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# St Vincent – Black Point Beach Modelling

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## Executive Summary

Black Point on the East coast of St Vincent and Grenada was modelled using a storm impact model. A total of 5 different storm events were simulated, based on peak wave parameters taken directly from observations made in July-October 2018 and from numerical and parametric models of hurricane events. Impacts from these events were assessed by calculating wave run up and beach level erosion and deposition during the events.

The results of the model simulations show that the 98th percentile (standard impact parameter R2%) of wave run up for the observed events were largely the same despite a noticeable difference in their boundary conditions. Therefore, for these events the impact on the coastline is largely the same. For tropical cyclone events, there is a variety in the impacts depending on the wind forcing used. ERA5 reanalysis winds are lower than those observed, but using Holland wind forcing, derived from the best track hurricane archive data for the same event (Hurricane Tomas in 2010) and results in much larger impacts, with wave runup over a metre higher than for the forcing taken from the observed events for the R2% assessment parameter. It has been noted that the parametric wind forcing, for a Category 4 hurricane in particular, results in waves that are outside the conditions that the model is known to be validated for and so should be considered suspect without further validation.

Changes in beach levels during the simulations was also calculated, with the work focusing on the upper 250m of the beach. The beach profile at Black Point was reconstructed based on LiDAR bathymetry collected by the UKHO in 2016-2017. All events smooth out the beach profile, removing small bumps and berms. There are small changes during the observed events, with a small berm being removed at the top of the beach and a slight increase in the height of the beach itself. There are large differences for the tropical cyclone wind events, with ERA5 winds having a lower impact than the observed events, with just a smoothing of the beach. The higher wind forcing from Holland winds results in a greater change where from 150 m offshore there is erosion of the beach, leading to a steepening of the beach slope and a higher beach crest. This would reduce the impact of the extreme event itself. Finally, parametric waves for a Category 4 hurricane result in heavy erosion 250m offshore all the way to the end of the beach with the beach crest being totally removed. This would result in water over-washing the beach completely. However, as previously mentioned, these wave parameters are outside the model validation and the results for this simulation should be treated with caution. It does however indicate the potential severity of the impact of a Category 4 Hurricane.

# 1. Introduction

This report details the beach modelling that was undertaken at Black Point, St Vincent and the Grenadines. This location was selected because there is a recognized risk of coastal erosion along the east (windward) coast of St Vincent and some wave data were collected in that location during July-October 2018 and January-March 2019. A single cross-shore beach profile was extracted from a recent LIDAR survey (Fugro, 2017). This was processed and formulated as an input to a storm impact model XBeach (Roelvink *et al.*, 2010). A locally deployed Nortek Acoustic Waves and Currents (AWAC) instrument with Acoustic Surface Tracking (AST) provided wave and water level data to use as boundary conditions. The period June-November is the hurricane season in the Caribbean Sea, although hurricanes mostly pass to the north of St Vincent, and higher waves plus occasional swell from distant storms occur during that period. Thus, the July-October 2018 deployment was used to identify the maximum wave height and maximum wave period, occurring during that time. A Category 1 hurricane from 2010 (Tomas), which passed close to St Vincent, has also been simulated with a variety of wind conditions (Jevrejeva et al. in preparation), the waves this generated were also used as boundary conditions. A surge model for the same tropical cyclone provided the water levels (Jevrejeva et al. in preparation).

Simulating the impact of storm events on a natural, sandy coastline requires a numerical model capable of simulating wave action, and the resulting wave run up, and morphological changes. The model selected was XBeach: XBeach is a model that simulates wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and back-barrier during storms (Roelvink *et al.*, 2010). This is a good match to the requirements of the project, and will be used to simulate the required extreme events.

A total of five different sets of boundary conditions were used: (i) an event that comprised the maximum significant wave height (Hs) recorded during the period July-October 2018, and (ii) one with the maximum peak wave period (Tp) during the same time. The other three sets were derived from three different sets of wind data used to force a wave model for the Hurricane Tomas event. These are from (i) the ERA5 hindcast (Copernicus Climate Change Service, 2017), (ii) the Holland parametric wind model and (iii) an enhanced storm where the intensity was increased from Category 1 to Category 4 (on the Saffir-Simpson hurricane scale). The events were simulated with morphology enabled and then disabled. The impact of wave run up was estimated using an R2% parameter, this is the $98^{th}$ percentile value of the wave run up during the simulation where only 2% waves will exceed this elevation.

The impact of the simulated extreme events on the beach profile was also assessed by comparing the beach profiles at the start and end of the simulation (morphology-enabled only). This shows what impact the specific event has on the upper beach. Additionally, the erosion and deposition characteristics of the upper beach will be assessed by calculating the change in beach elevations between the start and end of the simulation. The models have been set up to run the specific configurations, e.g. observed peak events and tropical cyclone extreme events but it is possible to use the model configuration to run operationally to provide wave run up warnings and beach erosion warnings. To this end, a framework that automatically acquires the water level and wave forecast data, prepares it for the model, runs the model and then produces warnings/plots to end users, is proposed. The system would also need to be robust and able to handle errors, such as ‘no new forecast data’, ‘model produces a runtime error’, ‘model has run out of disk space’, etc.

## 2. Study Location

The location of this study is at Black Point on the east coast of St Vincent. Figure 1 shows a regional map of the area around St Vincent and the Grenadines, with a close-up map of the island in the bottom right corner. Figure 2 is a picture of Black Point itself. The beach in the foreground is where the beach profile was extracted from the LIDAR survey data.

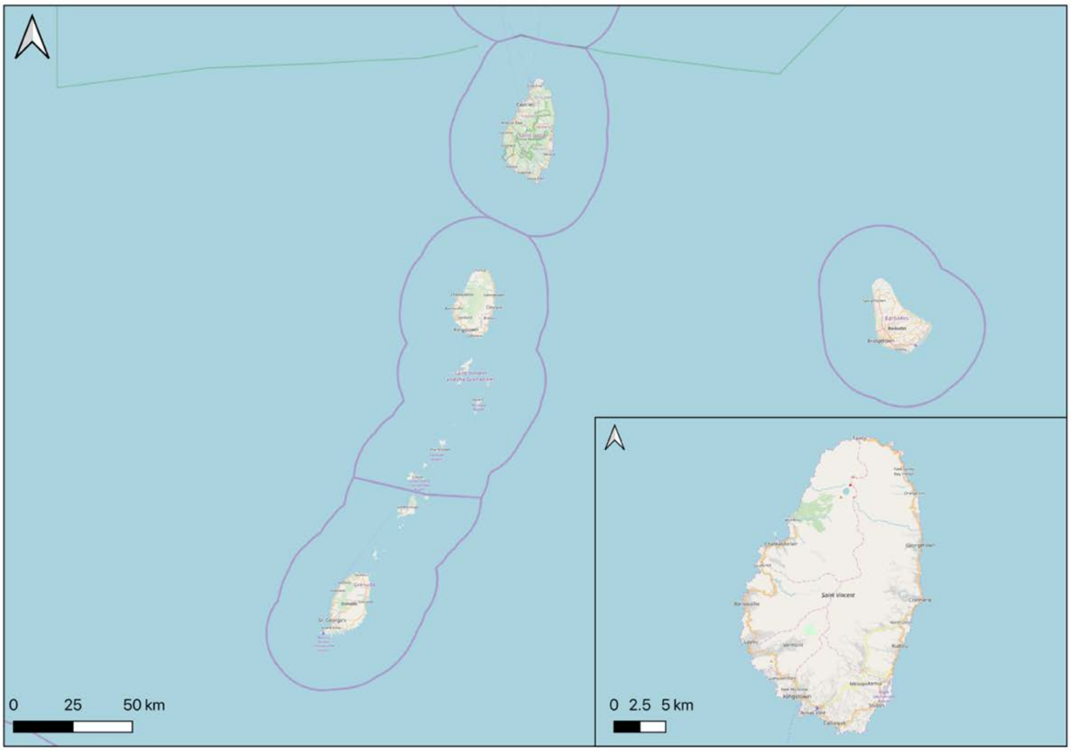


**Figure 1: Map showing part of the Windward Islands, in the Caribbean region where St Vincent is located.**

**Figure 2: Picture of Black Point, looking south, beach profile used in simulations in the foreground**

## 3. Methodology

This section details the methods used to simulate the storm events at Black Point on St Vincent, it covers the model used, methods to create the boundary conditions and beach profile.

