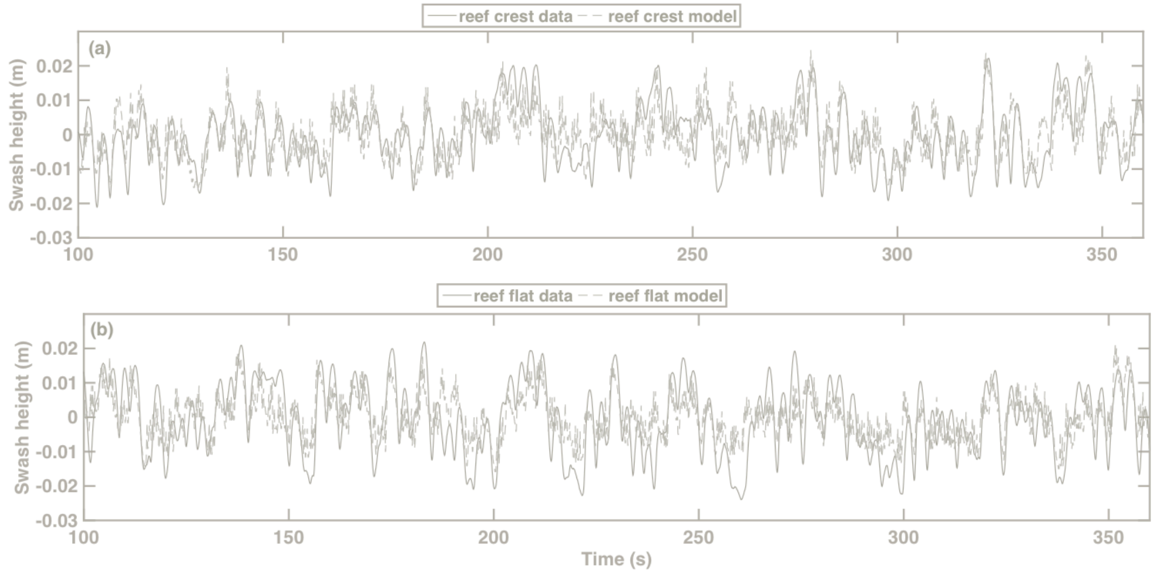


Figure 1. (a) Map of the study area. The solid black line indicates the location of the bathymetric transect used in the numerical model. (b) Bathymetry obtained from the transect indicated on the map (bathymetry courtesy of CONABIO), including a beach profile surveyed in March, 2014 (courtesy of CINVESTAV-Merida).



~~**Figure 2. Model validation using the reef flat and reef crest measurements of (a) significant wave height and (b) wave setup (blue represents the reef flat and red the reef crest). Circles and triangles indicate laboratory data and crosses model data. (c) Profile of the physical model used in the laboratory experiments. The solid black line indicates the reef flat and the dashed red line indicates the reef crest profile. The blue line represents the water level used in the experiments, and the solid black lines indicate the locations of the capacitance sensors.**~~



~~**Figure 3. Swash height time series for the reef (a) with and (b) without crest.**~~

