Coastal Dynamics 2017
Paper No. 021

WAVE DYNAMICS AND FLOODING ON LOW-LYING TROPICAL REEF-LINED COASTS

Ap van Dongeren[1], Curt Storlazzi[2], Ellen Quataert[1], and Stuart Pearson[1,3]

Abstract

Many tropical islands and coasts are lined with coral reefs. These reefs are host to valuable ecosystems that support abundant marine species and provide resources for fisheries and recreation. As a flood defense, reefs protect coastlines from coastal storm damage and flooding by reducing the majority of incident wave energy. However, during storm and large swell conditions, coastal wave-driven flooding and overwash still occur due to high water levels, (infra) gravity waves, and/or low-frequency wave resonance. The wave and flooding effects cause erosion, damage to infrastructure, agricultural crops, and salinization of precious drinking water supplies. These impacts, which are likely to increase due to climate change and ongoing development on the islands, may cause many low-lying tropical islands and coastal areas to become uninhabitable before the end of the century. This paper investigates aspects of wave dynamics for the case of a small island in the tropical Pacific Ocean, shows projections of flooding under climate change scenarios, and outlines approaches to generalize the results to other islands, including mitigation options.

Key words: hydrodynamics, flooding, coral reefs, tropical islands, numerical modeling, coasts and climate

1. Introduction

Many tropical islands and coasts are lined with coral reefs. These reefs are host to valuable ecosystems that support abundant marine species and provide resources for fisheries and recreation. As a flood defense, reefs protect coastlines from coastal storm damage and flooding by reducing as much as 98% of incident wave energy (Ferrario et al., 2014). However, during storm and large swell conditions, coastal wave-driven flooding and overwash still occur due to high water levels, (infra) gravity waves, and/or low-frequency wave resonance. The wave and flooding effects cause erosion, damage to infrastructure and agricultural crops, and salinization of precious drinking water supplies. These impacts, which are likely to increase due to climate change and ongoing development on the islands, may cause many low-lying tropical islands and coastal areas to become uninhabitable before the end of the century. This paper investigates wave dynamics at a small island in the tropical Pacific Ocean, shows projections of flooding under climate change scenarios, and outlines approaches to generalize the results to other islands, including mitigation options.

2. Wave dynamics and flooding on coral reef-lined islands

In general, coastal flooding is caused by a combination of waves, tides, and wind-induced surges. In many cases, these events occur during storms, but along reef-lined coasts, coastal flooding can also occur during "blue sky conditions" (Hoeke et al., 2013) when remotely-generated swell waves impact the coast. These incident-band waves break in a narrow surf zone on the reef crest, dissipating most of the wave energy and resulting in little energy in this band being transmitted shoreward. However, the radiation stress associated with this breaking produces a set up that can be quite large, on the order of a meter (Quataert et al., 2015; Cheriton et al., 2016). In addition, the groupiness of the incoming waves causes the breakpoint to vary in time and space, which produces a time-variation in the surface elevation that drives breakpoint-generated

---

[1] Department of Applied Morphodynamics, Unit of Marine and Coastal Systems, Deltares, Delft, Netherlands. Ap.vanDongeren@deltares.nl

[2] Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, California, USA. cstorlazzi@usgs.gov

[3] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands

infragravity waves propagating to shore (Symonds et al., 1982; Pomeroy et al., 2013).

