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1 **Wave transformation and shoreline water level on Funafuti**
2 **Atoll, Tuvalu**

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16
17 **Key Points**

- 18 • Shoreline water level is elevated by setup at low tide and SS waves at high tide
19 • IG waves elevate shoreline water level at all tide stages
20 • The geomorphic window on Fatato Island is open for 71% of the time

22 **Abstract**

23 The influence of sea swell (SS) waves, infragravity (IG) waves, and wave setup on maximum
24 runup (R_{max}) is investigated across different tidal stages on Fatato Island, Funafuti Atoll,
25 Tuvalu. Field results illustrate that SS waves are tidally modulated at the shoreline, with
26 comparatively greater wave attenuation and setup occurring at low tide versus high tide. A
27 shoreward increase in IG wave height is observed across the 100 m wide reef flat at all tidal
28 elevations, with no tidal modulation of IG wave height at the reef flat or island shoreline. A 1D
29 shock-capturing Green-Naghdi solver is used to replicate the field deployment and analyse
30 R_{max} . Model outputs for SS wave height, IG wave height and setup at the shoreline match field
31 results with model skill > 0.96 . Model outputs for R_{max} are used to identify the temporal window
32 when geomorphic activity can occur on the beach face. During periods of moderate swell
33 energy, waves can impact the beach face at spring low tide, due to a combination of wave setup
34 and strong IG wave activity. Under mean wave conditions, the combined influence of setup,
35 IG waves and SS waves results in interaction with island sediment at mid-tide. At high tide, SS
36 and IG waves directly impact the beach face. Overall, wave activity is present on the beach
37 face for 71% of the study period, a significantly longer duration than is calculated using mean
38 water level and topographic data.

39

40

41 **1. Introduction**

42 The cause of inundation on atoll islands is commonly linked to extreme spring tides that can
43 submerge low lying areas on sedimentary reef landforms [*Lin et al.*, 2014; *Woodroffe*, 2008;
44 *Yamano et al.*, 2007]. However, recent research has predicted that wave overtopping will
45 become the most frequent cause of island flooding as sea levels rise [*Hoeke et al.*, 2013;
46 *Merrifield et al.*, 2014]. Runup generated from distant source swell waves or locally generated
47 storm waves can overtop and flood atoll islands; causing significant damage to infrastructure
48 [*Ford et al.*, 2013; *Hoeke et al.*, 2013; *Shimozono et al.*, 2015]. Notwithstanding the concerns
49 raised by such episodic events, geomorphic change can also occur under non-extreme
50 conditions when waves interact with sediment on the beach face [*Kench and Brander*, 2006].
51 To date, few studies have examined the temporal exposure of reef island shorelines to different
52 frequency wave processes.

53 Shoreline water level on atoll reefs is primarily influenced by sea swell (SS) waves, infragravity
54 waves (IG), wave setup, and tidal elevation [*Merrifield et al.*, 2014]. Incident SS wave energy
55 (> 0.04 Hz) is dissipated through wave breaking at the reef edge and by friction across the reef
56 flat [*Hearn*, 1999; *Péquignet et al.*, 2011]. Field experiments have demonstrated a strong tidal
57 control on SS wave transmission across the reef, with attenuation between 70% (high tide) and
58 100% (low tide) [*Ford et al.*, 2013; *Kench and Brander*, 2006; *Péquignet et al.*, 2011].
59 Consequently, field results indicate that the potential for SS wave driven geomorphic change
60 at the island shoreline is typically constrained to high tide [*Brander et al.*, 2004; *Kench and*
61 *Brander*, 2006]. Despite these findings, few studies have extended the analysis of wave
62 transformation beyond a near shoreline instrument to include runup limits on the beach face.

63 IG frequency waves (< 0.04 Hz) are released when SS waves interact with the reef edge
64 [*Péquignet et al.*, 2014; *Pomeroy et al.*, 2012]. Field measurements across narrow atoll reefs
65 (~ 100 m) indicate that IG waves contribute the main form of shoreline energy under mean and
66 swell wave conditions [*Ford et al.*, 2013]. During a long period swell event, runup at IG
67 frequencies was reported to overwash berm elevation on a number of Pacific atolls [*Hoeke et*
68 *al.*, 2013]. However, measurements on wide fringing reefs indicate that IG waves generated
69 under mean wave conditions will peak near the reef edge (~ 100 m) and be dissipated by friction
70 across the reef flat [*Péquignet et al.*, 2014; *Pomeroy et al.*, 2012; *Van Dongeren et al.*, 2013].
71 Numerical analysis of wave transformation under extreme typhoon conditions show that
72 damaging IG waves can impact the shoreline on wide and shallow fringing reefs [*Shimozono*
73 *et al.*, 2015]. Wave breaking at the reef edge also generates a setup water level across the reef

74 flat [Gourlay, 1996]. On average, setup on coral reefs has been measured to be 25% of incident
75 H_s [Jago *et al.*, 2007; Vetter *et al.*, 2010]. However, Becker *et al.* [2014] identify a strong tidal
76 control; with maximum setup at low tide exceeding 40% of incident H_s , and a relatively small
77 setup at high tide (<10% of H_s). Large setup results in less attenuation from friction on the reef
78 flat, allowing larger wave heights at the shoreline and an elevated point of interaction for SS
79 and IG waves on the beach face.

