Response to Referee #1 (Ron Hoeke) comments on

Rapid simulation of wave runup on morphologically diverse, reef-lined coasts with the BEWARE-2 meta-process model

Robert McCall, Curt Storlazzi, Floortje Roelvink, Stuart Pearson, Roel de Goede, and José Antolínez

We would like to thank Dr Hoeke for his suggestions and constructive comments on this manuscript. We have attempted to address the points made by the referee in the updated manuscript and/or have provided our rebuttal below. In the following, the referee's comments are given in **black** font and our response in **blue** font.

We have been advised that we are not able to upload the updated manuscript to the discussion portal at this time. In lieu of providing the referee with an updated copy of the manuscript, we have therefore included screenshots of changes to the manuscript, where appropriate, at the end of this document.

1. Overall: In my view, this paper is what it says it is, i.e.: "a useful tool for early warning systems and current and future coastal flood risk analysis" for a broad range of fringing-reef morphologies. Given the high uncertainties of coastal flood risk and lack of available EWS across much of the world's vulnerable reef-lined coasts, it makes it very worth reporting.

   We thank the referee for his support of the topic addressed in this manuscript.

   However, the paper could be substantially improved in several ways. Among them:

2. The authors should be more up-front and clearer about what is different between this paper and the earlier BEWARE paper (Pearson et al., 2017), which many readers may already be familiar with. Besides the addition of (a lot) of new (real-world) profiles and related training data for the surrogate model, why has the Bayesian approach apparently been abandoned? Or are you just not calling the training steps "Bayesian" anymore?

   This suggestion was also provided by Referee #2. We have attempted to clarify the differences between the original BEWARE model (Pearson et al., 2017) and the BEWARE-2 model in the introduction section (e.g., lines 74–78, see also screenshot in Figure 3 at the end of this document). The most important difference that we aim to highlight is the move from parametric reef profile shapes used in BEWARE (and other metamodels referred to later by the referee), which are too simplified to well describe the natural extreme bathymetric variability of coral reefs (Scott et al., 2020), towards the 195 representative reef profiles (RRPs) used in BEWARE-2, which encompass a far greater variability in reef geometries seen across the globe. The Bayesian approach to estimate wave runup has indeed been replaced in BEWARE-2 by probabilistic matching of target profiles to the RRPs and weighted nearest neighbor probability matching of target oceanic forcing conditions to database conditions. This modification in probabilistic approach is now explicitly stated in Section 2.2 (lines 226–229, see also screenshot in Figure 6 at the end of this document).

3. Related - most of the complex logic appears to be used for matching the target reef profile to the representative reef profiles (RRPs, which were developed primarily in an earlier work); comparatively simple inverse distance weighted interpolation of the full-fidelity (XB-NH) model "training data" is then seems to be used to estimate target profile and target conditions (albeit with some interesting heuristic relationships used to post-hoc estimate effects of bed friction and beach slope). That seems (in my experience anyway) a different approach compared to most coastal hybrid/meta-models, which seek to emulate the dynamics themselves over a given morphology (e.g. Zornoza-Aguado, et al 2024). Would it not be easier (in the modern age) supply all training data (including the reef profiles themselves) to some kind of conditioned neural network (NN), either a simple one, such as the RBF approach used by Rueda et al 2019

and others, or a deep NN, or explore any of the rapidly evolving more complex black-box ML approaches? Maybe you don't need that level of complexity due to the profile 1-D nature of the problem and a more first-principle morphological approach is better? I think the explaining the rational used here and how it diverges (or doesn't) from other contemporary meta/hybrid modelling approaches for coastal extremes would greatly improve the paper.

The referee makes an interesting point here regarding the need for (or usefulness of) more complex machine learning (ML) methods with which to train the BEWARE-2 model. This is a question that we had also considered during the development and training. We found, in line with the referee's statement, and as explored in earlier work by Scott et al. (2020), that most of the complexity in the ML methodology is required to simplify the multidimensional geometric parameter space (in this case through probabilistic matching to RRPs). In contrast, training across the gridded and (relatively) small dimensional space of oceanic forcing conditions appeared to be easily achieved using a relatively simple ML method (essentially a weighted nearest neighbor approach).