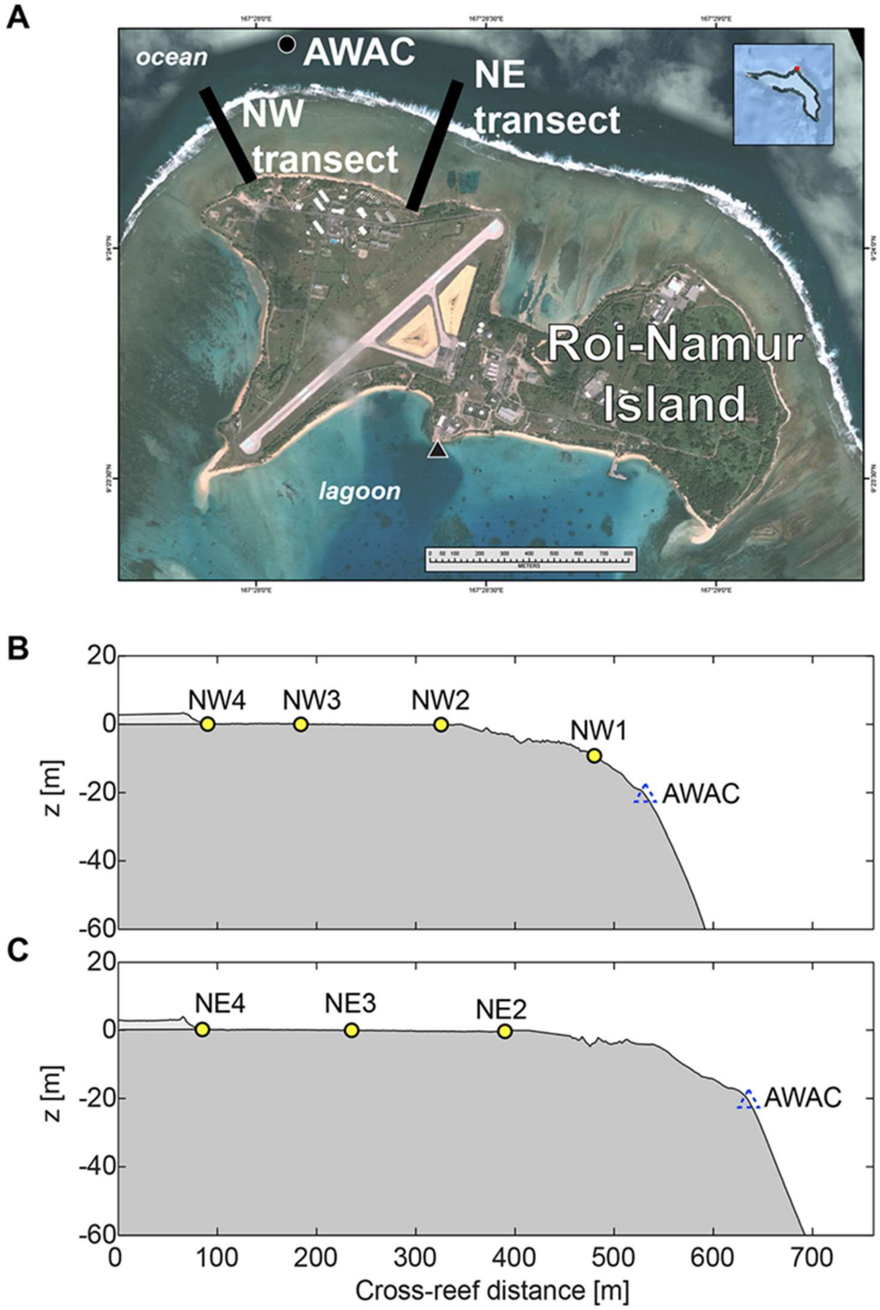

Figure 1 Aerial image of the study sites on Roi-Namur, showing locations of cross-reef transects (solid black lines), the offshore AWAC (black circle), and the lagoon sensors (black triangle). Bathymetric profiles of cross-reef transects are shown in (B)-(C), showing relative depths of pressure sensors (yellow circles) and the offshore AWAC (dashed triangles), as well as their cross-shore distances. Please note that the AWAC location shown in (B) and (C) is only meant to show relative depth to the other sensors; because the AWAC was not directly in-line with either transect, the cross-reef distances may not be not accurate.

Furthermore, for specific combinations of reef width, water depth, and incident wave period, resonance may occur on the reef and cause large sea surface amplitudes at the shoreline (Cheriton et al., 2016; Gawehn et al., 2016). All factors – set-up, resonance, infragravity waves, and incident-band waves – contribute to potential flooding of the coastline. The outstanding questions are: what are the dynamics of energy transfer and wave generation; can we predict these dynamics using numerical models; what is the outlook with respect to flooding under climate change scenarios; and what are possible mitigating measures? These questions can be answered by analyzing field data and applying numerical models. The present paper reviews how this was done for one particular island in the Kwajalein Atoll, Republic of the Marshall Islands, with an extension to generalize results.

3. Methods

3.1 *Field site and data*

The field site is located on the northern shore of Roi-Namur, Kwajalein Atoll, in the Republic of the Marshall Islands (Figure 1). The island is characterized by a relatively narrow intertidal reef flat, a steep fore reef, and a steep beach slope leading to an island with an elevation of mere meters above MSL. The island has been subject to extensive flooding, most notably in 2008 (Hoeke et al., 2013) and 2014 (Cheriton et al., 2016). An array of bottom-mounted pressure sensors collected data for several months in winter of 2014(?) along two arrays, on the North-West (NW) and North-East (NE) side of the islet.

3.2 *Numerical modeling*

When modeling such wave-driven flooding events, it is important to apply a model that incorporates all these physical processes to accurately predict the frequency and magnitude of flood events. In this study, we use a number of high-resolution implementations of the XBEACH model, a high-fidelity, physics-based two-dimensional area model for the nearshore and coast (Roelvink et al., 2009). Van Dongeren et al. (2013) and Quataert et al. (2015) have shown the applicability of this model to simulate waves and wave-driven water levels over coral reefs. Here we show XBEACH's application to not only accurate reproduce those processes, but also wave transformation and coastal flooding on Kwajalein Atoll.