80 Recent research on wave transformation across atoll reefs has focused on wave overtopping
81 [Hoeko *et al.*, 2013; Merrifield *et al.*, 2014; Quataert *et al.*, 2015], without considering the
82 processes that promote wave activity on the beach face. Sea level, tidal oscillations, setup, IG
83 waves, and SS waves combine to determine reef flat water level and the point of maximum
84 runup at the shoreline [Merrifield *et al.*, 2014]. In turn, reef flat water level and runup influence
85 the temporal window for geomorphic activity on sedimentary islands. Therefore it is necessary
86 to investigate wave transformation in the context of the processes that impact shoreline water
87 level in order to understand the key drivers of geomorphic change on atoll landforms.

88 This research considers how SS waves, IG waves and wave setup influence shoreline water
89 level on atoll islands. Wave transformation data is presented from field measurements taken
90 over a 62 day period on Funafuti Atoll. Funafuti is often cited as being especially vulnerable
91 to sea level rise, with spring tides frequently flooding island infrastructure [Lin *et al.*, 2014;
92 Yamano *et al.*, 2007]. Analysis of sea level records also suggest Funafuti is currently
93 experiencing a rise in mean sea level of 5 mm/yr, three times the global average [Becker *et al.*,
94 2012]. Despite this highlighted vulnerability, no attempt has been made to quantify the wave
95 processes that impact island shorelines on Funafuti Atoll. Field results are presented first to
96 understand how tide level and incident wave conditions influence SS waves, IG waves and
97 setup on the reef flat. A fully non-linear Boussinesq (Green Naghdi) model is then used to
98 replicate field conditions and estimate maximum wave runup at the shoreline. Model results
99 for maximum runup are deconstructed to understand the influence that SS waves, IG waves
100 and setup have on elevating water level at the shoreline. A thorough review of model
101 performance and sensitivity is presented before numerical results are used to extend field
102 measurements from a near shoreline instrument to the runup limit.

103 **2. Field Setting**

104 Field data were collected on the ocean-facing reef flat near Fatato Island on Funafuti Atoll,
105 Tuvalu. Fatato is an uninhabited island, 87 m wide and 860 m long, comprised of coarse coral

106 gravel. The island is located on a 300 m wide reef flat with an ocean side reef width of 100 m
107 and an average fore-reef slope of 23.5° (Figure 1). A discontinuous cemented rubble bank is
108 located on the inner reef flat (Figure 1d). The cemented bank is the remains of a rubble rampart
109 that was deposited 30 m from the reef edge during Tropical Cyclone Bebe in October 1972
110 [Maragos and Beveridge, 1973]. A ~ 10 m wide conglomerate platform is located between the
111 area of cemented rubble and the beach face, with the seaward edge 0.3 m below mean sea level
112 (MSL). The island beach is located from 0.39 m above MSL and forms a steep beach face
113 (12.2°), with a berm elevated 3.5 m above MSL (Figure 1d). Sediment on the ocean-facing
114 beach is predominantly gravel sized (-4.2 to -6.4 phi) with some sand sized sediment from 1.15
115 to -0.32 phi [Ryan, 2012]. Fatato Island is located on the south-east side of Funafuti, facing
116 143° and is directly exposed to waves approaching between 60° and 213° . Mean H_s near
117 Funafuti is 1.2 m in summer and 1.4 m in winter (30 year Wave Watch 3 data), with mean peak
118 direction (D_p) shifting from 145° in summer to 135° in winter [Durrant et al., 2014].

119 **3. Methodology**

120 **3.1 Field campaign**

121 *3.1.1 Wave data*

122 Over a 62 day field deployment waves were measured by three separate wave and tide
123 instruments located: offshore, on the outer reef flat, and near the island shoreline (Figure 1d).
124 The instruments were deployed to record pressure (water level) at 1 Hz for 2048 s (~ 34 min)
125 every 3 hours. Data collection started at 12 pm on 4 June 2013 and ended at 9 pm on 5 August
126 2013, resulting in 500 synchronised bursts. In order to measure incident waves, a Nortek
127 AWAC was deployed at a depth of 19 m on the fore reef slope. In addition, two RBR Tide and
128 Wave recorders (TWRs) were deployed on the reef flat. The outer reef flat TWR was deployed
129 70.4 m seaward of the island beach (32 m shoreward of the reef edge) at an average depth of
130 0.9 m below MSL. The shoreline TWR was positioned at the seaward edge of the conglomerate
131 platform (MSL - 0.38 m); 11.6 m seaward of the beach sediment (Figure 1d). Both TWRs were
132 bolted to the reef with sensors 0.05 m above the bed.

133 Pressure data from the AWAC was corrected for signal attenuation using the method described
134 in Tucker and Pitt [2001]. Zero-down crossing analysis of the 1 Hz pressure data from each
135 burst, from each instrument, was undertaken to calculate wave height and period. Following
136 Ford et al. [2013] and Pomeroy et al. [2012] a 0.04 Hz spectral band-pass filter was used to
137 separate water level oscillations into SS and IG frequencies before calculating the significant

138 wave height associated with SS (H_{ss}) and IG (H_{ig}) waves. Power spectral density was calculated
 139 from the unfiltered water level data using a Fast Fourier Transform with 8 degrees of freedom
 140 and an overlapping Hamming window [Welch, 1967]. Wave setup ($\bar{\eta}_i$) at each reef flat sensor
 141 was calculated by identifying the difference in mean depth between the reef sensor and the
 142 offshore sensor, relative to the difference in topographic elevation:

$$143 \quad \bar{\eta}_i = \bar{h}_i - (\bar{h}_o + \Delta h_i), \quad (1)$$

144 where \bar{h}_i is the burst average depth at the reef flat sensor, \bar{h}_o is the burst average water depth
 145 at the offshore sensor, and Δh_i is the difference in elevation between the offshore sensor and
 146 the reef flat ($\Delta h=18.33$) and shoreline ($\Delta h=18.82$) sensors. This method assumes no setup or
 147 set-down at the offshore sensor.

