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# Journal of Coastal Research

## Model Skill and Sensitivity for Simulating Wave Processes on Coral Reefs Using a Shock-Capturing Green-Naghdi Solver

--Manuscript Draft--

<b>Manuscript Number:</b>	
<b>Full Title:</b>	Model Skill and Sensitivity for Simulating Wave Processes on Coral Reefs Using a Shock-Capturing Green-Naghdi Solver
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<b>Order of Authors Secondary Information:</b>	
<b>Abstract:</b>	<p>Wave flume data from published benchmark experiments were used to extensively evaluate numerical model skill and sensitivity for applying a shock-capturing Green-Naghdi (GN) model to simulate nonlinear wave transformation processes on complex coral reefs. Boussinesq-type models that utilise nonlinear shallow water equations (NSWEs) to represent wave breaking and dissipation hold significant potential for understanding coastal hazards associated with global environmental change and sea-level rise. These fully nonlinear phase-resolving models typically require a threshold condition to switch from dispersive equations to shock-capturing NSWEs in areas of active wave breaking. However, limited information exists regarding how this splitting approach influences the behaviour of different surf-zone processes that contribute to wave runup and inundation on coral reefs. This paper presents a comprehensive analysis of model sensitivity to explore how input parameters that control wave breaking and dissipation influence the behaviour of sea-swell (SS) waves, infragravity (IG) waves, wave setup, runup and solitary waves on coral reefs. Results show that each wave process exhibits unique sensitivity to the free-surface slope threshold (<math>B</math>) that is used to represent areas of active wave breaking by locally switching from the weakly-dispersive GN equations to the shock-capturing NSWEs. However, accurate representation of all wave processes can be achieved if the wave-face steepens to at least 35 degrees (<math>B \geq 0.7</math>) before breaking is initiated. Results from this research support and encourage the use of nonlinear phase-resolving wave models as tools for academic research, coastal management, coastal engineering and hazard forecasting on atoll and fringing reef environments.</p>
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Dear Editor,

We are pleased to submit our article titled Model Skill And Sensitivity For Simulating Wave Processes On Coral Reefs Using A Shock-Capturing Green-Naghdi Solver to be considered for publication in the Journal of Coastal Research. This research paper presents a comprehensive review of model behaviour, skill and sensitivity for simulating nonlinear wave processes on coral reefs in high resolution. Our hope is that this paper opens the door for scientists, managers and engineers to use nonlinear phase-resolving models to examine the impacts of future environmental change to coral reef landforms.

We have prepared all figures in greyscale to suit publication in print and online and have no conflicts of interest.

Regards  
Eddie Beetham  
School of Environment,  
University of Auckland

1 **Model Skill and Sensitivity for Simulating Wave Processes on Coral Reefs Using a**  
2 **Shock-Capturing Green-Naghdi Solver**

3

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9

10 **LRH: Beetham, Kench, and Popinet**

11 **RRH: Analysis of Green-Naghdi model skill on coral reefs**

12

## ABSTRACT

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Wave flume data from published benchmark experiments were used to extensively evaluate numerical model skill and sensitivity for applying a shock-capturing Green-Naghdi (GN) model to simulate nonlinear wave transformation processes on complex coral reefs. Boussinesq-type models that utilise nonlinear shallow water equations (NSWEs) to represent wave breaking and dissipation hold significant potential for understanding coastal hazards associated with global environmental change and sea-level rise. These fully nonlinear phase-resolving models typically require a threshold condition to switch from dispersive equations to shock-capturing NSWEs in areas of active wave breaking. However, limited information exists regarding how this splitting approach influences the behaviour of different surf-zone processes that contribute to wave runup and inundation on coral reefs. This paper presents a comprehensive analysis of model sensitivity to explore how input parameters that control wave breaking and dissipation influence the behaviour of sea-swell (SS) waves, infragravity (IG) waves, wave setup, runup and solitary waves on coral reefs. Results show that each wave process exhibits unique sensitivity to the free-surface slope threshold ( $B$ ) that is used to represent areas of active wave breaking by locally switching from the weakly-dispersive GN equations to the shock-capturing NSWEs. However, accurate representation of all wave processes can be achieved if the wave-face steepens to at least 35 degrees ( $B \geq 0.7$ ) before breaking is initiated. Results from this research support and encourage the use of nonlinear phase-resolving wave models as tools for academic research, coastal management, coastal engineering and hazard forecasting on atoll and fringing reef environments.

**ADDITIONAL INDEX WORDS:** *wave transformation, Green-Naghdi, model sensitivity, phase-resolving model, infragravity waves, wave setup, runup.*

37

## INTRODUCTION

38 Coral reefs are characterised by a steep sloping offshore fore-reef that quickly  
39 transitions into a shallow and near-horizontal reef flat. This abrupt transition results in energetic  
40 wave breaking at the reef edge, where approximately 86% of incident wave energy is dissipated  
41 (Ferrario *et al.*, 2014). Wave energy is further dissipated through friction on the reef flat, with  
42 up to 97% reduction of incident wave energy by the shoreline (Ferrario *et al.*, 2014). The rate  
43 of dissipation through breaking and friction are both influenced by reef depth, leading to  
44 consistent measurements of tidally modulated wave heights at the shoreline (Kench and  
45 Brander, 2006). The dependence of shoreline wave height on reef depth means that sea-level  
46 rise (SLR) is expected to increase wave energy impacting reef fringed landforms, resulting in  
47 widespread flooding and coastal erosion within the 21<sup>st</sup> century (Storlazzi *et al.*, 2015).  
48 However, incident wave attenuation on coral reefs is associated with a transfer of energy to  
49 free-propagating infragravity waves (Péquignet, Becker, and Merrifield, 2014; Pomeroy *et al.*,  
50 2012) and an increase in reef flat water level through wave setup (Becker, Merrifield, and Ford,  
51 2014; Vetter *et al.*, 2010). The behaviour of these secondary wave motions on coral reefs is not  
52 comprehensively understood and this knowledge gap presents a significant limitation for  
53 process based management and engineering on reef coastlines facing SLR. The significance of  
54 these secondary wave motions is evident in the fact that all documented cases of wave  
55 overtopping on reef landforms identify infragravity waves as the primary process contribution  
56 to flooding (Cheriton, Storlazzi, and Rosenberger, 2016; Ford, Becker, and Merrifield, 2013;  
57 Roeber and Bricker, 2015; Shimozono *et al.*, 2015).

58 Accurate modeling of wave transformation processes, swash dynamics, runup and  
59 overtopping on coral reefs landforms is critical for understanding the physical vulnerability of  
60 reef coastlines facing SLR and environmental change (Reyns *et al.*, 2013). However, for  
61 models to be an effective hazard management tool, they must accurately represent all the

62 nonlinear wave transformation processes that influence runup and inundation (Roeber and  
63 Bricker, 2015). Previous attempts to model the impact of SLR on reef landforms (*e.g.* Storlazzi  
64 *et al.*, 2015, Storlazzi *et al.*, 2004) rely on phase-averaging techniques that oversimplify energy  
65 transfer from incident waves to secondary surf-zone processes and do not simulate high  
66 frequency water level motions associated with SS waves, runup or overtopping. Recently,  
67 Roeber and Bricker (2015) show that phase-averaging models typically used in coastal hazard  
68 assessments do not resolve nonlinear energy transfers in the surf-zone or wave generated  
69 flooding. A ‘free-surface’ or phase-resolving model is required to directly simulate all surf-  
70 zone processes, runup and overtopping motions.