In general sense, we expect inverse distance weighted methods, such as the method we apply in BEWARE-2, to be comparable in performance to Global Basis Function-type methods (such as RBF, splines, etc.), as long as the data we are using are gridded, as is the case for the oceanic forcing conditions. If the oceanic forcing condition training data had been scattered, we would expect Global Basis Function-type methods to outperform our more simple weighted distance approach.

Despite its relative simplicity, the method used in BEWARE-2 to probabilistically match target to database oceanic conditions, as opposed to simple interpolation at the target condition, does provide further information on the uncertainty (confidence bands) of the runup prediction (i.e., Step 2 in Section 2.2.2 and Figure 3 in the manuscript). In this case, the simple approach therefore seems sufficient. We have included reference to this in Section 2.2.2 (lines 226–229) of the updated manuscript (see also Figure 6 at the end of this document).

The referee also makes an interesting suggestion to develop a new ML model based on the entirety of the training data (i.e., combined variation of profiles and oceanic forcing conditions), for instance through application of Radial Basis Functions (RBFs). There has been some very interesting progress made in this field in recent years. For instance, Ricondo et al. (2024) applied RBF to develop a meta-model of surf-zone hydrodynamics on reefs. In line with other existing parametric and meta-models, however, this ML model was developed for idealized reef profiles with a limited set of geometric parameters. Application of an RBF-type approach with morphologically diverse, real-world, reef profiles is still far from mathematically trivial, as the problem can be extremely ill-conditioned.

Although we do not currently consider the development of a new Neural Network (NN) meta-model to be necessary to simulate wave runup, or easily achievable for morphologically diverse reef profiles, we are providing open access to the BEWARE-2 training dataset for further research. We would be happy to support others in developing more advanced meta-models, for instance that may be able to provide estimates of more hazard indicators than wave runup such as overtopping volumes, resulting topographic change, etc.

4. The validation presented is limited to comparisons between the full-fidelity (XB-NH) model and the surrogate model. While this is the norm for many hybrid modelling studies, it would be nice to see some comparisons of the surrogate model (alongside XB-NH) to real-world observation as was done in the earlier BEWARE paper. There are lots of empirical/statistical/analytic/hybrid approaches that estimate wave runup – how much better is BEWARE-2? Given the information, it is difficult to assess how much better BEWARE-2 might be compared to these other approaches.

To the best of our knowledge, validation of a metamodel against the original model it has been trained to imitate is the norm, as also stated by the referee. The recommendation of the referee to include real-world observations (also echoed by Referee #2) is one that we fully agree with (see also Section 4.3 of the manuscript), but also one that is currently very difficult to fulfill: field observations of wave runup on coral reef-lined beaches, particularly during energetic forcing conditions, are practically non-existent (e.g., Winter et al. 2020).

To our knowledge, the only published observations of wave runup on coral reef-lined coasts with concurrent boundary forcing conditions are presented in Quataert et al. (2020). These have a vertical resolution of approximately 1 m (limited by the individual features identified in the images), and represent an approximation of the maximum wave runup over a half hour period. As these data are necessarily quite coarse and have additionally previously been used to verify the XBeach model, we do not think it is appropriate to use these data to “validate” the BEWARE-2 metamodel.

The lack of observational data is further reflected in the validation sections of earlier metamodel studies. For instance, the original BEWARE model (Pearson et al. 2019) made use of three numerical model predictions of wave runup at Funafuti (Basilisk GN model; Beetham et al. 2015) and one empirical model estimate of wave runup at Roi-Namur (Hunt runup formulation; Cheriton et al. 2016). The HyCReWW model (Rueda et al. 2019) used the same observations as used by Pearson et al. (2019), alongside laboratory scale observations (which have in the past also been used to validate XBeach; Lashley et al., 2018), and one observation of wave runup at Lahaina (source not provided). Liu et al. (2023) similarly used numerical model simulations of wave runup at La Saline (XBeach; Bruch et al. 2020) and Roi-Namur (XBeach; Quataert et al. 2020) to validate their wave runup metamodel. To a great extent therefore, the available data of wave runup used in earlier studies are in fact laboratory scale observations that have been used to validate the XBeach model, or numerical model results of, primarily, the XBeach model.