148 3.1.2 Topography

149 A laser level total station was used to measure reef and island topography on 10 across reef
 150 transects; including the instrument profile. The profiles were combined with RTK-GPS survey
 151 points from the reef flat to create a terrain model of the reef flat and shoreline. This shallow
 152 water topography data was combined with satellite imagery and single beam echo-sounding
 153 data from *Hoeko et al.* [2014] to create a bathymetry map of the atoll reef flat near Fatato Island
 154 (Figure 1c). All references to topography used in field and model analysis are relative to MSL
 155 = 0.

156 3.2 Green-Naghdi model

157 Field conditions were simulated using a Green-Naghdi free-surface solver from the open source
 158 model, Basilisk [Popinet, 2015]. The GN solver extends the non-linear shallow water (NSW)
 159 solver from Popinet [2011] to include a weakly dispersive source term for wave propagation
 160 and shoaling. The combination of GN and NSW terms have been proven to provide an efficient
 161 solution of wave dispersion, wave breaking, and wet-dry interaction in shallow coastal
 162 environments [Bonneton et al., 2011; Lannes and Marche, 2015; Tissier et al., 2012]. In 1D,
 163 the Basilisk GN solver has been verified against benchmark data for: solitary wave runup on a
 164 plain beach, solitary wave overtopping a sea wall, and wave propagation over a bar [Popinet,
 165 2014]. In 2D, the model has been successfully tested against benchmark data for: wave
 166 propagation over an ellipsoid shoal, solitary wave runup on a conical island, and tsunami
 167 propagation and runup from the Tohoku earthquake [Popinet, 2015].

168 3.2.1 Numerical scheme

169 A brief outline of the Basilisk GN model is given here. The reader is encouraged to refer to
 170 *Popinet* [2015] for a full description, or the Basilisk website for the documented source code
 171 [*Popinet*, 2014].

172 In integral form, the GN equation set is:

173

$$174 \quad \partial_t \int_{\Omega} \mathbf{q} d\Omega = \int_{\partial\Omega} \mathbf{f}(\mathbf{q}) \cdot \mathbf{n} d\partial\Omega + \int_{\Omega} \mathbf{S} d\Omega \quad (2)$$

175

176 where $\partial\Omega$ is the boundary and \mathbf{n} is the unit normal vector of a given subset of space, Ω . For
 177 conservation of mass and momentum in shallow water, \mathbf{q} and $\mathbf{f}(\mathbf{q})$ are from the NSW system
 178 outlined in *Popinet* [2011], and are written as:

179

$$180 \quad \mathbf{q} = \begin{pmatrix} h \\ h u_x \\ h u_y \end{pmatrix}, \quad \mathbf{f}(\mathbf{q}) = \begin{pmatrix} h u_x & h u_y \\ h u_x^2 + \frac{1}{2} g h^2 & h u_x u_y \\ h u_x u_y & h u_y^2 + \frac{1}{2} g h^2 \end{pmatrix} \quad (3)$$

181

182 where u is the velocity vector and h is water depth.

183 The weakly dispersive source term in (2) is \mathbf{S} , defined as:

184

$$185 \quad \mathbf{S} = \begin{pmatrix} 0 \\ -hg\nabla z_b + h\left(\frac{g}{\alpha}\nabla\eta - \mathbf{D}\right) \end{pmatrix} \quad (4)$$

186

187 where z_b is bathymetry elevation, η is free surface elevation, and α is a dispersion constant.

188 The second part of (4), $h((g/\alpha)\nabla\eta - \mathbf{D})$, is the dispersive term that is added to the original

189 NSW system [Popinet, 2015]. If this second term is removed or equal to zero the system
190 reduces to a non-dispersive NSW model.

191 3.2.2 Wave breaking

192 Wave breaking is represented by switching off the dispersive source term if the local free-
193 surface slope exceeds a user-defined breaking threshold (B); by default B=1. Removing the
194 dispersive term refers the model to a NSW system, where wave breaking is handled as a shock
195 [Popinet, 2015]. Similar methods for wave breaking in Boussinesq-type models have been
196 successfully applied to coral reef environments [Roerber and Cheung, 2012; Shimozono et al.,
197 2015]. The dispersion term is also removed if a cell has a ‘dry’ neighbour (where $h < 10^{-10}$ m is
198 considered dry). Therefore, wet-dry interaction is handled by the NSW equations that include
199 a hydrostatic reconstruction technique from Audusse et al. [2004] to guarantee positivity of
200 water depth [Popinet, 2011; 2012]. For the simulations presented here, implicit quadratic
201 bottom friction is added using (5):

$$202 \quad \mathbf{S}_f = -C_f \|\mathbf{u}\| \mathbf{u} \quad (5)$$

203 where C_f is a non-dimensional coefficient that controls the rate of attenuation. A constant C_f
204 value was used across the model domain for the simulations presented here.