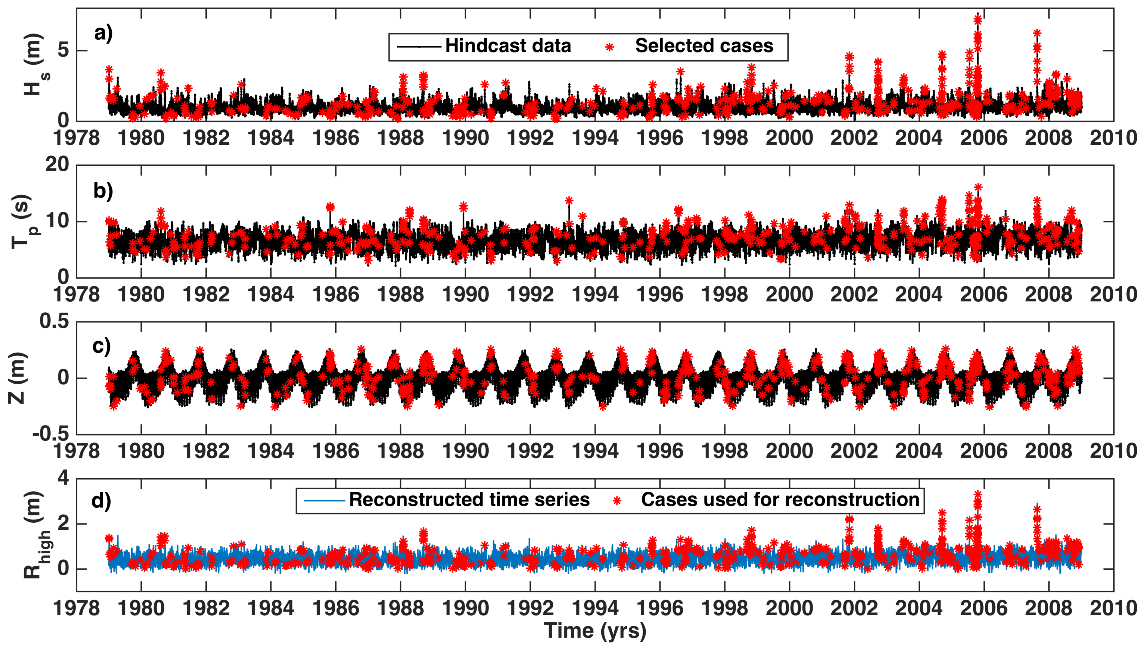


Figure 24. Reconstructed time series, including the extreme water level, R_{high}, for the current reef profile using the 30-year hindcast wave conditions (wave height and period; H_s and T_p) and astronomical tide (Z). ~~.~~ (a)–(c) Black lines indicate available hindcast data and red stars indicate 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. $R_{high}=R_{2\%}+Z$.

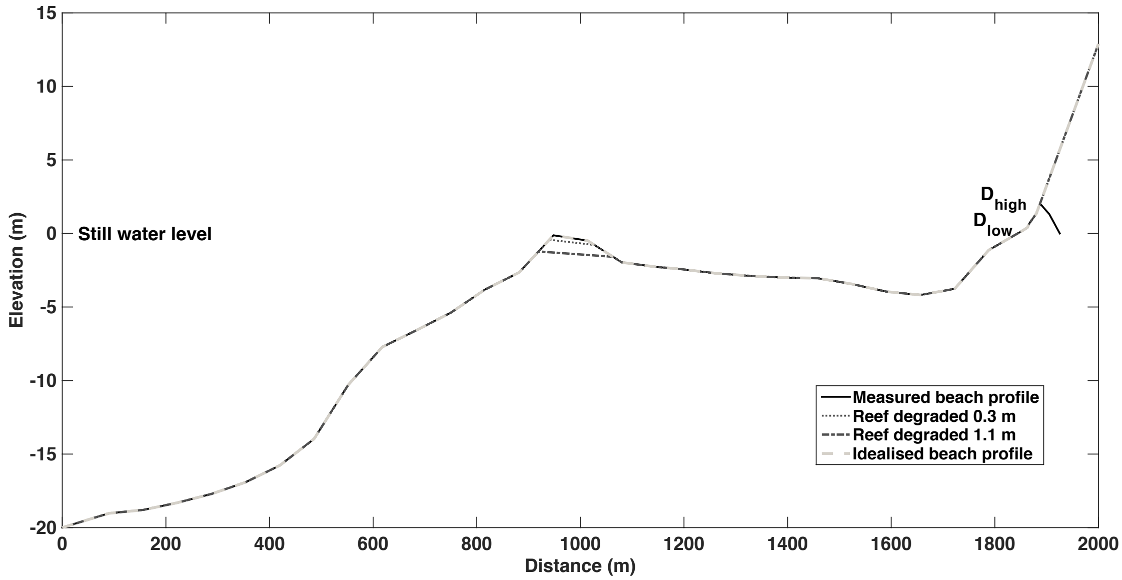


Figure 35. Measured beach profile (solid black line) and idealised profile with beach extended beyond the dune (dashed grey line). D_{high} represents the dune crest and D_{low} the foot of the dune. The degraded profiles (0.3 m and 1.1 m) are indicated by the dotted dark grey and dashed black lines respectively.