The question whether BEWARE-2 is a better predictor of wave runup than other models is complicated by the fact that application of other metamodels to complex reef profiles is rather dependent on the subjective assessment of key reef geometry parameters, such as the reef platform width and depth, and the fore reef slope. For instance, given the observed reef profile presented in Figure 1 of this document, users of existing metamodels are required to decide what the characteristic reef platform width and depth is, which subjectively could include, or not, the reef profile from 80–180 m cross-shore position, thereby substantially affecting the prediction of wave runup. It is therefore quite tricky to objectively assess the improvement of BEWARE-2 over earlier metamodels on such complex profiles without introducing (unconscious) bias. We therefore deliberately chose to steer away from this topic in the manuscript, and instead allow for fully independent comparison of the advantages and disadvantages of the various metamodels in practical situations by the wider coastal science and engineering community.

On simpler, “idealized”, reef profiles the difference in accuracy of the runup prediction of BEWARE-2 compared to other metamodels trained on XBeach-generated data (e.g., Pearson et al., 2019; Rueda et al., 2019; Liu et al., 2023) is expected to be negligible, as for these cases the metamodels have been shown to accurately mimic the results of the XBeach model.

We would finally like to state that several coauthors on this manuscript are currently involved in research projects aimed at meeting the need for field observations and full-scale laboratory measurements of wave runup on coral reef-lined coasts. We have every intention of using these field observations to scrutinize the accuracy of BEWARE-2 once the data become available and to share these findings with the coastal science and engineering community in a following manuscript once those data have been collected and analyzed.

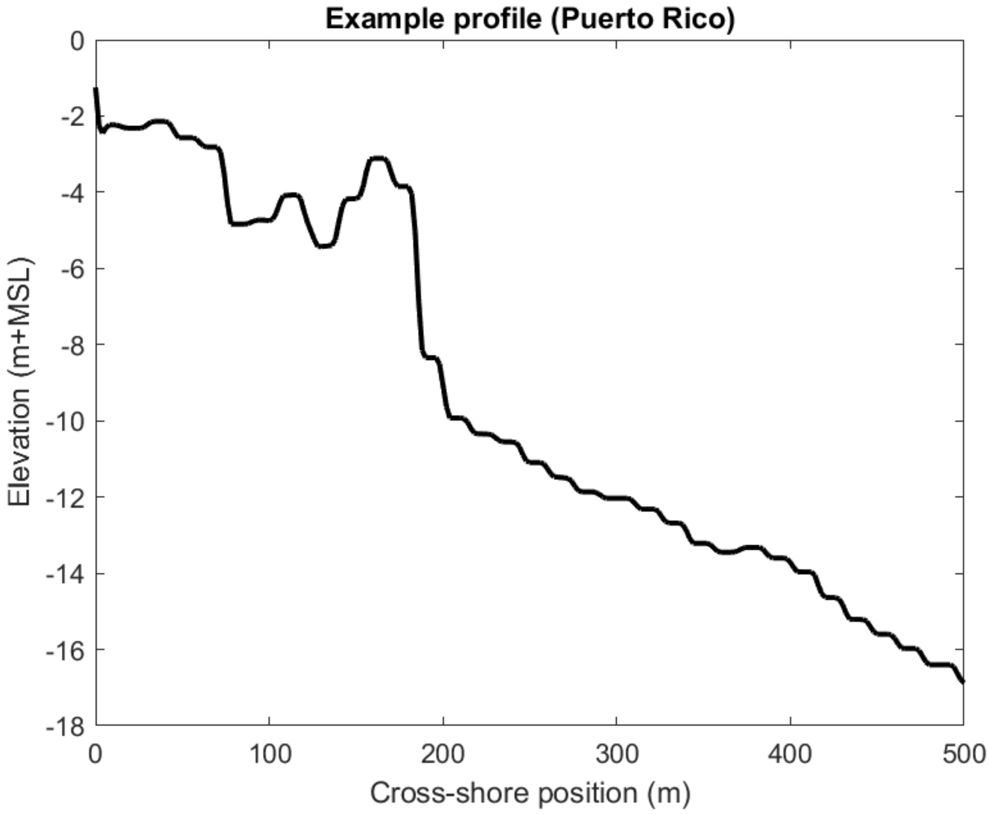

Figure 1: Example of a complex coral reef profile that is not easily described by reef platform width and depth geometric parameters.

