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1 **NONHYDROSTATIC AND SURFBEAT MODEL PREDICTIONS OF** 2 **EXTREME WAVE RUN-UP IN FRINGING REEF ENVIRONMENTS**

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19 **Keywords:** Wave run-up, Coral reefs, XBeach, Infragravity waves, Numerical modelling,
20 Coastal flooding

21 **Abstract**

22 The accurate prediction of extreme wave run-up is important for effective coastal engineering
23 design and coastal hazard management. While run-up processes on open sandy coasts have
24 been reasonably well-studied, very few studies have focused on understanding and predicting
25 wave run-up at coral reef-fronted coastlines. This paper applies the short-wave resolving,
26 Nonhydrostatic (XB-NH) and short-wave averaged, Surfbeat (XB-SB) modes of the XBeach
27 numerical model to validate run-up using data from two 1D (alongshore uniform) fringing-reef
28 profiles without roughness elements, with two objectives: i) to provide insight into the physical
29 processes governing run-up in such environments; and ii) to evaluate the performance of both
30 modes in accurately predicting run-up over a wide range of conditions. XBeach was calibrated
31 by optimizing the maximum wave steepness parameter (*maxbrsteep*) in XB-NH and the

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32 dissipation coefficient (α) in XB-SB) using the first dataset; and then applied to the second
33 dataset for validation. XB-NH and XB-SB predictions of extreme wave run-up (R_{max} and $R_{2\%}$)
34 and its components, infragravity- and sea-swell band swash (S_{IG} and S_{SS}) and shoreline setup
35 ($\langle\eta\rangle$), were compared to observations. XB-NH more accurately simulated wave
36 transformation but under-predicted shoreline setup due to its exclusion of parameterized wave-
37 roller dynamics. XB-SB under-predicted sea-swell band swash but overestimated shoreline
38 setup due to an over-prediction of wave heights on the reef flat. Run-up (swash) spectra were
39 dominated by infragravity motions, allowing the short-wave (but not wave group) averaged
40 model (XB-SB) to perform comparably well to its more complete, short-wave resolving (XB-
41 NH) counterpart. Despite their respective limitations, both modes were able to accurately
42 predict R_{max} and $R_{2\%}$.

43 **1 Introduction**

44 Wave run-up is defined as the uprush of water above the still water level (SWL) on a beach or
45 structure. Run-up is the result of two nearshore processes: i) the time-averaged surface
46 elevation at the shoreline (i.e. wave setup); and ii) the time-varying fluctuations about that
47 mean (i.e. swash) [1,2]. Its accurate prediction is essential for the effective design of coastal
48 structures, beach nourishment planning and for predicting the extent of damage associated with
49 storms [3,4].

50 Accurately predicting run-up is especially important for tropical and sub-tropical regions
51 fronted by reef structures. These regions, which often have low-lying coastal areas, are often
52 threatened by severe tropical storms with impacts ranging from severe beach and dune erosion
53 to the complete inundation of the adjacent coastal communities [5-7]. Coastal inundation is
54 often a result of several interacting meteorological and coastal processes; however, on steeper
55 coasts without continental shelves, the contribution of wave processes such as run-up becomes
56 more dominant than that due to storm surge [8,9].

57 Coastal engineers and managers typically parameterise run-up using Iribarren-based empirical
58 models (Equations (1) and (2)) developed for open, sandy coasts which use offshore wave
59 height (H_{m0}), period (T_p) and a constant beach slope (β) as input values to predict the magnitude
60 of run-up [10-12,2]. These relationships typically quantify extreme wave run-up as either of
61 two characteristic values: i) R_{max} , the maximum run-up at any specific time; and ii) $R_{2\%}$, the
62 value exceeded by only 2% of the run-up maxima in the distribution.

$$\frac{R_{max}}{H_{m0}} \text{ or } \frac{R_{2\%}}{H_{m0}} = f(\xi_0) \quad (1)$$

$$\xi_0 = \frac{\tan\beta}{\sqrt{\frac{2\pi H_{m0}}{gT_p^2}}} \quad (2)$$

63 where, g is the gravitational acceleration and ξ_0 is the Iribarren number.

64 However, these formulations are not readily applicable to the fringing reef environments
 65 commonly found in tropical and subtropical regions, as run-up depends not only on the beach
 66 slope at the shoreline but also on the reef morphology itself. The presence of these reef
 67 structures results in significantly more complex nearshore hydrodynamic processes than on
 68 typical sandy profiles [13,14,5,7]. Fringing reefs are characterized by a seaward sloping reef
 69 face leading up to a shallow reef flat platform that extends towards the beach. Wave
 70 transformation in these environments is subject to several simultaneous and interacting
 71 processes [15], which include: shoaling; dissipation by wave breaking [16]; wave-induced
 72 setup [5,17]; nonlinear energy transfer to higher and/or lower (infragravity) frequencies [18-
 73 20]; dissipation by bottom friction [21]; low-frequency wave reflection; and resonance [22],
 74 where a significant amount of wave energy is distributed about the natural frequency of the
 75 reef. This reef flat resonance may in turn result in an amplification of run-up at the shoreline,
 76 further adding to the complexity of making accurate predictions in such environments [23-26].

77 Although not originally developed for and tested using reef-type environments, numerical
 78 models are now widely applied to reef systems given their ability to accurately represent
 79 complex nearshore processes [27-32,26]. These numerical models generally fall into two
 80 categories groups: i) phase-resolving models and ii) phase-averaged models. Phase-resolving
 81 models utilize a grid resolution high enough to completely describe the sea-surface and resolve
 82 individual waves. These models are then able to capture the higher frequency wave motions
 83 (short-waves); however, this comes at greater computational expense. In contrast, phase-
 84 averaged models describe wave processes in a stochastic manner, typically based on linear
 85 wave theory and empirical formulations. As such, phase-averaged models require a lower grid
 86 resolution and are considerably less computationally demanding [33]. Nearshore wave models
 87 have been primarily developed for mild-sloping, sandy coastal environments. Thus, when they
 88 are applied to steep reef environments it is expected that some of their inherent
 89 parameterizations (e.g. for simulating wave breaking and frictional dissipation) would require
 90 some adjustment [33]. However, wave transformation models derived using the mild-slope

91 approximation have been shown to perform reasonably accurately with minimal parameter
92 tuning, even on slopes up to 1:3, which is steeper than typical coral reef slopes (e.g. [34-36]).

93 Therefore, the choice of numerical model should be carefully considered based on the relative
94 importance of the wave processes and the manner in which they are simulated in each model.
95 Given that low-frequency motions often dominate near the shoreline of fringing reef
96 environments, it is imperative that the numerical model applied be able to correctly describe
97 the non-linear transfer of wave energy to the infragravity (low-frequency) band [28,33,20]. For
98 this study, we consider the XBeach numerical model that combines both phase-resolving and
99 phase-averaged approaches. The XBeach nonhydrostatic mode (XB-NH) resolves all wave
100 motions including short-waves; while the surfbeat mode (XB-SB) resolves long-wave motions
101 but is short-wave averaged. The overall ability of XBeach to accurately simulate infragravity
102 motions in a wide range of coastal environments has been demonstrated in many studies [37-
103 41].

104 With respect to its application to fringing reef systems, Van Dongeren et al. [30] applied XB-
105 SB to study low-frequency wave dynamics over a fringing reef at field scales. The study
106 showed the increasing dominance of infragravity (low-frequency) waves shoreward of the reef
107 crest. In their comparison of nearshore models for wave transformation across reef
108 environments, Buckley et al. [33] concluded that XB-SB was indeed capable of handling the
109 transformation of wave energy from the sea-swell (high-frequency) band to the infragravity
110 band. More recently, Quataert et al. [42] applied XB-SB to investigate the influence of the reef
111 characteristics on the nearshore hydrodynamics and the potential for wave-driven flooding in
112 light of climate-driven sea level rise. This study found that run-up increased with narrower,
113 smoother reef flats and steeper, rougher reef slopes. While highly informative, the main
114 limitation of their study was the fact that their model was not quantitatively validated for wave
115 run-up. While each of the above-mentioned studies applied XB-SB, Storlazzi et al. [43]
116 recently used the short-wave resolving mode XB-NH to successfully simulate sea-swell band
117 wave run-up and flooding on an atoll island. However, like that of Quataert et al. [42], the
118 modelled run-up and associated inundation extent were only qualitatively compared to
119 observations. Likewise, Pearson et al. [44] concluded that XB-NH was able to simulate reef
120 hydrodynamics with reasonable accuracy and recommended its use as an early warning tool to
121 predict flooding on reef-lined coasts.

122 Despite the promising results displayed by XBeach to-date, the performance of either mode to
123 predict wave run-up at reef coasts has not been rigorously validated using experimental data.
124 Thus, it is primary aim of the present paper to evaluate the model in simulating extreme wave
125 run-up in such systems. In particular, attention is given to the physical processes that need to
126 be captured for accurate run-up predictions. This is done by comparing both the short-wave
127 resolving and short-wave averaged modes of the model to two laboratory (physical model)
128 experiments carried out in large-scale wave flumes by: i) Demirbilek et al. [24]; and ii) Buckley
129 et al. [17].

130 In Section 2, the experiments used for model-data comparison are described, followed by a
131 brief overview of the XBeach numerical model and the equations pertinent to this study. In
132 addition, the metrics and objective functions used to quantify model accuracy are presented.
133 Section 3 presents the results of the model calibration through its application to the Demirbilek
134 et al. [24] dataset; while Section 4 presents the results of the model validation and application
135 to the Buckley et al. [17] dataset. Section 5 provides an in-depth discussion on the performance
136 of the short-wave resolving and short-wave averaged modes; and examines the contribution of
137 various physical processes to model results. Section 6 concludes the paper by addressing the
138 overarching research objective and making recommendations for future studies.

139 **2 Methods**

140 **2.1 Description of the Experiments**

141 **2.1.1 Demirbilek et al. [24] Experiment**

142 The experiment was conducted in a 35-m long, 0.7-m wide and 1.6-m high wave flume at the
143 University of Michigan. The reef platform was constructed from polyvinyl chloride (PVC) with
144 a composite reef slope (1:5; 1:18.8; 1:10.6), a 4.8-m wide reef flat and a 1:12 beach slope
145 (Figure 1). Applying a geometric scaling of 1:64, this reef flat width of 307 m in field
146 (prototype) scale is a proxy for a typical fringing reef on southeast coast of Guam [24]. The
147 flume generated irregular waves with a plunger-type wave maker which corresponded to a
148 JONSWAP-type spectrum with a peak enhancement factor of 3.3. The experiments under
149 consideration comprised of 29 tests without wind generation and with significant wave heights
150 (H_{m0}) varying from 3.2 to 8.5 cm, spectral peak periods (T_p) from 1 to 2.5s, and still-water
151 depths on the reef flat (h_r) from 0 to 5.1 cm. Water-surface elevations were measured using 8
152 capacitance-wire wave gauges, all synchronously sampling at 20 Hz for 900 s. Wave run-up

153 was measured using a 1-m long capacitance wire gauge installed on the beach slope. A
154 summary of the 29 test conditions is provided in Table 1.

155 **2.1.2 Buckley et al. [17] Experiment**

156 The experiment was carried out in the 55-m long Eastern Scheldt wave flume located at
157 Deltares, the Netherlands. The reef profile was built using marine plywood to form a 1:5 reef
158 slope, a 14-m horizontal reef flat and a 1:12 sloping beach (Figure 1). Using a geometric scaling
159 of 1:36, the experimental set-up corresponds to a 500-m long reef flat in field (prototype) scale
160 which is analogous to coral reef flats found globally [17]. Irregular waves were generated with
161 a TMA-type spectrum using a piston-type wave maker with second-order wave generation and
162 active reflection compensation for any offshore directed waves. The experiment consisted of
163 16 tests with h_r varying from 0 to 9 cm, H_{m0} from 4 to 24 cm and T_p from 1.3 to 2.3 s. Water-
164 surface elevations were measured using resistance gauges positioned at 18 locations sampled
165 synchronously at 40 Hz for 42 minutes (2520 s). Wave run-up was measured using a “wave
166 rake” equipped with vertical sensors positioned along the beach slope [45,46]. The apparatus
167 recorded the position of the highest wet sensor point during each run-up event. It should be
168 noted that the sensors had a horizontal resolution of 2.5 cm for the first 100 cm and a resolution
169 of 5 cm for the remaining 120 cm. A summary of the 16 test conditions is provided in Table 2.

170 **2.2 The XBeach Numerical Model**

171 XBeach is an open-source, two-dimensional numerical model in the horizontal plane (2DH)
172 which solves horizontal equations for wave propagation, long waves and mean flow, sediment
173 transport and morphological changes [37]. The model has two main modes: i) Nonhydrostatic
174 (XB-NH) which resolves all wave motions (short-wave resolving); however, at a more
175 significant computational expense; and ii) Surfbeat (XB-SB) that resolves motions on the scale
176 of wave groups but treats short-wave motions in a phase-averaged manner (short-wave
177 averaged), requiring considerably less computational effort. It should be noted that although
178 XB-SB mode does not resolve sea-swell frequency motions, it does compute steady setup,
179 (un)steady currents and infragravity wave motions, which tend to dominate during extreme
180 (dissipative) events and in fringing reef environments [37,18,47].