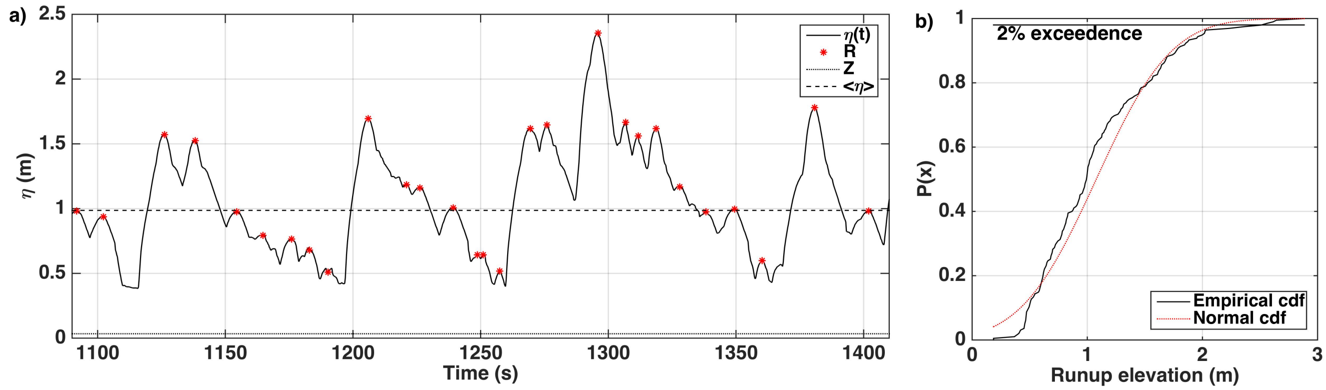


Figure 4. (a) Example of a section of the water level elevation time series relative to mean sea level (η(t)) extracted from the wet–dry boundary of the SWASH simulations, showing astronomical tide Z, run-up maxima, R, and setup at the shoreline <η>. (b) The 2 % exceedance value was extracted from the cumulative distribution function (cdf) of the R values.

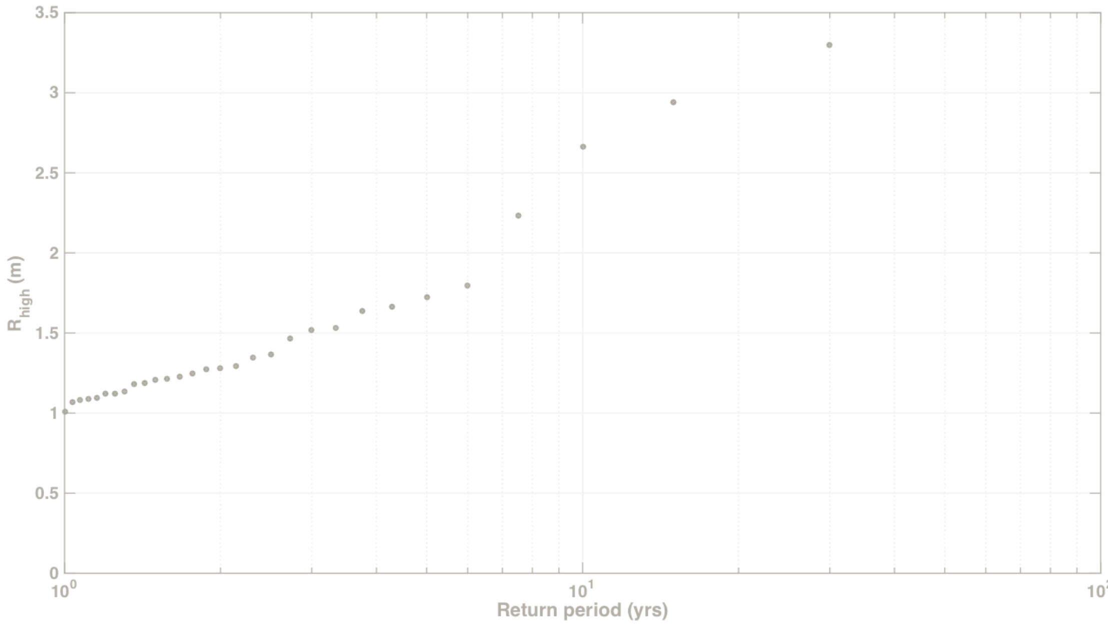


Figure 6. Return value of R_{high} for the current reef profile.