71         Coral reef morphology creates an inherent challenge for applying phase-resolving wave  
72 models because there is a rapid transition from dispersion dominant processes on the fore-reef  
73 slope to flux dominant processes at the reef edge (Fang, Liu, and Zou, 2016; Roeber and  
74 Cheung, 2012b). The first challenge is to propagate waves through the shoaling zone in a way  
75 that captures the asymmetrical transformation in wave shape and height prior to breaking  
76 (Huntley, 2013). The second challenge is to resolve wave breaking processes in a way that  
77 represents wave shape, dissipation and the generation of secondary wave motions (Roeber and  
78 Cheung, 2012b). To overcome these challenges, recent advances have focused on developing  
79 fully nonlinear Boussinesq-type solvers that apply ‘shock-capturing’ techniques to locally  
80 represent wave breaking using nonlinear shallow water (NSW) equations (Bonneton *et al.*,  
81 2011a; Bonneton *et al.*, 2011b; Lannes and Marche, 2015; Popinet, 2015; Roeber and Cheung,  
82 2012b; Tissier *et al.*, 2012a). A number of recent studies have shown that shock-capturing  
83 Boussinesq-type models can represent incident wave shoaling, breaking and attenuation on  
84 coral reefs, while also replicating the generation of infragravity waves and wave setup  
85 (Beetham *et al.*, 2016; Fang, Liu, and Zou, 2016; Roeber and Cheung, 2012b; Shimosono *et*  
86 *al.*, 2015; Su, Ma, and Hsu, 2015). These studies are all based on different solutions for the

87 Boussinesq and NSW equations and collectively highlight the capability of phase-resolving  
88 models to simulate nonlinear wave processes on complex coral reef environments. Each of  
89 these models also applies a threshold condition for wave instability that is used to locally and  
90 temporarily switch from dispersive equations to shock-capturing equations in areas of active  
91 wave breaking. Complex techniques for switching between source terms include: a momentum  
92 gradient threshold (Roeber and Cheung, 2012b); a Froude number threshold (Su, Ma, and Hsu,  
93 2015); and a wave height to water depth threshold (Shimozono *et al.*, 2015). However, the  
94 simplest approach that represents how wave breaking is physical triggered is a threshold free-  
95 surface slope (Beetham *et al.*, 2016; Bonneton *et al.*, 2011b; Fang, Liu, and Zou, 2016; Popinet,  
96 2015). Regardless of the method, the threshold value chosen to initiate wave breaking has a  
97 significant influence on breakpoint location and therefore directly influences the generation  
98 and behaviour of secondary wave processes. However, the exact sensitivity of different surf-  
99 zone processes to wave breaking parameterisation remains unknown.

100         The aim of this research is to quantify the sensitivity of different surf-zone processes  
101 that contribute to wave runup and overtopping on coral reefs to the parameters that influence  
102 wave breaking and dissipation in the open source Green-Naghdi model from Popinet (2015).  
103 The Green-Naghdi (GN) equations are a large amplitude solution of the Boussinesq equations  
104 which makes them particular suitable to coastal reef environments (Fang, Liu, and Zou, 2016).  
105 With the growing application of shock-capturing Boussinesq-type models on coral reef  
106 environments, it is important for users to understand how threshold values chosen to initiate  
107 wave breaking influence the full spectrum of wave transformation processes. This paper  
108 presents results from a comprehensive sensitivity analysis of how the free-surface slope  
109 threshold value ( $B$ ) influences SS wave dissipation, IG wave behaviour, setup magnitude,  
110 runup elevation and solitary wave dynamics on morphologically complex coral reefs. The  
111 combined influence from friction is accounted for by testing the sensitivity of  $B$  when

112 combined with different friction coefficient ( $C_f$ ) values. A series of published benchmark  
113 scenarios were used to undertake this analysis, including: include irregular wave  
114 transformation on a 2D reef (Demirbilek, Nwogu, and Ward, 2007); solitary wave interaction  
115 with a 2D reef (Roerber and Cheung, 2012b); and solitary wave interaction with a 3D reef  
116 (Lynett *et al.*, 2011).

## 117 **METHODS**

118 This research uses the shock-capturing Green-Naghdi model developed by Popinet  
119 (2015) to simulate laboratory scale scenarios of wave interaction with coral reefs. The Green-  
120 Naghdi solution is an attractive option for coral reefs because the weakly-dispersive equations  
121 can be applied to relatively large amplitude waves ( $a/h_o \sim 1$ ) propagating across nontrivial  
122 variations in topography ( $B_z/h_o \sim 1$ ), where  $a$  is the characteristic wave amplitude,  $h_o$  is water  
123 depth and  $B_z$  is the topographic gradient (Popinet, 2015). These characteristics provide a fully  
124 nonlinear solution of wave behaviour in shallow water, but are limited to weakly-dispersive  
125 scenarios relatively close to the shoreline ( $h_o^2/L_o^2 \ll 1$ ), where  $L_o$  is the offshore wave length  
126 (Bonneton *et al.*, 2011b, Lannes and Marche, 2015, Popinet, 2015). For a description of the  
127 governing equations and numerical scheme of the model used in this paper, the reader is  
128 referred to Popinet (2015) or the Basilisk website (Popinet, 2014), where the documented  
129 source code and a series of examples are freely available.

### 130 **Wave Breaking**

131 The weakly-dispersive finite-difference solver for wave propagation and shoaling is  
132 locally removed in areas of wave breaking, allowing wave shape and dissipation to be solved  
133 with a finite-volume solution of the NSW equations (Popinet, 2015). Similar approaches to  
134 represent wave breaking are becoming increasingly popular in a new generation of shock-

135 capturing GN models (Bonneton *et al.*, 2011a; Bonneton *et al.*, 2011b; Lannes and Marche,  
136 2015; Popinet, 2015; Tissier *et al.*, 2012a; Tissier *et al.*, 2012b). In Popinet (2015), the weakly  
137 dispersive GN equations are used unless the local free-surface slope ( $\|\nabla \eta\|$ ) exceeds a user  
138 defined threshold ( $B$ ), which by default is 1 ( $45^\circ$ ). At each time-step, on all cells where  $\|\nabla \eta\| >$   
139  $B$  is true (as calculated by the GN equations), the dispersive function is locally deactivated and  
140 the finite volume NSW solution is applied to resolve wave shape and dissipation throughout  
141 the breaking process. Therefore, the dispersion equations may be re-applied shoreward of the  
142 breakpoint if reef flat water depth can accommodate broken wave heights to a point that the  
143 free-surface slope decreases below the  $B$  threshold. This is important for accurately propagating  
144 reformed wave energy across the reef flat, at which point friction becomes the main form of  
145 dissipation. For the simulations presented here, an implicit quadratic bottom friction term (1)  
146 was included as:

$$147 \quad \mathbf{S}_f = -C_f \|\mathbf{u}\| \mathbf{u}, \quad (1)$$

148 where  $C_f$  is a non-dimensional coefficient that influences the rate of dissipation across the reef  
149 flat.