Abstract:

Are the unit details on verification necessary? The upper limit runup of range (20.9 m) is non-intuitive until the semi-infinite beach slope is defined in the methods section. In my view it would be better to normalise RMSE and bias and perhaps represent them as percentages for the abstract so this stated range is not needed.

Thank you for this suggestion, we have included the normalized RMSE (SI) and normalized bias to the abstract alongside the RMSE and bias (lines 14–16; see also Figure 2 at the end of this document).

A little difficult to follow… also, what is the difference with this paper and the earlier BEWARE paper (https://doi.org/10.1002/2017JC013204)? That is front of mind to readers such as myself, who are aware of the earlier work.

We were not entirely sure what section the referee is referring to as difficult to follow. We have added explicitly the objective to provide wave runup information on morphologically diverse reef profiles in the abstract (lines 12–13; see also Figure 2 at the end of this document) and that this differs from earlier metamodels in general. We do not believe it necessary to highlight differences with specific models (i.e., Pearson et al., 2017) in the abstract.

Introduction

Ln 30 - : since publication of Hoeke et al 2013, the number of case studies attributing remotely generated swell as the primary proximal factor in island flooding events has expanded – I recommend adding a few more recent examples (e.g. Wadey, et al 2017, Ford et al 2018, Wandres, et al 2020, Hoeke, et al 2021) to highlight its pervasiveness among oceanic islands.

Thank you, we have included these references in lines 35–36.

Ln 64: (Pearson et al., 2017; Rueda et al., 2019; Liu et al., 2023), consider adding Beetham and Kench, 2018 to this list?

The RIOT model of Beetham and Kench (2018) is slightly different to the others originally listed here, both in model type and output information, but is certainly worth including in the overview. We have included as a "numerical model informed empirical relation" (line 67; see also Figure 3 at the end of this document).

Also, while all of these meta-modelling approaches may suffer "limited number of schematic coral reef bathymetries" how do their approaches compare to BEWARE-2? Is BEWARE-2 only better because more training data has been introduced or are there other improvements/considerations in the overall approach?

Here we refer to our response to Key Points 2 and 4 of this referee: the main objective of BEWARE-2 is to incorporate morphological diversity of reef profiles (Key Point 2) and that objective quantification of the improvement in wave runup prediction is difficult, particularly in the absence of real-world observations (Key Point 4).

Methods

Ln 94-115: I found this section circuitous and hard to follow, with poor economy of words. At the very least end Ln 98 with "… using morphological clustering technique, as summarised in the following paragraph."

We edited this section in the attempt to increase legibility. We thank the referee for his suggestion, which we have incorporated in the manuscript (see also Figure 4 at the end of this document).

Figure 2: This just looks like random coloured spaghetti – maybe sorting by mean profile steepness or runup would make this more sensible? Also, runup based on what boundary conditions? Is this normalised somehow?

The ordering of the profiles was not clear in the caption in this version of the manuscript. We have included in the caption that the profiles <u>are</u> ordered by mean profile steepness (profile above MSL – 15 m). We have also added that wave runup was calculated for identical wave conditions on all profiles (not normalized). In line with the suggestion by Referee #2, we have adjusted the color scheme of the figure (see also Figure 5 at the end of this document).

Ln 299 "… 5, 25, 50, 75, and 95% depth exceedance values, i.e., the depth exceeded by a given percentage of the observed profiles at each cross-shore location" not sure I understand this …

We have reworded this section to clarify (lines 308–313; see also Figure 7 at the end of this document).

Benefits and limitations and/or Conclusion sections:

I think it would be worthwhile to point out that the reef-lined coasts of many nations do not have the high resolution bathytopo information (e.g. based on LIDAR surveys) needed to make use of tools like BEWARE-2 – this paper is opportunity to point out the extremely high value of such underpinning data.

We have included this point at the end of Section 4.1 (lines 469–471; see also Figure 8 at the end of this document).