### a. Storm Impact Model

XBeach can be set up in a variety of ways, the main choices are (i) Non-hydrostatic (wave resolving) or Hydrostatic mode, and (ii) 1DH or 2DH. In hydrostatic mode the short-wave amplitude variation is solved separately from the long waves, currents and morphological change: this reduces the computational cost massively but at the expense of the phase of the short waves not being simulated. Running in non-hydrostatic mode results in a more complete model that solves all processes including short wave motions, with the downside of an increased computational cost.

The main advantage to using the non-hydrostatic mode is that the incident band (short waves) runup and over-washing are included. As the project is assessing wave runup, it was necessary to run in non-hydrostatic mode. Given the quality of the bathymetry in the region and the higher computation cost of non-hydrostatic computations, XBeach was run in 1DH mode requiring a single cross shore beach profile. This greatly reduces the computational cost over a 2D variant, at the cost of ignoring longshore gradients. Longshore currents can still be generated by the model based on the incoming wave direction, being determined by Snell's Law. Figure 3 shows an example XBeach model, in this case a 2D model of Hurricane Sandy.

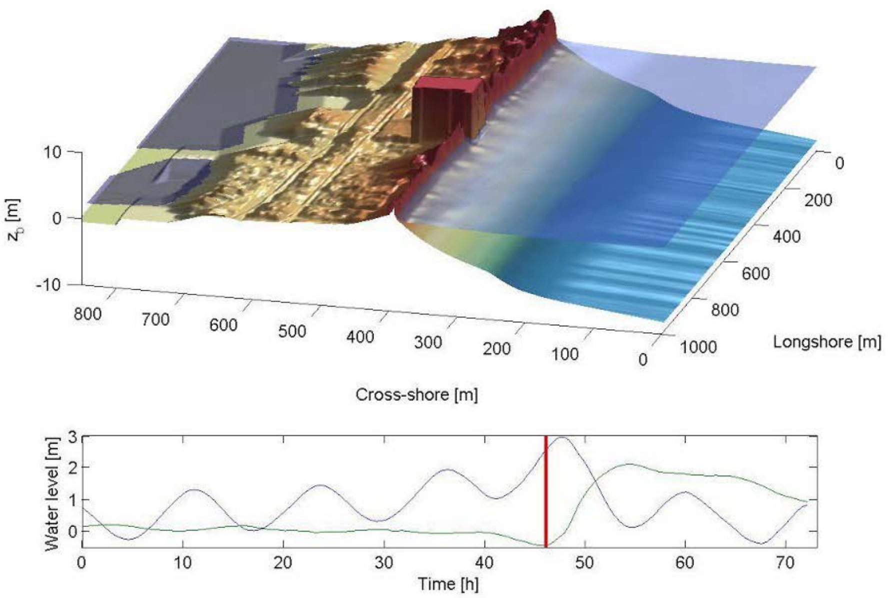


**Figure 3: Example of an XBeach model (2D Hurricane Sandy)**

## b. Bathymetry Survey

A LiDAR bathymetry survey of St Vincent, Grenada and the Grenadines was undertaken by Fugro in 2016-2017, for the UK Hydrographic Office, as part of the Commonwealth Marine Economies Programme (CMEP) this started on the 28/11/2016 and finished on 25/01/2017. The survey area covered is shown in figure 4 (Fugro, 2017).

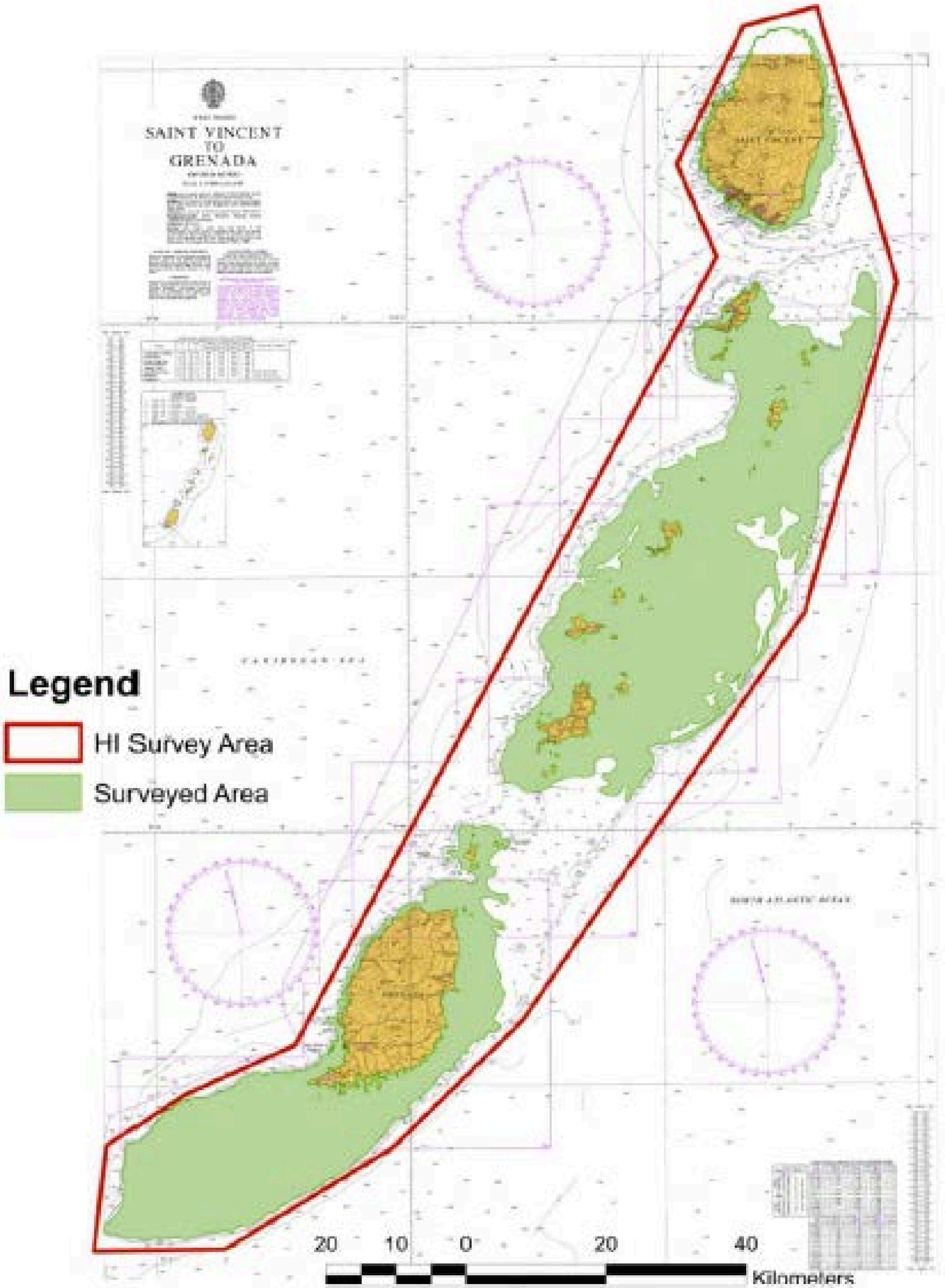


**Figure 4: Bathymetry survey area.**

The bathymetry collected off Black Point had issues with data missing from the nearshore. A profile was selected that crossed as much of the bathymetric data in this vicinity as possible. Gaps in the data were interpolated, to provide a complete beach profile to use in the storm impact simulations. This profile can be seen in figure 5.