181 XB-NH computes depth-averaged flow due to waves and currents using the non-linear shallow
182 water equations (Equations (3) and (4)). It also includes a nonhydrostatic pressure correction
183 which is derived in a manner similar to a one-layer version of the SWASH model [48]. In the
184 present study, we apply the 1D equations; however, as noted above, 2DH is possible:

$$\frac{\partial \eta}{\partial t} + \frac{\partial uh}{\partial x} = 0 \quad (3)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} - v_h \frac{\partial^2 u}{\partial x^2} = -\frac{1}{\rho} \frac{\partial(\bar{q} + \rho g \eta)}{\partial x} - c_f \frac{u|u|}{h} \quad (4)$$

185 where x and t are the horizontal spatial and temporal coordinates, respectively, η is the free
 186 surface elevation, u is the depth-averaged cross-shore velocity, v_h is the horizontal viscosity
 187 (following Smagorinsky [49]), h is the local water depth, ρ is the density of water, \bar{q} is the
 188 depth-averaged dynamic (nonhydrostatic) pressure normalised by the density and c_f is the bed
 189 friction factor. In the present study we obtain the friction factor using the Manning's roughness
 190 coefficient, n :

$$c_f = \frac{n^2 g}{\sqrt[3]{h}} \quad (5)$$

191 XB-NH incorporates depth-limited wave breaking with a shock-capturing momentum
 192 conservation scheme but as a depth-integrated model, it does not explicitly simulate
 193 overturning or plunging breakers; that is, the vertical structure of flow is not taken into account.
 194 To control the computed location and magnitude of wave breaking a hydrostatic front
 195 approximation is applied where the pressure distribution under breaking bores is assumed to
 196 be hydrostatic [50]. Following Smit et al. [51], the model considers waves to be hydrostatic
 197 bores (i.e. the nonhydrostatic pressure correction term (\bar{q}) is turned off, see Equation (4)) if the
 198 local surface steepness ($\delta\eta/\delta t$) exceeds a maximum value (the “*maxbrsteep*” parameter, by
 199 default = 0.6) and this persists until $\delta\eta/\delta t$ is less than a specified secondary steepness value
 200 (the “*secbrsteep*” parameter, by default is equal to half the specified *maxbrsteep* value). Higher
 201 *maxbrsteep* values allow for steeper wave faces prior to wave-breaking and shifts the
 202 breakpoint shoreward.

203 XB-SB solves short-wave motions using the wave-action equation with time-dependent forcing,
 204 similar to that of the HISWA model [52]. XB-SB uses a single representative frequency and
 205 the wave-action equation (Equation (6)) is applied at the timescale of the wave group.

$$\frac{\partial A}{\partial t} + \frac{\partial c_{gx} A}{\partial x} = -\frac{D_w}{\sigma} \quad (6)$$

$$A(x, t) = \frac{S_w(x, t)}{\sigma(x, t)} \quad (7)$$

$$\sigma = \sqrt{gk \tanh kh} \quad (8)$$

206 The wave action, A is calculated by Equation (7) where S_w is the wave energy density, σ is the
 207 intrinsic wave frequency (Equation (8)), h is the local water depth and k is the wave number;
 208 while, D_w is a dissipation term to account for wave breaking; and c_{gx} is the wave-action
 209 propagation speed in the x direction.

210 To simulate wave breaking, XB-SB applies a dissipation model [53] for use with short-wave
 211 groups and a roller model [54,55] to represent momentum stored in surface rollers which cause
 212 a shoreward delay in wave forcing. The radiation stress gradients that result from these
 213 variations in wave action exert forces on the water column that give rise to infragravity waves,
 214 unsteady currents and wave setup which are obtained by solving the non-linear shallow water
 215 equations (Equations (3) and (4)) but in hydrostatic form with a short wave-induced force term
 216 derived from the wave-action balance (Equation (6)); thus, in a phase-resolving manner. The
 217 total wave energy dissipation due to wave breaking, $\overline{D_w}$ (Equation (9)) is determined by a
 218 representative wave period, T_{rep} ; the fraction of breaking waves, Q_b ; the wave-group varying
 219 short-wave energy, E_w ; the root-mean-square wave height, H_{rms} ; water depth, h ; and a
 220 calibration coefficient for dissipation, α (*alpha*, by default = 1).

$$\overline{D_w} = 2 \frac{\alpha}{T_{rep}} Q_b E_w \frac{H_{rms}}{h} \quad (9)$$

$$Q_b = 1 - \exp\left(-\left(\frac{H_{rms}}{H_{max}}\right)^n\right), H_{rms} = \sqrt{\frac{8E_w}{\rho g}}, H_{max} = \gamma h \quad (10)$$

221 where n is a coefficient (by default = 10); H_{max} is the maximum wave height; and γ is the
 222 breaker parameter (by default = 0.55).

223 Calibration of the above wave dissipation model (Roelvink, 1993, Equations (9 and 10)) may
 224 be achieved by varying either of two free parameters: (i) *gamma* (γ), which controls the fraction
 225 of breaking waves, Q_b ; however, this is only until $H_{rms}/h > 0.6$, after which $Q_b = 1$ and varying
 226 *gamma* no longer has an effect (as per Equation (10)); and ii) *alpha* (α), a proportionality
 227 parameter which controls the intensity of breaking and represents the magnitude of energy
 228 dissipation for a given Q_b . Typically for spilling breakers ($\zeta_0 < 0.5$, Equation (2); (Battjes,
 229 1974)), γ is varied and α is expected to be of the order 1. However, given the plunging nature
 230 ($0.5 > \zeta_0 > 3.3$, Table 1, Table 2) of the waves observed during the physical experiments, we
 231 choose to calibrate the XB-SB model using the *alpha* parameter. In general, higher *alpha*
 232 values result in increased wave dissipation.

233 The only change to the published version of XBeach that was made as part of this present study
 234 was the inclusion of a TMA spectral wave boundary condition to match the offshore waves
 235 produced during Buckley et al. [17] experiment. This modification was achieved by applying
 236 the following transformation function, φ to the calculated JONSWAP spectrum [56]:

$$\varphi(f, h) = \frac{1}{2r} \tanh^2(kh) \quad (11)$$

237 where r is the ratio of group velocity to phase velocity. This option is now available in the
 238 “XBeachX” release of November, 2017.

239 **2.3 Data Processing and Performance Metrics**

240 In order to assess model performance, the following wave characteristics and near-shore
 241 processes were investigated. It should be noted that all data processing (for both the physical
 242 experiment and numerical model results) was carried out by excluding the initial spin-up time
 243 to ensure steady-state conditions on the reef flat, which were identified by examining the
 244 measured time-series. This spin-up time was 100 s for the Demirbilek et al. [24] experiment
 245 (leading to a total simulation period of 900 s per case) and 480 s for that of Buckley et al. [17]
 246 (total simulation period of 2520 s per case).

247 **2.3.1 Mean water level**

248 The mean water level, $\bar{\eta}$ was calculated by taking the average of the surface elevation time
 249 series at each instrument location, relative to SWL.

250 **2.3.2 Root-mean-square wave height**

251 The surface elevation time series were used to determine the one-dimensional wave energy
 252 spectra, $C_{\eta\eta}(f)$ by applying the Welch’s average periodogram method and Hanning filter with
 253 a 50% maximum overlap. For the observations and the XB-NH results, the total root-mean-
 254 square wave height, $H_{rms,TOT}$ was then determined as follows:

$$H_{rms,TOT} = \sqrt{8 \int_0^{\infty} C_{\eta\eta} df} \quad (12)$$

255 XB-SB uses a representative frequency for the sea-swell band wave energy and does not
 256 produce the sea-swell band spectra. Therefore, the high-frequency (sea-swell band) root-mean-
 257 square wave height, $H_{rms,SS}$ as computed by the model was used. The low-frequency
 258 (infragravity-band) root-mean-square wave height, $H_{rms,IG}$ was then obtained from the variance

259 of the simulated long-wave surface elevation time series using Equation (12). The modelled
 260 total wave height $H_{rms,TOT}$ was then calculated as follows:

$$H_{rms,TOT} = \sqrt{H_{rms,SS}^2 + H_{rms,IG}^2} \quad (13)$$

261 For this research a split frequency equal to half the peak frequency ($f_{split} = f_p/2$) is considered
 262 for the separation of sea-swell and infragravity bands, following [57]. This choice of split
 263 frequency is based on the tendency that, offshore, the majority of sea-swell band energy $> f_p/2$,
 264 while most of the bound long-wave (infragravity band) energy $< f_p/2$. Combining the two
 265 spectra results in a minimum of spectral density around $f_p/2$ separating the high- and low-
 266 frequency peaks, which is consistent with the observations here (Figure 4 and Figure 10).

267 2.3.3 Run-up

268 Wave run-up is commonly described by the value exceeded by only 2% of the values in the
 269 run-up distribution ($R_{2\%}$). This statistic was extracted by applying the local peak method to both
 270 modelled and observed run-up time series [58]. Due to the relatively high sampling frequency,
 271 the individual run-up maxima (peaks) above the SWL were identified by assessing whether or
 272 not each data point was significantly larger than the points around it based on a specified
 273 threshold value (Figure 2). $R_{2\%}$ was then determined from the cumulative distribution function
 274 of the discrete run-up maxima [2]. Maximum run-up, R_{max} was determined by finding the
 275 maximum of the run-up peaks (relative to SWL). The steady setup at the shoreline, $\langle \eta \rangle$ was
 276 obtained by taking the mean of the modelled and observed run-up time series (relative to SWL)
 277 [1,58,2]. Note that a distinction is made here between $\bar{\eta}$, the mean water level offshore and
 278 over the reef profile; and $\langle \eta \rangle$, the mean water level at the shoreline obtained from the run-up
 279 time series.

280 Swash motions were obtained from the modelled and observed run-up time series as the time-
 281 varying vertical fluctuations at the shoreline (relative to $\langle \eta \rangle$). Significant swash in both the
 282 sea-swell (S_{SS}) and infragravity- (S_{IG}) bands were obtained from the swash energy spectra [1,2]:

$$S_{SS} = 4 \sqrt{\int_{f_{split}}^{\infty} C_{\eta\eta} df} \quad \text{and} \quad S_{IG} = 4 \sqrt{\int_0^{f_{split}} C_{\eta\eta} df} \quad (14)$$

283

284

285 2.4 Objective Functions

286 The model-data comparisons of the above-mentioned performance metrics were carried out by
 287 applying the following objective functions: Root-Mean-Square Error (RMSE) (Equation (15));
 288 Scatter Index (SCI) (Equation (16)); and Relative Bias (Equation (17)). In the following
 289 equations, Ψ is used as a stand-in for $\bar{\eta}$, $H_{rms,TOT}$, R_{max} , $R_{2\%,<\eta>}$, S_{SS} and S_{IG} , in a sample size
 290 N :

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^N (\Psi_{XBeach}^i - \Psi_{observed}^i)^2} \quad (15)$$

$$SCI_{\Psi} = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^N (\Psi_{XBeach}^i - \Psi_{observed}^i)^2}}{\frac{1}{n} \sum_{i=1}^N \Psi_{observed}^i} \quad (16)$$

$$Rel. bias_{\Psi} = \frac{\sum_{i=1}^N (\Psi_{XBeach}^i - \Psi_{observed}^i)}{\sum_{i=1}^N \Psi_{observed}^i} \quad (17)$$

291 3 Model Calibration: Application to Demirbilek et al. [24] Experiment

292 In this section the XBeach model is calibrated for fringing reef environments by applying it to
 293 the Demirbilek et al. [24] dataset and optimizing the key parameters in both XB-NH and XB-
 294 SB. This was achieved by minimizing the combined root-mean-square error ($RMSE_{TOT}$) which
 295 considers both $H_{rms,TOT}$ and $\bar{\eta}$ predictions at the 8 gauge locations (Equation (18)).

$$RMSE_{TOT} = RMSE_{H_{rms,TOT}} + RMSE_{MWL} \quad (18)$$

296 The choice to calibrate the model considering both $H_{rms,TOT}$ and $\bar{\eta}$ predictions aims to ensure
 297 that the model's accuracy in predicting either parameter is not improved at the expense of the
 298 other. This was observed by Buckley et al. [33] in their evaluation of various nearshore
 299 numerical models for reef environments. In that study it was shown how optimizing a model
 300 considering $H_{rms,SS}$ alone can often result in an increase in error in $H_{rms,IG}$ and $\bar{\eta}$ predictions.

301

302 3.1 Numerical Model Setup

303 The numerical simulations were configured using a 1D approach to best represent the actual
 304 flume conditions. For the XB-NH simulations, a uniform horizontal grid size, Δx of 2.5 cm was

305 applied; while Δx was allowed to vary from 2.5 cm at the beach slope to 5 cm offshore for the
306 XB-SB simulations. It should be noted that for the stated grid resolutions, the two modes had
307 comparable run times. Both modes were forced with parametric JONSWAP spectra and initial
308 water-levels at the offshore boundary to match those observed during the experiments (Table
309 1). The model run-time for both modes was set to 900 s with outputs at 20 Hz at each gauge
310 location to match the experimental data. Additionally, bottom friction was specified using a
311 Manning coefficient, $n = 0.01 \text{ s/m}^{1/3}$ (Equation (5)) to represent the relatively smooth plastic
312 bottom as recommended by Zijlema [59] in his analysis of the same case. A numerical run-up
313 gauge was specified to track the moving waterline with a minimum depth for the determination
314 of the last wet point, $rugdepth$ of 0.2 cm to represent the sensitivity of the capacitance wire
315 used during the physical experiment.

316 Numerical simulations were first carried out using default values to provide an estimate of
317 model performance prior to calibration. For calibration, the key model parameters governing
318 wave dissipation by breaking were identified as: i) the maximum breaking wave steepness in
319 XB-NH ($maxbrsteep$); and ii) the wave dissipation coefficient in XB-SB ($alpha$) (Section 2.2).

320 For each test, these two parameters were then systematically varied over the range of physically
321 acceptable values [60]. The $maxbrsteep$ parameter was varied from 0.3 to 0.8 and $alpha$ from
322 0.5 to 2.0; both in increments of 0.05. Calibration was achieved by minimizing $RMSE_{TOT}$
323 (Equation (18)) and finding the optimal parameter values. These optimal parameter values and
324 the reduction in error compared to results with default values ($\Delta RMSE_{Hrms,TOT}$) are summarized
325 for all runs in Table 1.

326 **3.2 Wave Transformation**

327 With default parameters, both XBeach modes correctly simulated the wave heights offshore
328 (Gauges 1 – 3, see Figure 1 for gauge locations); however, XB-NH slightly overestimated
329 $H_{rms,TOT}$ in the shoaling region (Gauges 4 and 5) for the majority of the tests simulated (Figure
330 3). Likewise, $H_{rms,TOT}$ on the reef flat (Gauges 7 and 8) was over-predicted for both modes;
331 however, significantly more so by XB-SB. This suggests that the model, with default settings,
332 was dissipating wave energy at a slower rate than physically occurred.

333 Calibrating the maximum breaking wave steepness, $maxbrsteep$ (Table 1) in XB-NH improved
334 $H_{rms,TOT}$ both in the shoaling region and on the reef flat, with an average reduction in root-
335 mean-square error, $\Delta RMSE_{Hrms,TOT} = 0.1 \text{ cm}$. Similarly, calibrating the wave dissipation
336 coefficient, $alpha$ (Table 1) in XB-SB significantly improved the $H_{rms,TOT}$ predictions on the

337 reef flat but at the expense of slightly under-predicting the shoaling wave height
338 ($\Delta RMSE_{Hrms,TOT} = 0.1$ cm). Despite this significant improvement, XB-SB still shows a minor
339 overestimation of wave heights on the reef flat (Figure 3).