205 3.3 Model experiments

206 Sensitivity analysis was undertaken to identify the appropriate C_f and B values to use on
207 Funafuti. Four B slopes (0.4, 0.6, 0.8 and 1) and 8 C_f values (0.01, 0.02, 0.03, 0.04, 0.05, 0.06,
208 0.08 and 0.1) were tested using 10% of the field data (50 bursts). Each B value was simulated
209 with each C_f value using the 50 test bursts; a total of 1600 simulations. The 50 consecutive
210 bursts used to test model sensitivity encompassed a range of incident conditions between 23
211 June and 29 June 2013, and notably included a swell event that coincided with spring tides.
212 Model outputs for H_{ss} , H_{ig} , and $\bar{\eta}$ at the shoreline were compared with field measurements to
213 identify the C_f and B combination that best represents conditions on Funafuti. All 500 bursts
214 from the field campaign were then simulated using the B and C_f combination that produced the
215 lowest combined error for H_{ss} , H_{ig} , and $\bar{\eta}$ at the shoreline. Model outputs for H_{ss} , H_{ig} , $\bar{\eta}$, and
216 wave spectra from the 500 bursts were then compared with field data at the reef flat and
217 shoreline, before model outputs were used to analyse maximum water level on the beach face.

218 3.3.1 Model inputs

219 The Basilisk GN solver was used with a 1D grid to simulate wave transformation across the
220 atoll reef. Reef bathymetry was interpolated to a uniform 1D transect with $\Delta x=1$ m, and still
221 water level was offset according to the tide level of each burst. To reduce boundary reflection,
222 imported waves were propagated across a flat shelf (100 m deep) for 650 m before interacting
223 with the offshore atoll. Measured water level from the offshore instrument was interpolated
224 to 10 Hz to use as the boundary wave field for each simulation.

225 3.3.2 Output data analysis

226 Each test burst simulated 2048 s of wave activity. It took ~ 100 s for waves to reach the shoreline
227 and ~ 300 s for mean water level to stabilise on the reef. Therefore, only output data between
228 512 s and 2048 s was considered for analysis. To compare model results with field results,
229 time-series water level was extracted at 10 Hz, at each of the three instrument positions (Figure
230 1d). H_{ss} , H_{ig} , $\bar{\eta}$ and wave spectra were calculated from each model instrument using the same
231 methods applied to field data.

232 3.3.3 Maximum runup analysis

233 Maximum water level data were extracted at the end of each model run and used to identify
234 maximum wave runup (R_{max}) for each simulation. Of note, field data were unable to be
235 collected for runup and all R_{max} results are based on model outputs. R_{max} was calculated relative
236 to the still water tide level and then separated into SS, IG, and setup components using model
237 data for H_{ss} , H_{ig} , and $\bar{\eta}$ from the shoreline field instrument position (Figure 1d). First, the
238 difference between tide level and R_{max} was calculated. Second, the setup contribution was
239 identified (equal to $\bar{\eta}$ at the shoreline), and subtracted to determine the combined SS and IG
240 contribution. The remaining R_{max} value was split into SS and IG components proportional to
241 the values of H_{ss} and H_{ig} at the shoreline. Note, this method calculates maximum runup to the
242 nearest horizontal meter ($\Delta x = 1$ m) and does not account for the influence that wave period
243 has on swash elevation.

244 3.3.4 Performance metrics

245 Mean absolute error (MAE) and model skill were used to quantify model performance when
246 predicting H_{ss} , H_{ig} and $\bar{\eta}$. MAE (6) and skill (7) are based on residual values where the
247 observed value (O_i) was subtracted from modeled value (P_i). Model skill is based on the method
248 used in *Lowe et al.* [2009]. Skill is equal to one when $P_i = O_i$, meaning skill values closer to
249 one identify a better representation of measured processes.

250

$$251 \quad MAE = |P_i - O_i| \quad (6)$$

252

$$253 \quad Skill = 1 - \frac{\sum |(P_i - O_i)|}{\sum (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (7)$$

254 **4. Field Observations**

255 **4.1 Tide and wave conditions**

256 Two semi-diurnal spring tides were recorded during the 62 day data collection period. A spring
257 tidal range of ~2 m was observed, where the maximum high tide was + 1.08m relative to MSL
258 = 0, and the minimum low tide was -1.0 m, relative to MSL = 0. Two neap tides were also
259 recorded, with a larger diurnal range between +0.45 m -0.35 m and a lower semi-diurnal
260 oscillation (Figure 2a). On average, offshore significant wave height (H_o) was 1.17 m, and H_{max}
261 was 2.0 m (Figure 2c,d; Table S1). Four moderate swell events were measured during the
262 deployment (where $H_o \geq 1.9$ m and $T_s > 10.5$ s). The largest swell event started on June 23rd
263 and peaked at $H_o = 2.1$ m; with $H_{max} = 3.7$ m and $T_s = 15.5$ s. The swell arrived during a spring
264 tide, with a number of bursts coinciding with spring high tide. Between swell events H_o
265 occasionally dropped below 1 m but remained above 0.68 m (Figure 2).

266 **4.2 Wave transformation**

267 *4.2.1 Sea swell waves*

268 On average, incident wave height decreased by 50% between the offshore instrument and the
269 outer reef. On the reef flat, wave height was tidally modulated, especially under low and
270 moderate incident wave conditions (Figure 3a). Mean attenuation was lowest at high tide (35%)
271 compared to mid (51%) and low tides (65%). All bursts recorded wave activity at the outer reef
272 flat; with H_{ss} falling between a minimum of 0.22 m and a maximum of 1.17 m (mean = 0.56 m,
273 Table S1).