Screenshots from updated manuscript (track-changes):

Abstract. Low-lying, tropical coral reef-lined coastlines are becoming increasingly vulnerable to wave-driven flooding due to population growth, coral reef degradation, and sea-level rise. Early-warning systems (EWS) are needed to enable coastal authorities to issue timely alerts and coordinate preparedness and evacuation measures for their coastal communities. At longer time scales, risk management and adaptation planning require robust assessments of future flooding hazard considering uncertainties. However, due to diversity in reef morphologies and complex reef hydrodynamics compared to sandy shorelines, there have been no robust, analytical solutions for wave runup to allow the development of large-scale coastal wave-driven flooding EWS and risk assessment frameworks for reef-lined coasts. To address the need for ~~a~~ fast, robust ~~prediction of runup along reef-lined coasts~~predictions of runup that account for the natural variability of coral reef morphologies, we constructed the BEWARE-2 (Broad-range Estimator of Wave Attack in Reef Environments) meta-process modeling system. We developed this meta-process model using a training dataset of hydrodynamics and wave runup computed by the XBeach Non-Hydrostatic+ process-based hydrodynamic model for 440 combinations of water level, wave height, and wave period, on 195 ~~morphologically diverse~~ representative reef profiles ~~.~~ that encompass the natural diversity in real-world fringing coral reef systems. Through this innovation, BEWARE-2 can be applied in a larger range of coastal settings than meta-models that rely on a parametric description of the coral reef geometry. In validation, the BEWARE-2 modeling system produced runup results that had a relative root-mean square error of ~~0.63 m and bias of 0.26 m,~~ 13% and relative bias of 5% relative to runup ~~of 0.17–20.9 m~~ simulated by XBeach Non-Hydrostatic+ for a large range of oceanographic forcing conditions and for a diverse reef morphologies (root-mean square error and bias 0.63 m and 0.26 m, respectively, relative to mean simulated wave runup of 4.85 m). Incorporating parametric modifications in the modeling system to account for variations in reef roughness and beach slope allows systematic errors (relative bias) in BEWARE-2 predictions to be reduced by a factor of 1.5–6.5 for relatively coarse or smooth reefs, and mild or steep beach slopes. This prediction is provided by the BEWARE-2 modeling system 4–5 orders of magnitude faster than the full, process-based hydrodynamic model and could therefore be integrated in large-scale EWS for tropical, reef-lined coasts, as well as used for large-scale flood risk assessments.

Figure 2: Screenshot of updated abstract

Together, these severely limit the use of parametric models (e.g., Stockdon et al., 2006; Merrifield et al., 2014) in coral reef environments (see also Astorga-Moar and Baldock, 2023). Processes-based models (e.g., Roelvink et al., 2009, 2018) have been adapted for coral reef-lined coasts by modifying the typical wave action and/or non-linear shallow water equations and parameterizing the hydrodynamic roughness in wave and friction factors (Van Dongeren et al., 2013; Quataert et al., 2015; Buckley et al., 2018; Lashley et al., 2018; de Ridder et al., 2021). However, although accurate, these models are very computationally expensive (e.g., Quataert et al., 2020) and therefore too slow for EWS (Winter et al., 2020; WMO, 2022b). To capture the accuracy of process-based models in operationally feasible computational time frames, surrogate models, including metamodels (Pearson et al., 2017; Rueda et al., 2019; Liu et al., 2023)~~and~~ , machine-learning models (Franklin and Torres-Freyermuth, 2022), and numerical model-informed empirical relations (Beetham and Kench, 2018), have been developed by running process-based models over a limited number of schematic coral reef bathymetries. However, as demonstrated by Scott et al. (2020), the natural variability in coral reef widths, depths, slopes, and rugosities (bathymetric variability) far exceeds the limited schematic bathymetries used in current surrogate models, limiting their accuracy and global applicability in EWS.