340 Considering the spectral wave transformation across the reef profile, XB-NH agreed well with
341 observations at each instrument location (Figure 4). Although XB-SB does not compute the
342 high-frequency wave spectra, it did simulate the low-frequency component of the spectra
343 similarly well to XB-NH. In particular, the spectra over the reef flat (Figure 4g and h) are
344 dominated by energy in the infragravity band, with peaks occurring at frequency, $f \approx 0.02$ Hz
345 or period, $T \approx 50$ s. If we consider the reef-beach system to be an open basin with natural
346 periods, T_m :

$$T_m = \frac{4l_r}{(2m - 1)\sqrt{gh_r}}, m = 1, 2, 3, \dots \quad (19)$$

347 where l_r (= 4.8 m) is the width of the reef flat, $h_r = 1.6$ cm (for test no. 31, Table 1) and m is
348 the mode; we see that the low-frequency peaks correspond to the first reef oscillation mode (m
349 = 1) at $T_l = 48.46$ s. The first mode has a node at the reef crest and an anti-node at the shoreline;
350 thus, leading to the resonant amplification of low-frequency motions at the shoreline [22,59].
351 This energy within the infragravity band manifests itself as long-period oscillations of the run-
352 up signal, on top of which, short-period waves act and result in the individual run-up maxima
353 (Figure 2).

354 **3.3 Mean Water Level**

355 When calibrated, there was a minor reduction of the root-mean-square error in $\bar{\eta}$ predictions
356 for both XB-NH and XB-SB. Considering default settings, XB-NH accurately simulated
357 setdown while $\bar{\eta}$ on the reef flat (setup) was slightly underestimated for some of the tests
358 (Figure 5a and b). On the other hand, XB-SB underestimated wave setdown and slightly over-
359 predicted $\bar{\eta}$ on the reef flat (Figure 5b and c). Calibration resulted in a slightly better
360 representation of $\bar{\eta}$ over the reef flat in the XB-SB model, but had little influence on the XB-
361 NH predictions.

362 **3.4 Run-up**

363 The extreme wave run-up ($R_{2\%}$ and R_{max}) model predictions, using both optimal and default
364 parameter values, were compared to observations. The calibration improved $R_{2\%}$ predictions in
365 both modes, but considerably more so in the XB-SB model (Figure 6). XB-NH (Figure 6b)

366 shows minor scatter and negligible relative bias compared to XB-SB (Figure 6d). The
367 somewhat high positive bias shown by XB-SB even after calibration is attributed to its
368 overestimation of wave energy on the reef flat.

369 With respect to R_{max} , calibration reduced scatter equally between the two XBeach modes
370 (Figure 7). On the other hand, the relative bias was significantly reduced in XB-SB (Figure 7d)
371 with no change to the XB-NH predictions (Figure 7b).

372 **3.5 Calibrated Parameter Values**

373 To assess whether the optimal values for the parameters governing wave dissipation (Table 1)
374 may have some relationship to surfzone processes (i.e. related to key non-dimensional
375 parameters), we consider the role of the following parameters [61,33]: i) Iribarren number,
376 based on the fore-reef slope (ζ_0 , see Equation (2)); ii) the relative reef flat submergence
377 ($(h_r + \bar{\eta})/H_{m0}$); and iii) the offshore wave steepness ($s_0 = 2\pi H_{m0}/gT_p^2$). Optimal
378 *maxbrsteep* parameter values show no clear dependence on any of the three parameters (Figure
379 8a, b and c). Similarly, optimal *alpha* parameter values show no clear relationship with
380 Iribarren number nor offshore wave steepness (Figure 8d and f). However, there appears to be
381 a general trend of increasing optimal *alpha* value with increased relative reef flat submergence
382 (Figure 8e). This is in line with Yao et al. [61] who found that the water depth on the reef flat
383 strongly affected the characteristics of wave breaking over fringing reefs and that the influence
384 of the reef slope may be less significant.

385 With no clear correlation identified, the means of the optima were selected as the calibrated
386 parameter values (*maxbrsteep* = 0.5 and *alpha* = 1.4) to be applied to the second dataset for
387 validation (Table 1).

388 **4 Model Validation: Application to Buckley et al. [17] Experiment**

389 In this section the optimal parameter settings (*maxbrsteep* = 0.5 and *alpha* = 1.4) are validated
390 on the fringing reef profile of Buckley et al. [17].

391 **4.1 Numerical Model Setup**

392 For XB-NH a constant grid resolution of $\Delta x = 2.5$ cm was applied; while for XB-SB, Δx was
393 allowed to vary from 5 cm at the beach slope to 10 cm offshore. It should be noted that for the
394 stated grid resolutions, the run time for the XB-SB simulations was on average half that of XB-
395 NH. Both XBeach modes were forced with TMA-type spectra and initial water-levels to match

396 those observed offshore during the physical measurements (Table 2). The model run-time for
397 both modes was set to 2520 s with outputs at 40 Hz at each of the 18 gauge locations to match
398 the physical experiment.

399 Taking the average of the optimized parameter values previously obtained with the Demirbilek
400 et al. [24] experiment (Section 3.5, Table 1), the XB-NH simulations were forced with
401 $maxbrsteep = 0.5$; and the XB-SB simulations with an $alpha = 1.4$. To represent the wooden
402 flume bottom, a Manning coefficient, $n = 0.012 \text{ s/m}^{1/3}$ [62] was applied. Likewise, a numerical
403 run-up gauge with $rugdepth = 0.4 \text{ cm}$ was specified to represent the precision of the run-up
404 rake used during the physical experiment, which is slightly less accurate than the capacitance
405 wire used in the previous case. This $rugdepth$ value takes into account the minimum thickness
406 of water necessary to be registered by the instrument plus the possible error due to the
407 horizontal spacing of the rake sensors. Both XBeach modes were also run with default settings
408 for comparison.

409 **4.2 Wave Transformation**

410 Compared to the model with default settings, the reduced maximum breaking wave steepness
411 had little impact on XB-NH $H_{rms,TOT}$ predictions (Figure 9). On the other hand, the increased
412 $alpha$ value improved XB-SB $H_{rms,TOT}$ predictions on the reef flat but at the expense of further
413 reducing $H_{rms,TOT}$ in the shoaling region. Overall XB-NH (average $RMSE_{H_{rms,TOT}} = 0.6 \text{ cm}$)
414 simulated wave transformation more accurately than XB-SB (average $RMSE_{H_{rms,TOT}} = 0.9 \text{ cm}$)
415 (Table 2).

416 Using the TMA-type boundary condition, the computed spectrum at Gauge No. 1 agrees well
417 with observations (Figure 10a). XB-NH simulates the transformation of wave energy from the
418 high-frequency to low-frequency bands across the reef profile and is in good agreement with
419 observations (Figure 10). As XB-SB resolves low-frequency waves only, its exclusion of wave
420 energy at higher frequencies is to be expected. XB-SB overpredicts the low-frequency wave
421 energy offshore (Figure 10a); however, predictions become increasingly more accurate post
422 wave-breaking (Figure 10e, f, g and h). Like the previous case, the reef flat is dominated by
423 low-frequency motions (Figure 10g and h) with peaks around $f \approx 0.01 \text{ Hz}$ ($T \approx 100 \text{ s}$). Applying
424 Equation (19), this corresponds to the first mode based on the natural periods of the reef at T_I
425 $= 89 \text{ s}$ ($f_I = 0.011 \text{ Hz}$). Thus, infragravity motions would increase from the reef crest (Figure
426 10e) to the inner reef flat (Figure 10h) and shoreline.

427 4.3 Mean Water Levels

428 Compared to the model with default settings, the reduction in *maxbrsteep* had little impact on
429 the mean water level ($\bar{\eta}$) predictions using the XB-NH model (Figure 11). What is striking,
430 however, is the consistent under-prediction of $\bar{\eta}$ on the reef flat by XB-NH. This was observed
431 for the majority of the 16 tests simulated but more noticeably so in those with higher H_{m0} . On
432 the other hand, XB-SB accurately simulates $\bar{\eta}$ on the reef flat but does not quite capture
433 setdown. The increased *alpha* value resulted in a reduction in $\bar{\eta}$ on the reef flat and a slight
434 increase in the error compared to the model with default settings (Figure 11). Despite this, the
435 overall error values of the XB-SB (avg. $RMSE_{MWL} = 0.3$ cm) simulations were markedly lower
436 than those of XB-NH (avg. $RMSE_{MWL} = 0.5$ cm) (Table 2).

437 4.4 Run-up

438 Compared to default settings, the XB-NH and XB-SB models with the new parameter values
439 (*maxbrsteep* = 0.5 and *alpha* = 1.4) show significant improvement in both scatter and relative
440 bias for $R_{2\%}$ (Figure 12) and R_{max} (Figure 13) predictions. Like the previous case, this
441 improvement is most noticeable in the XB-SB model which shows a high relative bias in its
442 $R_{2\%}$ predictions (with default settings) (Figure 12c). Overall both modes with calibrated
443 parameter settings show minor scatter and relative bias error values. Both XBeach modes
444 perform comparably well despite the fact that sea-swell band motions are not explicitly
445 computed by XB-SB and the consistent under-prediction in $\bar{\eta}$ on the reef flat observed by XB-
446 NH.

447 5 Discussion

448 5.1 The Influence of Key Parameters Governing Wave Breaking Dissipation

449 The key parameters controlling the dissipation of wave energy by breaking in XB-NH
450 (*maxbrsteep*) and XB-SB (*alpha*) were optimized for fringing reef environments using the
451 Demirbilek et al. [24] dataset. To have confidence in the model predictions, the parameter
452 values obtained through calibration should be physically based. In XB-NH, the onset of wave
453 breaking is controlled by the maximum breaking wave steepness criterion and specified by the
454 *maxbrsteep* (by default = 0.6) parameter. On the other hand, the dissipation coefficient, *alpha*
455 (by default = 1) is a calibration constant in the wave breaking formulation and governs the rate
456 of dissipation by breaking waves. The steep forereef slopes of fringing-reef environments are

457 known to cause intense dissipation of waves in a relatively narrow zone (reef crest) which then
458 reform as bores and propagate across the reef flat before reaching the shoreline as run-up. The
459 model must therefore correctly capture this wave attenuation to ensure the accuracy of the
460 wave-height estimates on the reef flat. In XB-NH this was achieved by reducing *maxbrsteep*
461 (calibrated value = 0.5) and allowing wave-breaking to initiate sooner. In XB-SB, *alpha* was
462 increased (calibrated value = 1.4) to mimic the rapid and intense dissipation of wave energy at
463 the reef crest.

464 Our results are also in line with Roelvink et al. [63] who found that reducing *maxbrsteep* to 0.4
465 led to an improved representation of wave-heights over a dike profile; and with Van Geer et al.
466 [64] who recommended a higher-than-default *alpha* value of 1.26 in their systematic derivation
467 of optimal XBeach 1D settings for application on mild-sloping sandy coasts in the Netherlands.
468 Similarly, Su et al. [65] found optimal *alpha* values between 1.1 and 1.6 in their application of
469 a similar dissipation model [66] to the Demirbilek et al. [24] dataset. However, the reduced
470 *maxbrsteep* value is in contrast with Buckley et al. [33] who found much higher optimal values
471 for the equivalent parameter in his application of the SWASH (one-layer) model to the same
472 case [24]. Though XB-NH and SWASH (one-layer) are comparable, the models utilize slightly
473 different criteria for the hydrostatic front approximation. Additionally, Buckley et al. [33]
474 optimized their model considering sea-swell root-mean-square wave height ($H_{rms,SS}$) alone,
475 whereas both the total root-mean-square wave height ($H_{rms,TOT}$) and mean water level ($\bar{\eta}$) are
476 considered here. Therefore, the difference between results is not unexpected.

477 The overall impact of reducing *maxbrsteep* in XB-NH and increasing *alpha* in XB-SB were
478 similar for both modes; that is, an improved representation of wave energy on the reef flat was
479 observed. Use of these new parameter values also resulted in a reduction in the maximum wave-
480 height (more so in XB-SB), a slightly earlier onset of breaking and a reduction in $\bar{\eta}$ on the reef
481 flat (negligible in the XB-NH mode). Given that the identified parameter values are based on
482 a 1D (alongshore uniform) fringing reef profile without large bottom roughness, further work
483 should assess how these parameter values may change for different types of reefs in a field
484 setting displaying different morphological and bottom roughness characteristics.

485 It may be argued that XB-SB, having more tuneable parameters, may be better calibrated for a
486 particular site and range of conditions once data is available; while, XB-NH, as a more
487 complete model may be more applicable to areas where data is limited. However, in the present
488 study we considered only a single parameter in each model mode for calibration. Likewise,

489 both models were calibrated on one dataset and then applied to another for validation, with no
490 further tuning. Thus, their performance here is considered comparable.

491 **5.2 Wave Transformation and Mean Water Level on the Reef Flat**

492 XB-NH with calibrated parameter values accurately simulated the transformation of waves
493 from high to low frequencies across the reef profile (Figure 4 and Figure 10). In addition, the
494 model was able to capture wave shoaling over the reef slope and wave breaking near the reef
495 crest (Figure 3 and Figure 9). However, despite the accurate representation of $H_{rms,TOT}$, $\bar{\eta}$ on
496 the reef flat was consistently under-predicted for the Buckley et al. [17] experiment (Figure
497 11). Moreover, increasing the maximum wave breaking steepness offered little improvement,
498 as seen in the model results with default settings ($maxbrsteep = 0.6$). On the other hand, XB-
499 SB with calibrated parameter values under-predicted $H_{rms,TOT}$ in the shoaling region but
500 overestimated $H_{rms,TOT}$ on the reef flat. Unlike its short-wave resolving counterpart, XB-SB was
501 able to quite accurately predict $\bar{\eta}$ on the reef flat which suggests that the discrepancy is specific
502 to the XB-NH mode.

503 Considering previous studies, similar results using short-wave resolving wave models were
504 obtained by Stansby and Feng [67] who also found significant under-predictions in mean water
505 level (setup) when their non-linear shallow water wave model was compared to observations
506 for a laboratory experiment with a steep dike profile (1:2 slope). That study found significant
507 variation in the observed velocity, with high velocities in the upper (roller) region and almost
508 stagnant water below. However, their depth-averaged model, like XB-NH, was unable to
509 accurately capture these distinct zones in the water column.