The model can be run in two modes: surf-beat mode and non-hydrostatic mode. The surf-beat mode takes into account the temporal variation of wave height on the wave-group scale, which drives infragravity waves. For non-hydrostatic XBEACH calculations, depth-averaged flow due to waves and currents are computed using the non-linear shallow water equations, including a non-hydrostatic pressure. The main advantage of the non-hydrostatic mode is that the incident-band (short wave) motions, including runup and overwash, are resolved in the model. This is especially important on steep slopes where incident-band motions may be large, but has the disadvantage of being computationally more expensive than the surf-beat mode.

XBEACH in surf-beat mode has been applied in reef environments (Pomeroy et al., 2012; Van Dongeren et al., 2013) and proved to accurately predict the key reef hydrodynamics. In this paper, we will apply the model in non-hydrostatic mode in order to also capture incident band wave runup and associatedovertopping and flooding of the island.

Using a seamless bathymetric-topographic dataset generated by USGS (Figure 2), a 2D model of the Roi-Namur Island was set up as a rectilinear model with varying mesh grid sizes (Figure 2b and 2c). Grid sizes are smaller (2x5 m) on the reef at the northern side of the island because waves propagate in from the northern offshore boundary. In order to avoid adverse computational effects, the model boundaries were in deep water so that wave and water level boundaries could be specified all around the model area. Because waves are coming from the north, this did not affect the wave transformation around the area of interest. At the offshore (northern) boundary, a weakly reflective boundary condition was applied where outgoing waves and currents can pass through to deep sea with minimal reflection. A weakly reflective boundary