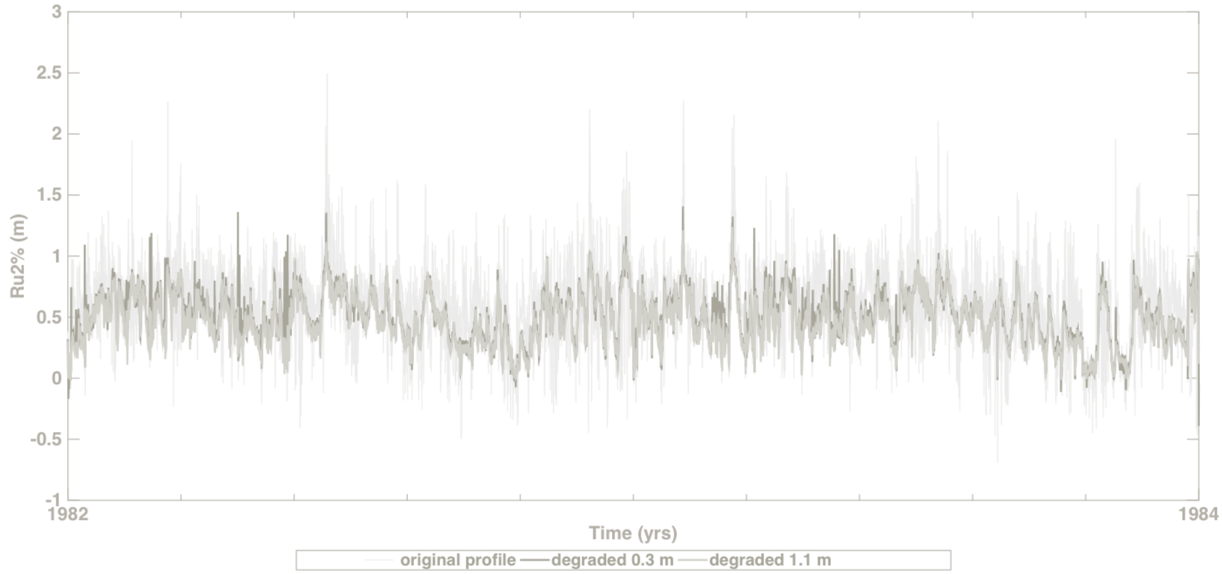


Figure 7. A section of the $Ru_{2\%}$ time series for the different reef profiles.

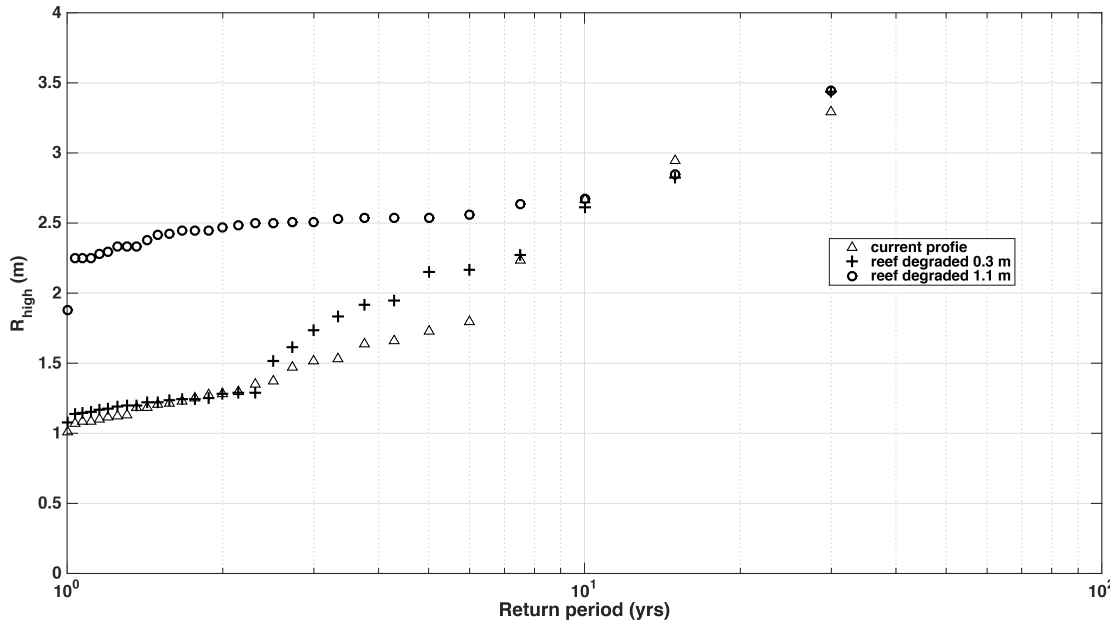


Figure. 58. Return value of R_{high} for the current reef profile (~~solid dots~~triangles), the reef degraded by 0.3 m (crosses) and for the profile with the reef degraded by 1.1 m (open circles).