510 With respect to reef environments, Yao et al. [68] also compared their fully non-linear
511 Boussinesq model to the results of several laboratory fringing reef experiments. Like the
512 present study, their model showed good agreement when applied to the Demirbilek et al. [24]
513 dataset but also under-predicted setup on the reef flat when applied to a steeper reef profile (1:6
514 slope) under plunging waves. Likewise, Fang et al. [31] concluded that their Boussinesq
515 numerical model, like several others, had a tendency to underestimate setup on the reef flat.
516 This was especially the case for highly non-linear waves.

517 Collectively, these findings lend support to those of Buckley et al. [17] who found, by analysing
518 the detailed cross-shore momentum balances through the surfzone, that excluding wave roller
519 dynamics led to an under-prediction in mean water level on the reef flat. A wave roller,

520 described simply as passive areas of circulating water transported onshore by breaking waves,
521 is considered to be one of the main contributors to nonlinear wave forcing in the surfzone [69].
522 Depth-averaged short-wave resolving models, based on either non-linear shallow water or
523 Boussinesq equations, do not simulate wave overturning or plunging. Consequently, they
524 exclude the formation and impact of wave rollers that act as an additional source of kinetic
525 energy (KE) and result in a higher $\bar{\eta}$ on the reef flat. Thus, XB-NH may accurately predict
526 $H_{rms,TOT}$ a measure of potential energy (PE) but under-predict the total wave energy (PE + KE).
527 In line with the findings of Fang et al. [31], the under-prediction of wave-induced setup became
528 more significant with increased wave nonlinearity (A_0/h) (Table 2). By disabling the roller
529 model in XB-SB we are able to demonstrate the impact of the wave roller on setup predictions
530 (Figure 14). XB-SB, without wave roller dynamics, also considerably underestimates $\bar{\eta}$ on the
531 reef flat, further confirming the importance of including these dynamics in wave models
532 applied to steep reef slopes.

533 **5.3 Extreme Wave Run-up**

534 When applying the model to the Buckley et al. [17] experiment, both XBeach modes showed
535 some deviations from observations in their prediction of wave heights and mean water levels:
536 XB-NH in its under-prediction of setup on the reef flat and XB-SB with its over-prediction of
537 wave energy on the reef flat. Yet, both modes predicted $R_{2\%}$ (Figure 12) and R_{max} (Figure 13)
538 with a high degree of accuracy, with only minor scatter and relative bias error values. To further
539 investigate this, the model performance in simulating the individual physical processes that
540 contribute to total run-up (shoreline setup and swash) was also assessed (Figure 15).

541 Even though XB-NH under-predicted shoreline set-up, $\langle\eta\rangle$ (Rel. bias = -0.082), the overall
542 scatter is relatively small and likely within acceptable limits ($SCI \leq 0.15$, following Roelvink
543 et al. [70]) (Figure 15a). Likewise, infragravity-band swash, S_{IG} is quite accurately predicted
544 by XB-NH with almost no bias (Figure 15c). On the other hand, sea-swell band swash, S_{SS}
545 shows relatively high scatter but minor positive relative bias (Figure 15e). It appears that the
546 accurate representation of the dominant S_{IG} parameter coupled with the minor underestimation
547 of $\langle\eta\rangle$ and minor over-prediction of S_{SS} allowed the XB-NH model to estimate total run-up
548 reasonably well.

549 From the cumulative frequency curves (Figure 16a, b and c) we see that compared to
550 observations, the XB-NH curve is shifted to the left but with a similar steepness. This shift
551 suggests that the mean of the XB-NH run-up time series is lower than that of the observed, as

552 seen also in the $\langle\eta\rangle$ model-data comparison (Figure 15a). On the other hand, the similarity in
553 shape suggests that the standard deviation of the XB-NH run-up time series is similar to what
554 was observed, as can also be seen in the S_{IG} and S_{SS} comparisons (Figure 15c and e).

555 In contrast, the XB-SB cumulative frequency curves are shifted slightly to the right of that
556 observed, suggesting that the mean of the distribution is higher than that of the observed (Figure
557 16a, b and c). This is also observed in the $\langle\eta\rangle$ model-data comparison plot where the model
558 shows acceptable scatter but a high positive rel. bias (Figure 15b). In line with previous studies,
559 XB-SB predicts S_{IG} (Figure 15d) more accurately than S_{SS} (Figure 15f); with S_{SS} predictions
560 showing substantial scatter and negative relative bias. Although more accurate, S_{IG} predictions
561 show relatively high scatter and positive bias. This is attributed to the XB-SB model's
562 overestimation of wave energy on the reef flat. Although not shown here, it is also worth noting
563 that XB-SB, with the roller model turned off, considerably under-predicted total run-up and its
564 components: $\langle\eta\rangle$, S_{SS} and S_{IG} .

565 In line with previous studies, our results also show the presence of a trapped infragravity wave
566 over the reef flat (Figure 4 and Figure 10) which is resonantly amplified at the shoreline [22,59].
567 Both the modelled and observed swash spectra confirm that the majority of the energy at the
568 shoreline is indeed in the infragravity band (Figure 16d, e and f). This fact, along with the
569 overestimation of $\langle\eta\rangle$ compensated for the under-prediction of S_{SS} by XB-SB and allowed the
570 short-wave averaged (but wave-group resolving) model to perform comparably well to XB-
571 NH.

572 **6 Conclusions**

573 The short-wave resolving and short-wave averaged modes of the XBeach numerical model
574 were applied to simulate wave run-up for two fringing reef profiles. To mimic the rapid and
575 intense wave dissipation during breaking, the key parameters in each model (*maxbrsteep* in
576 XB-NH and *alpha* in XB-SB) were calibrated on a dataset of wave breaking and run-up over a
577 relatively steep composite slope [24]. The calibrated model was then applied to the second
578 dataset of wave transformation and run-up over an even steeper constant slope for validation
579 [17]. Results show good agreement with observations and suggest that in fringing reef
580 environments XB-SB is able to perform on-par with XB-NH in predicting extreme wave run-
581 up. This is in contrast with literature on typical, sandy coasts [47,71,72] but may be explained,

582 in part, by the dominance of infragravity motions at the shoreline; and secondly, due to the
583 exclusion of wave roller dynamics in XB-NH.

584 This study demonstrated the ability of the XBeach numerical model to accurately predict
585 extreme wave run-up. Given the limited applicability of the existing empirical models to
586 fringing reef-lined coasts, XBeach may prove to be a powerful tool for coastal flood mitigation
587 in tropical and subtropical regions. Future work should examine the effect of coral reef
588 roughness on run-up predictions by applying the model to a fringing reef with large bottom
589 roughness (e.g. Buckley et al. [73] dataset). As both experiments considered here had smooth
590 bottoms, the influence of bottom friction was not assessed. Likewise, both datasets comprised
591 one-dimensional profiles. Therefore, future work should also extend the application of XBeach
592 to field cases in 2DH to assess the influence of alongshore variability in reef morphology on
593 run-up. Finally, the incorporation of wave roller dynamics in the short-wave resolving XB-NH
594 model should be considered. Such an approach would build on work done by Madsen et al. [74]
595 who applied a geometrical approach to determine the shape, position and overall impact of the
596 wave roller on the momentum flux.

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802	($H_{m0}/2$) and h = offshore water depth.	29
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816	degrees-of-freedom.	33
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818	(c) 48 (Demirbilek et al. [24] experiment) for XB-NH (blue) and XB-SB (red) before (dashed lines) and	
819	after (solid lines) calibration showing root-mean-square error (RMSE) values for the calibrated runs.	
820	Note: tests were selected to cover the range of offshore wave and water level conditions simulated.	34
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822	XB-SB (red) before (unfilled) and after (filled) calibration showing SCI and Relative Bias error values	
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824	represent $\pm 25\%$ error.	35
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826	before (unfilled) and after (filled) calibration showing SCI and Relative Bias error values (Demirbilek	
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830	with non-dimensional wave parameters: ξ_0 (a, d), $(hr + \eta)Hm0$ (b, e) and s_0 (c, f).	37
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833	with default (<i>maxbrsteep</i> = 0.6, <i>alpha</i> = 1) and calibrated (<i>maxbrsteep</i> = 0.5, <i>alpha</i> = 1.4) parameter	

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838 et al. [17] experiment) for XB-NH (blue) and XB-SB (red). Dashed black lines represent the split
839 frequency ($f_{split} = fp2$) and the resolution of the spectra is 0.01 Hz with approximately 125 degrees-
840 of-freedom..... 39

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843 0.6 , $alpha = 1$) and calibrated ($maxbrsteep = 0.5$, $alpha = 1.4$) parameter values showing root-mean-
844 square error (RMSE) values. Note: tests were selected to cover the range of offshore wave conditions
845 simulated..... 40

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847 XB-SB (red) with default ($maxbrsteep = 0.6$, $alpha = 1$) and calibrated ($maxbrsteep = 0.5$, $alpha = 1.4$)
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849 solid lines represent perfect agreement. Black dashed lines represent $+ - 25\%$ error..... 41

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851 with default ($maxbrsteep = 0.6$, $alpha = 1$) and calibrated ($maxbrsteep = 0.5$, $alpha = 1.4$) parameter
852 values showing SCI and Relative Bias error values (Buckley et al. [17] experiment). Black solid lines
853 represent perfect agreement. Black dashed lines represent $+ - 25\%$ error. 42

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855 showed the highest nonlinearity ($A0h$) and root-mean-square error in mean water level predictions
856 ($RMSE_{MWL}$) for XB-NH (blue), XB-SB with roller model (red solid) and XB-SB without roller model
857 (red dash-dot). 43

858 **Figure 15** Modelled and observed (a, b) shoreline setup, (c, d) infragravity-band swash and (e, f) sea-swell
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860 SCI and Rel. bias error values. 44

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862 representative tests no. (a, d) 5, (b, e) 10 and (c, f) 14 (Buckley et al. [17] experiment) for both XBeach
863 modes. Horizontal dashed lines represent 2% exceedance, vertical dashed lines represent the split
864 frequency ($f_{split} = fp2$) and the resolution of the spectra is 0.01 Hz with approximately 125 degrees-
865 of-freedom..... 45

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871 **Table 1 Summary of test conditions (Demirbilek et al. [24] experiment) with Iribarren number**
872 **(ξ_0) based on the forereef slope (1:10.6), relative reef flat submergence ($(h_r + \bar{\eta})/H_{m0}$), offshore**
873 **wave steepness (s_0), optimal *maxbrsteep* and *alpha* values and the reduction in error ($\Delta RMSE_{TOT}$)**
874 **achieved through calibration.**

Test No.	H_{m0} (cm)	T_p (s)	h_r (cm)	ξ_0	$\frac{h_r + \bar{\eta}}{H_{m0}}$	s_0	XB-NH		XB-SB	
							Opt. <i>maxbrsteep</i>	$\Delta RMSE_{TOT}$ (cm)	Opt. <i>alpha</i>	$\Delta RMSE_{TOT}$ (cm)
15	6.2	1	5.1	0.47	0.90	0.04	0.45	0.00	2	0.07
16	5.2	1.5	5.1	0.78	1.08	0.01	0.35	0.11	2	0.14
17	7.8	1.5	5.1	0.63	0.76	0.02	0.4	0.14	1.4	0.09
18	8.5	2	5.1	0.81	0.73	0.01	0.5	0.02	1.4	0.19
19	8.3	2.5	5.1	1.02	0.76	0.01	0.8	0.07	1.4	0.21
20	6.1	1.25	5.1	0.60	0.92	0.03	0.4	0.08	1.8	0.06
21	8.2	1.75	5.1	0.72	0.73	0.02	0.4	0.11	1.4	0.13
26	5.8	1	1.6	0.49	0.41	0.04	0.8	0.02	1.25	0.04
27	5.5	1.25	1.6	0.63	0.47	0.02	0.75	0.02	1.35	0.08
28	4.7	1.5	1.6	0.82	0.55	0.01	0.3	0.02	1.75	0.17
29	7.1	1.5	1.6	0.66	0.42	0.02	0.3	0.07	1.2	0.07
30	7.6	1.75	1.6	0.75	0.42	0.02	0.35	0.16	1.35	0.19
31	8.5	2	1.6	0.81	0.41	0.01	0.45	0.09	1.35	0.24
32	7.9	2.5	1.6	1.05	0.46	0.01	0.7	0.04	1.35	0.23
33	5.6	1	0	0.50	0.20	0.04	0.8	0.03	1.15	0.02
34	4.5	1.5	0	0.83	0.27	0.01	0.3	0.06	1.4	0.16
35	4.5	1.5	0	0.83	0.29	0.01	0.35	0.05	1.4	0.16
36	6.8	1.5	0	0.68	0.26	0.02	0.35	0.08	1.1	0.05
37	7.6	1.75	0	0.75	0.26	0.02	0.35	0.31	1.2	0.15
38	8.4	2	0	0.81	0.26	0.01	0.4	0.22	1.4	0.32
39	7.7	2.5	0	1.06	0.31	0.01	0.7	0.01	1.4	0.30
44	3.2	1	3.1	0.66	1.03	0.02	0.8	0.00	1.65	0.02
45	6.1	1	3.1	0.48	0.59	0.04	0.8	0.02	1.1	0.01
46	5.9	1.25	3.1	0.61	0.63	0.02	0.8	0.01	1.35	0.06
47	5	1.5	3.1	0.79	0.74	0.01	0.35	0.01	1.65	0.12
48	7.5	1.5	3.1	0.65	0.53	0.02	0.4	0.02	1.35	0.07
57	7.7	1.75	3.1	0.74	0.55	0.02	0.35	0.08	1.25	0.11
58	8.5	2	3.1	0.81	0.52	0.01	0.45	0.05	1.3	0.19
59	8.2	2.5	3.1	1.03	0.55	0.01	0.7	0.02	1.4	0.26
Average (avg.)							0.51	0.07	1.42	0.13