## 150 **Application to Coral Reefs**

151 Shock-capturing GN models have been used to simulate wave transformation,  
152 infragravity waves and setup on laboratory scale (Fang, Liu, and Zou, 2016) and field scale  
153 (Beetham *et al.*, 2016) coral reefs. Simulations presented in Beetham *et al.* (2016) show that  
154 the GN model from Popinet (2015) can accurately represent field scale wave transformation  
155 processes. However, the Popinet (2015) model has yet to be evaluated against benchmark data  
156 for wave runup and overtopping on coral reefs. Therefore, the Popinet (2015) GN model was  
157 used in this research to provide a new and comprehensive evaluation of the model skill and

158 sensitivity for simulation nonlinear wave transformation processes, runup and overtopping  
159 processes on a range of coral reef environments. Such benchmarking is required for confidently  
160 using the model as a research and coastal hazard management tool.

161 A visual description of how the shock-capturing GN model represents wave processes  
162 on coral reefs is presented in Figure 1, in the context of irregular wave transformation on an  
163 idealised reef morphology. This example highlights how the shock-capturing scheme is  
164 implemented near the reef edge to produce an asymmetrical wave bore profile on the outer reef  
165 flat, characterised by a vertical face and gradual tail. Figure 1 also highlights how incident  
166 wave attenuation is associated with setup of mean water level on the reef flat (Figure 1a) and a  
167 distinct transfer of energy into the IG wave band (Figure 1d-e). This example shows that  
168 maximum wave runup elevation is a function of remnant SS wave energy, IG wave oscillations  
169 and wave setup.

## 170 **Outline of Test Cases**

171 Benchmark test one (BM1) simulated wave transformation processes across a ‘typical’  
172 Guam fringing reef (Figure 2a) from the University of Michigan (UM) wind wave flume  
173 experiment presented by Demirbilek, Nwogu, and Ward (2007). The UM experiment was  
174 initially undertaken to evaluate the Boussinesq model by Demirbilek and Nwogu (2007), and  
175 has subsequently become a standard benchmark for applying wave models to coral reef  
176 environments (*e.g.* Buckley, Lowe, and Hansen, 2014; Demirbilek and Nwogu, 2007;  
177 Demirbilek, Nwogu, and Ward, 2007; Filipot and Cheung, 2012; Nwogu and Demirbilek,  
178 2010; Sheremet *et al.*, 2011; Shimozono *et al.*, 2015; Su, Sheremet, and Smith, 2011; Zijlema,  
179 2012). Here, the Popinet (2015) GN model was evaluated against fifteen incident scenarios  
180 from the UM dataset. The model was used in 1D, with measured water level from wave gauge  
181 1 (WG1) imported as the wave boundary condition. Model outputs for SS wave height ( $H_{ss}$ ),

182 IG wave height ( $H_{ig}$ ), wave setup ( $\bar{\eta}$ ) and maximum runup ( $R_{max}$ ) were compared with flume  
183 data to assess model accuracy and sensitivity. A comprehensive sensitivity analysis was  
184 undertaken to identify how systematic variations in  $B$  and  $C_f$  influence each output parameter  
185 ( $H_{ss}$ ,  $H_{ig}$ ,  $\bar{\eta}$  and  $R_{max}$ ). Results presented below identify the  $B$  and  $C_f$  combinations that best  
186 represents the range of processes across the surf and swash zone, out of 14  $C_f$  values and 8  $B$   
187 values (112 combinations) for the 15 test conditions (1,680 simulations). Pressure sensor data  
188 from the wave flume experiment were retrieved from  
189 <http://cirp.usace.army.mil/pubs/techreports.php>.

190 Benchmark test two (BM2) simulated a solitary wave breaking on an emerged 1D reef  
191 crest using nine combinations of  $B$  and  $C_f$ . These nine combinations were chosen because they  
192 represent the most sensitive and most accurate values from BM1. Data obtained during the  
193 Hawaii reef (HI reef) experiment from the O.H. Hinsdale Wave Research Laboratory at Oregon  
194 State University presented in Roeber and Cheung (2012) were used to evaluate model results.  
195 The HI reef test simulated a 0.75 m solitary wave breaking on an emerged reef crest, with water  
196 plunging into and propagating across a shallow lagoon (Figure 2b). BM2 tested numerical  
197 representations of dispersion, nonlinearity, wave breaking, overtopping and wet/dry dynamics  
198 (Roeber and Cheung, 2012b). Bathymetry and water level data from the wave flume  
199 experiment were downloaded from [http://hydraulic.lab.irides.tohoku.ac.jp/app-def/S-](http://hydraulic.lab.irides.tohoku.ac.jp/app-def/S-102/2014/?page_id=56)  
200 [102/2014/?page\\_id=56](http://hydraulic.lab.irides.tohoku.ac.jp/app-def/S-102/2014/?page_id=56).

201 Benchmark test three (BM3) was taken from the National Tsunami Hazard Mitigation  
202 Program benchmarking repository (NTHMP, 2012). BM3 simulated a solitary wave interacting  
203 with a complex 3D shelf that has a triangular extension and an emerged conical island (Figure  
204 2c), from the flume experiments by Lynett *et al.* (2011). BM3 used the GN model in 2D (depth  
205 averaged) and required solutions for dispersion, shoaling, refraction, diffraction, breaking,

206 overtopping and wet/dry dynamics. The 3D shelf experiment has become a popular Boussinesq  
207 model benchmark scenario (Fang *et al.*, 2013; Shi *et al.*, 2012; Roeber and Cheung, 2012a;  
208 Yamazaki *et al.*, 2012) with bathymetry and wave gauge data available online  
209 ([http://coastal.usc.edu/currents\\_workshop/problems.html](http://coastal.usc.edu/currents_workshop/problems.html)). The same nine combinations of  $C_f$   
210 and  $B$  from BM2 were tested again in BM3.

## 211 **Output Data Analysis**

212 For BM1, time-series data for free-surface water level from the UM wave flume and  
213 numerically modeled water level outputs at each WG location were analysed using the same  
214 techniques. Simulations ran for 900 s, with mean depth across the platform stabilising after  
215 approximately 100 s of wave activity. Data were extracted at 20 Hz (consistent with flume  
216 experiment) and trimmed to only include the final 700 s of wave activity when the wave field  
217 was developed across the reef. A spectral filter with a 0.25 Hz (4 s) cut-off was used to separate  
218 SS and IG wave components. The 0.25 Hz separation is approximately double the peak incident  
219 wave period used in the wave basin experiments. Significant wave heights for SS ( $H_{ss}$ ) and IG  
220 ( $H_{ig}$ ) components were then calculated using a zero down-crossing routine in Matlab. Wave  
221 setup ( $\bar{\eta}$ ) was calculated as the mean free-surface displacement. Wave spectra were calculated  
222 from the raw pressure signal using the first 8192 samples from  $t = 200$  s, with an overlapping  
223 hamming window and 16 degrees of freedom. Maximum runup ( $R_{max}$ ) was calculated from  
224 numerical model outputs using profile data for maximum water level across the reef flat.  $R_{max}$   
225 values reported in Demirbilek and Nwogu (2007) were used to evaluate numerical model  
226 outputs.