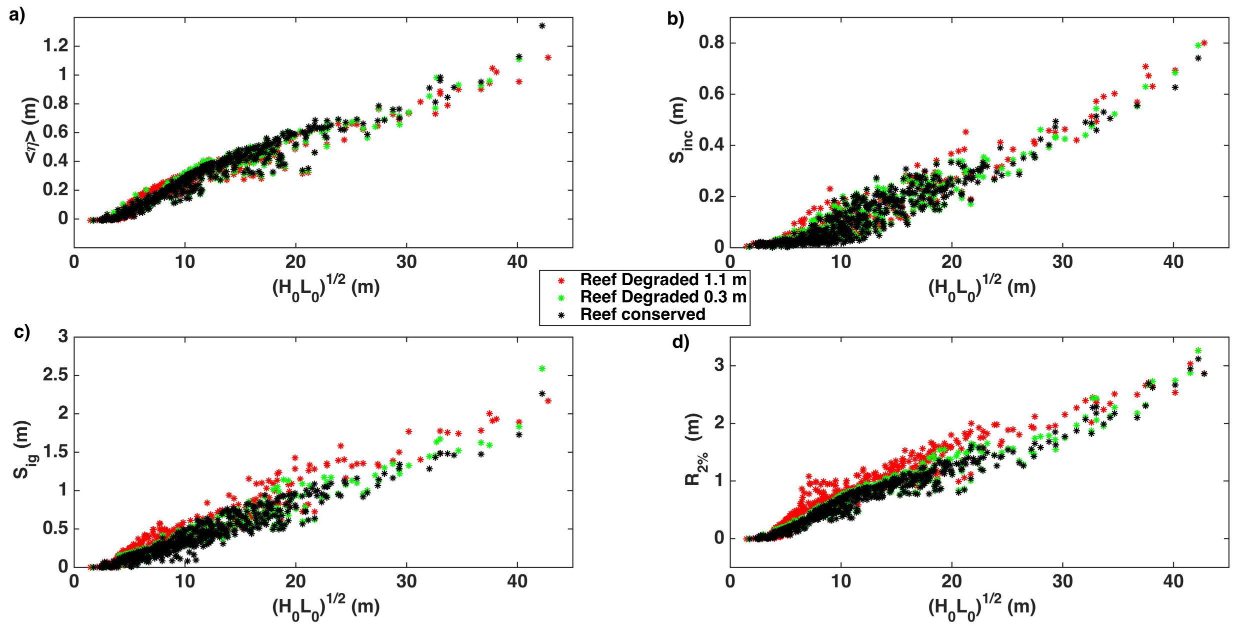


Figure 6. (a) Wave setup, <η>, (b) incident swash (S_{inc}), (c) infragravity swash (S_{ig}) and (d) extreme runup ($R_{2\%}$) against incident wave conditions. Black dots represent the data for the conserved reef profile, green the values for the reef degraded by 0.3 m and red those associated with the reef degraded by 1.1 m.