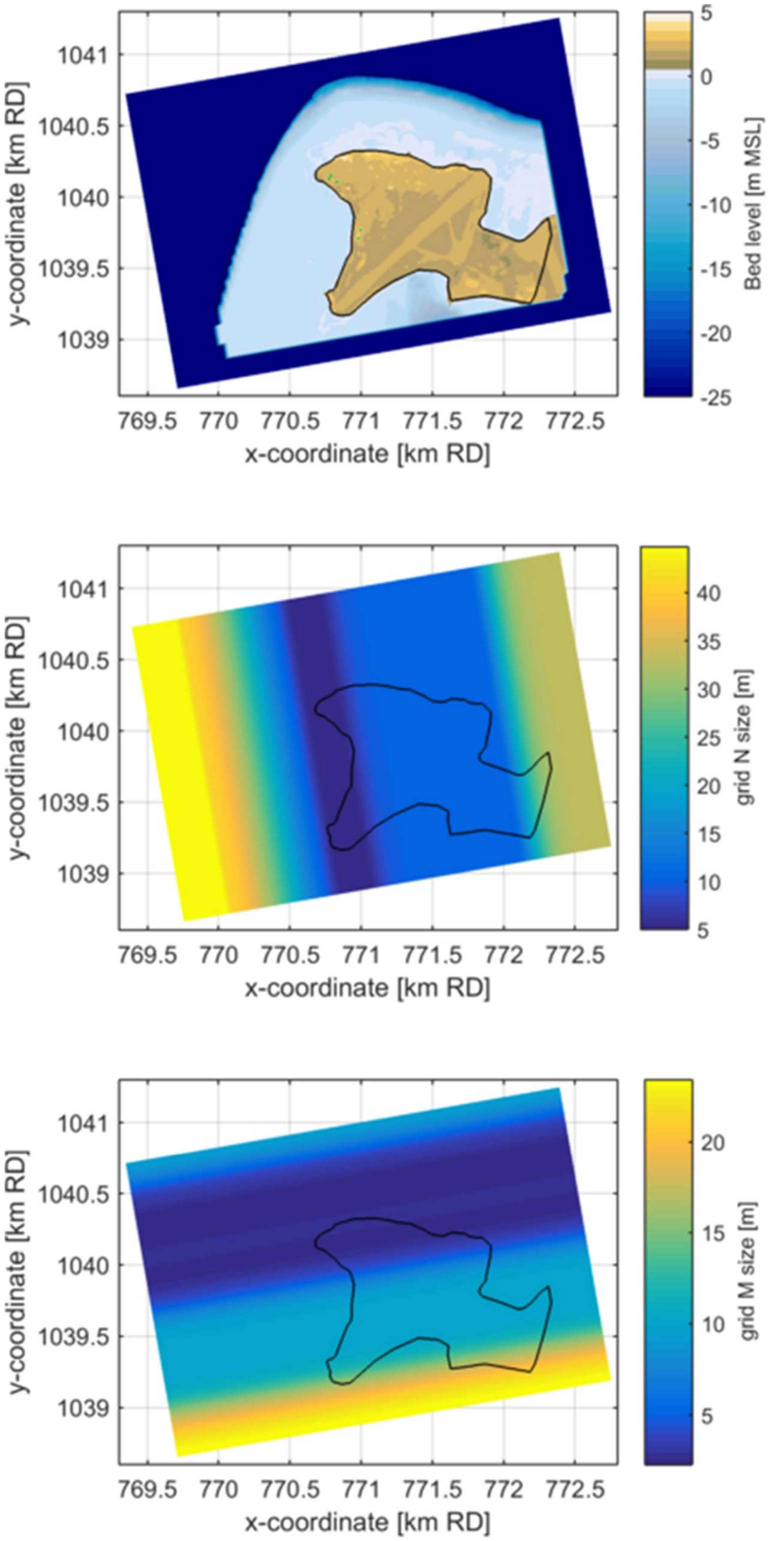

Figure 2 Two-dimensional non-hydrostatic model bathymetry (top panel) and grid sizes in east-west and north-south direction (bottom panels).

condition was applied at the lagoon (southern) model boundary so outgoing waves and currents can pass through to the lagoon with minimal reflection.

The 2D model was forced with observed data (Cheriton et al., 2016). From the measured wave conditions (wave height, wave period, mean direction, and directional spreading), a sequence of hourly-varying JONSWAP spectra was created. From these spectra, XBEACH generated time series for the short-period incident and bound long wave energy with an approach described by van Dongeren et al. (2003). The measured offshore water level was averaged per hourly burst of data and subsequently used as initial surface elevations at the offshore model boundary.

The 2D model was calibrated for the friction parameter c_f by comparing modeled and measured wave and water level data for both the NW and NE transects (Figure 1a). The calibrated 2D model was then used to validate the marginal flooding event of 2014, and further assess the impact of three future sea-level rise scenarios (MSL+0.5m, MSL+1.0m, MSL+1.5m and MSL+2.0m) on the flooding extents and depths on the island.

The XBEACH model produces overwash elevations and depth of water over topography; in conjunction with information on the duration of large wave events driving inundation from the historical data, we can estimate overtopping volumes that would fill topographic lows or infiltrate through permeable surfaces directly into the subsurface. Thus XBEACH provides water volumes and durations of inundation events, providing boundary information for hydrogeologic models to investigate freshwater sustainability.

Because the long-term (1950s-2000s) rates of sea-level rise at Kwajalein (+1.43 mm/yr; National Ocean Service, 2011) are approximately equal to the rates of global sea-level rise (e.g., Nicholls and Cazenave 2010), we can assume that there is no significant net vertical land motion (e.g., uplift or subsidence) of the atoll. The bathymetry and topography that exist today therefore should be accurate over the predicted timeframe (100+ yr) that the model results are valid.

4. Results

For the calibration of the only free parameter, c_f, a 24-h simulation period during the overwash event on March 2014 was used. Spatially-varying roughness was applied to include the high density live coral patches and relatively smooth sections of uncolonized reef pavement on the reef flat. The coral patches were given c_f of 0.04, based on the c_f value used in the 2D model in Van Dongeren et al. (2013). The model is calibrated by finding the optimum value for c_f in the areas with low bed roughness.

Modeling results are compared with the measured mean water levels, root-mean-squared (rms) incident (IC), infragravity (IG), and very-low frequency (VLF) wave heights at Roi-Namur, along both NW and NE transects (Figure 3 shows the NW transect; the other transect shows very similar results and re thus not presented here). The predictive skill of the model was determined by calculating the bias and scatter index (SCI) (van der Westhuysen, 2010). The best results both in terms of bias and scatter index were achieved for a c_f of 0.002 (Figure 3). However, the inner reef mean water levels are underestimated by the model for both transects, even though the water level is predicted correctly at the other reef flat wave gauges. This was caused by a systematic offset in the mean burst pressure measured by the inner reef wave gauges due to biofouling of the sensors.