227 Model skill was used to quantify how close numerical outputs were to wave flume  
228 measurements in all benchmark tests using equation (2), where  $P_i$  is the model value,  $O_i$  is the  
229 wave flume value and vertical bars indicate absolute values.

230 
$$\text{Skill} = 1 - \frac{\sum |(P_i - O_i)|^2}{\sum (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (2)$$

231 A skill value of one indicates a perfect match between predicted and observed data and a skill  
 232 value of zero indicates that there is no agreement between the predicted and the observed (Lowe  
 233 *et al.*, 2009). Model skill was calculated individually for each wave statistic ( $H_{ss}$ ,  $H_{ig}$ , setup,  
 234 runup) in BM1. Mean skill averaged across these output parameters was then used to  
 235 understand overall model accuracy and sensitivity for representing wave processes at the  
 236 shoreline. For BM2 and BM3, model skill was calculated using time-series data for the free-  
 237 surface water elevation, from numerical and wave flume outputs at each wave gauge location.

238 **RESULTS**

239 This section describes the results from each of the benchmark tests and presents a  
 240 comprehensive analysis of model behaviour on coral reefs. Collectively, these results identify  
 241 values for  $B$  and  $C_f$  that are suitable for accurately simulating nonlinear wave transformation  
 242 processes, runup and overtopping on coral reef environments.

243 **Benchmark Test 1: Wave Transformation and Runup**

244 Model outputs from BM1 show that the shock-capturing GN equations are capable of  
 245 replicating flume measurements of SS wave height, IG wave height, setup and runup with  
 246 maximum model skill between 0.90 and 0.99 (Table 1). This section outlines the sensitivity of  
 247 each individual wave process to variations in  $B$  and  $C_f$  and identifies values that provide the  
 248 most accurate representation of all wave processes at the shoreline, including runup elevation.

249 **Model Sensitivity to the Breaking Slope Threshold ( $B$ )**

250 The breaking slope threshold influences the water depth where wave breaking is  
 251 triggered and determines whether waves break on the reef slope, reef edge or reef flat. The  $B$

252 value therefore influences the rate and mode of incident wave dissipation which has  
253 implications for IG wave behaviour and the magnitude of wave setup on the reef flat. Maximum  
254 model skill for  $H_{ss}$  at the shoreline was 0.90, achieved using  $B = 0.4$  (Figure 3a; Table 1).  
255 However, skill = 0.89 was achieved using  $B$  values between 0.4 and 1.2, indicating that a range  
256 of values can be used to predict shoreline wave height (Figure 3a). Model outputs for  $H_{ss}$  at the  
257 shoreline (WG9) were consistently higher using  $B = 0.4$ , with a slight decrease in skill and  
258 wave height observed when  $B$  increased from 0.4 to 0.7 (Figure 3a; Figure 4a-i). However,  $H_{ss}$   
259 values were highly variable using these lower  $B$  values, with 11% difference in outputs between  
260  $B = 0.4$  and  $B = 0.7$ . In comparison, consistent outputs for  $H_{ss}$  were achieved using higher  $B$   
261 values (0.7-1.2), characterised by 0.9% variation (Table 1). Overall, maximum skill was  
262 associated with  $B = 0.4$  but high skill and minimum sensitivity were achieved for  $H_{ss}$  using  $B$   
263  $\geq 0.7$ , especially when combined with  $C_f \leq 0.008$ .

264         Infragravity waves were highly sensitive to  $B$ , with a 16.7% difference between  
265 minimum and maximum values for  $H_{ig}$  at the shoreline (Figure 3b; Table 1). Interestingly, this  
266 range decreased dramatically to only 1% variability between  $H_{ig}$  outputs using  $B \geq 0.7$ . IG  
267 wave height at the shoreline was highest using  $B = 0.4$ , with a linear decrease in  $H_{ig}$  observed  
268 as  $B$  increased to 0.7 and consistent outputs between  $B = 0.7$ -1.2 (Figure 4a-i). However,  
269 maximum model skill (0.98) for shoreline  $H_{ig}$  was achieved across a range of  $B$  values between  
270 0.4 and 0.8 (Figure 3b). Lower  $B$  slopes achieved maximum skill when combined with high  
271 friction, compared to higher  $B$  values generating maximum skill across a range of low and  
272 moderate friction values (Figure 3b). Overall, it was possible to achieve high model skill using  
273 all  $B$  values (depending on friction) but IG behaviour was highly variable using  $B \leq 0.6$ ,  
274 compared to consistent  $H_{ig}$  predictions with minimal sensitivity associated with  $B \geq 0.7$  (Figure  
275 3b).

276 Model outputs for setup magnitude at WG9 were highest using  $B = 0.4$ , with a 15.1%  
277 decrease in setup observed between  $B = 0.4$  and  $B = 0.7$ . Higher  $B$  values ( $\geq 0.7$ ) produced  
278 consistent setup magnitudes, with minimal variation between  $B = 0.7$  and  $B = 1.2$ . Low  $B$  values  
279 over-predicted setup and were associated with a 7.5% decrease in model skill. The increase in  
280 setup using low  $B$  values explains why  $H_{ig}$  and  $H_{ss}$  were highest and often over-predicted using  
281  $B \leq 0.6$ . Maximum skill for wave setup (0.99) was achieved using  $B = 1$  but skill above 0.98  
282 was achieved across a wide range of friction values when combined with  $B \geq 0.7$  (Figure 3b).

283 Maximum runup elevation is influenced by the magnitude of  $H_{ss}$ ,  $H_{ig}$  and setup at the  
284 shoreline. Therefore, model outputs for  $R_{max}$  reflect the combined sensitivity of all surf-zone  
285 processes.  $H_{ss}$ ,  $H_{ig}$  and setup were all largest using  $B = 0.4$ , which resulted in significantly over-  
286 predicted wave runup outputs (Figure 4j-r) and low skill (Figure 3e), unless unrealistically high  
287 friction values were used. Maximum  $R_{max}$  skill (0.94) was achieved using  $B = 0.7$  (combined  
288 with  $C_f = 0.01$ ), with peak skill for most friction coefficients associated with  $B = 0.7$ . Runup  
289 skill above 0.92 was achieved across a range of  $B$  values between 0.6 and 1.2, with higher  
290 friction required to produce accurate runup results when combined with low  $B$  values. Runup  
291 elevation was 20% lower (on average) and much closer to flume measurements when using  $B$   
292  $\geq 0.7$ .