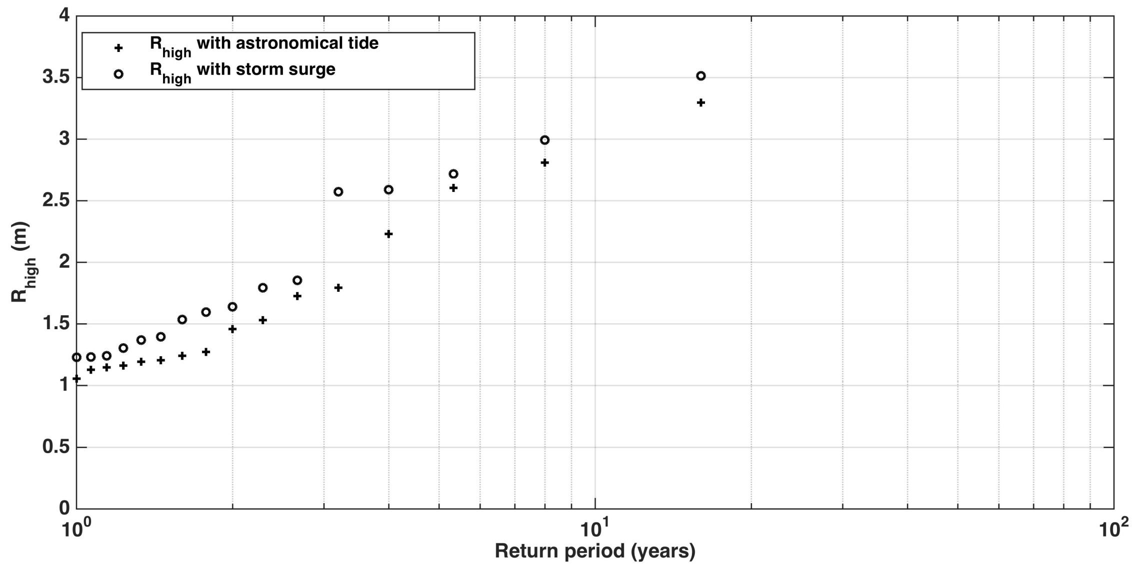
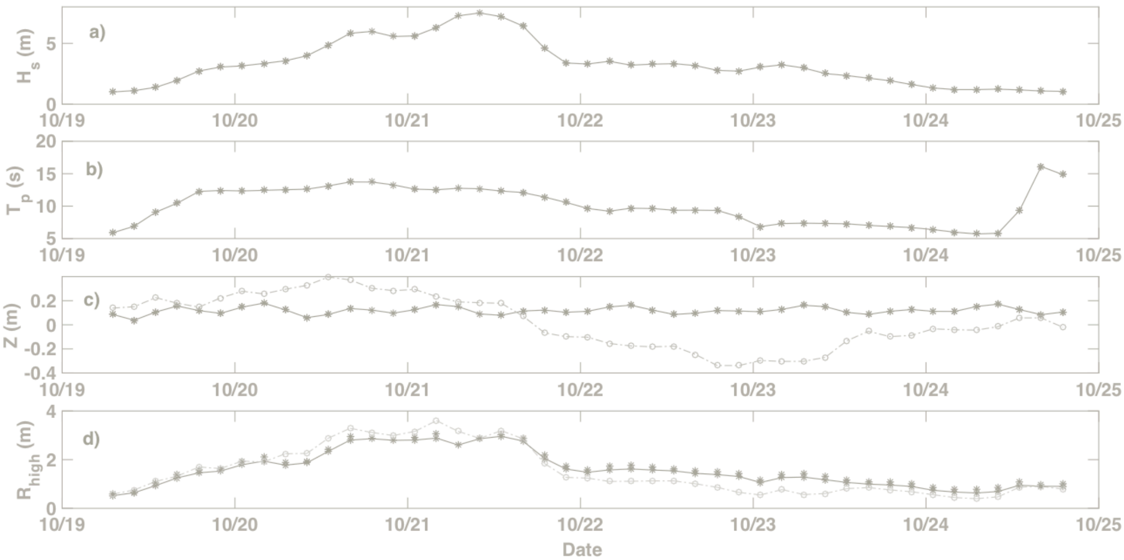


Figure 7. Return value of R_{high} for the model run with the storm surge (open circles) and without (crosses) for the time period of 1993-2008.