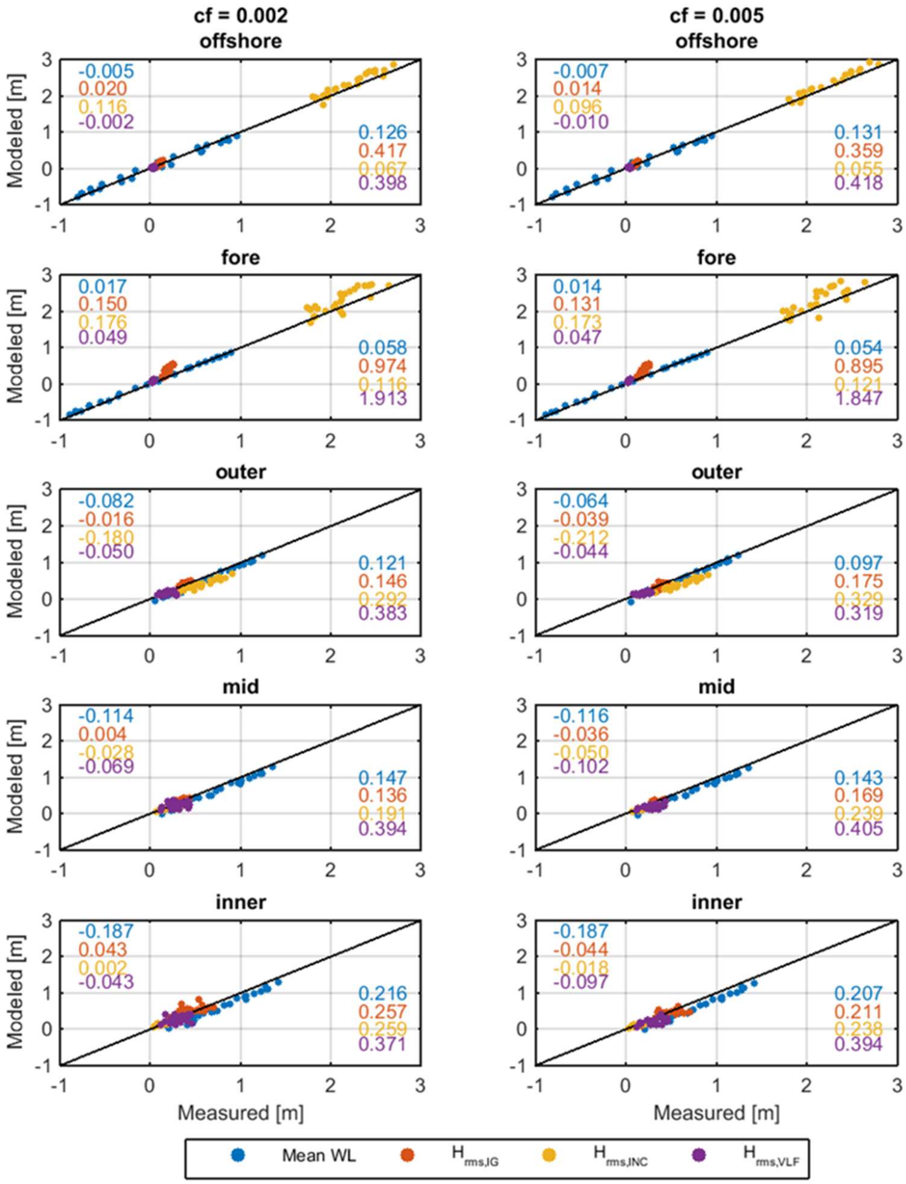

Figure 3 Scatter plots of measured vs. computed hydrodynamics for the NW transect: c_f = 0.002 (left panels) and c_f = 0.005 (right panels). Top to bottom: offshore (NW1) to the inner reef (NW4) location. For all key hydrodynamics; mean water levels (blue), IC wave height (yellow), IG wave height (red), and VLF wave height (purple). Top left corner indicates the BIAS and bottom right corner the SCI.

The modeled maximum inundation extents and depths on the island resulting from the overwash event in March 2014 (Figure 4) were compared qualitatively with the observations. The reported overwash on the north-east corner near the runway was not simulated by the model. However, small areas at the western side of the island are flooded in the model.

Figure 4 Modeled inundation depth for the calibrated 2D model during the March 2014 overwash event on Roi-Namur. The color bar denotes the maximum water depth on the island during the March 2014 overwash event.

The calibrated 2D model was then forced with a range of future sea level rise scenarios. These inputs were used to perform 24 simulations for a duration of 6 cosine-shaped tidal cycles of 12 hr each with an amplitude of 0.717 m with respect to MHHW (Figure 5). For each scenario simulation, the tidal signal uniformly increased with the sea-level rise value obtained from the scenarios. In the three-day events, the waves were increased from H_{mean} over 30 hr, to a 12 h storm maximum at $H_{s,storm}$, and then decreased to H_{mean} over 30 hr (Figure 5). A peak in the tidal cycle occurred in the middle of the 12-hr storm maximum, to include a worst case scenario.

Model results were post-processed into water depths over the island at the end of the simulation for each scenario; see Figure 6 for a number of representative scenarios. The resulting maps show that flood extents and depths during storm conditions increase with sea-level rise. For the most severe scenarios, the island is completely flooded.