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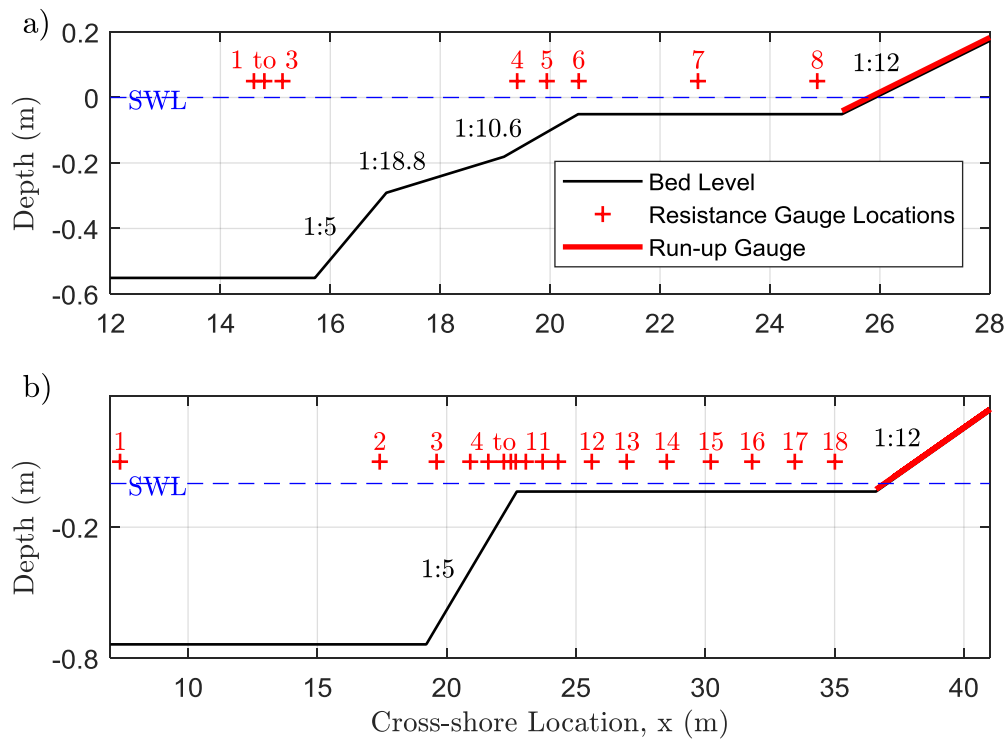
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877 **Table 2 Summary of test conditions (Buckley et al. [17] experiment), Iribarren number (ξ_0) based**
878 **on the forereef slope (1:5), wave nonlinearity (A_0/h) and error values in root-mean-square wave**
879 **height ($RMSE_{Hrms,TOT}$) and mean water-level ($RMSE_{MWL}$) predictions. Note: A_0 = offshore wave**
880 **amplitude ($H_{m0}/2$) and h = offshore water depth.**

Test No	H_{m0} (cm)	T_p (s)	h_r (cm)	ξ_0	A_0/h	XB-NH			XB-SB		
						$RMSE_{Hrms,TOT}$ (cm)	$RMSE_{MWL}$ (cm)	$RMSE_{TOT}$ (cm)	$RMSE_{Hrms,TOT}$ (cm)	$RMSE_{MWL}$ (cm)	$RMSE_{TOT}$ (cm)
1	4	2.26	4	2.82	0.03	0.27	0.05	0.32	0.49	0.06	0.55
2	8	2.26	4	2.00	0.05	0.47	0.27	0.74	0.80	0.17	0.97
3	12	2.26	4	1.63	0.08	0.57	0.47	1.04	0.90	0.36	1.26
4	16	2.26	4	1.41	0.11	0.72	0.63	1.35	1.00	0.38	1.38
5	20	2.26	4	1.26	0.14	0.60	0.86	1.46	0.97	0.48	1.45
6	24	2.26	4	1.15	0.16	0.61	1.10	1.71	1.10	0.54	1.64
7	8	1.31	4	1.16	0.05	0.69	0.40	1.09	0.64	0.24	0.88
8	8	3.2	4	2.83	0.05	0.64	0.34	0.98	1.10	0.31	1.41
9	8	2.26	0	2.00	0.06	0.41	0.55	0.96	0.63	0.29	0.92
10	8	2.26	2	2.00	0.06	0.46	0.41	0.87	0.63	0.27	0.90
11	8	2.26	6	2.00	0.05	0.57	0.17	0.74	0.80	0.18	0.98
12	8	2.26	9	2.00	0.05	0.66	0.11	0.77	0.85	0.12	0.97
13	16	2.26	0	1.41	0.11	0.50	0.85	1.35	0.76	0.41	1.17
14	16	2.26	2	1.41	0.11	0.52	0.78	1.30	0.78	0.41	1.19
15	16	2.26	6	1.41	0.11	0.77	0.60	1.37	1.10	0.45	1.55
16	16	2.26	9	1.41	0.10	0.94	0.41	1.35	1.30	0.41	1.71
Average (avg.)						0.59	0.50	1.09	0.87	0.32	1.18

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883

884 **Figure 1 Profiles of fringing reefs simulated, showing instrument locations for (a) Demirbilek et**
885 **al. [24] and (b) Buckley et al. [17] experiments.**

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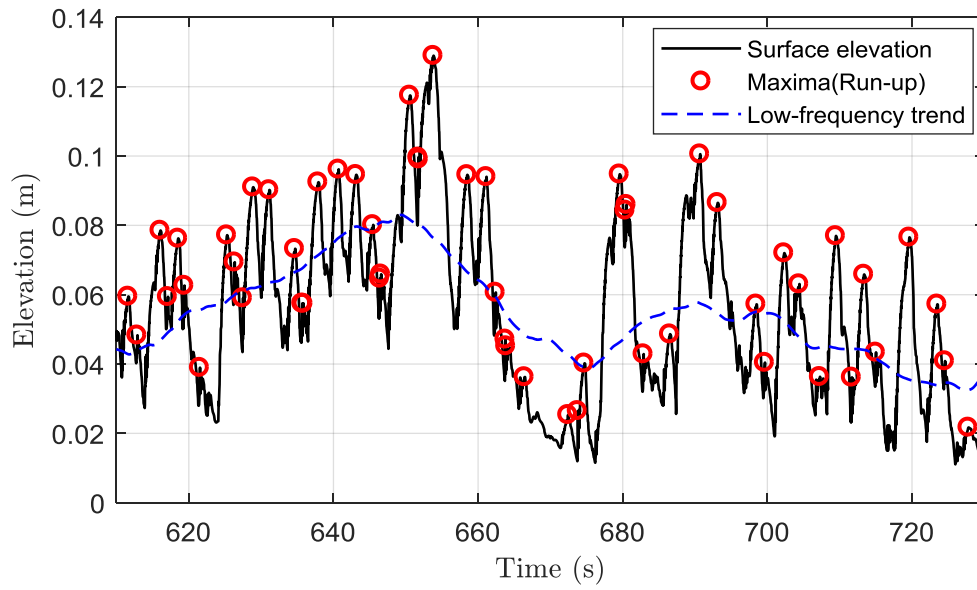
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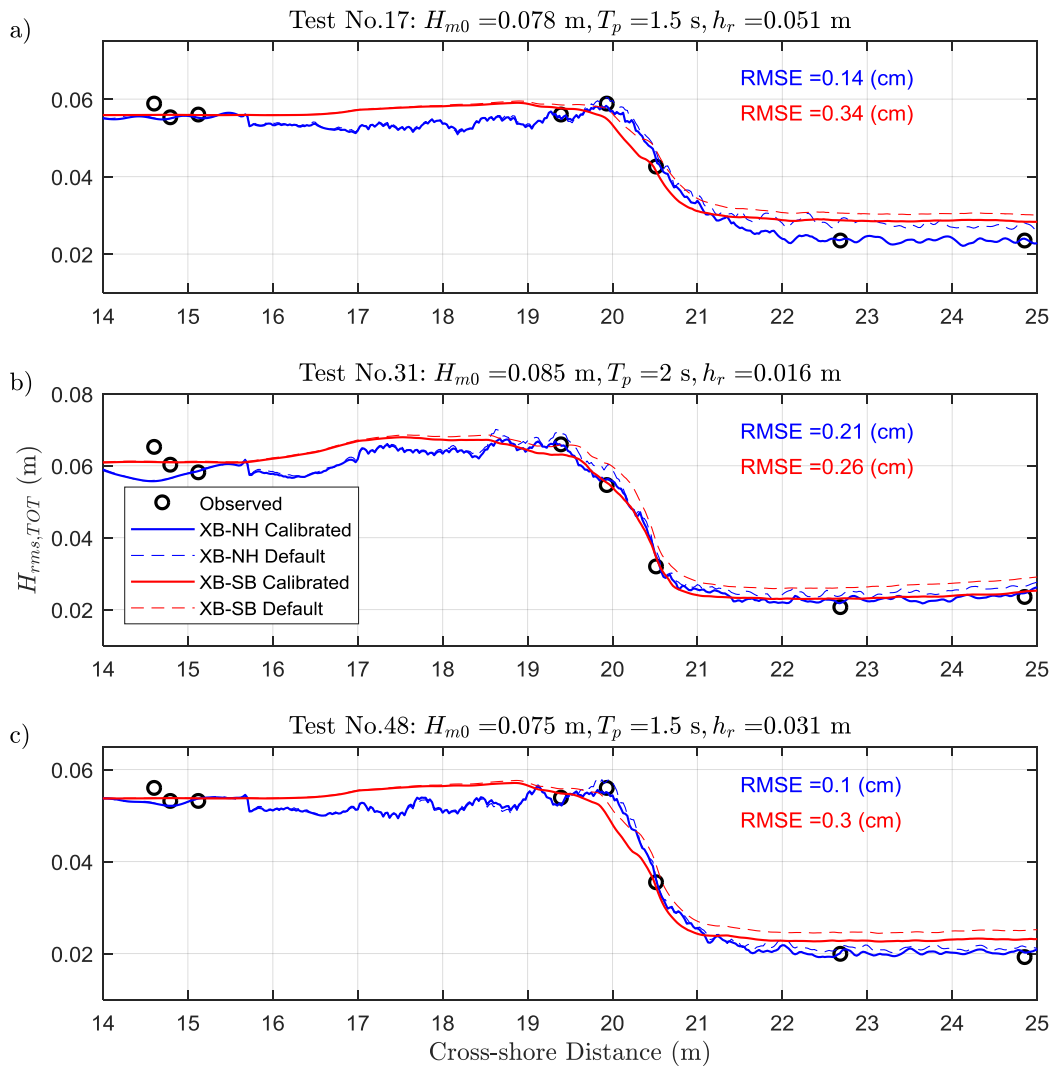


892

893 **Figure 2 Example run-up (swash)time series showing extracted maxima and low-frequency trend.**

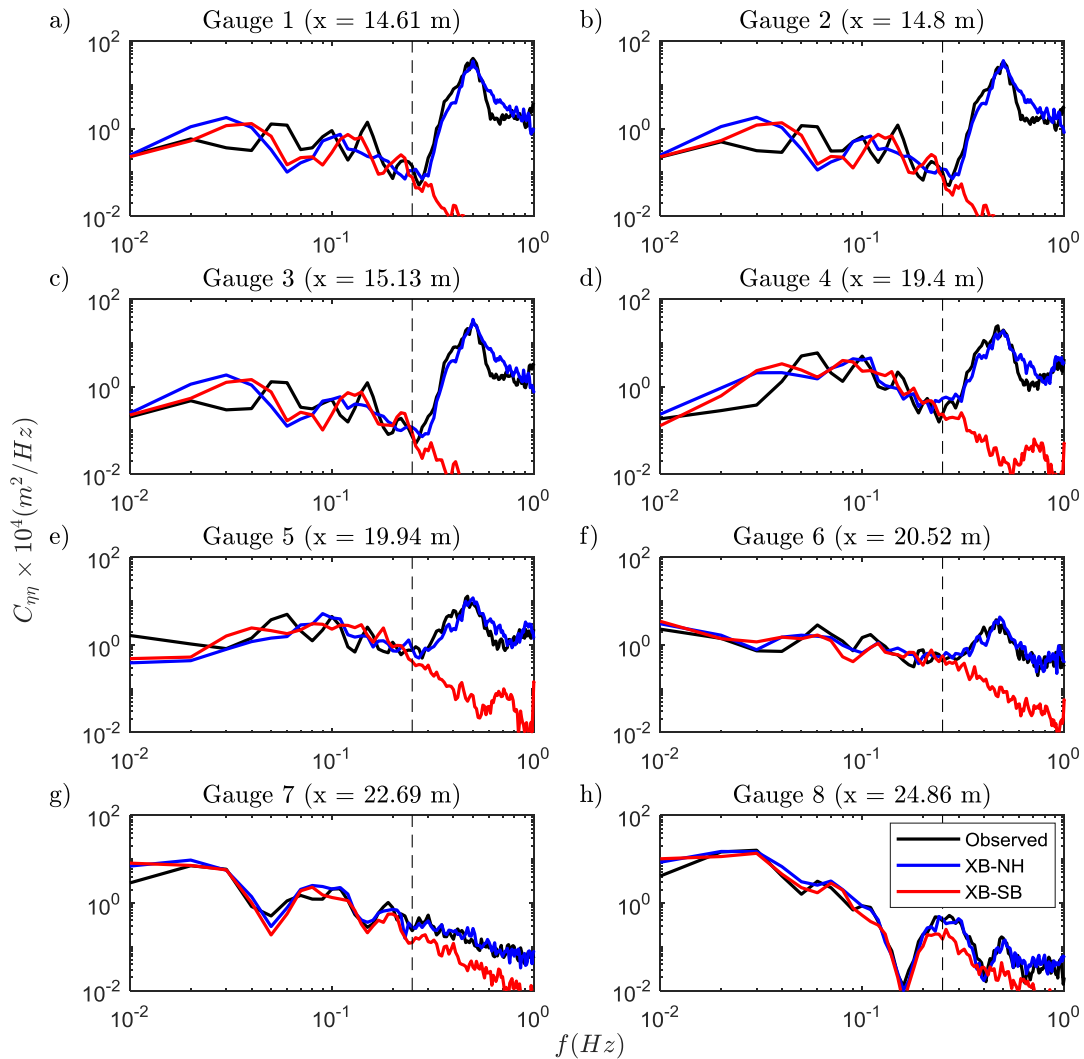
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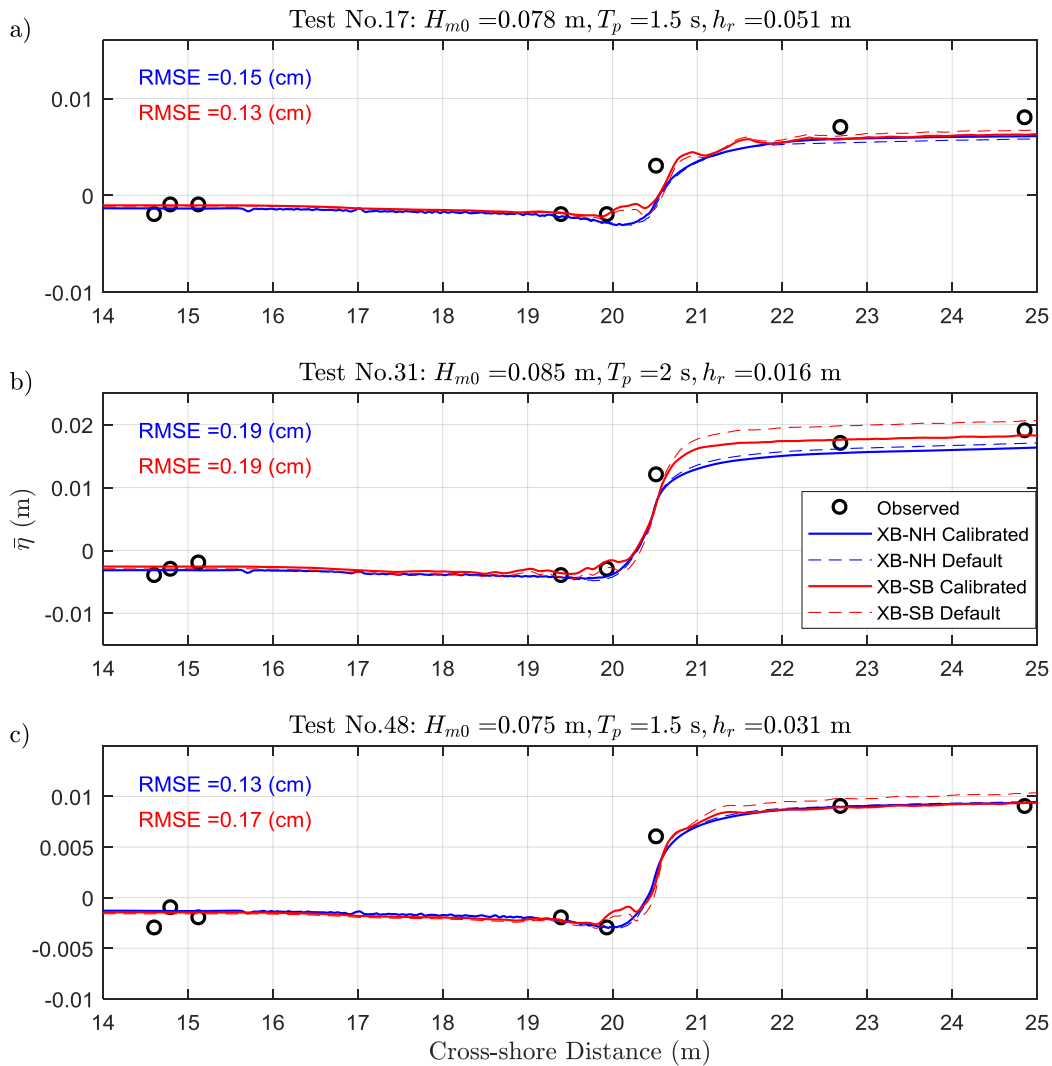
897