### 293 **Model Sensitivity to Friction Coefficient**

294 Quadratic bottom friction has a direct influence on wave attenuation across the model  
295 domain and has a significant impact on SS and IG wave transmission across the reef flat.  
296 Maximum model skill for  $H_{ss}$  (0.90) was associated with  $C_f = 0.004$ , with wave heights  
297 typically over-predicted using lower values and under-predicted using higher values (Figure  
298 4a-i). SS waves were reasonably sensitive to  $C_f$ , with an average 14.6% decrease in shoreline  
299  $H_{ss}$  observed as  $C_f$  increased from 0.001 to 0.01 (Table 1). Friction values above 0.01 resulted

300 significantly under-predicted wave heights (Figure 4) and a substantial decrease in skill (Figure  
301 3a). Maximum model skill for  $H_{ig}$  was achieved with  $C_f = 0.006$  (0.98), but skill  $> 0.95$  was  
302 achieved across a range of  $C_f$  values between 0.002 and 0.008 (Figure 3b). IG waves were  
303 highly sensitive to  $C_f$ , with an average 23.2% decrease in shoreline  $H_{ig}$  as  $C_f$  increased from  
304 0.001 to 0.01. IG wave transmission across the reef flat was highly influenced by  $C_f$ , with low  
305 friction resulting in shoreward amplification and high friction resulting in shoreward  
306 dissipation. Friction had no influence on wave setup, with only 0.7% variability between  
307 outputs and skill  $> 0.98$  achieved by all  $C_f$  values (Figure 3c). Wave runup was highly sensitive  
308 to  $C_f$ , with a 31% decrease in  $R_{max}$  observed when  $C_f$  increased from 0.001 to 0.01 (Table 1).  
309  $R_{max}$  was typically over-predicted using  $C_f \leq 0.06$  and under-predicted using  $C_f \geq 0.02$ , with  
310 close predictions of flume runup and high skill ( $>0.92$ ) achieved using  $C_f = 0.005 - 0.01$  (Figure  
311 4j-r). Runup results reflect how SS waves and IG waves respond to friction, with low friction  
312 associated with slightly larger SS waves and significantly larger IG wave heights at the  
313 shoreline. Runup sensitivity to  $C_f$  is primarily associated with how friction influences IG wave  
314 transmission across the reef flat.

### 315 **Maximum Shoreline Skill**

316 Model skill values calculated for each individual wave processes were most consistent when  
317 using higher  $B$  values (0.7 - 1.2) with moderate friction ( $C_f = 0.002 - 0.008$ ). To quantify the  
318 accuracy and sensitivity of surf-zone processes, mean skill at WG9 was calculated by averaging  
319 skill values for  $H_{ss}$ ,  $H_{ig}$  and setup. The best representation of all wave processes at WG9 (mean  
320 skill = 0.95) was achieved using  $B = 0.8$  and  $C_f = 0.003$ , with skill  $> 0.94$  associated with all  $B$   
321 values between 0.6 and 1.2 combined with  $C_f$  between 0.001 and 0.006 (Figure 3d). Wave  
322 processes at WG9 were highly sensitive to low  $B$  values, with a 14% decrease in the sum  
323 amplitude of  $H_{ss}$ ,  $H_{ig}$  and setup between  $B = 0.4$  and  $B = 0.7$ . Higher  $B$  values produced  
324 consistent outputs with less than 1% variation between  $B = 0.7$  and  $B = 1.2$ . Output sensitivity

325 to low  $B$  values was most pronounced for IG waves (17%) and setup (16%), with SS waves  
326 observing slightly less variation (12%). Overall, model skill at WG9 was higher and outputs  
327 were more consistent when using  $B$  values between 0.7 and 1. Increasing friction from 0.001  
328 to 0.01 had no impact on setup but did force a linear decrease in SS and IG wave height at  
329 WG9 (Figure 4). Friction had a major influence on IG wave behaviour on the reef flat, with a  
330 23% decrease in  $H_{ig}$  recorded between  $C_f=0.001$  and  $C_f=0.01$ , compared to a 15% decrease  
331 in  $H_{ss}$  (Table 1). Overall, the most accurate representation of all wave processes at WG9 (skill >  
332 0.94) was achieved using  $C_f$  values between 0.001 and 0.006, combined with  $B \geq 0.7$ .

333 Mean skill at WG9 was combined with runup skill to identify input values for  $C_f$  and  $B$   
334 that provide the best representation of all shoreline processes that are of key interest to coastal  
335 management applications. Maximum shoreline skill was associated with  $B = 0.7$  and  $C_f = 0.005$ ,  
336 with consistent outputs and high skill (>0.93) achieved using  $B = 0.7-1$ , combined with  $C_f =$   
337  $0.004 - 0.007$  (Figure 3f). Including  $R_{max}$  in the assessment of shoreline skill shifted the location  
338 of maximum skill to a lower  $B$  value and a slightly higher friction value, compared to maximum  
339 skill at WG9. However, the location of maximum skill at  $C_f = 0.005$  and  $B = 0.7$  is within the  
340 maximum 5% skill contour for each individual wave process (Figure 3f).

### 341 Spectral Wave Transformation

342 Systematic analysis of model skill revealed that the most accurate representation of all  
343 wave processes at the shoreline was achieved using  $B = 0.7$  and  $C_f = 0.005$ . However,  
344 calibrating the model to achieve the best representation of shoreline wave processes does not  
345 necessarily confirm that wave processes across the reef platform were accurately represented.  
346 Therefore, wave spectra calculated from numerical model outputs were compared with flume  
347 measurements at different wave gauge locations across the reef to further evaluate the accuracy  
348 of using  $B = 0.7$  and  $C_f = 0.005$  (Figure 5). Spectra results show a generally strong agreement

349 between the numerical model and the wave flume at the reef slope (WG5) and across the reef  
350 flat (WG7-9). These spectral density plots highlight that the GN model adequately represents  
351 the dissipation of SS wave energy across the reef and captures the transfer of energy into long-  
352 period IG motions on the reef flat. Further, spectra calculated from GN model outputs show a  
353 close match with wave flume spectra across a wide range of incident wave conditions and reef  
354 depths that represent high tide, mean tide, low tide and dry reef scenarios (Figure 5).

### 355 **Benchmark Test 2: Solitary Wave Breaking on a 2D Reef**

356 The HI reef benchmark experiment was simulated using three  $C_f$  values (0.001, 0.005,  
357 0.01) combined with three  $B$  values (0.4, 0.7, 1), a total of nine model runs. These values  
358 encompass the range tested in BM1 and include the combination of  $B = 0.7$  and  $C_f = 0.005$  that  
359 achieved maximum skill at the shoreline. This test requires a solitary wave to pass over a dry  
360 reef crest (WG10) and is therefore a fundamental benchmark scenario for wave overtopping  
361 processes on coral reefs. Skill values reported in this section are based on comparison of free-  
362 surface water level between the numerical model and wave flume.