274 H_{ss} was significantly lower at the shoreline compared to the reef flat; with a mean of 0.25 m
275 and a range of 0 m to 0.61 m. On average, offshore waves attenuated by 78% at the shoreline.
276 Results show that H_{ss} was tidally modulated across all incident heights. Average attenuation
277 was again greater at low tides (90%), compared to mid (80%) and high (64.5%) tides. Wave
278 height was smallest at low tide (mean = 0.12 m), with 20 bursts recording no wave activity.

279 Larger incident waves (>1.5 m) exhibited less attenuation at low tide, but were significantly
280 attenuated at high tide (Figure 3g). In comparison, smaller incident waves (<1.5 m) were
281 rapidly attenuated at low tide but underwent minimal dissipation at high tide.

282 4.2.2 IG waves

283 At the outer reef, H_{ig} was primarily controlled by incident waves and only minimally affected
284 by the tide (Figure 3c). On average, H_{ig} at the outer reef ranged from 10% to 29% of H_o (mean
285 = 17%). H_{ig} increased across the reef flat, and at the shoreline, mean H_{ig} was 25% of H_o . At the
286 shoreline there was a slight tidal influence on small IG waves ($H_{ig} < 0.5$ m); with the largest IG
287 waves observed at mid tide (Figure 3h). At low tide H_{ig} was smaller; possibly due to higher
288 friction on the shallow reef flat. At high tide H_{ig} was also relatively smaller; perhaps as a result
289 of decreased SS wave breaking and attenuation. During large incident conditions, results show
290 that H_{ig} was not tidally modulated and was often larger than H_{ss} at the shoreline (Figure 3).

291 4.2.3 Wave setup

292 Mean setup was 0.18 m (16% of H_o) at the outer reef and at the shoreline (Table S1). Setup at
293 the outer reef was greater at low tide, with a mean of 0.32 m (26% of H_o). At high tide, mean
294 setup on the reef flat was 0.07 m (6% of H_o). Mean setup at the shoreline was 0.3 m at low tide,
295 inclusive of the 20 bursts that recorded no wave activity. Wave setup at the reef and shoreline
296 was strongly correlated to tidal level and incident wave height, with maximum setup generated
297 by large waves at low tide (Figure 3). The largest setup observed during the deployment was
298 0.81 m (38.6% of H_o) at the outer reef and 0.89 m (42% of H_o) at the shoreline. This observation
299 was associated with $H_o = 2.1$ m and $T_o = 15.5$ s at low tide (-0.73 m) at the peak of the 23 June
300 swell event.

301 4.3 Shoreline exposure

302 The island beach was situated 0.39 m above MSL. Consequently, waves could directly interact
303 with the beach face when the tide exceeded +0.39 m. From the offshore instrument, it is
304 apparent that tidal elevation exceeded 0.39 m on 112 of the 500 bursts (22.4% of the experiment
305 period). The shoreline instrument was located 0.77 m below the beach face. Mean depth at the
306 shoreline instrument (tide + setup) exceeded 0.77 m on 125 of the 500 bursts (25% of the
307 experiment period). This data suggests that any interaction between oceanic processes and the
308 beach face was confined to 25% of the field deployment period. However, this figure does not
309 account for runup above still water level caused by SS or IG waves. The connection between

310 wave processes and island sediment is further investigated numerically based on maximum
311 runup outputs.

312 **5. Model Results**

313 **5.1 Sensitivity to breaking and friction parameters**

314 Modeled wave heights at the shoreline were sensitive to changes in C_f (friction coefficient) and
315 B (slope threshold used to turn off the dispersive term to handle wave breaking using the NSW
316 equations). Lower C_f values (< 0.03) resulted in an over-predicted shoreline wave height; with
317 mean error between 0.03 m and 0.057 m (Figure 4). Higher C_f (> 0.06) resulted in under-
318 predicted shoreline wave heights, with mean error between 0.04 m and 0.06 m (Figure S1).
319 The lowest error was found with $C_f = 0.04$. Each friction value had a stronger correlation and
320 lower error with $B = 0.8$ or $B = 1$. Lower B values (0.6 and 0.4) often resulted in slightly over
321 predicted wave heights at high tide. The lowest mean error (0.02 m), highest model skill (0.994)
322 and strongest correlation ($R^2 = 0.985$) was achieved using $C_f = 0.04$ and $B = 1$ (Figure 4).

323 IG wave height was more sensitive to C_f and B values. Lower friction values resulted in
324 significantly over-predicted H_{ig} at the shoreline, with mean error between 0.06 m and 0.15 m
325 for $C_f \leq 0.02$ (Figure 4). $C_f > 0.06$ resulted in under predicted IG wave heights with mean
326 error between 0.07 and 0.12 m (Figure S1). Higher B values (0.8 and 1) gave a much better
327 prediction of field conditions compared to low slopes (0.6 and 0.4). The best representation of
328 H_{ig} at the shoreline was achieved using $C_f = 0.04$ and $B \geq 0.8$. IG error was slightly lower
329 with $B = 0.8$ compared to $B = 1$ (Figure 4).

330 Model values for wave setup were close to field measurements for most B and C_f combinations
331 (Figure S1). The only deviation from a near perfect prediction was found using $B = 0.4$ or $C_f >$
332 0.06 (Figure 4). For each friction value, $B = 1$ achieved the best prediction of wave setup. $C_f =$
333 0.01 and $B = 1$ gave the best representation of wave setup; however any C_f value between 0.01
334 and 0.05 produced a very good match with field data where $B = 1$ (Figure 4).