To address this need for a fast, accurate EWS ~~for tropical, reef-lined coasts,~~ that accounts for the natural variability of coral reefs, we developed the Broad-range Estimator of Wave Attack in Reef Environments (BEWARE-2), a computationally efficient meta-process modeling system that estimates runup (wave-driven set-up and swash) based on complex, process-based hydrodynamic model simulations. We developed BEWARE-2 using insights from the development of the BEWARE-1 meta model (Pearson et al., 2017) and real-world coral reef profile clustering techniques of Scott et al. (2020), and trained the model to be suitable for application on a very large range of morphologically diverse, reef-lined coasts. Here we first detail the creation of a training database of representative, morphologically diverse reef profiles and the matching of real-world reef profiles to those representative profiles. Next, we document the application of the process-based hydrodynamic model XBeach Non-Hydrostatic+ (de Ridder et al., 2021) to the representative reef profiles over a broad range of oceanographic forcing conditions ~~. Then we~~ to generate hydrodynamic training data. We subsequently describe the application of ~~the meta-model to compute runup. Subsequently, we address meta-model validationand skill quantification~~BEWARE-2 to compute wave runup on a large variety of real-world coral reef profiles, describe the meta-process model validation, and quantify the predictive skill. Lastly, we discuss the meta-process model benefits, limitations, application, and next steps.

Figure 3: Screenshot of updated section of the Introduction.

A database of 195 representative, ~~shore-normal,~~ cross-reef profiles was created by combining ~~175 representative~~ parametric reef profiles from Pearson et al. (2017)~~and Scott et al. (2020), as well as a set of 20~~ , real-world reef profiles from Scott et al. (2020) , and additional wide reef profiles ~~(defined as profiles that reach a depth of 15 m at distances greater than 1.5 km offshore)~~ identified in this study (Figure 1). Coral reef profiles included in the BEWARE-1 model (Pearson et al., 2017) comprise 30 parametric representations of coral reef profile geometries found in literature from 10 sites around the world (Quataert et al., 2015), with reef flat widths ranging from 0–500 m and fore reef slopes from 0.1–0.5. The reef profiles of Scott et al. (2020) and the wide reef profiles identified in this study (defined as profiles that reach a depth of 15 m at distances greater than 1.5 km offshore), were extracted from a dataset of real-world 30,166 coral reef profiles (Storlazzi et al., 2019), covering the coral reef-lined coasts of the United States of America (U.S.), including the States of Hawai'i and Florida; the Territories of Guam, American Samoa, and U.S. Virgin Islands; and the Commonwealths of Puerto Rico and the Northern Mariana Islands. The dataset consists of transects with a 2 m cross-shore resolution spaced at 100 m intervals along the 3,300+ kilometers of coastline. ~~Scott et al. (2020) removed 9,712 wide reef profiles from the dataset due to inherent uncertainties in the application of XBNH on these profiles, and reduced the remaining~~ Of these transects, Scott et al. (2020) clustered 20,454 ~~reef profiles to~~ profiles with reef widths less than 1.5 km into 500 cluster groups and representative profiles, using data reduction techniques on morphology and hydrodynamics of the reef profiles. ~~The 20 wide reef profiles selected~~ To allow for the application of BEWARE-2 in areas with wide reefs, such as barrier or extremely wide fringing reefs, additional profiles were derived in this study ~~were derived from the~~ from the remaining 9,712 ~~wide reef profiles excluded by Scott et al. (2020), following application of the same using morphological clustering technique~~reef transects with widths greater than 1.5 km. These profiles were clustered based on the submerged morphology in an identical fashion to that of Scott et al. (2020), leading to the identification of 20 representative wide reef profiles.

~~For the development of BEWARE-2, a set of 175~~ The 550 reef profiles described in the previous paragraph (i.e., 30 profiles following Pearson et al. (2017), 500 profiles following Scott et al. (2020), and 20 wide reef profiles), henceforth termed the intermediate representative reef profiles (iRRPs), were subsequently reduced to set of 195 representative reef profiles (RRPs) ~~was developed based on the 30 initial~~ for application in the BEWARE-2 training dataset. In this, 175 representative reef profiles (~~iRRPs)~~ RRPs) were developed using the 30 iRRPs of Pearson et al. (2017) and 500 iRRPs of Scott et al. (2020), neither of which contain any very wide coral reef profiles ~~, and are henceforce~~ (here termed the 530 normal iRRPs). In general, these 530 normal iRRPs have shapes characteristic of atoll and fringing reef profiles. Following the methodology of Scott et al. (2020), the 530 normal iRRPs were reduced to 175 normal RRPs by means of hierarchical clustering based on two sets of features,

Figure 4: Screenshot of updated section of the Methodology with reference to the training set reef profiles.