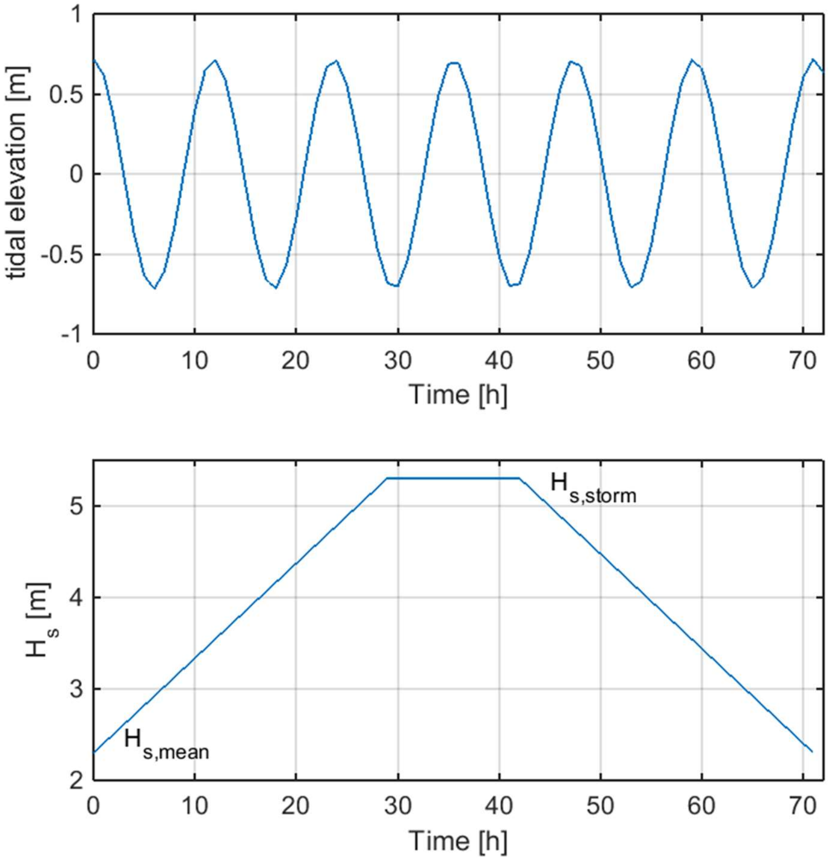

Figure 5 Tidal and wave forcing for the climate change scenario simulations with the 2D model. Tidal elevation (top panel) is with respect to MHHW and with no sea-level rise. Wave heights (bottom panel) increase from $H_{s,mean}$ to $H_{s,storm}$ and then decrease back down to $H_{s,mean}$.

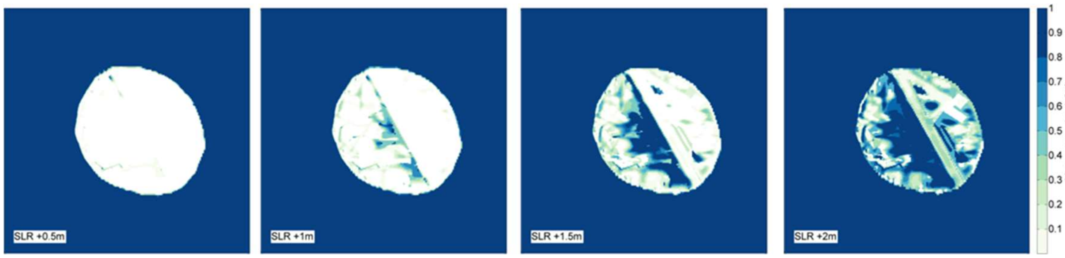

Figure 6 Modeled flooding of an atoll island as a result of four sea level rise scenarios (MSL+0.5m, MSL+1.0m, MSL+1.5m and MSL+2.0m).

5. Generalization of results

The effect of intrinsic reef geometry, hydrodynamic forcing, and climate-scenarios on wave impacts is generalized for other islands. This is done by running the XBEACH model in transect mode for 200,000 variations of reef width, reef roughness, beach slope, water depth, and offshore wave parameters (Figure 7).