### 363 **Model Skill and Sensitivity**

364 All combinations of  $B$  and  $C_f$  were capable of accurately representing wave shape and  
365 timing seaward of the reef crest (WG1-8), with mean skill across the first 8 gauges between  
366 0.96 and 0.99 (Figure 6). Variation in skill throughout the shoaling process was attributed to  
367 friction, with maximum skill associated with  $C_f = 0.005$  and slightly less skill with higher or  
368 lower friction (Figure 6). The value used for  $B$  had less influence on offshore skill with  $B = 0.4$   
369 and 0.7 producing near identical wave profiles and skill outputs (Figure 6).  $B = 1$  was associated  
370 with slightly less skill between WG1 and WG8 (Figure 6). The wave face became vertical at  
371 the upper reef slope (WG9) before breaking on the reef crest (WG10) between  $t = 12-15$  s  
372 (Figure 7). Maximum model skill at WG9 was associated with  $C_f = 0.005$ , with skill = 0.99

373 achieved by all  $B$  values. Skill at WG9 was slightly lower using  $C_f = 0.01$  and much lower  
374 using  $C_f = 0.001$ . For all input combinations, model skill decreased between WG9 and WG10  
375 and continued to decrease until WG12, before increasing again at WG13-14 (Figure 6). The  
376 highest skill between WG10 and WG12 was consistently achieved using  $C_f = 0.005$ , with skill >  
377 0.9 achieved across all wave gauges, regardless of  $B$ . Maximum skill in the lagoon was located  
378 at WG13 and WG14, with skill > 0.95 achieved using  $C_f = 0.001$  and  $C_f = 0.005$  (Figure 6).  
379 The  $B$  value associated with maximum skill at each wave gauge in the lagoon was variable, but  
380 mean skill between WG9 and WG14 was slightly higher using  $B = 0.7$  (0.948) compared to  $B$   
381 = 0.4 (0.945) or  $B = 1$  (0.947). Overall, mean skill across all wave gauges was maximum using  
382  $C_f = 0.005$  and  $B = 0.7$ , which is consistent with outputs from BM1.

383 Model outputs from BM2 show that the shock-capturing GN equations can replicate  
384 the highly nonlinear scenario of at 0.75 m solitary wave breaking on an emerged reef crest.  
385 Using  $B = 0.7$  and  $C_f = 0.005$ , skill was calculated separately for the initial forward propagating  
386 wave ( $t = 0-20$  s) and the reflected water level surges ( $t = 20-60$  s). Forward wave propagation  
387 and shoaling between WG1 and WG8 was simulated with skill > 0.997, consistent with the  
388 numerical wave producing a close visual match to time-series outputs from the wave flume  
389 (Figure 7). Numerical representation of wave breaking between WG9 and WG10 was  
390 characterised by skill > 0.988, confirming the models ability to represent wave shape,  
391 amplitude and timing. A significant decrease in forward propagating skill (0.775) was observed  
392 at WG11, where the broken wave initially plunged into the lagoon creating a 0.37 m high spike  
393 in water level that lasted for 0.4 s in the wave flume. Numerical outputs at WG11 did create a  
394 similar surge event but the timing was slightly delayed, the amplitude was higher (0.45 m) and  
395 the spike remained at peak amplitude for longer (0.58 s) compared to flume measurements.  
396 Forward propagating model skill increased again between WG12 and WG14, indicating that  
397 surge timing, amplitude and shape was reasonably well represented before the wave reflected

398 off the right boundary at  $x = 87$  m. The reflected bore propagated back across the lagoon  
399 between  $t = 20$ - $30$  s, with the reflected signal characterised by skill  $> 0.9$  at all lagoon sensors  
400 (WG11 - WG14). Less skill (0.87) was observed at WG10 as the surge passed back over the  
401 reef crest, but the timing and amplitude of the modeled reflection remained consistent with  
402 flume measurements. Flume data show that a series of short period oscillations were created as  
403 the reflected wave propagated into deeper water on the upper reef slope. The reflected signal  
404 at WG9 was close to flume measurements (skill = 0.99) showing similar timing and amplitude  
405 for the short period waves and longer period surge. Skill decreased slightly as the reflected  
406 waves propagated towards WG2 (skill = 0.95) but the water level dynamics associated with the  
407 reflected wave propagating seaward were accurately captured in the numerical model (Fig. 7).

### 408 **Benchmark Test 3: Solitary Wave Breaking on a 3D Reef**

409 The 3D shelf with a conical island experiment from Lynett *et al.* (2011) is one of the  
410 only published benchmark tests that provide freely available data for evaluating 2D phase-  
411 resolving wave models. Benchmark test 3 was simulated using the same nine combinations of  
412  $B$  and  $C_f$  that were used in BM2. BM3 is a popular test for fully nonlinear Boussinesq models  
413 because it requires numerical solutions for wave dispersion, shoaling, breaking, diffraction,  
414 refraction, convergence and overtopping on a dry shoreline. Snapshots of the model free-  
415 surface show how the solitary wave washes over and refracts around the conical cone before  
416 surging up the beach-face and overtopping the berm (Figure 8).

### 417 **Model Skill and Sensitivity**

418 Maximum skill for each combination of  $B$  and  $C_f$  was recorded near the input boundary  
419 (WG1 and WG4) where skill varied between 0.95 and 0.97. Model skill decreased along the  $y$   
420  $= 0$  m transect (WGs 1, 2, 3, 7), with skill at WG2 (in front of the conical cone) between 0.85  
421 and 0.87 depending on input values (Figure 9). Numerical model outputs at WG2 show the

422 timing an shape of the initial wave passing the sensor were close to measurements from the  
423 wave flume and suggest that the decrease in model skill is associated with reflections passing  
424 over the sensor between  $t = 20-40$  s (Figure 10b). Model outputs directly leeward of the conical  
425 cone (WG3) were sensitive to the timing and shape of the initial surges of water passing over  
426 and bending around the cone (Figure 10c). Maximum skill at WG3 was 0.88, associated with  
427  $C_f = 0.001$  and  $B = 0.4$ , with minimum skill (0.77) associated with  $C_f = 0.01$  and  $B = 1$ . Leeward  
428 model performance increased further from the cone, with skill at WG7 between 0.86 ( $C_f =$   
429  $0.001$ ;  $B = 1$ ) and 0.90 ( $C_f = 0.005$ ;  $B = 0.4$ ). Sensors across the  $y = 5$  m transect (WGs 4, 5, 6,  
430 8) recorded wave processes lateral to the cone and nearly always produced higher skill when  
431 compared against gauges on the  $y = 0$  m transect, especially for forward propagating waves  
432 (Figure 9). Mean skill across all sensors was highest using  $C_f = 0.005$  combined with  $B = 0.4$   
433 (0.882) or  $B = 0.7$  (0.880). High skill values using  $B = 0.7$  and  $C_f = 0.005$  are consistent with  
434 BM1 and BM2 and confirm the use of these values for laboratory scale simulations of wave  
435 dynamics on coral reefs.

## 436 **Velocity**

437 Velocity data were recorded at WG2 and WG3, capturing flow dynamics on seaward  
438 and leeward sides of the conical island (Figure 11). In front of the island, WG2 recorded the  
439 velocity signal of the steepening solitary wave, with  $U_x$  recording a close match to flume  
440 measurements using  $B = 0.7$  and  $C_f = 0.005$  (Figure 11a). Numerical outputs at WG2 also  
441 recorded a similar  $U_x$  signal as reflected water level motions initially surged back over the  
442 sensor at  $t = 7-18$  s. Leeward of the island, flume measurements recorded a sharp increase in  
443  $U_x$  as the wave surged over the island at  $t = 7.5$  s (Figure 11b). Model results for  $U_x$  at WG3  
444 produced the same plunge, followed by a similar trough, between  $t = 8.5$  and 22 s. Modeled  $U_y$   
445 data at WG2 and WG3 produced low velocities and did not identify the minor oscillations  
446 observed in the flume until  $t > 22$  s (Figure 11d,e). Data from WG10 measured velocity at the

447 upper reef slope away from the island, with numerical outputs for  $U_x$  and the more significant  
448 variations in  $U_y$  showing a reasonable agreement with flume measurements (Figure 11c,f).  
449 Note, skill was not calculated for velocity outputs due to missing sections of data from each of  
450 the wave flume sensors.