335 *5.1.1 Combined error*

336 The lowest error and highest model skill were achieved using $C_f = 0.04$. When applied to the
337 steep sloping, rough and shallow atoll reef at Funafuti, the model gave the best prediction of
338 H_{ss} , H_{ig} and $\bar{\eta}$ when a breaking slope of 0.8 or 1 was combined with $C_f = 0.04$. Using $C_f = 0.04$
339 the sum MAE from H_{ss} , H_{ig} and $\bar{\eta}$ for both $B = 1$ and $B = 0.8$ was 0.084 m (Table S2). $B = 1$
340 gave a better prediction for H_{ss} and setup but $B = 0.8$ gave a slightly better prediction for H_{ig} .

341 However, there was minimal sensitivity between $B = 1$ and $B = 0.8$. Therefore, the values used
342 to simulate the entire field deployment and investigate R_{max} were $C_f = 0.04$ and the default slope
343 threshold, $B = 1$.

344 **5.2 Full experiment simulation**

345 *5.2.1 Model performance*

346 A comparison between model outputs and field data for the entire experiment using $C_f = 0.04$
347 and $B = 1$ are presented in Figure 5. Model performance across the 500 simulations was
348 characterised by Skill > 0.91 , MAE < 0.045 and $R^2 \geq 0.8$, based on outputs for H_{ss} , H_{ig} and
349 $\bar{\eta}$ at the reef flat and shoreline.

350 Field results show that H_{ss} at the reef and shoreline is primarily a function of tide level and
351 incident wave height. The high skill (>0.97) associated with modeled H_{ss} at the reef and
352 shoreline indicate that tidal controls and incident forcing were numerically replicated very well
353 (Figure 5). H_{ss} at the outer reef flat was generally over-predicted (MAE = 0.045 m), especially
354 during energetic conditions (Figure 5i). Modeled H_{ss} at the shoreline had smaller error (MAE
355 = 0.023 m), but the smaller wave heights observed at low tide were slightly under-predicted
356 (Figure 5l).

357 Model results show the same general pattern as measured H_{ig} at the reef flat and shoreline
358 (Figure 5c,f). Numerical simulations also reflect the increase in H_{ig} between the reef flat and
359 shoreline. Compared to H_{ss} and $\bar{\eta}$, model predictions of H_{ig} had greater error, lower skill, and
360 a weaker correlation to field results. The weaker prediction is possibly associated with the
361 observation that IG waves have no pronounced tidal modulation. Despite the deviation from a
362 perfect fit, IG wave dynamics across the reef flat were captured reasonably well in the
363 numerical model (Figure 5).

364 Modeled wave setup followed the same tidal modulation and relation to H_o as field
365 measurements (Figure 5). Figure 5d shows how the setup peaks at low tide were slightly under-
366 predicted at the reef flat, but well predicted at the shoreline. However, the low setup values at
367 high tide were slightly over-predicted at the shoreline (Figure 5g).

368 *5.2.2 Field and model wave spectra*

369 Measured wave data was used to run model simulations. Consequently, at the offshore sensor,
370 model spectra were almost identical to field measurements (Figure 6a,d). Field based spectra
371 depicted a bimodal peak in incident wave energy during the study period (Figure S2). A

372 shorter period peak at 0.094 Hz (10.6 s) was associated with mean wave conditions and the
373 latter two swell events. A longer period peak at 0.065 Hz (15.4 s) was associated with the first
374 two swell events (Figure 6a,d). Modeled spectra illustrated a similar bimodal peak in incident
375 wave spectra.

376 On the reef flat, the presence of energy at incident wave frequencies was limited to high tide,
377 with greater spectral density occurring during energetic conditions (Figure 6b). Spectra on the
378 reef flat peaked in the IG band at 0.0049 Hz (204 s), with a secondary peak in the swell
379 frequency band (0.072 Hz) during larger incident conditions (Figure 6b). At the outer reef flat,
380 modeled wave spectra identified a clear IG wave signal. However, peak energy occurred at a
381 lower frequency (0.037 Hz, 270 s). The presence of swell wave energy on the reef flat at high
382 tide was evident in model spectra, with peak energy at 0.072 Hz; the same as field
383 measurements.

384 Field based spectra demonstrate that SS waves were nearly fully dissipated at the shoreline,
385 with energy concentrated at IG frequencies (Figure 6c). However, some incident frequency
386 energy was present at the shoreline at high tide or during swell events. IG wave energy was
387 present at the shoreline during mean wave conditions at high tide but was amplified throughout
388 the tide cycle when larger incident waves were present. Field data indicates that IG wave energy
389 increased between the reef flat and shoreline where spectral density peaked at 0.0068 Hz (146
390 s). Modeled spectra at the shoreline showed a similar spectral density to field results, but with
391 a slightly higher peak frequency of 0.0061 Hz (163 s). The over-predicted IG period may be a
392 result of using the model in 1D, and therefore omitting the alongshore processes that influence
393 long-wave behaviour.

394 **5.3 Maximum runup**

395 The Basilisk GN model was able to replicate water level variations on the reef flat associated
396 with SS waves, IG waves, and wave setup. Combined, these processes influence shoreline
397 water level and the maximum runup point that is reached under a particular set of incident
398 conditions. Model results were analysed to identify R_{max} for each burst. Across all simulations
399 R_{max} was located between the inner reef flat and upper beach face (Figure 7a). The elevation of
400 R_{max} relative to MSL is primarily a function of incident wave height and tide level (Figure 7b).
401 Large waves at low tide produced an elevated setup and energetic IG waves that resulted in the
402 same runup elevation as small waves at high tide (Figure 7). During 67 bursts (13.4%), R_{max}
403 reached the top of the conglomerate platform and was level with the toe of beach (MSL + 0.39

404 m). Wave interaction with the mid beach face ($R_{max} > 0.5$ m) occurred during 287 bursts;
405 accounting for 57.4% of the experiment (Figure 7c). Collectively, waves reached or exceeded
406 the beach toe for 70.8% of the experiment (354 bursts). Numerical runup results indicate that
407 the geomorphic window of interaction between waves and island sediment is open for a much
408 longer period of time than was estimated using mean water level.