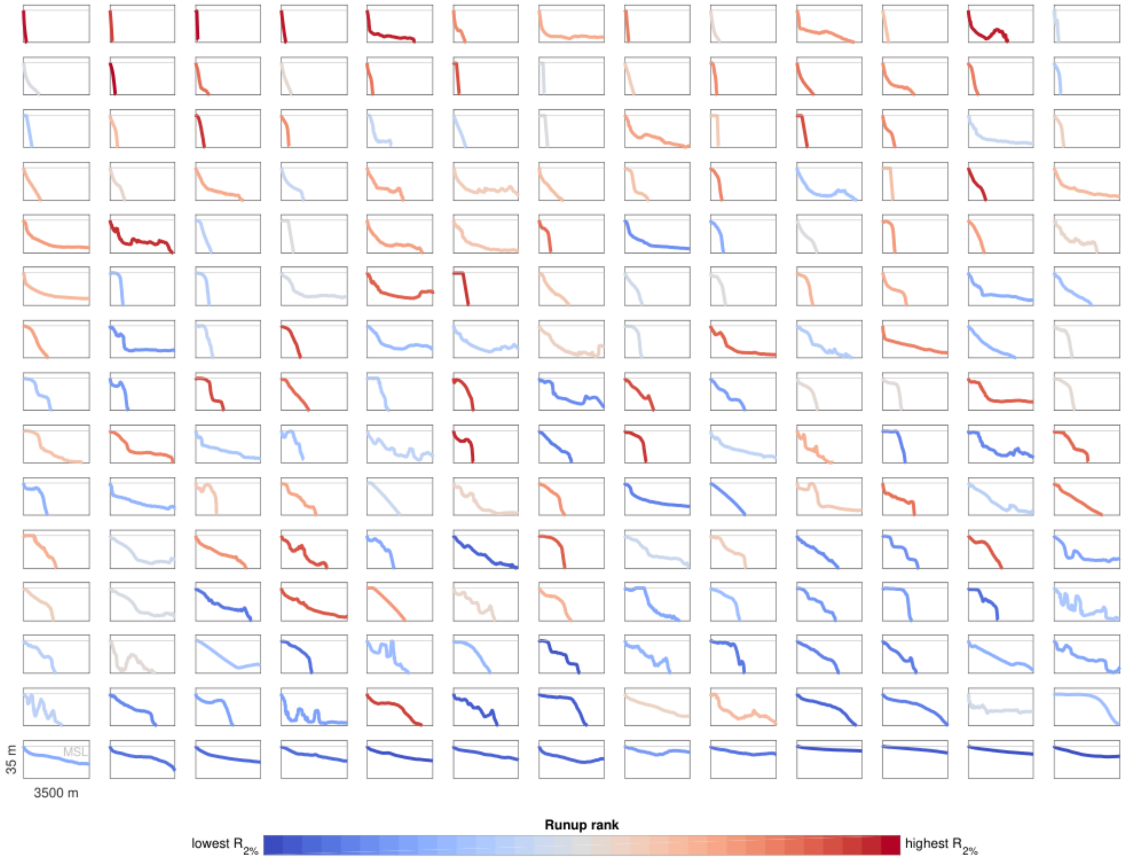

Figure 2. Overview of the morphology of the 195 representative reef profiles (RRPs), ordered from top left to bottom right by cross-shore distance to the 15 m depth contour (W_{reef}, see Section 3.2). The RRPs are color-coded according to ~~projected~~ the relative ranking of runup simulated by XBNH for a single representative wave condition ($H_{s,0} = 5$ m, $T_p = 12$ s), with ~~yellow~~ blue indicating profiles with ~~low resulting~~ relatively lower wave runup and ~~black~~ red those with ~~high resulting~~ relatively higher wave runup. ~~In general, the RRPs with narrower and steeper shallow (< 5 m depth) portions of the profile have greater resulting runup.~~

Figure 5: Screenshot of updated Figure 2.

$$p_{p_{C_{DB}|C_T}(n)} = \frac{\mathrm{GMIND}(n)}{\sum_{m=1}^{8}\mathrm{GMIND}(m)} \qquad (3)$$

The weighted nearest neighbour-type approach described above to assign probability weights to database conditions is different from the Bayesian-based interpolation applied in the BEWARE-1 meta-model. However, in Section 2.4 we will show that the relatively simple and explainable machine-learning approach applied in BEWARE-2 is easily sufficiently accurate for practical application.