## 451 **DISCUSSION**

452 The three benchmark experiments used to evaluate the Popinet (2015) shock capturing  
453 GN solver collectively show that the model can skilfully represent surf-zone processes, runup,  
454 water level dynamics and overtopping on topographically complex coral reef environments. Of  
455 the three benchmark experiments, BM1 provides a comprehensive assessment for applying the  
456 model to simulate nonlinear wave transformation processes that contribute to wave driven  
457 runup and inundation. BM2 and BM3 provide more detail on how the model represents  
458 nonlinear transformations in wave shape and directly test how the GN equations can be applied  
459 to simulate wave overtopping scenarios. Physical phenomenon that contribute to wave runup  
460 and inundation on atoll islands include: SS waves, IG waves and setup (Merrifield *et al.*, 2014).  
461 Field measurements demonstrate how each of these processes respond differently to incident  
462 wave conditions and reef depth (Becker, Merrifield, and Ford, 2014; Ford, Becker, and  
463 Merrifield, 2013; Kench and Brander, 2006; Pomeroy *et al.*, 2012). Further, these processes  
464 influence the behaviour of each other, complicating a conceptual understanding of how  
465 environmental conditions influence runup on reef fringed coastlines. Recent developments in  
466 numerical modeling (*e.g.* Popinet, 2015; Roeber and Cheung, 2012b; Su, Ma, and Hsu, 2015)  
467 allow these nonlinear interactions to be simulated under controlled boundary conditions, and  
468 provide a unique tool for exploring how physical processes will respond to environmental  
469 change. However, appropriate and efficient use of these new modeling techniques relies on a  
470 comprehensive understanding of how numerical outputs are influenced by parameters that are  
471 typically used for model ‘tuning’ and calibration (Oreskes *et al.*, 1994). Systematic analysis

472 from BM1 revealed how SS attenuation, IG transmission, setup and runup each exhibit  
473 individual sensitivity to breaking and friction parameters. Therefore, a combined assessment  
474 of all parameters is required to achieve a realistic representation of processes that impact the  
475 shoreline. In general, outputs were more sensitive to the friction coefficient ( $C_f$ ) than to the slope  
476 threshold used for locally removing dispersion ( $B$ ). However, the model was highly sensitive  
477 to  $B = 0.4$  ( $21.8^\circ$ ) because wave breaking was initiated too far offshore. Wave setup was  
478 significantly over-predicted using  $B = 0.4$  which meant that IG waves were not sufficiently  
479 dissipated by friction processes on the reef flat. Model outputs observed minimal sensitivity  
480 and maximum skill using slope thresholds between  $B = 0.7$  ( $35^\circ$ ) and  $B = 1.2$  ( $\sim 50^\circ$ ). These  
481 findings are consistent with Buckley, Lowe, and Hansen (2014) where a breaking slope of  $\sim 55^\circ$   
482 was found to give the best prediction of UM measurements when using the nonlinear phase-  
483 resolving model SWASH (SWASH default is  $25^\circ$ ). Using a high breaking slope can be  
484 explained physically in this context because of the steep sloping fore-reef on coral reefs  
485 typically produces plunging breakers.

486 Higher friction values were associated with both SS and IG waves being under-  
487 predicted at the shoreline. IG waves were highly sensitive to friction, with  $H_{ig}$  over-predicted  
488 at WG9 using low friction but dramatically under-predicted using high friction. However,  
489 skilful predictions for IG wave height were achieved using a  $C_f$  range between 0.002 and 0.008.  
490 Model results highlight the role of friction as a primary control for low frequency wave  
491 behaviour on coral reefs. Wave setup was consistently well predicted, with minimal sensitivity  
492 to friction, unless  $B = 0.4$  was used. Accounting for  $R_{max}$  added an additional level of  
493 complexity when trying to achieve an accurate prediction of all processes at the shoreline.  
494 Maximum runup was highly sensitive to SS and IG dynamics, leading to over-predicted runup  
495 with low friction and under-predicted runup using high friction. However, skilful predictions  
496 were achieved using moderate friction (0.005 to 0.01) and any  $B$  value above 0.6. The best

497 representation of all processes was found using  $C_f = 0.005$  and  $B = 0.7$ . These same input values  
498 were capable of skilfully replicating solitary wave transformation on complex 2D and 3D reef  
499 structures, with a slight decrease in skill observed when using the model in 2DH (two  
500 horizontal dimensions). Collectively, the three benchmark scenarios show that the GN model  
501 is capable of simulating the range of wave frequencies and nonlinear dynamics associated with  
502 wave transformation on coral reef systems.

## 503 CONCLUSIONS

504 A benefit of fully nonlinear free-surface models is that any feedbacks between different  
505 frequency wave processes are directly resolved (Shimozono *et al.*, 2015). For example, the  
506 attenuation of irregular SS waves is associated with the formation of IG motions and setup that  
507 in turn influence the transmission of broken and reformed SS waves across the reef flat. These  
508 feedbacks are critical for accurately representing the range of processes that promote elevated  
509 sea-level and coastal flooding, as recently highlighted by Roeber and Bricker (2015). However,  
510 the interlinked nature of these models also means that the sensitivity of each process needs to  
511 be carefully understood before being applied to real world scenarios. Simulations presented  
512 here are the first step towards applying the GN solution to study the complex interplay of  
513 processes associated with wave transformation on coral reef coastlines. Results suggest that the  
514 combination of weakly dispersive Green-Naghdi equations and nonlinear shallow water  
515 equations implemented in Popinet (2015) and other model packages have significant potential  
516 for simulating detailed wave processes on reef environments. Consequently, this type of  
517 modeling can become a powerful research tool to explore wave dynamics on reef systems in  
518 context of future environmental change.

519

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523

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649 Table 1. Summary of numerical model skill and sensitivity when compared to flume measurements of  
 650 SS wave height, IG wave height, setup and runup at the shoreline. Values assigned to the WG9 column  
 651 represent the mean skill across all wave process ( $H_{ss}$ ,  $H_{ig}$  and setup) at the shoreline and shoreline skill  
 652 is the average skill from all wave processes at WG9 and runup. A statistical summary of model skill is  
 653 first presented, based on all simulations, to provide an indication of how variable outputs are when  
 654 inputs are modified. To quantify model sensitivity, the percent difference between minimum and  
 655 maximum values were calculated for all  $C_f$  values, all  $B$  values and the higher and lower range of  $C_f$   
 656 and  $B$  values.  $B$  and  $C_f$  values associated with maximum skill are presented as recommended values for  
 657 predicting each wave process. The range of  $B$  and  $C_f$  combinations that can be used while maintaining  
 658 model skill within 5% of maximum skill are shown as the minimum and maximum  $B$  and  $C_f$  values that  
 659 make up this range.