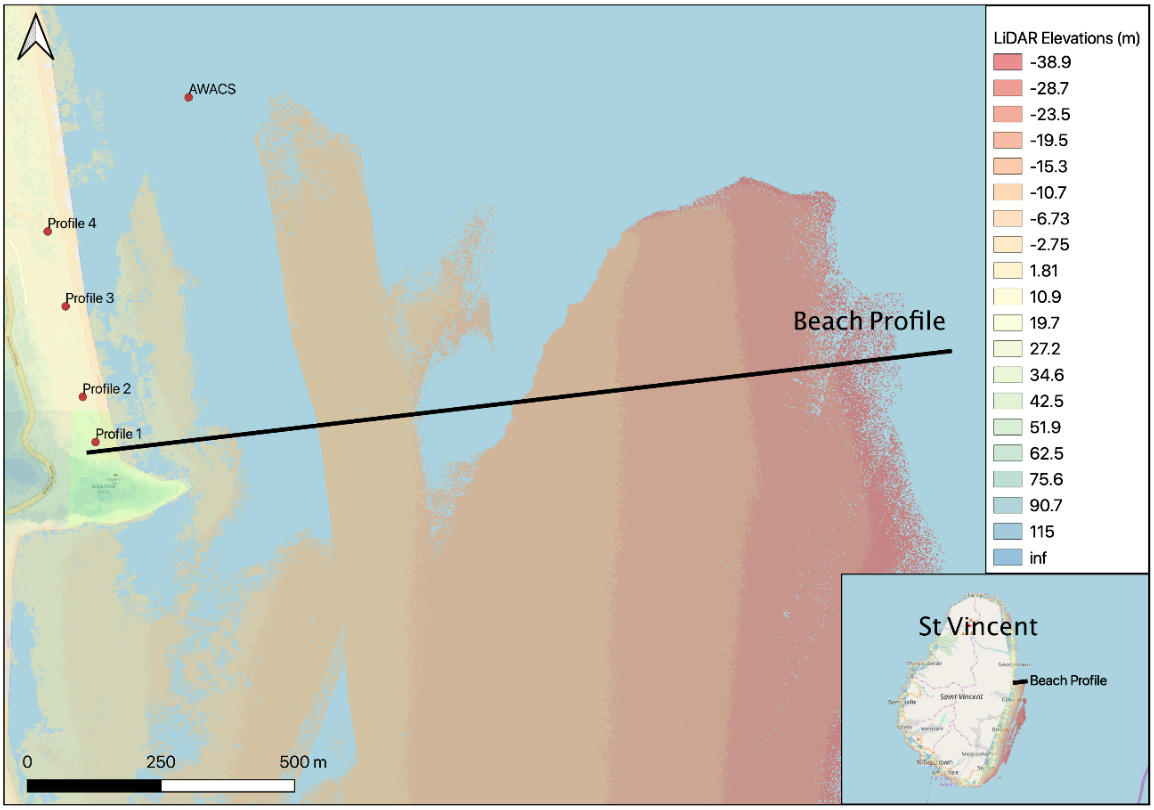


**Figure 5: Map showing location of beach profile extracted from LIDAR (black line). The points on the map marked Profile 1 through 4 are the locations of the top of the upper beach profiles collected through the SANDWATCH method (Cambers and Diamond, 2010)**.

## c. Beach Profile

As well as using LIDAR survey data, upper beach profiles were collected locally by the SVG Government National Parks, Rivers and Beaches Authority, using the SANDWATCH method (Cambers and Diamond, 2010). The data were provided by Ms Abena White. The method comprises of starting from a known point and measuring the angle of the beach slope at a known cross shore distance, this is repeated with each cross-shore distance being punctuated by its angle relative to the last. Figure 5 shows the four locations at which this was undertaken. However, the height of the initial starting point was measured relative to LW, which was calculated for the period at which the beach profile was collected. Using the tidal analysis of the AWAC surface water level dataset to convert the upper beach profiles into Chart Datum from relative to LW resulted in disparities between the profiles and the LiDAR survey. It was decided that, with the uncertainties in the upper beach profiles, not to utilise them for this work.

Another issue found was that, for the morphology-disabled runs, the initial beach profile provided by the LIDAR was too "noisy" and resulted in poor wave run-up output. This was resolved by using a sliding window averaging process on the beach profile, reducing the noise and smoothing the profile. This problem did not affect the morphology-enabled simulation as the morphological processes remove the "noise" from the profile. Figure 6 shows both the initial LiDAR and 10 m averaged profile.

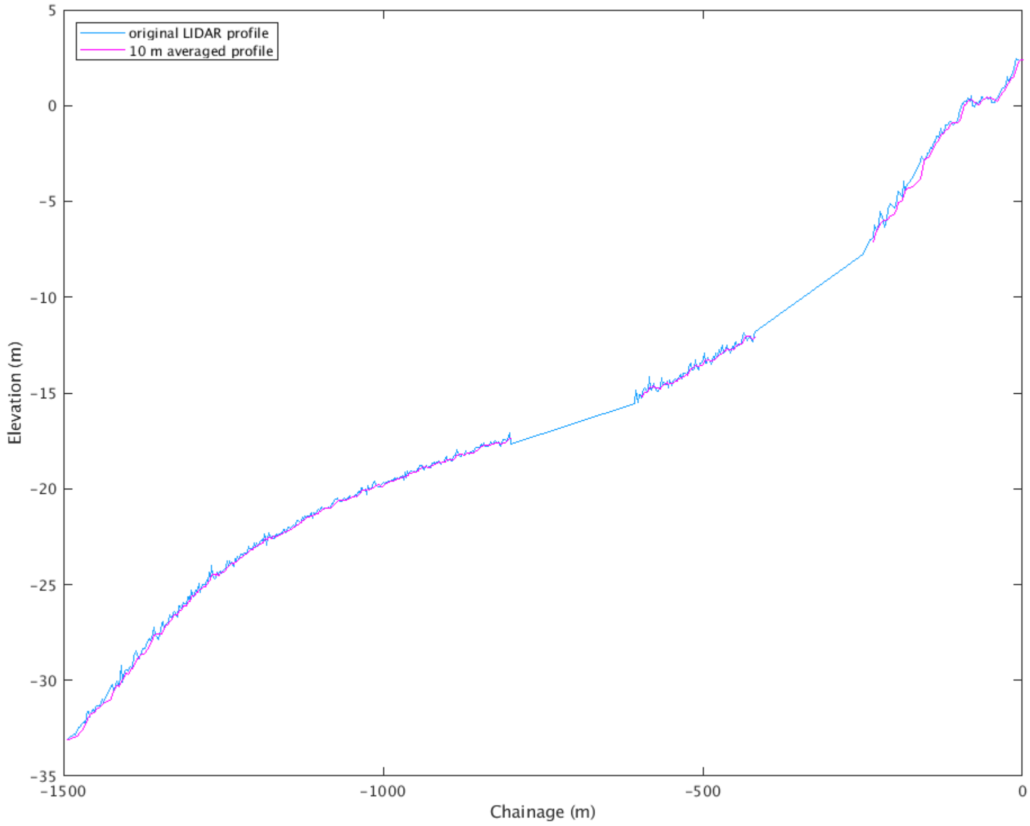


**Figure 6: Beach profiles used for the storm impact modelling, the LIDAR profile used by the morphology simulations and the 10 m sliding window averaged profile used by the morphology disabled simulations.**

## d. Boundary Conditions

Boundary conditions for the storm events were provided from a range of sources, both observed and model based. The observed data was provided by an acoustic wave and current profiler (Nortek AWAC), deployed off Black Point between July and October 2018. The two periods with the largest "wind" (peak Hs) and largest "swell" (peak Tp) were used to define two of the five extreme events listed in table 1. The AWAC also uses an acoustic surface tracking (AST) system to track the surface water level as well as logging bottom pressure. These data records were scrutinised and the acoustic surface level water was used as extreme water level input. However, as these levels were relative to the AWAC and not Chart Datum (the beach profile datum) a tidal analysis was performed to allow a mean sea level (Z0) parameter to be calculated that could then be converted to Chart Datum providing a water level time series for the peak Hs and Tp events. The simulations were run for 50400 seconds for the peak Tp and peak Hs and 43200 seconds for the model-based boundary conditions with the hourly observed values before and after the assigned peak value used at the boundary. Figure 7 shows the time series for the three parameters across the Hs and Tp simulations.