409 The combined processes that contribute to R_{max} vary through the tide cycle (Figure 7d). At low
410 tide (<-0.4 m), wave setup is the primary mechanism contributing to shoreline water level. At
411 mid tide stages (-0.4 m $>$ $+0.3$ m), the influence of setup decreases significantly and IG waves
412 become the dominant contribution to runup level (Figure 7d). As tide level increases there is a
413 linear increase in the portion of runup associated with SS waves. SS waves become the
414 dominant runup mechanism at tides above $+0.65$ m. However, at tides between -0.4 m and $+1$
415 m, IG waves remain a significant contributor to R_{max} . Overall, wave setup is important at low
416 tide, SS waves are important at high tide, and IG waves contribute a consistently high
417 percentage of R_{max} at all tide stages (Figure 7d, Table 1).

418 5.3.1 Swell driven shoreline exposure on June 23

419 The largest waves measured during the field experiment ($H_o = 2.10$ m, $T_o = 15$ s) coincided with
420 spring tides on June 23, 2013. The swell event generated significant wave setup and IG activity,
421 and model results indicate the presence of waves on the beach face throughout the tide cycle
422 (Figure 8). The swell peaked at low tide (-0.73 m), when a 0.9 m setup resulted in a mean
423 shoreline depth 0.05 m above MSL (Figure 8a). Model results show that the combined runup
424 from IG and SS waves was able to surge over the conglomerate platform and impact the beach
425 face to an elevation of 1.05 m. Runup was primarily associated with wave setup (51.1%), and
426 IG waves (31.9%), but there was also a small SS wave contribution (17%).

427 At high tide ($+0.61$ m), the swell event generated a runup of 2.03 m above tide level and an
428 R_{max} elevation of 2.64 m above MSL (Figure 8b). The deeper reef flat resulted in significantly
429 less wave setup that accounted for 15% of R_{max} . Large IG waves at the shoreline ($H_{ig} = 0.72$ m)
430 accounted for 48% of R_{max} and therefore acted as the main control on runup elevation. SS waves
431 were also able to propagate across the reef to account for 37% of R_{max} . The highest runup above
432 MSL occurred during a spring high tide (MSL + 0.98 m), when the swell was decreasing
433 (Figure 8c). The combined influence of setup (10.5%), IG waves (43%), and SS waves (46.5%)
434 resulted in R_{max} 2.82 m above MSL. Note that under large incident conditions waves do reflect

435 off the shoreline at high tide and interfere with the oncoming wave field, resulting in the peaks
436 observed in the maximum water level line from Figure 9b,c.

437 **6. Discussion**

438 **6.1 Tidal modulation of reef flat processes**

439 Field observations from Funafuti show that H_{ss} is strongly modulated by water depth across
440 the reef, a function of tide level and setup (Figure 3). Tidal modulation of shoreline wave height
441 has been well documented on a range of fringing, atoll, and platform reefs [*Ford et al.*, 2013;
442 *Kench and Brander*, 2006; *Lugo-Fernandez et al.*, 1998; *Péquignet et al.*, 2011]. The majority
443 of these studies present a strong relationship between wave height and mean reef depth,
444 concluding that SS activity at the shoreline is limited to high tide. Few studies have recorded
445 shoreline wave activity at low tide. Field results from Funafuti emphasise how large setup at
446 low tide can submerge the reef flat and enhance the potential for waves to impact the shoreline
447 throughout the tidal cycle. Compared to other field studies, the narrow reef and consistent
448 exposure to moderate or high energy waves create a relatively active shoreline wave regime.
449 As a result, SS and IG waves are almost always present at the shoreline during low and high
450 tide.

451 Tidal modulation of wave setup has been identified on coral reefs [*Becker et al.*, 2014; *Gourlay*,
452 1996]. The results from this study support observations of *Becker et al.* [2014], which identified
453 the presence of maximum setup at low tide, and a lower setup at high tide. Field measurements
454 from a high energy fringing reef [*Vetter et al.*, 2010] and low energy reef platform [*Jago et al.*,
455 2007] have found that, on average, setup is 25% of H_o (incident H_s). Mean setup at the shoreline
456 on Funafuti was 15.6% of H_o across all tides. However, setup at low tide ranged from 16.8%
457 to 42% of H_o (mean = 28%), and at high tide setup ranged from 0% to 16.2% of H_o (mean =
458 6.2%). Similar tidal controls and incident wave height scaling were observed on atoll reefs in
459 the Marshall Islands [*Becker et al.*, 2014].