Figure 6: Screenshot of updated Methodology section with reference to difference in Bayesian approach relative to BEWARE-1.

2.4.1 Validation dataset

The ability of the BEWARE-2 meta-process model to predict $R_{2\%}$ on morphologically diverse reefs and under varying hydrodynamic forcing conditions is quantified using a validation dataset of 24,000 process-based, XBNH model simulations that are separate from the dataset of simulations used to train the meta-process model. To develop the validation dataset, five normal, and one to two wide, real cross-shore profiles were selected from each of the seven geographic regions (Guam, Saipan-Tinian, American Samoa, Hawai'i, Florida, Puerto Rico, and the US Virgin Islands) included in the dataset of Storlazzi et al. (2019), for a total of 35 normal and 13 wide reef profiles. ~~Profiles~~ Normal reef profiles representative of the ~~diversity in morphology of normal reefs in~~ morphological diversity at every geographic region in the dataset of Storlazzi et al. (2019, i.e., 20,454 profiles in total, see Section 2.1.1) were selected ~~statistically for each geographic region by first determining~~ by first statistically determining the the ~~cross-shore profile of the~~ 5, 25, 50, 75, and 95% depth exceedance values ~~,~~ at every cross-shore position (i.e., the depth exceeded by a given percentage of the observed profiles at ~~each~~ every cross-shore ~~location (~~position; Figure 4, dashed lines). Subsequently, the ~~nearest real profiles to the~~ observed, real-world profiles most similar to the cross-shore varying 5, 25, 50, 75, and 95% depth exceedance ~~profiles~~ values (Figure 4, solid lines) were selected for the validation dataset. Wide reef profiles were similarly selected for each geographic region from the dataset of wide coral reef profiles of Storlazzi et al. (2019, i.e., 9,712 profiles in total, see Section 2.1.1). For all geographic regions except American Samoa, the nearest observed profiles to the 25% and 75% depth exceedance of wide profiles were selected for the validation dataset. In American Samoa, the only wide profile included in the database of Storlazzi et al. (2019) was selected. None of the 48 (35 normal and 13 wide reef) validation profiles were identical to the RRPs included in the training dataset.

Figure 7: Screenshot of updated Methodology section with reference to statistical exceedance depth profiles.

The XBNH model is reasonably well validated, as described in the Introduction and Methods sections, but is not perfect. A key limitation of BEWARE-2 is the one-dimensional nature of the underlying XBNH model simulations and thus the meta-process model dataset, which is unlikely to be very accurate in highly two-dimensional situations, such as in the presence of reef channels (e.g., Storlazzi et al., 2022). In addition, BEWARE-2 shows notably lower skill in reproducing XBNH runup values for very wide reef profiles (characteristic of barrier and extremely wide fringing reefs), likely due to the relatively low profile coverage (only 20 RRPs) and large number of possible permutations. Although this may be improved by including a greater number of wide RRPs in the dataset, the real-world accuracy of the underlying XBNH model may likely be lower for very wide reef profiles than other reefs for which it has been validated, as one-dimensional XBNH models are unable to account for wind growth of waves or large-scale topographic refraction (Scott et al., 2020). Further extension of BEWARE-2 for these reef types is therefore currently constrained by the inherent uncertainty in applying XBNH to very wide reef profiles. A final key limitation of BEWARE-2 is the underlying reef profile dataset, which is heavily biased toward data from U.S. (fringing) coral reef-lined coasts (due to consistent LiDAR data availability at the time of BEWARE-2 development) and may lack important other characteristic reef profiles such as barrier and platform reefs. Collection and dissemination of accurate, high resolution bathymetric data at other coral reef-lined coasts around the world would greatly aid application of BEWARE-2, as well as other process-based and meta-models, in global efforts to reduce the impacts of coastal flooding.

Figure 8: Screenshot of updated Discussion section.

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