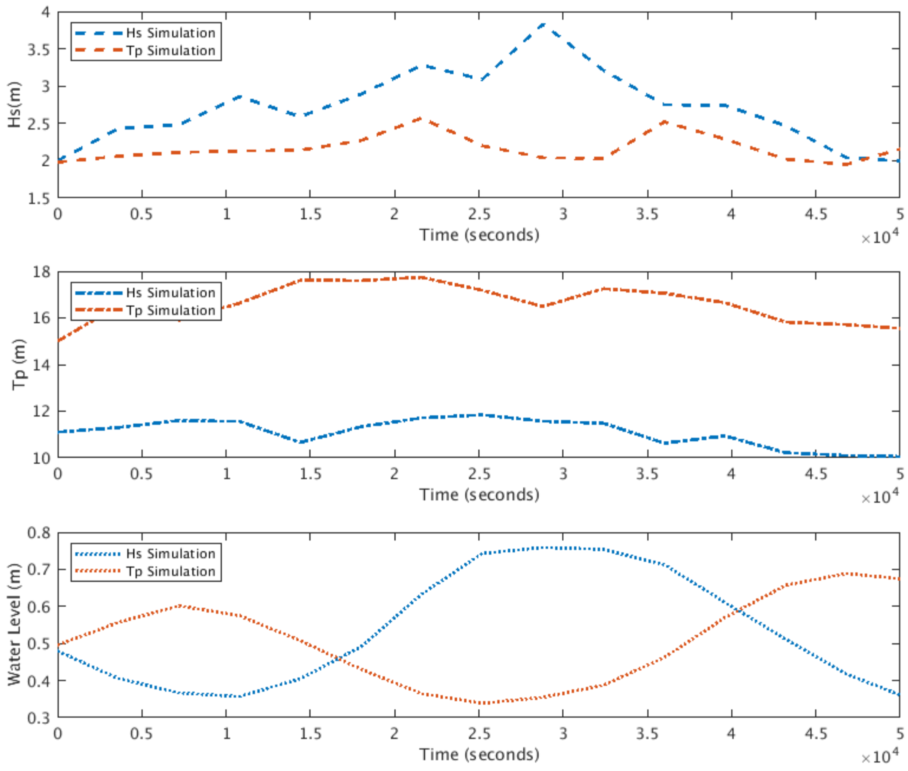


**Figure 7: Boundary Conditions for the Tp and Hs scenarios. Top plot shows Hs over the simulation, middle shows Tp and bottom shows changes in water level. The blue lines refer to the max Hs simulation whereas the orange denotes the max Tp event.**

**Table 1: Simulation Boundary conditions peak values**

| Simulation | Hs (s) | Tp (s) | EWL (m) |
|---|---|---|---|
| 1. Peak Hs | 3.83 | 11.57 | 0.76 |
| 2. Peak Tp | 2.57 | 17.74 | 0.36 |
| 3. ERA5 (Tomas) | 4.54 | 9.35 | 0.76 |
| 4. Holland Winds (Tomas) | 7.22 | 11.24 | 0.76 |
| 5. Enhanced winds, parametric wave model | 13.2 | 14.9 | 0.76 |

Water levels for these events were defined using the numerical model NEMO, set up as a regional 2D tide and surge model for the whole Caribbean Sea on a 12km grid (Jevrejeva et al., in prep.). It was set up for a tropical cyclone configuration which simulated a hypothetical tropical cyclone event, this model was forced using two different wind datasets: the ERA5 reanalysis winds on a ~30km grid (CSC, 2017) and the Holland parametric storm model (Holland, 1980; Holland et al., 2010) to reproduce the winds for a tropical cyclone, using the tropical cyclone parameters from archive data from the International Best Track Archive for Climate Stewardship database (IBTrACS, Knapp et al., 2010a). Waves for events 3-4 (Table 1) were generated from the WaveWatch III model on the same regional Caribbean Sea model extent and resolution as the NEMO surge model, applying boundary conditions from a global wave model. The final event had its boundary waves derived using a parametric wave model, based on Hurdle and Stive (1989) to produce waves for a more severe storm condition, than ever recorded in this location. The observed events had varied wave input conditions, at the offshore boundary, that comprised an hourly JONSWAP wave spectrum based on the AWAC observations. The non-observed events also used a JONSWAP wave spectrum offshore, but the underlying wave parameters used to generate were constant for the whole model run.

## e. Beach Morphology

To assess the impact of beach morphology the storm impact model was run with morphology enabled and disabled for both the Peak Hs and Peak Tp sets of boundary conditions, resulting in four different model runs. In addition, 3 additional sets of boundary conditions were created based on tropical cyclone model forcing, as described above. These model output forcing simulations were run with morphology enabled in order to see the impact of the storm on the beach. By comparing the profile at the start and end of the model run, changes to the profile, and erosion and deposition along the profile can be calculated. The total change of the profile also gives an indication of the total gain or loss of sediment during the storm event, this has also been calculated from the differences between the start and end profiles.

## 4. Results

The outputs of the model simulations as detailed in the methodology section were processed and the relevant parameters were extracted, e.g. water level at 0.5 second intervals at the shoreline, bed levels at the start and end. The results of the processing and analysis are shown below.

### a. Wave Run up

Wave run up is output from the model at a defined interval (0.5 seconds). This parameter corresponds to whatever elevation of the beach profile the water is currently interacting with. To compare the impact of extreme events, the R2% parameter is used, which is the 98$^{th}$ percentile of wave run up i.e. this elevation is only exceeded by 2% of waves during the simulation of the storm event. The R2% parameter for each simulation is highlighted in red for each simulation in Table 2. Other percentile values are shown to illustrate the distribution of wave run up during the simulation. The wave run up at 0.5 second intervals has been also plotted as a time series and histogram for each of the events, (figures 8 through 12)

**Table 2: Percentile results of water level at beach during the six simulated events.**

| Percentile | Max Hs Morph on (m) | Max Hs Morph Off (m) | Max Tp Morph on (m) | Max Tp Morph off (m) | ERA5 winds (m) | Holland winds (m) | Parametric winds (m) |
|---|---|---|---|---|---|---|---|
| 5$^{th}$ | 0.48 | 0.59 | 0.42 | 0.60 | 0.71 | 0.61 | 0.16 |
| 10$^{th}$ | 0.56 | 0.63 | 0.53 | 0.64 | 0.78 | 0.77 | 0.36 |
| 25$^{th}$ | 0.73 | 0.77 | 0.70 | 0.76 | 0.93 | 1.11 | 0.7 |
| 50$^{th}$ | 0.97 | 1.06 | 0.98 | 1.12 | 1.15 | 1.58 | 1.19 |
| 75$^{th}$ | 1.29 | 1.39 | 1.39 | 1.48 | 1.42 | 2.26 | 1.93 |
| 90$^{th}$ | 1.69 | 1.68 | 1.86 | 1.84 | 1.74 | 2.88 | 2.68 |
| 95$^{th}$ | 2.02 | 2.06 | 2.20 | 2.31 | 1.96 | 3.19 | 3.15 |
| **98$^{th}$ (R2%)** | **2.38** | **2.40** | **2.48** | **2.42** | **2.19** | **3.46** | **3.80** |
| 100$^{th}$ | 2.84 | 2.87 | 3.24 | 2.96 | 2.45 | 4.59 | 8.13 |

Table 2 shows that the first four events (Tp and Hs, morphology on and off) have largely the same run up (within 0. 1 m) despite having fairly different boundary conditions. The end result, or impact on the coastline, is largely the same in terms of R2%. For the tropical cyclone boundary conditions there is variety of impacts, ERA5 winds give a lower impact than either observed event with a R2% 0.2 m lower. However, the Holland winds and enhanced winds have much greater impacts, with R2% over a metre higher than the observed events. There is also significant variation in the max or 100$^{th}$ percentile values with the parametric wave simulation (Cat 4 hurricane) seeing wave run ups of over 8 m, albeit rarely. The Holland winds produce a runup of over 4.5 m, almost double the other simulations. It should be noted that the parametric waves simulation should be considered with caution, as it simulates conditions outside those for which XBeach has been validated. For the observed events the maximum runup is greater for the Tp simulation due to the longer wave period throughout the simulation, although as shown this does not have much impact on the R2% impact parameter.

## b. Time series of wave run up and histogram

For each simulation the time series of wave run up has been plotted along with a 100-bin histogram of the same data. All the morphology enabled events show a log-normal distribution with a tail capturing the low probability/high impact waves. Non-morphology enabled events show a "noisier" distribution where peaks in the distribution curve can be seen. This is due to the variability in the LIDAR profile that, even when it has been smoothed, still has small irregularities that result in higher than expected water levels, due to water not receding and being trapped behind the peaks. Given the increased "noise" in the distribution non-morphology events were not run for the tropical cyclone events as it was found that the model runs were unstable with this fixed profile when driven by the larger waves resulting from the tropical cyclone winds. Figures 8 to 12 show the different simulations based on their boundary conditions. For the peak Hs and Tp simulations both sets of results are shown for morphology enabled and disabled in the same figure.