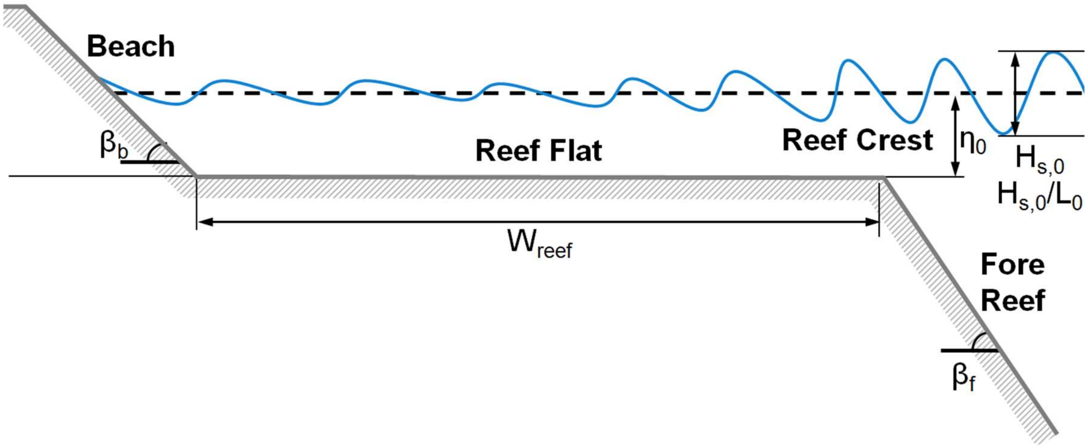

Figure 7 Schematic reef profile indicating the intrinsic geomorphic (beach slope, reef width, fore reef slope) and extrinsic hydrodynamic forcing (wave height, water level, wave steepness) parameters investigated in the Bayesian Network.

The result all of these simulations were compiled in a Bayesian Network (Guttierez et al., 2015; Poelhekke et al. 2016), which for this case is called BEWARE (Bayesian Estimator of Wave Attack on Reef Environments) (Pearson et al., 2017 submitted). The network relates various combinations of geomorphic and forcing parameters to the associated responses in terms of on reef wave heights and run-up (Figure 8). This dataset can be easily manipulated, with minimaleffort, to constrain the parameter range for specific reef geometries and/or forcing conditions that then yield the distributions - including uncertainties - of reef hydrodynamics and the resulting wave-driven water levels and flooding on the coast.

Coastal managers can use this data set to assess their coast's safety under different climatic scenarios, but it can also be incorporated in early warning systems where this Bayesian Network can be driven by input obtained from *a priori* known reef parameters and wave- and water-level forecasts from large-scale numerical prediction models.

6. Conclusions

Coral reef-lined islands are susceptible to wave-induced flooding, even in "blue sky" conditions. In this paper, we have shown that it is possible to accurately model reef hydrodynamics, including, wave runup and flooding, on a small atoll island. This model is then used to assess flooding under future climate-change induced scenarios. Lastly, the model is used to investigate the effects of reef geomorphology and offshore hydrodynamic forcing on reef hydrodynamics and the resulting wave–driven flooding of small, low-elevation islands.

Acknowledgements

This work was funded by the U.S. Department of Defense's Strategic Environmental Research and Development Program (RC-2334), the U.S.G.S. Coastal and Marine Geology Program, and Deltares Strategic Research in the "Hydro- and morphodynamics during extreme events" program (1230002).