	$H_{ss}$	$H_{ig}$	Setup	WG9 (Mean)	Runup	Shoreline
<b>Model skill</b>						
Maximum	0.901	0.977	0.988	0.949	0.944	0.936
Max 5% range	0.856	0.928	0.938	0.902	0.896	0.889
Mean	0.858	0.887	0.973	0.906	0.798	0.879
SD	0.057	0.141	0.025	0.065	0.14	0.07
Minimum	0.668	0.419	0.902	0.692	0.419	0.664
<b>Output sensitivity: range between minimum and maximum values</b>						
$B$ (0.4-1.2)	11.9%	16.7%	15.9%	14.8%	20.0%	16.1%
$B$ (0.4-0.7)	11.1%	16.7%	15.1%	14.3%	20.0%	15.7%
$B$ (0.7-1.2)	0.9%	1.7%	1.0%	1.2%	1.2%	1.2%
$C_f$ (0.001-0.01)	14.6%	23.2%	0.7%	12.8%	30.1%	17.2%
$C_f$ (0.001-0.005)	7.6%	12.2%	0.3%	6.7%	19.4%	9.9%
$C_f$ (0.006-0.01)	6.1%	10.0%	0.3%	5.5%	10.8%	6.8%
<b>Recommended <math>B</math> values</b>						
Maximum skill	0.4	0.5	1	0.8	0.7	0.7
5% range: minimum	0.4	0.5	0.5	0.5	0.6	0.6
5% range: maximum	1.2	1.2	1.2	1.2	1.2	1.2
<b>Recommended <math>C_f</math> values</b>						
Maximum skill	0.004	0.006	0.0001	0.003	0.01	0.005
5% minimum	0.0001	0.002	0.0001	0.0001	0.005	0.002
5% maximum	0.008	0.008	0.04	0.01	0.01	0.01

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## Figure Captions

663 Figure 1. Example of model capability for simulating irregular wave transformation ( $H_s = 2.6$   
664 m,  $T_s = 10.5$  s) on an idealised coral reef ( $h_r = 1$  m) with a 1:6 fore-reef slope and 1:14 beach  
665 slope. (a) Across reef variations in free-surface water level (wave profile), mean water level  
666 (setup) and maximum water level. (b-e) Water level time-series outputs at different locations  
667 across the model domain showing the raw signal and the low pass filtered (0.04 Hz) infragravity  
668 wave signal.

669 Figure 2. Model bathymetry for each benchmark test showing the location of wave gauge (WG)  
670 sensors used to compare numerically modeled outputs with measured wave basin data. (a)  
671 Benchmark 1 is the idealised Guam reef from a series of flume experiments undertaken in the  
672 University of Michigan wave laboratory (Demirbilek, Nwogu, and Ward, 2007). (b)  
673 Benchmark 2 is the Hawaii Reef (HI reef) bathymetry used in the O.H. Hinsdale Wave Flume  
674 (Roeber and Cheung, 2012b). (c) Benchmark 3 uses the model in 2D with a complex reef  
675 bathymetry that has a steep slope, a triangular shelf and a conical island (Lynett *et al.*, 2011).

676 Figure 3. Model skill contour lines are presented in grey to show how  $B$  and  $C_f$  values influence  
677 the accuracy of wave processes at the shoreline, individually and collectively, from BM1.  
678 Shoreline skill at WG9 is presented for (a) SS wave height, (b) IG wave height and (c) setup at  
679 the shoreline. (d) Mean skill at WG9 is the average of individual skill values for  $H_{ss}$ ,  $H_{ig}$  and  
680  $\bar{\eta}$  at the shoreline. (e)  $R_{max}$  skill. (f) Shoreline skill as the average skill from  $H_{ss}$ ,  $H_{ig}$ ,  $\bar{\eta}$  at  
681 WG9 and  $R_{max}$ . Maximum skill is identified with a black marker and the associated  $C_f$  and  $B$   
682 value is written inside each plot. Black contour lines indicate  $C_f$  and  $B$  combinations that  
683 produce a skill value within 5% of the maximum skill. Note, the x-axis is a log scale.

684 Figure 4. (a-i) Measured (wave flume) outputs for SS wave height ( $H_{ss}$ ), IG wave height ( $H_{ig}$ )  
685 and wave setup are compared to numerical model outputs using a selection of different  $C_f$  and  
686  $B$  values for the 15 UM test scenarios. (j-r) Numerical model outputs for runup elevation are  
687 compared to wave flume measurements for the same selection of  $B$  and  $C_f$  values. The dashed  
688 line represents a perfect fit ( $y = x$ ) and can be used to visually identify how close model outputs  
689 are to flume measurements. Skill values written in plots a-i represent mean skill at WG9, with  
690 runup skill presented in plots j-r.

691 Figure 5. Wave spectra calculated from the GN model outputs using  $C_f = 0.005$  and  $B = 0.7$   
692 (black) are compared to wave spectra calculated from wave flume data (grey) at the upper reef

693 slope (WG5), outer reef flat (EG7), central reef flat (WG8) and the shoreline (WG9). Eight of  
694 the fifteen UM scenarios are presented to show how the model behaves under different incident  
695 wave conditions under high tide (rows 1-2), mean tide (rows 3-4), low tide (rows 5-6) and dry  
696 reef (rows 7-8) conditions. Note that the x and y axes are both log scale.

697 Figure 6. Across reef variation in free-surface water level skill at the 14 wave gauge locations  
698 from BM2, using different  $B$  values (represented using different line symbols) and friction  
699 values. (a)  $C_f = 0.001$ , (b)  $C_f = 0.05$  and (c)  $C_f = 0.01$ . (d) Wave flume bathymetry and wave  
700 gauge locations are presented to highlight the spatial influence variation in skill across the reef.

701 Figure 7. (a-l) Free-surface water level across the model domain at different time snapshots are  
702 presented to show wave propagation, breaking and plunging processes from the GN model  
703 (black line), using  $C_f = 0.005$  and  $B = 0.7$ , compared with wave flume measurements at each  
704 wave gauge location (grey circles). (m-x) Comparison of time-series water level measurements  
705 from the GN model (black) and wave flume (grey) using  $B = 0.7$  and  $C_f = 0.005$ .

706 Figure 8. Snapshots of free-surface water level at different times during the 3D shelf simulation  
707 for BM3, using  $B = 0.7$  and  $C_f = 0.005$ .

708 Figure 9. Comparison of model skill for representing free-surface water level at different wave  
709 gauge locations, relative to distance from the incident boundary for the  $y = 0$  m (WGs 1, 2, 3,  
710 7),  $y = 5$  m (WGs 4, 5, 6, 8) at  $y = 10$  m (WG9) transect, for each combination of  $C_f$  and  $B$ .  
711 Mean skill value across all WG locations is presented inside each subplot.

712 Figure 10. Time-series outputs for free-surface water level at each wave gauge location from  
713 the GN model using  $C_f = 0.005$  and  $B = 0.7$  (black) are compared to water level measurements  
714 from the wave flume (grey).

715 Figure 11. Modeled velocity outputs from the GN model using  $C_f = 0.005$  and  $B = 0.7$  (black)  
716 are compared to wave flume measurements (grey) at WG2 (seaward of conical cone), WG3  
717 (leeward of conical cone) and WG10 (lateral to conical cone).

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