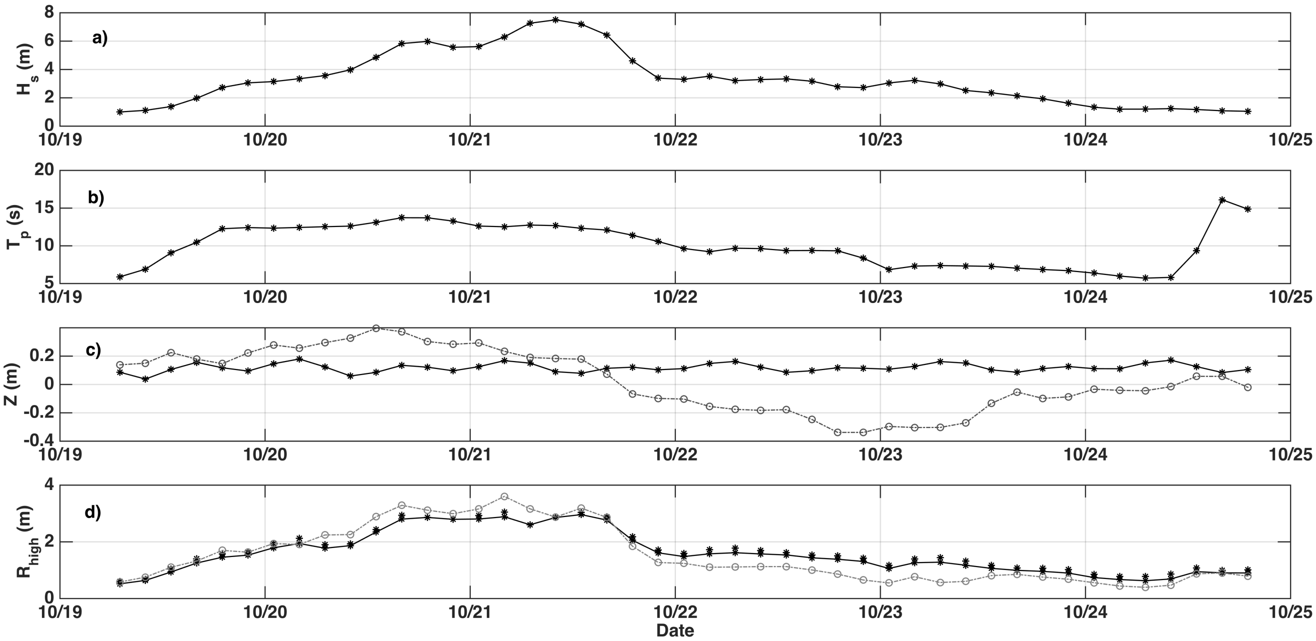
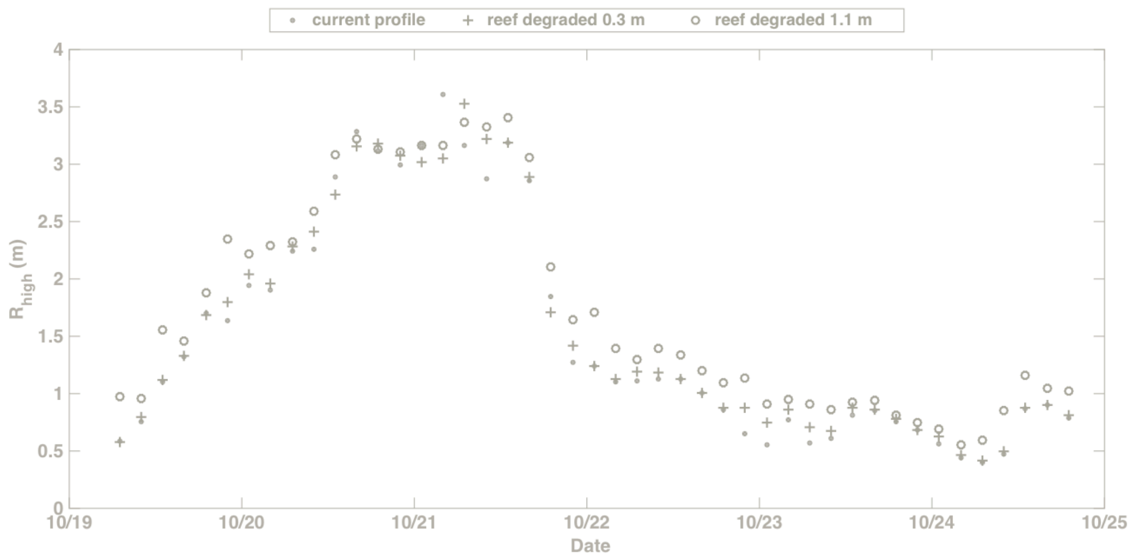


Figure ~~9~~8. (a) Significant wave height (H_s), (b) peak period (T_p), (c) sea level (Z) (black: ~~predicted~~ astronomical tide, grey: GoM sea level) and (d) R_{high} (black: without the storm surge, grey: with storm surge) during the pass of Hurricane Wilma (2005).



~~Figure 10. R_{high} during Hurricane Wilma (2005) for the current reef profile (solid dots), the reef degraded by 0.3 m (crosses) and for with the reef degraded by 1.1 m (open circles).~~