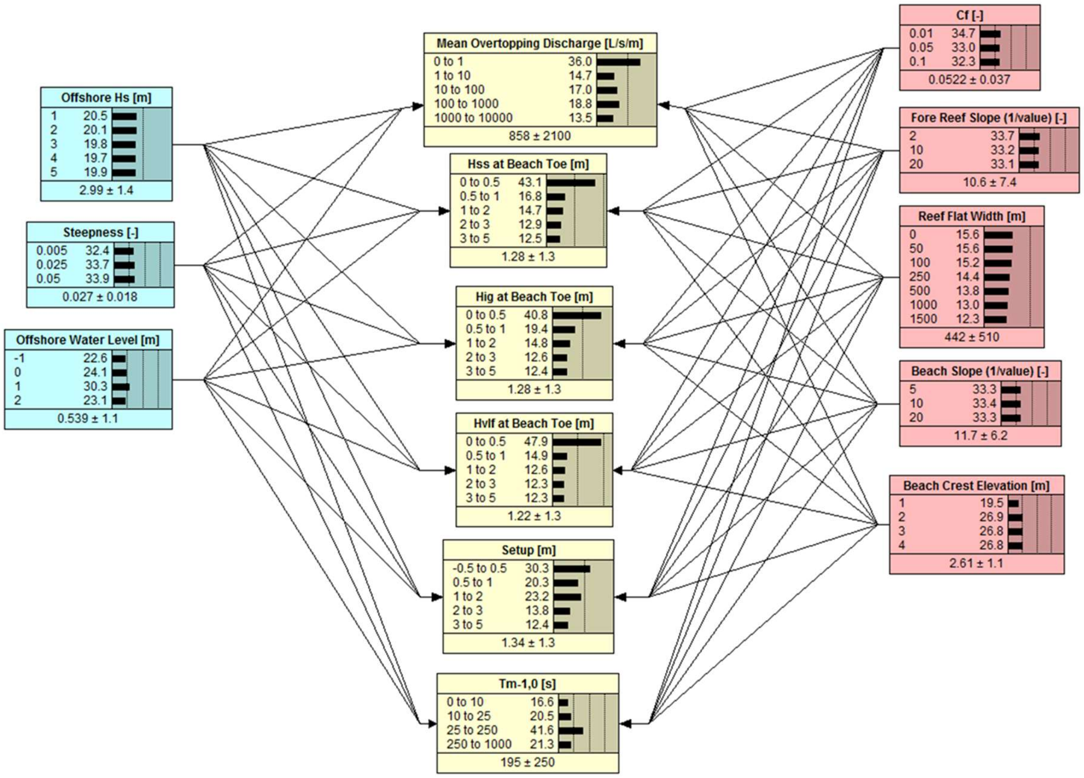

Figure 8 Bayesian Network showing distributions of hydrodynamic forcing parameters (left), intrinsic geomorphic parameters (right) and the hydrodynamic response on the reef (middle).

References Cited

Cheriton, O.M., Storlazzi, C.D. & Rosenberger, K.J., 2016. Observations of wave transformation over a fringing coral reef and the importance of low-frequency waves and offshore water levels to runup, overwash, and coastal flooding. Journal of Geophysical Research: Oceans, 121, pp.1–20.

Ferrario, F., M. W. Beck, C. D. Storlazzi, F. Micheli, C. C. Shepard, and L. Airoldi (2014), The effectiveness of coral reefs for coastal hazard risk reduction and adaptation, Nat. Commun., 5, 1–9, doi:10.1038/ncomms4794.

Gawehn, M., A. van Dongeren, A. van Rooijen, C. D. Storlazzi, O. M. Cheriton, and A. Reniers (2016), Identification and classification of very low frequency waves on a coral reef flat, J. Geophys. Res. Oceans, 121, doi:10.1002/2016JC011834.

Gutierrez, B.T. et al., 2015. Using a Bayesian network to predict barrier island geomorphologic characteristics. Journal of Geophysical Research: Earth Surface, 120, pp.2452–2475

Hoeke, R.K. et al., 2013. Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, 108, pp.128–138. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0921818113001483.

Nicholls RJ, and Cazenave A. (2010) Sea-level rise and its impact on coastal zones. Science, v. 328, p. 1517-1520.

Pearson, S.G., C.Storlazzi, A.van Dongeren, M. Tissier, A. Reniers (2017). Bayesian-based system to assesst wave-driven flooding hazards on coral reef-lined coasts. Submitted to J. Geophys. Res.

Poelhekke, L., W.S. Jäger, T.A. Plomaritis, A.R. Van Dongeren, R.T. McCall, O. Ferreira (2016). Predicting coastal hazards for sandy coasts with a Bayesian Network, Coastal Engineering, Volume 118, December 2016, Pages 21-34, ISSN 0378-3839, http://dx.doi.org/10.1016/j.coastaleng.2016.08.011.

Pomeroy A, Lowe RJ, Symonds G, Van Dongeren AR, Moore C (2012) The dynamics of infragravity wave transformation over a fringing reef. Journal of Geophysical Research, v. 117(C11022), doi:10.1029/2012JC008310.

Quataert, E, Storlazzi C, van Rooijen A, Cheriton O, van Dongeren A (2015) The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. Geophysical Research Letters, 42, 6407–6415, doi:10.1002/2015GL064861

Roelvink D, Reniers A, van Dongeren A, de Vries JV, McCall R, Lescinski J (2009) Modelling storm impacts on beaches, dunes and barrier islands, Coastal Engineering, v. 56(11-12), p. 1133–1152.

Symonds G, Huntley DA, Bowen AJ (1982) Long wave generation by a time-varying Breakpoint. Journal of Geophysical Research, v. 87(C1), p. 492–498.

Van der Westhuysen A J (2010), Modeling of depth-induced wave breaking under finite depth wave growth conditions. Journal of Geophysical Research, v. 115(C1), C01008, doi:10.1029/2009JC005433

Van Dongeren AR, Lowe RJ, Pomeroy A, Trang DM, Roelvink JA, Symonds G, Ranasinghe R (2013) Numerical modeling of low-frequency wave dynamics over a fringing coral reef. Coastal Engineering, v. 73, p. 178–190 , doi:10.1016/j.coastaleng.2012.11.004

Van Dongeren AR, Reniers AJHM, Battjes JA (2003) Numerical modeling of infragravity wave response during DELILAH. Journal of Geophysical Research, v. 108(C9), 3288, doi:10.1029/2002JC001332