898 **Figure 3 Modelled and observed total root-mean-square wave height ($H_{rms,TOT}$) profiles for**
 899 **representative tests no. (a) 17, (b) 31 and (c) 48 (Demirbilek et al. [24] experiment) for XB-NH**
 900 **(blue) and XB-SB (red) before (dashed lines) and after (solid lines) calibration showing root-**
 901 **mean-square error (RMSE) values for the calibrated runs. Note: tests were selected to cover the**
 902 **range of offshore wave and water level conditions simulated.**

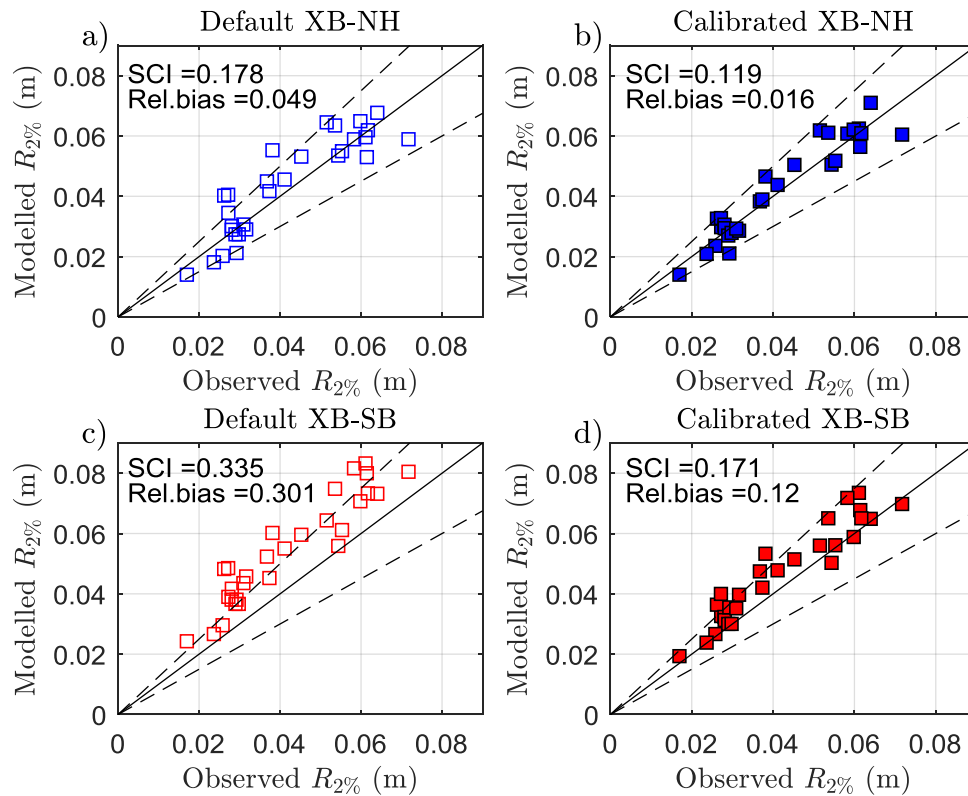


904

905 **Figure 4 Modelled and observed spectral transformation of wave energy from (a, b) offshore, (c)**
 906 **the shoaling region, (d, e, f) during breaking and (g, h) on the reef flat for representative test no.**
 907 **31 (Demirbilek et al. [24] experiment) for XB-NH (blue) and XB-SB (red). Dashed black lines**
 908 **represent the split frequency ($f_{split} = fp/2$) and the resolution of the spectra is 0.01 Hz with**
 909 **approximately 51 degrees-of-freedom.**

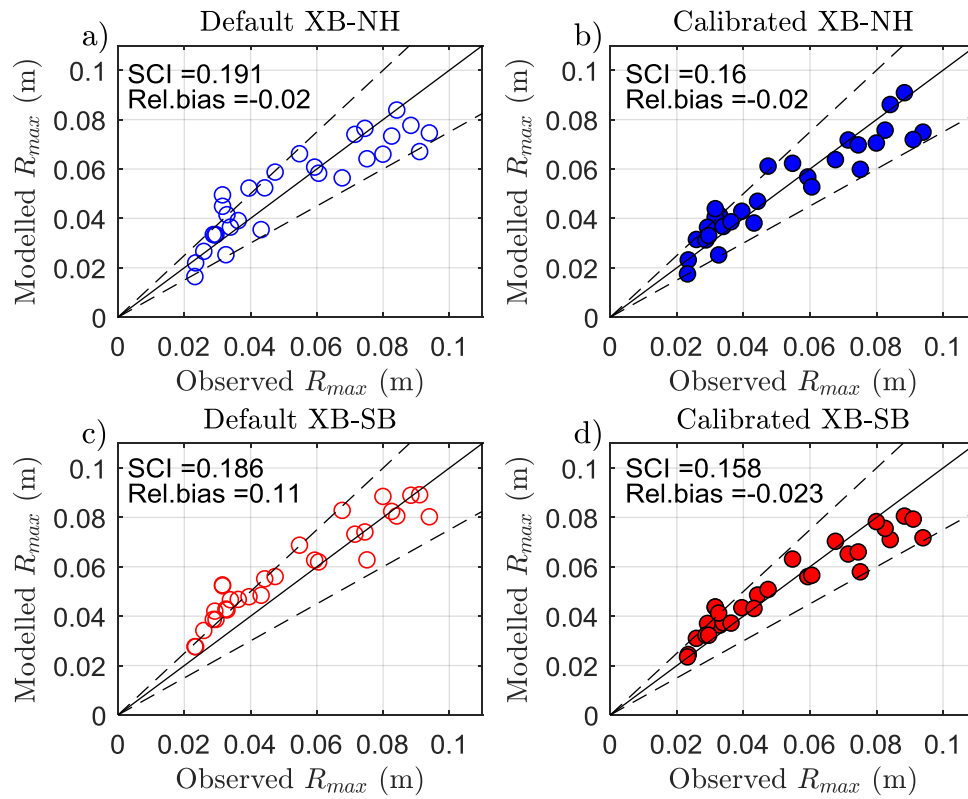


912 **Figure 5 Modelled and observed mean water level ($\bar{\eta}$) profiles for representative tests no. (a) 17,**
 913 **(b) 31 and (c) 48 (Demirbilek et al. [24] experiment) for XB-NH (blue) and XB-SB (red) before**
 914 **(dashed lines) and after (solid lines) calibration showing root-mean-square error (RMSE) values**
 915 **for the calibrated runs. Note: tests were selected to cover the range of offshore wave and water**
 916 **level conditions simulated.**



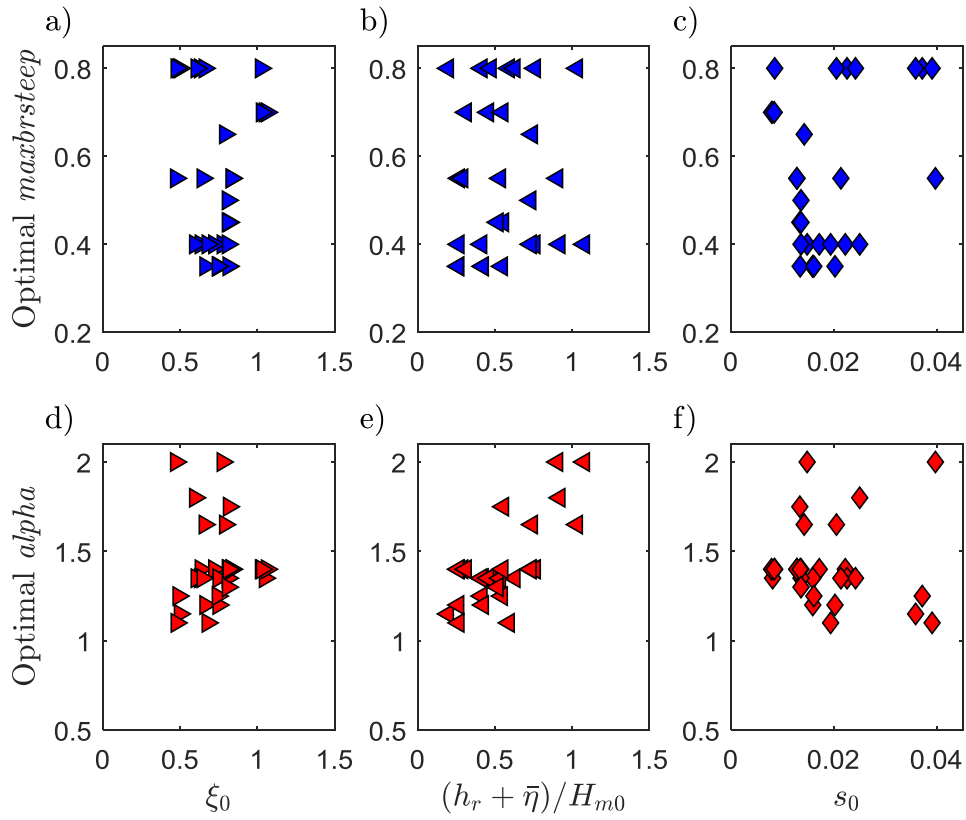
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919 **Figure 6 Modelled and observed two-percent exceedance run-up ($R_{2\%}$) comparison for XB-NH**
 920 **(blue) and XB-SB (red) before (unfilled) and after (filled) calibration showing SCI and Relative**
 921 **Bias error values (Demirbilek et al. [24] experiment). Black solid lines represent perfect**
 922 **agreement. Black dashed lines represent $\pm 25\%$ error.**