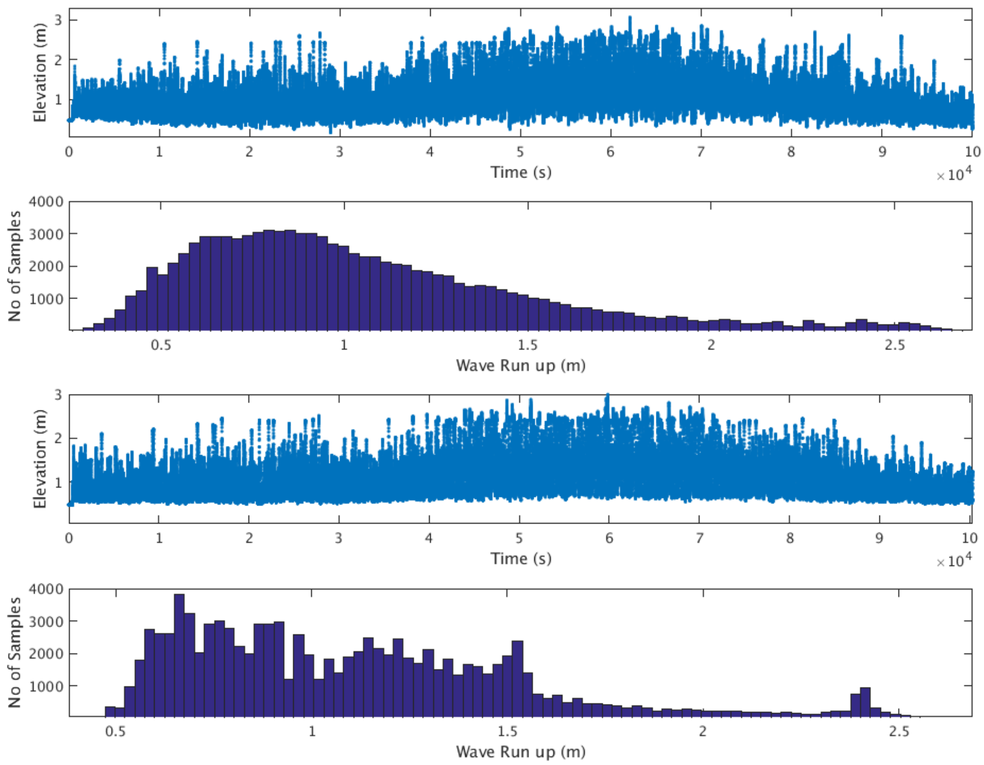


**Figure 8: Hs simulations time series and histogram, morphology enabled (top two panels) and disabled (bottom two panels).**

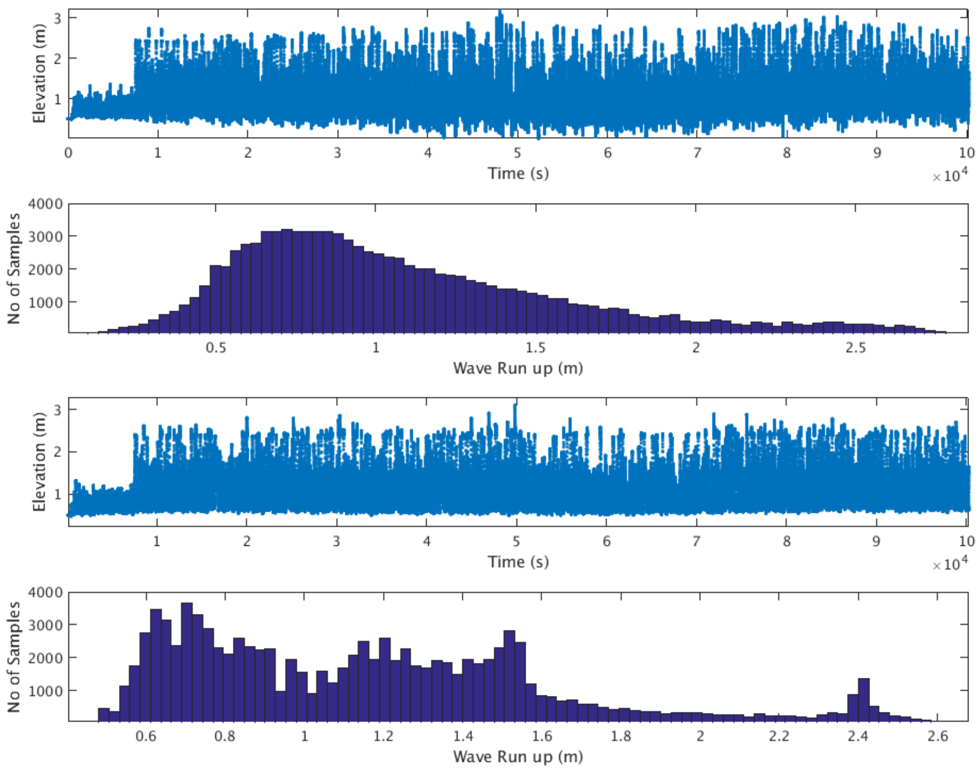


**Figure 9: TP simulations time series and histogram, morphology enabled (top two panels) and disabled (bottom two panels).**