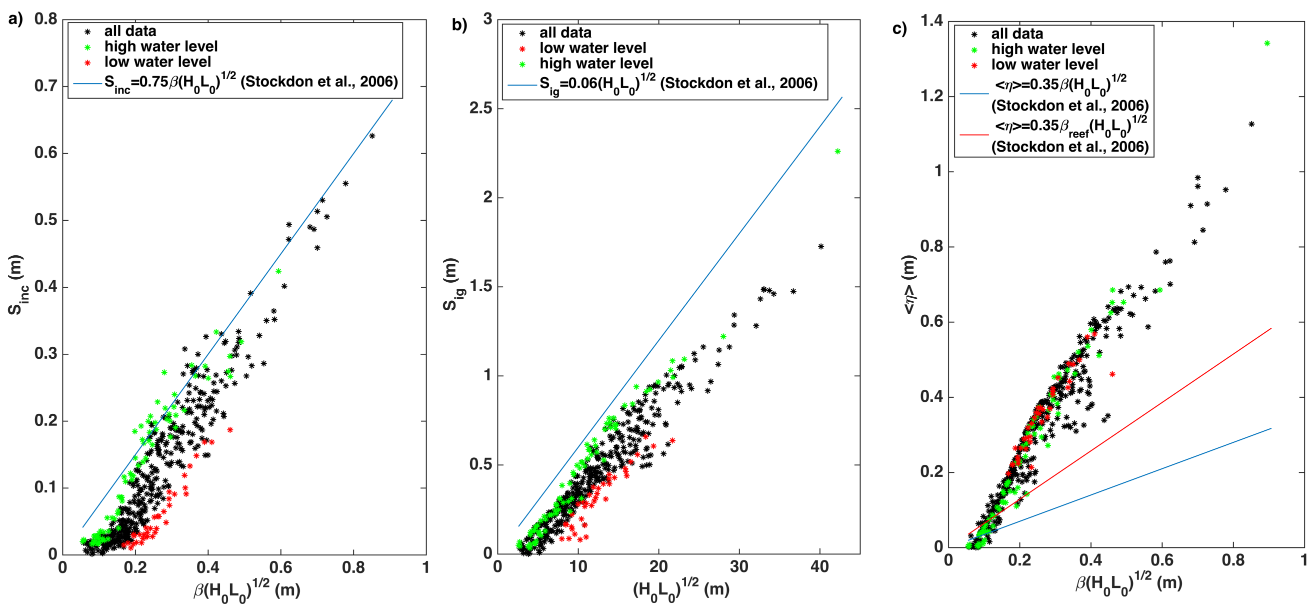


Figure 9. (a) Incident swash, (b) infragravity swash and (c) wave setup parameterised in a dimensional form of the Iribarren equation and in comparison to Stockdon et al. (2006) (blue lines) and a modified form for wave setup, which includes the reef face slope (red line). Black dots represent the selected hindcast cases, green the values associated with high water levels ($Z \geq Z_{15\%}$=0.1636 m) and red those associated with low water levels ($Z \leq Z_{15\%}$=-0.1636 m).

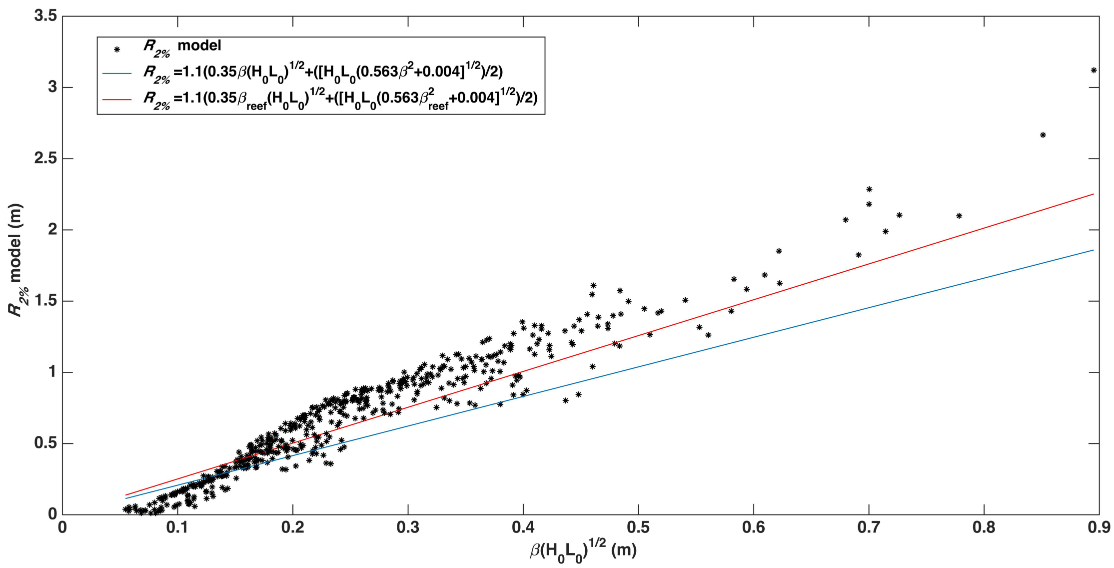


Figure 10. Extreme runup values (*$R_{2\%}$*) for the selected 30-year hindcast data (black dots) and the complete parameterisation suggested by Stockdon et al. (2006) with the beach face slope (blue line) and reef face slope (red line).