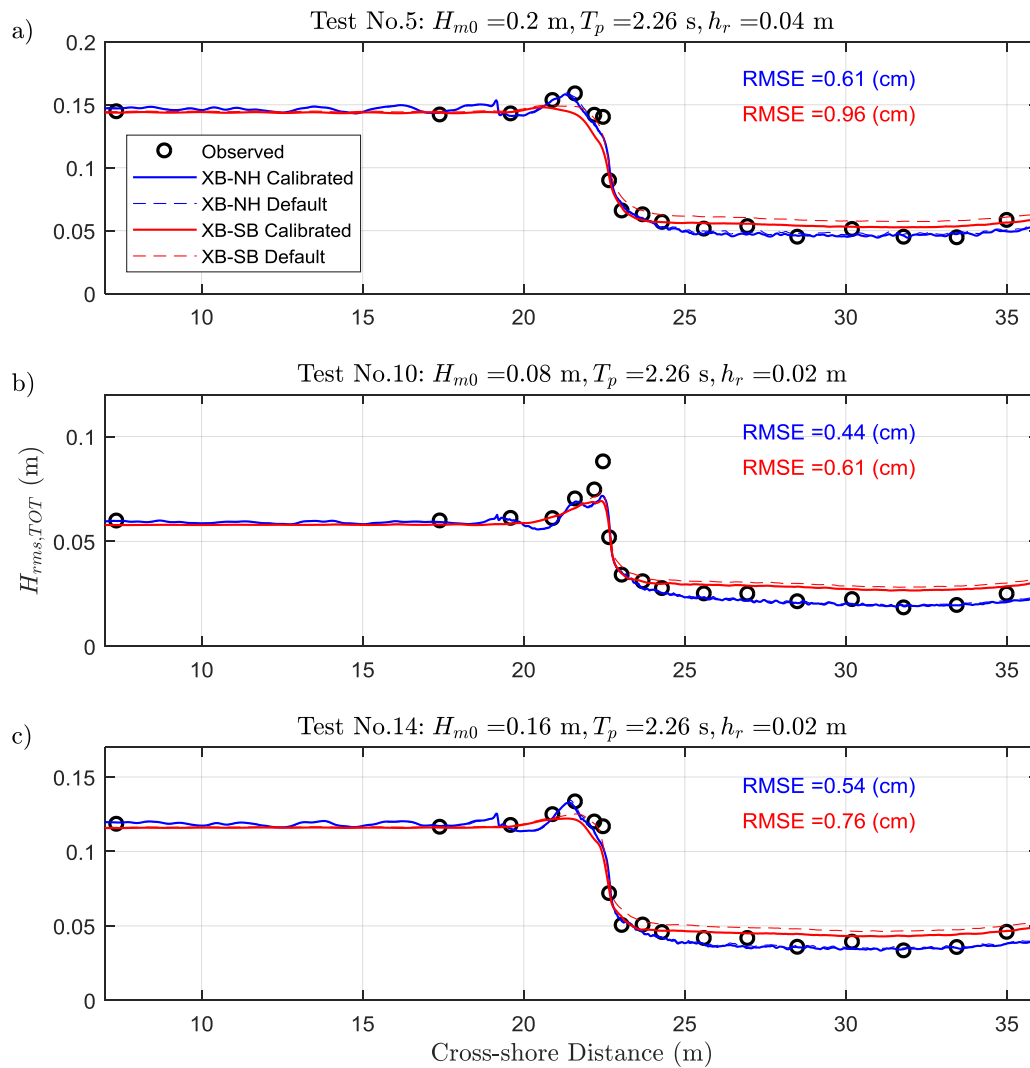
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924 **Figure 7 Modelled and observed maximum run-up (R_{max}) comparison for XB-NH (blue) and XB-**
 925 **SB (red) before (unfilled) and after (filled) calibration showing SCI and Relative Bias error values**
 926 **(Demirbilek et al. [24] experiment). Black solid lines represent perfect agreement. Black dashed**
 927 **lines represent $\pm 25\%$ error.**



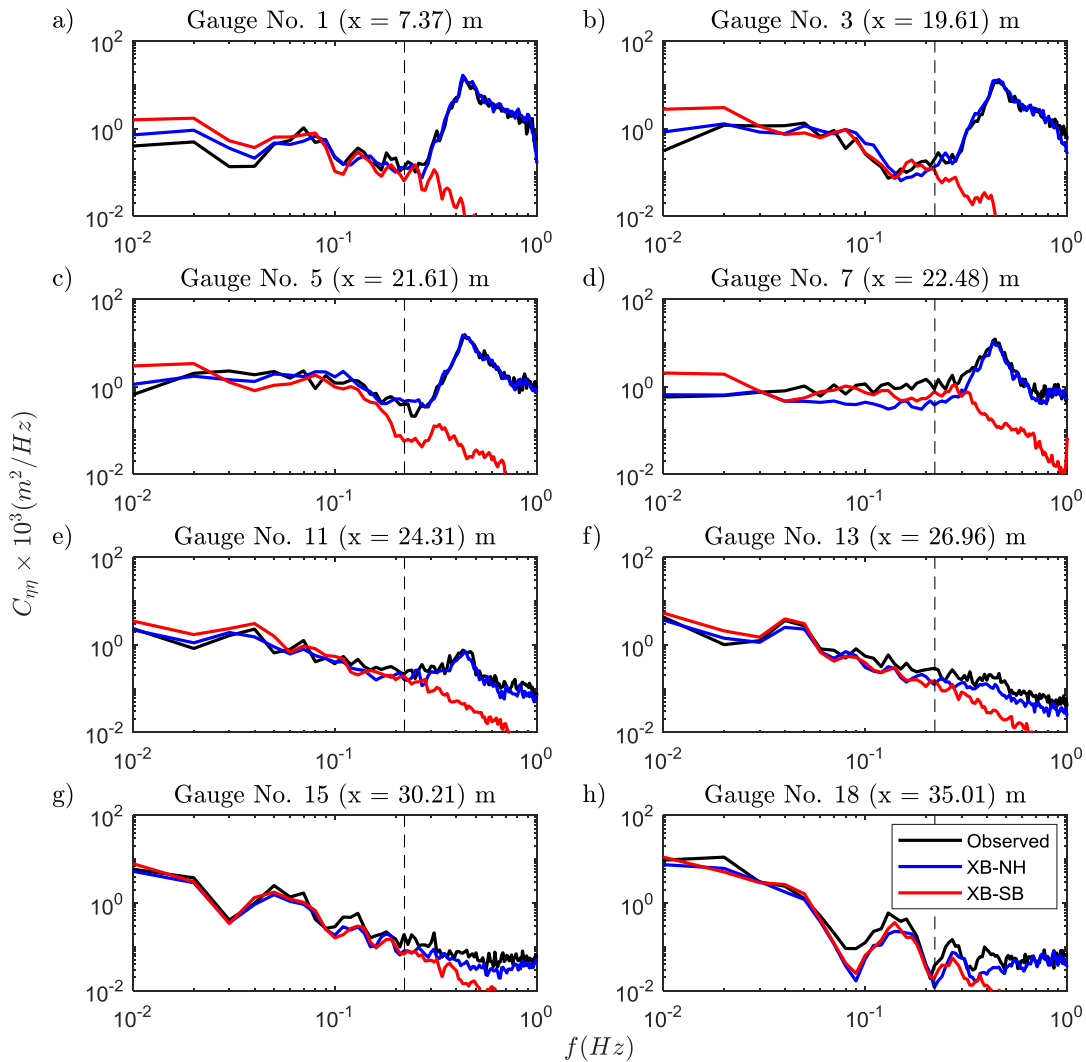
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929 **Figure 8** Optimal *maxbrsteep* in XB-NH (blue) and *alpha* in XB-SB (red) parameter values are
 930 compared with non-dimensional wave parameters: ξ_0 (a, d), $(h_r + \bar{\eta})/H_{m0}$ (b, e) and s_0 (c, f).



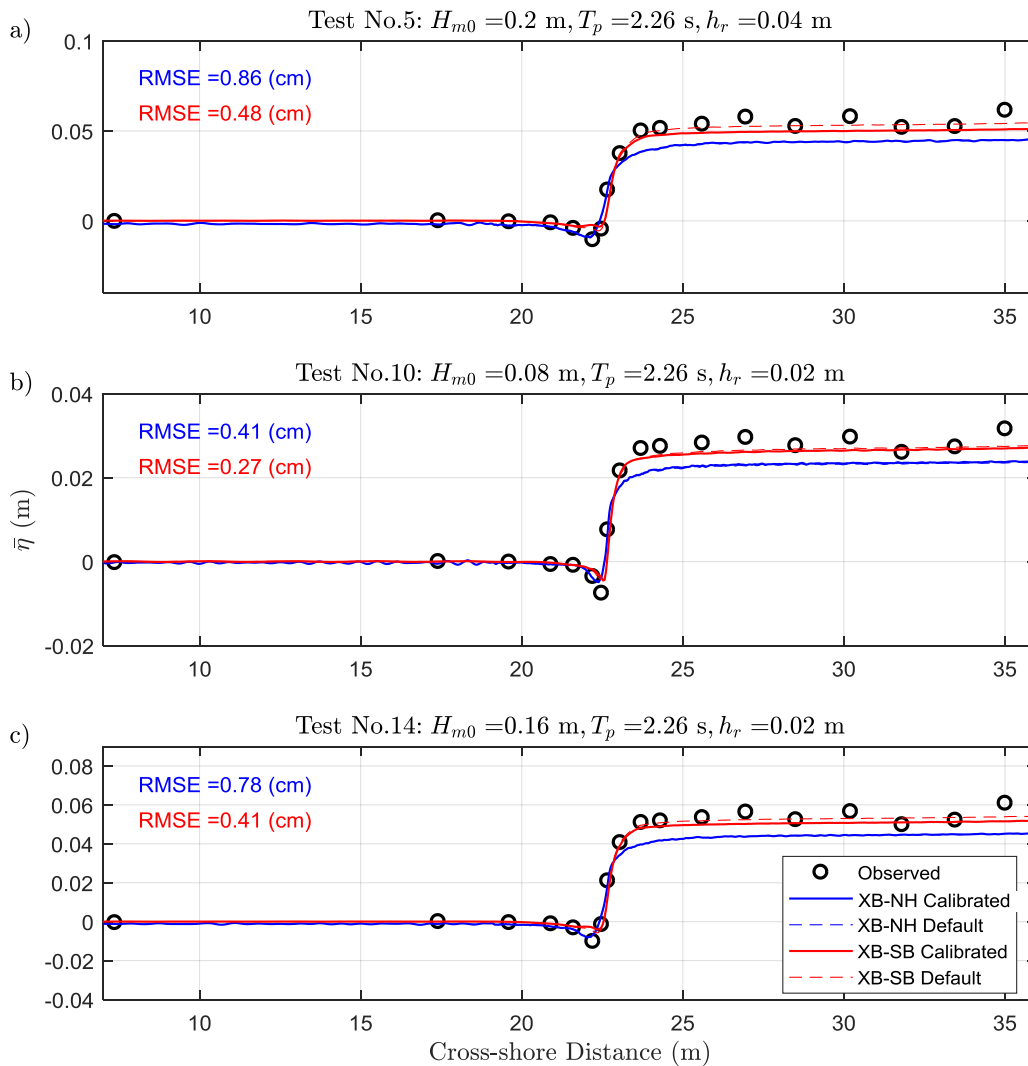
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932 **Figure 9 Modelled and observed total root-mean-square wave height ($H_{rms,TOT}$) profiles for**
 933 **representative tests no. (a) 5, (b) 10 and (c) 14 (Buckley et al. [17] experiment) for XB-NH (blue)**
 934 **and XB-SB (red) with default ($maxbrsteep = 0.6$, $alpha = 1$) and calibrated ($maxbrsteep = 0.5$, $alpha$**
 935 **$= 1.4$) parameter values (solid lines) showing root-mean-square error (RMSE) values. Note: tests**
 936 **were selected to cover the range of offshore wave conditions simulated.**

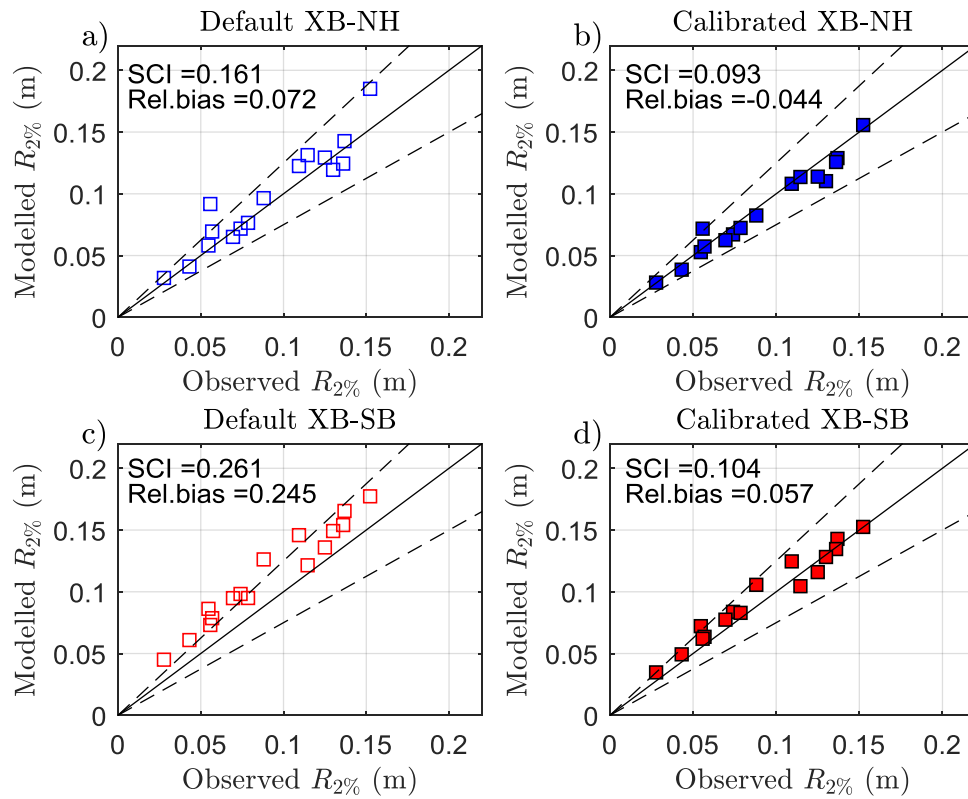


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939 **Figure 10** Modelled and observed spectral transformation of wave energy from (a, b) offshore, (c)
 940 the shoaling region, (d, e) during breaking and (f, g, h) on the reef flat for representative test no.
 941 **5** (Buckley et al. [17] experiment) for XB-NH (blue) and XB-SB (red). Dashed black lines
 942 represent the split frequency ($f_{split} = fp/2$) and the resolution of the spectra is 0.01 Hz with
 943 approximately 125 degrees-of-freedom.