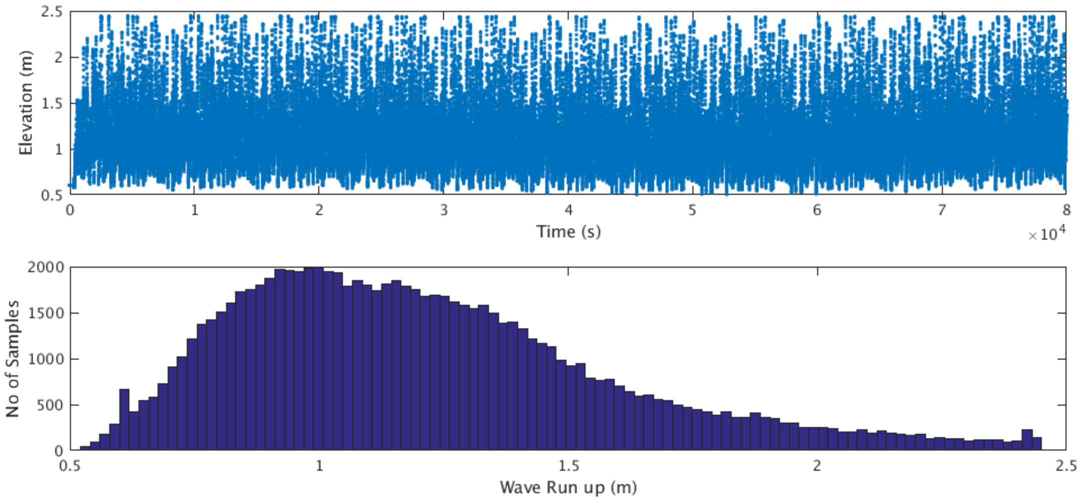


**Figure 10: ERA5 boundary condition simulation wave run up time series and histogram**

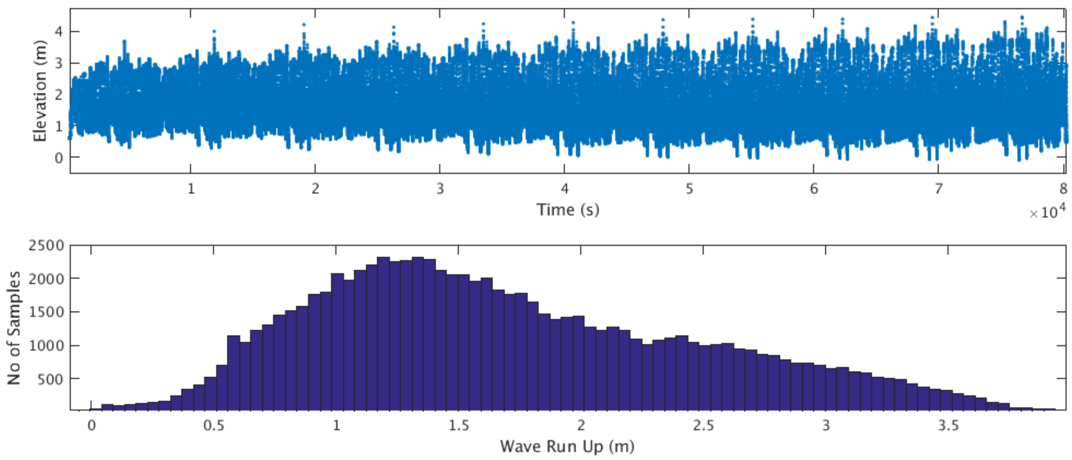


**Figure 11: Holland winds boundary condition simulation wave run up time series and histogram**

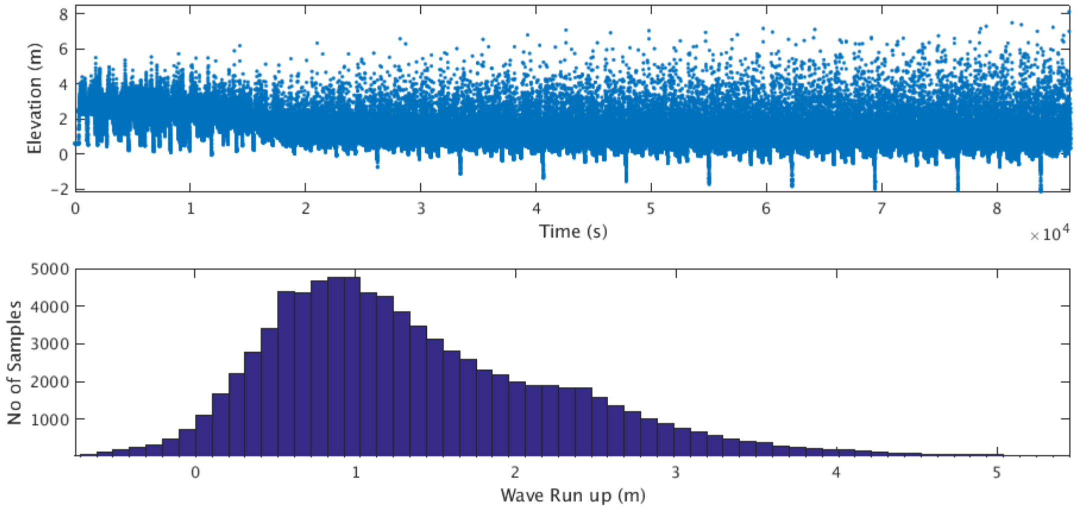


**Figure 12: Parametric waves with enhanced wind boundary condition simulation wave run up time series and histogram**

## c. Changes in Beach Levels

Across all morphology-enabled simulations, changes to the upper 250 metres of the beach profile were observed. During extreme events, significant changes can occur that would have a large impact on the beach, causing different degrees of erosion. Figure 13 shows the start profile and the end profile for each of the 5 sets of boundary conditions, for all events.

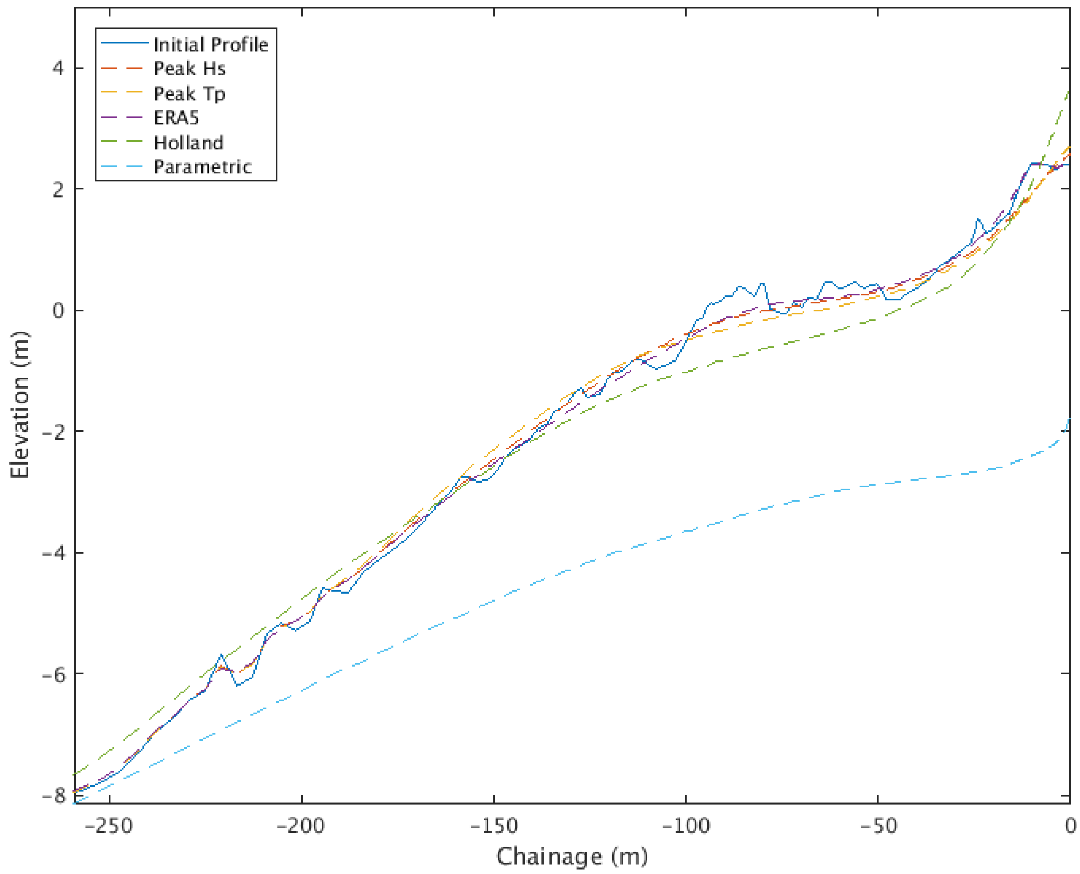


**Figure 13: Start and End profile for all 5 sets of boundary conditions. Start profile is the same for all simulations.**

All events result in smoothing out the starting profile, where berms and raised points in the profile are flattened out. The peak Tp and Hs simulations result in a similar profile, where they remove a small berm at the top of the beach and slightly increase the height of the beach profile. The ERA5 wind simulation shows a similar behavior but does not erode the berm at the top of the profile, during the simulation.

There are large changes in the beach for the Holland winds and parametric waves simulations: the waves generated by the Holland wind model erode the beach profile from -150 metres onwards resulting in lower beach elevations and a steeper upper beach. It does result in a much higher beach crest being created, which would help reduce the impact of the extreme event. The parametric waves simulation has resulted in a large amount of erosion from -250 metres onwards. The beach crest is totally lost and the beach is around 4 metres lower, this results in waves over-washing the beach completely. However, it should be pointed out the wave parameters used for this simulation are much larger than XBeach has been validated with and the results of this particular simulation should be treated with caution. It does indicate the potential severity of impact of a Category 4 Hurricane.

## d. Accretion and erosion of upper beach profile

Overall morphological change in the profile has been calculated using the difference between the start and end of the simulation. The following plots show this change. If a profile point has no change then it stays on the zero line. If it accretes then it will have a positive elevation change value, if it erodes it will have a negative elevation change value. Figures 14 to 18 show each of the 5 different boundary condition simulations.

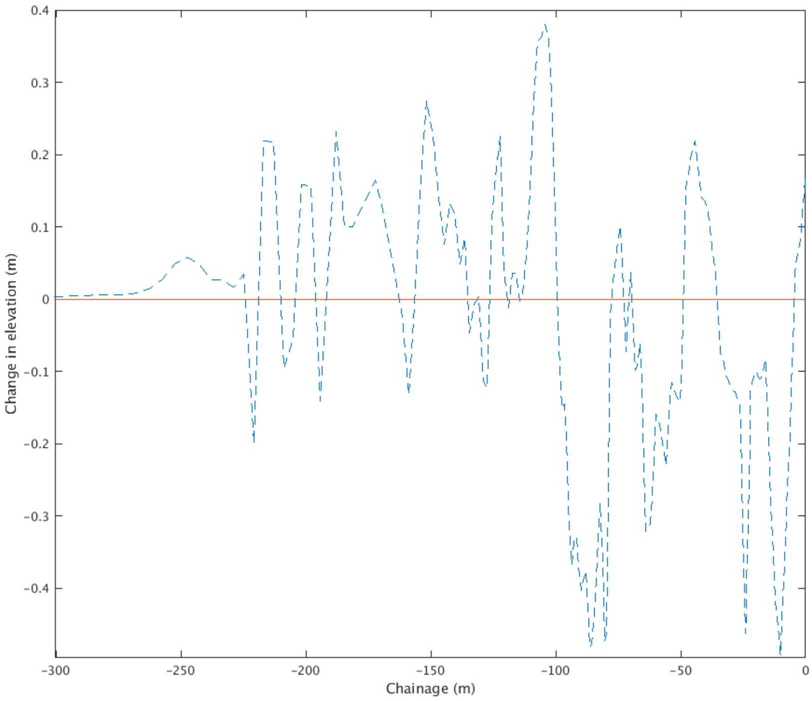


**Figure 14: Accretion and erosion of upper beach profile for maximum observed Hs morphology simulation**

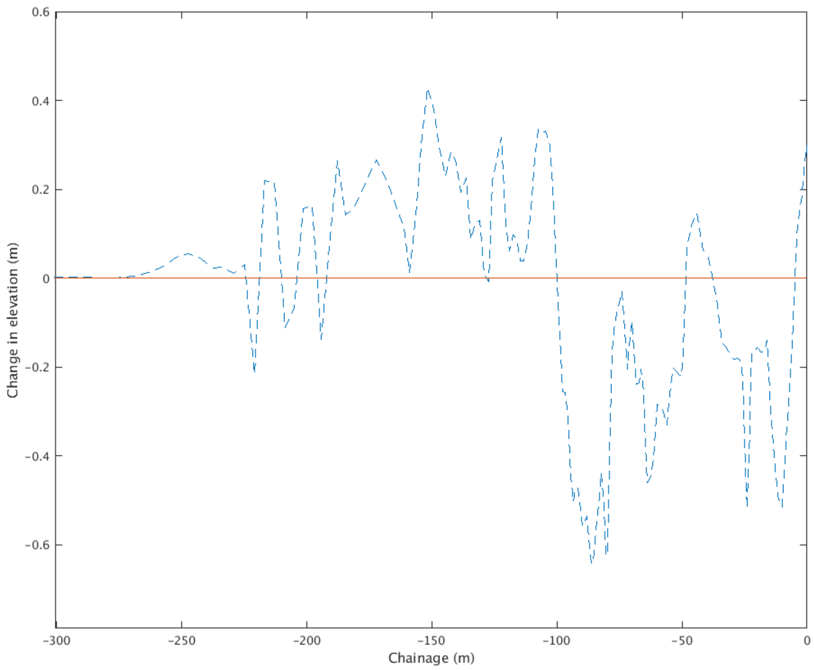


**Figure 15: Accretion and erosion of upper beach profile for maximum observed Tp morphology simulation**

Both the peak Hs and Tp events have a similar morphological response: in the upper 300 m between 250 m and 100 m offshore (-250 m to -100 m chainage) there is accretion of beach material of up to 0.4 m. Between 100 m offshore and the beach crest there is largely erosion of up to 0.6 m with some small deposition at around 50 m offshore. In both simulations the beach crest is increased due to the berm at the top of beach eroding and raising the height of the beach crest by 0.3 m.

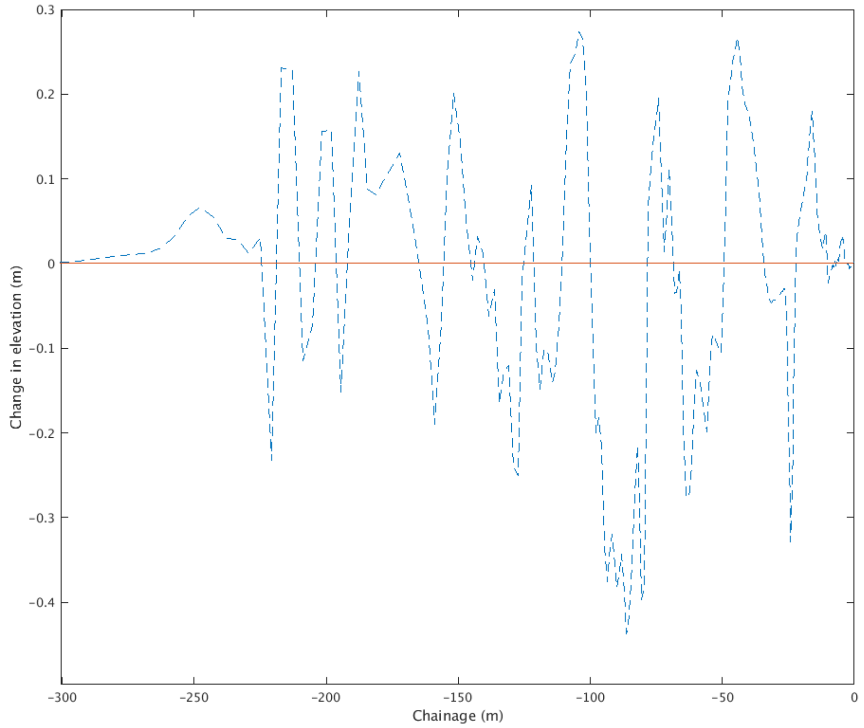


**Figure 16: Accretion and erosion of upper beach profile for ERA5 winds boundary condition simulation**

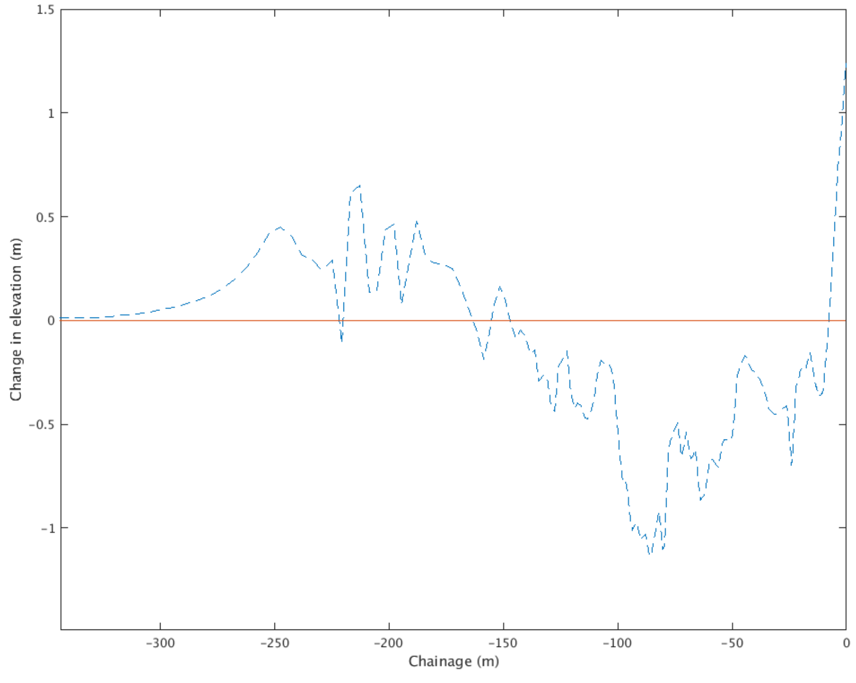


**Figure 17: Accretion and erosion of upper beach profile for Holland winds boundary condition simulation**

The ERA5 wind forcing produces no clear pattern of erosion and accretion, with the beach crest largely staying at the same elevation. These winds underestimate the observed winds, because of the limited resolution of the wind model, smoothing the wind field. Holland wind forcing produces larger boundary conditions resulting in around 0.5 m of deposition between 250 m and 175 m offshore, with up to 1 m of the beach eroded at 100 m, reducing to 0.5 m at 25 m offshore. However, the event does steepen the beach profile and build up the beach crest up 1.5 m over the starting profile. Parametric wave boundary conditions from an enhanced wind intensity result in a significant amount or erosion, from 250 metres offshore up to 5 metres of the beach is lost. However, the results of this simulation should be viewed with caution as the parametric wave parameters exceed the size of waves that XBeach has been validated for.

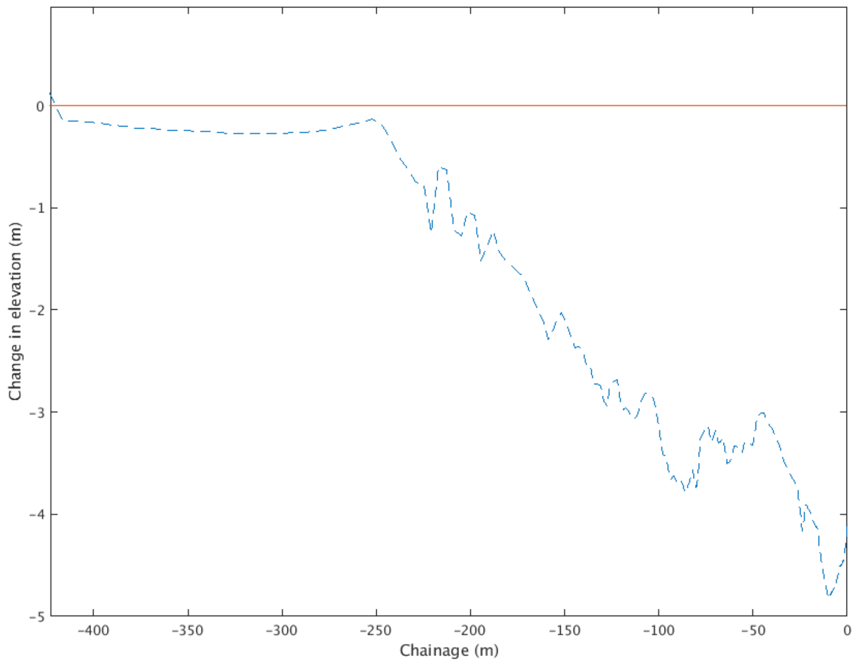


**Figure 18: Accretion and erosion of upper beach profile for Parametric wave boundary condition simulation, Category 4 hurricane winds**

# 5. Operational Storm Modelling system

The storm impact model could be operationalised, where it will run every time the latest output of a regional or global wave forecast model is available. To do this, a system framework is required that comprises of a computing system that is able to run the storm impact model in a forecast mode. This system would require near real time observations and forecast model products providing the wave and water level boundary conditions. Example operational modelling products that could be used are the 1/12 degree global ocean physical and wave analysis modelling products from CMEMS (Copernicus Marine Service Information, 2019a, 2019b).