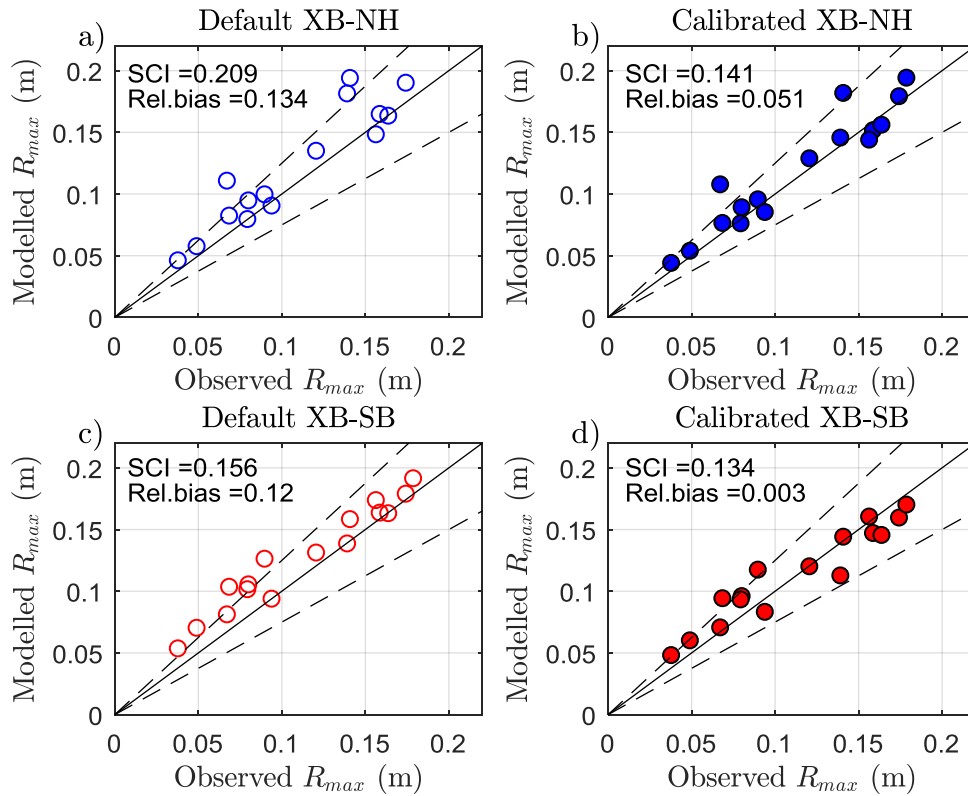
946 **Figure 11 Modelled and observed mean water level ($\bar{\eta}$) profiles for representative tests no. (a) 5,**
 947 **(b) 10 and (c) 14 (Buckley et al. [17] experiment) for XB-NH (blue) and XB-SB (red) with default**
 948 **($maxbrsteep = 0.6$, $alpha = 1$) and calibrated ($maxbrsteep = 0.5$, $alpha = 1.4$) parameter values**
 949 **showing root-mean-square error (RMSE) values. Note: tests were selected to cover the range of**
 950 **offshore wave conditions simulated.**



952

953 **Figure 12 Modelled and observed two-percent exceedance run-up ($R_{2\%}$) comparison for XB-NH**
 954 **(blue) and XB-SB (red) with default ($maxbrsteep = 0.6$, $alpha = 1$) and calibrated ($maxbrsteep =$**
 955 **0.5 , $alpha = 1.4$) parameter values showing SCI and Relative Bias error values (Buckley et al. [17]**
 956 **experiment). Black solid lines represent perfect agreement. Black dashed lines represent $\pm 25\%$**
 957 **error.**

958



959

960 **Figure 13 Modelled and observed maximum run-up (R_{max}) comparison for XB-NH (blue) and XB-**
 961 **SB (red) with default ($maxbrsteep = 0.6$, $alpha = 1$) and calibrated ($maxbrsteep = 0.5$, $alpha = 1.4$)**
 962 **parameter values showing SCI and Relative Bias error values (Buckley et al. [17] experiment).**
 963 **Black solid lines represent perfect agreement. Black dashed lines represent $+/- 25\%$ error.**

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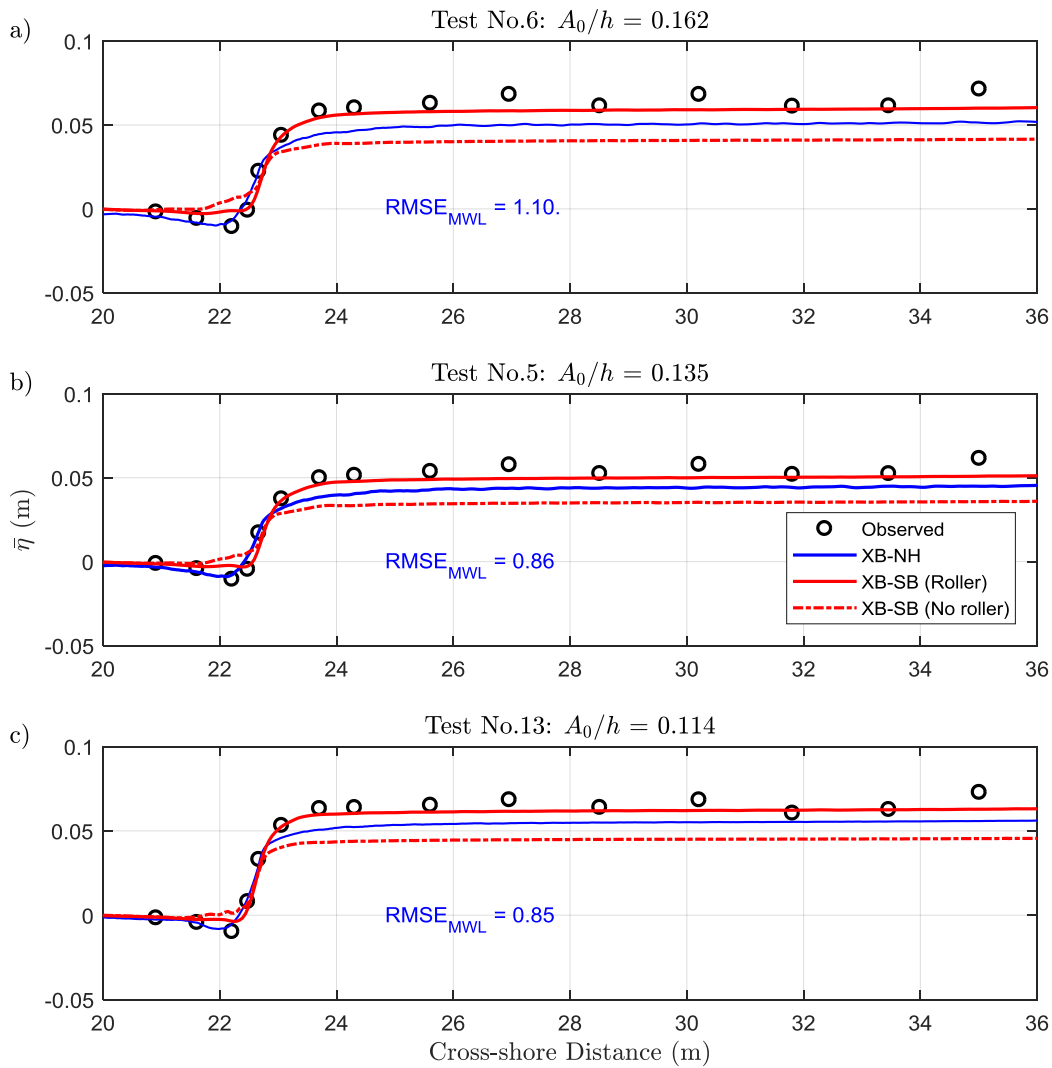
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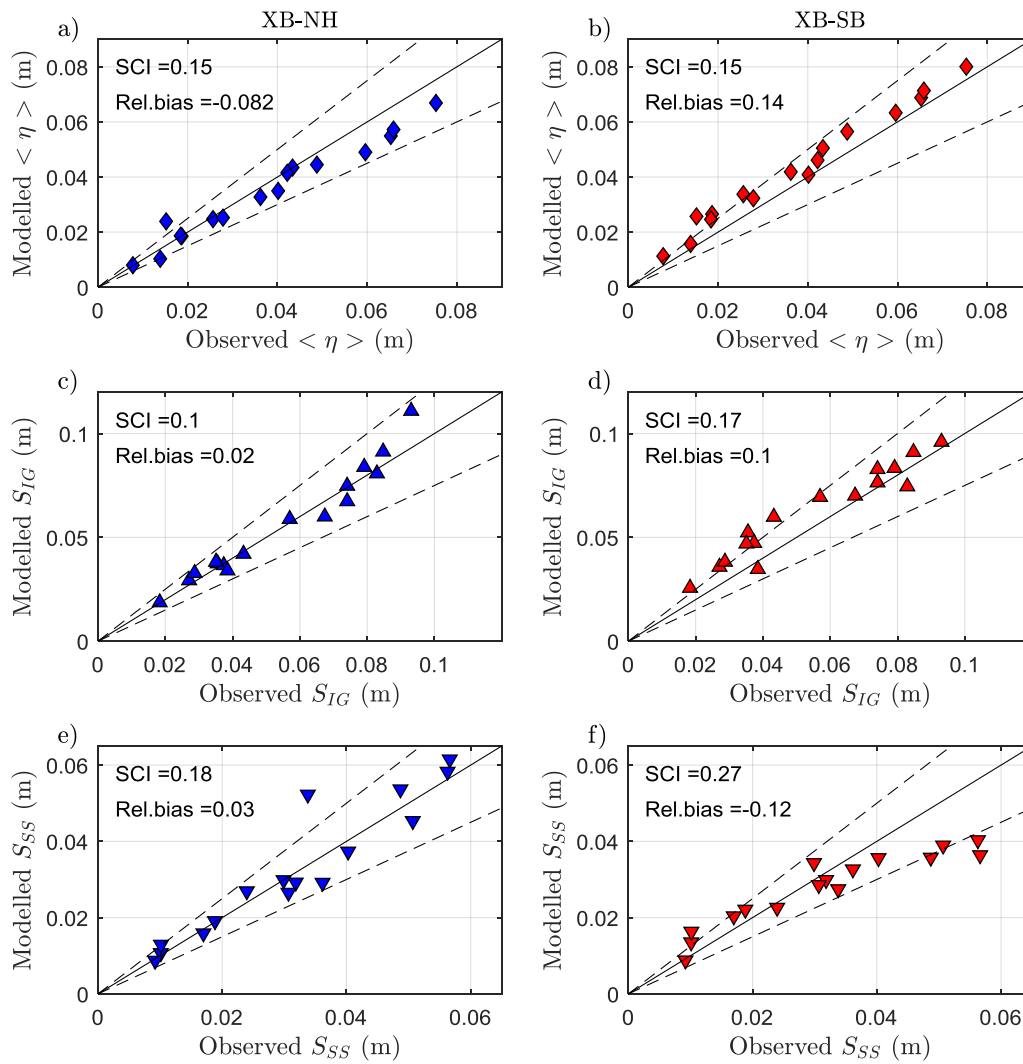
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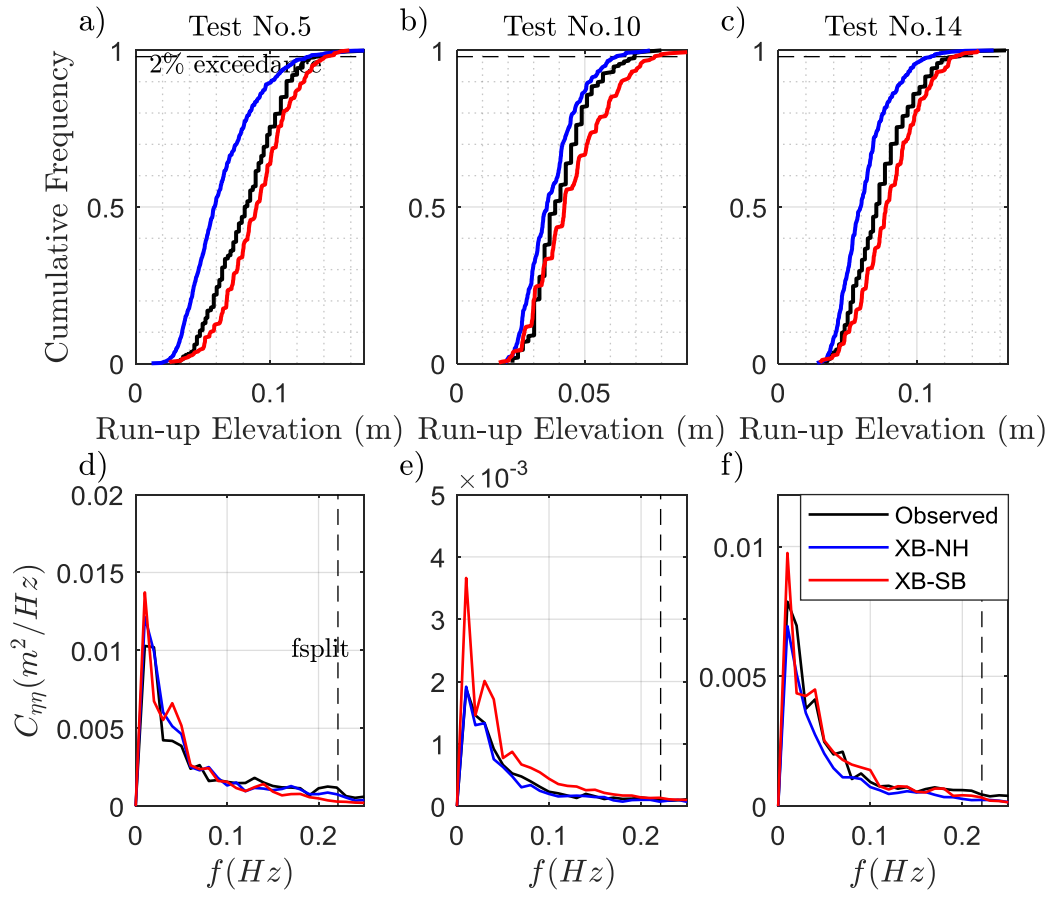


975 **Figure 14 Modelled and observed mean water level ($\bar{\eta}$) profiles for tests no. (a) 5, (b) 6 and (c) 13**
 976 **which showed the highest nonlinearity (A_0/h) and root-mean-square error in mean water level**
 977 **predictions (RMSE_{MWL}) for XB-NH (blue), XB-SB with roller model (red solid) and XB-SB**
 978 **without roller model (red dash-dot). Note: A_0 = offshore wave amplitude ($H_{m0}/2$) and h = offshore**
 979 **water depth.**



980

981 **Figure 15 Modelled and observed (a, b) shoreline setup, (c, d) infragravity-band swash and (e, f)**
 982 **sea-swell band swash for all 16 tests (Buckley et al. [17] experiment) for XB-NH (blue) and XB-**
 983 **SB (red) showing SCI and Rel. bias error values.**



984

985 **Figure 16 Modelled and observed cumulative frequency curves (upper) and swash spectra (lower)**
 986 **for representative tests no. (a, d) 5, (b, e) 10 and (c, f) 14 (Buckley et al. [17] experiment) for both**
 987 **XBeach modes. Horizontal dashed lines represent 2% exceedance, vertical dashed lines represent**
 988 **the split frequency ($f_{split} = fp/2$) and the resolution of the spectra is 0.01 Hz with approximately**
 989 **125 degrees-of-freedom.**