This framework would need to automate the following steps or processes:

1. Obtain boundary information from relevant web services, e.g. forecast wave and surge models
2. Process the data into a boundary format that the storm impact model can understand
3. Execute the model run
4. Check model runs properly e.g. no error messages
5. QA the results
6. Process results and produce visualisation (e.g. plots, threshold exceedance warnings via email)
7. Publish results e.g. to web site

One way to design this framework can be in the form of “workers” and “manager” processes. Figure 19 shows a flowchart of this system where workers are short lived processes designed to undertake the specified step in the framework. The worker processes communicate to a long running “manager” process. When a worker finishes, it communicates with the manager the success or failure of the job. If it is successful the manager will start the next worker and if it is unsuccessful, the manager process is then able to try and resolve issues or communicate where the issue occurred to the administrator of the framework. This framework would be robust and able to handle errors or exceptions intelligently so that issues are resolved or highlighted quickly.

Figure 19 also shows another component of the framework where a scheduler process is able to start the system by launching the first worker e.g. download latest model products. By using a worker/manager system where direct connections are not required, this improves the robustness of the system with respect to:

- Fatal errors or bugs in code
- Latency or reliability of the system (different workers could potentially run on different computing systems)
- Ability to restart and stop management process independently of workers

The framework would be built using well established python modules (e.g. numpy) to ensure support into the future. Single developer or unsupported python modules should be avoided (e.g. base-map) to minimise compatibility and security problems e.g. python module being unable to support a new enough version of python and therefore being a security risk.

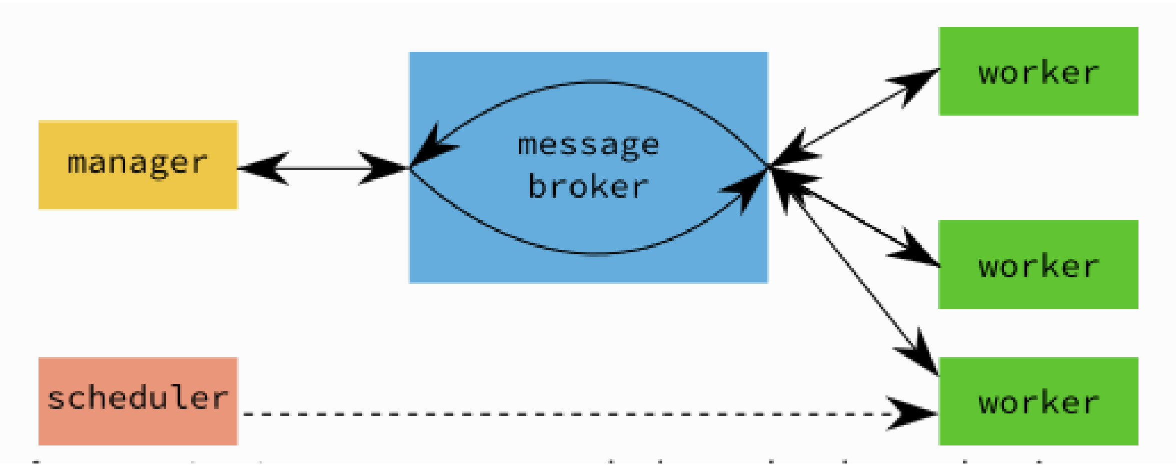


**Figure 19: Example of worker/manager framework.**

A proposed form for the system would be in form of a manager Python script that reads a user defined config file for platform and computer specific parameters (directory paths etc.) and then loads a framework library that is able to run each of the worker processes and listen for the response from the worker. If successful the manager will then run the next worker, if not then the manager will undertake a prescribed action (e.g. inform admin, try the worker again after a delay etc.). In this example the first worker process will be started using a cronjob scheduler, this has many benefits such as providing an email diagnostic of the system run, particularly if an error message is passed.

# 6. Conclusions

Each of the 5 wave boundary conditions that represent a range of storm events have been simulated onto a cross shore beach profile of the coastline at Black Point on the east (windward) coast of the island of St Vincent (the main island of St Vincent and the Grenadines), using the XBeach storm impact model. The simulations have shown that these events could potentially have large impacts on the coastline of St Vincent. It was found that the relatively low observed events have minimal impact on the beach profile beyond smoothing raised berms and mounds. The events slightly increase the height of the beach over the initial profile showing that the beach is able to withstand the observed extreme events and maintain its resilience. The observed data record is only a few months long so cannot be taken as a full representation of the ocean climate of St Vincent and the Grenadines.

The simulated storms, aimed to show the impacts of possible more extreme events, show a different result with increases of 1 and 1.4 m in runup (R2%) over the peak observed events for the two biggest impacting events. Also the beach profile is subject to significant change, with large amounts of material removed from the upper beach with up to a metre of beach level removed. The XBeach model for the extreme events shows that this material is deposited at the top of the beach, building it up by around 1.5 m. This would ameliorate the impact of the event, but the steepening of the beach profile as a result of this could also cause problems and result in greater erosion of the beach by future storm events after the extreme event modelled. The parametric wave boundary conditions for a Cat 4 storm should be interpreted with care but the result of this event is, in contrast to other simulations, a huge amount or erosion of the beach profile, up to 4 metres is removed, which would result in a large amount of overtopping and discharge during the extreme event. If this event was well represented it would have a huge impact on the coast of St Vincent, with largescale damage to the island.

The modelling system setup to simulate these events can be adapted into an operational system, this would lend itself well to provide early warning of potential extreme events. Having an operational system would also enable the model to be validated as the forecast can be compared to reality, with the model being tuned over time to provide a more accurate and useful warning system. The system described could be run on a low-cost computer system or web server allowing the results to be disseminated to stakeholders. With the warning provided, and the possible outcome assessed an effective strategy tailored to predicted events that aims to maximize the resilience of the coastline can be developed.

# References


Cambers, G. and Diamond, P. (2010) Adapting to climate change and educating for sustainable development Revised and expanded edition sandwatch. Available at: www.unesco.org/new/en/unesco/about-us (Accessed: 19 August 2019).

Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home

E.U. Copernicus Marine Service Information (2019a) GLOBAL OCEAN 1/12° PHYSICS ANALYSIS AND FORECAST UPDATED DAILY. Available at: http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_ANALYSIS_FORECAST_PHY_001_024 (Accessed: 19 August 2019).

E.U. Copernicus Marine Service Information (2019b) GLOBAL OCEAN WAVES ANALYSIS AND FORECAST UPDATED DAILY. Available at: http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_ANALYSIS_FORECAST_WAV_001_027 (Accessed: 19 August 2019).

Fugro (2017) St Vincent LIDAR survey.

Holland, G. J. (1980). An analytical model of the wind and pressure profiles in hurricanes. Monthly Weather Review, 108, 1212-1218.

Holland, G. J., Belanger, J.I. and Fritz, A. (2010).A Revised Model for Radial Profiles of Hurricane Winds. Monthly Weather Review, 138, 4393-4401.

Hurdle,D.P. and STive,R.J.H. (1989) Revision of SPM 1984 Wave Hindcast Model to avoid inconsistencies in engineering applications. Coastal Engineering, 12,339-351.

Knapp, K. R., Kruk, M., Levinson, D., Diamond, H., and Neumann, C. (2010). The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. Bull. Amer. Meteor. Soc., pages 363-376.

Roelvink, D. *et al.* (2010) 'XBeach model description and manual', *Unesco-IHE Institute for Water Education, Deltares and Delft University of Tecnhology. Report June*, 21, p. 2010.

Stockdon, H. F. *et al.* (2006) 'Empirical parameterization of setup, swash, and runup', *Coastal Engineering*, 53(7), pp. 573–588. doi: 10.1016/j.coastaleng.2005.12.005.