460 Field results from Funafuti indicate that there is minimal tidal influence on IG wave activity at
461 the reef flat or shoreline (Figure 3). Results show that H_{ig} increases between the reef flat and
462 shoreline and suggest that IG waves are primarily a function of incident wave conditions; not
463 reef flat water level. At Funafuti, H_{ig} at the shoreline scales between 10% and 43% of H_o (mean
464 = 26%), with no clear tidal control (Figure 3). Results from Majuro Atoll, on a reef with similar
465 morphology and wave exposure to Funafuti, also show H_{ig} at the shoreline to be between 10%
466 and 40% of H_o [*Ford et al.*, 2013]. On the narrow reefs (~100 m) at Funafuti and Majuro, IG

467 wave height was measured to increase across the reef flat and peak at the shoreline. IG waves
468 were also measured to increase in height across a wider (~250 m) and relatively smooth reef
469 on Kwajalein Atoll [Quataert *et al.*, 2015]. However, measurements on wide fringing reefs
470 (+400 m) typically show IG wave height and energy peaks within ~100 m of the reef edge
471 before dissipating across the reef flat to be minimal at the shoreline [Péquignet *et al.*, 2014;
472 Pomeroy *et al.*, 2012]. Pronounced tidal controls on IG wave height have also been observed
473 on wider fringing reefs, due to frictional dissipation across the inner reef flat [Van Dongeren
474 *et al.*, 2013]. Given the location of Fatato Island relative to the reef edge, IG waves are able to
475 impact the shoreline before any dissipation is observed.

476 **6.2 Model capability**

477 The majority of phase-resolving model work on reefs has focused on continental fringing reefs,
478 not atoll reefs that host low lying sedimentary islands [Nwogu and Demirebilek, 2010;
479 Shimozono *et al.*, 2015; Yao *et al.*, 2012; Zijlema, 2012]. Such Boussinesq-type models have
480 been shown to accurately replicate wave attenuation, wave setup, and IG wave dynamics when
481 evaluated against wave flume data. Few phase-resolving models have been evaluated using
482 field data from fringing or atoll reefs [Demirebilek and Nwogu, 2007; Roeber and Cheung,
483 2012]. This paper presents the first field evaluation using a phase-resolving model to simulate
484 wave transformation on an atoll reef. Model results from Funafuti show that the Basilisk GN
485 solver is capable of representing the key processes that contribute to elevated water depth at
486 the shoreline. Water level dynamics associated with SS wave attenuation and wave setup were
487 represented with skill > 0.97 and mean error <0.045 m. IG wave dynamics were also
488 represented reasonably well, with skill = 0.91. Wave height and setup predictions were slightly
489 sensitive to breaking and friction parameters, whereas IG wave heights were highly sensitive
490 to low B values and high friction.

491 Limitations to the model results cannot be overlooked. While wave transformation results were
492 tested against field data, no data was available to confirm model predictions of R_{max} . However,
493 the Basilisk GN model has been tested against benchmark runup scenarios [Popinet, 2014],
494 that give some confidence to R_{max} values. Beach porosity and percolation were also not
495 accounted for in runup estimations, possibly resulting in over-predicted runup levels. Further,
496 as the model was used in 1D, alongshore processes that influence wave transformation and
497 runup (e.g. refraction, wave convergence, alongshore currents and edge waves) were omitted.

498 **6.3 Maximum shoreline runup**

499 The unconsolidated sedimentary structure and low elevation make atoll islands susceptible to
500 wave over-topping and erosion during high energy wave events or periods of elevated sea level
501 [Hoeke *et al.*, 2013]. An understanding of the processes that contribute to increased wave
502 interactions with the shoreline is critical for coastal management, and to mitigate the potentially
503 adverse effects of future sea level rise on atoll landforms [Ferrario *et al.*, 2014]. Recent
504 research has highlighted that wave driven flooding can be caused by long period swell waves
505 which are generated by distant weather systems [Hoeke *et al.*, 2013]. However, large waves
506 typically need to coincide with high tide for overtopping to occur. Merrifield *et al.* [2014] show
507 that overtopping events happen every 2 – 5 years in the Marshall Islands but will occur multiple
508 times per year with any rise in mean sea level greater than 0.4 m. Results from Merrifield *et al.*
509 [2014] indicate that, on average, 52% of non-tidal water level was a result of wave setup, with
510 a further 48% associated with SS or IG waves. An overtopping event was also measured by
511 Ford *et al.* [2013] on Majaro Atoll, where land elevation was 2 m above the reef flat. Overwash
512 was generated by 2 m incident waves at high tide and was primarily driven by energetic IG
513 waves at the shoreline ($H_{ig} = 0.8$ m), with a low contribution from SS waves and setup ($H_{ss} =$
514 0.4 m, $\bar{\eta} \approx 0.2$ m).

515 The analysis presented here extends the current understanding of wave interactions with atoll
516 islands by focusing on the processes that promote wave interaction with the beach face. Results
517 provide the first assessment of wave processes impacting islands on Funafuti Atoll, where sea
518 level is currently rising at three times the global average rate [Becker *et al.*, 2012]. Funafuti
519 Atoll is also characterised by a narrow reef flat and steep fore-reef slope (23.5°), which
520 according to Quataert *et al.* [2015] increases the risk of wave driven flooding when exposed
521 to a rise in mean sea level. The elevated ocean berm on Fatato prevented any overtopping
522 events, but results do highlight the temporal nature of wave processes that operate on the beach
523 face. Significantly, IG waves are identified as having the dominant influence on runup
524 elevation (41%), compared to wave setup (27.4%) and SS waves (31.6%). However, it is
525 apparent that the runup mode shifts through the tide cycle. At low tide, SS wave height is
526 significantly dissipated (78%), and IG wave activity is slightly limited by spring low tides and
527 higher friction. Wave setup is at a maximum at low tide and provides the main control on
528 shoreline water level, along with a significant presence of IG wave height. At mid-tide, larger
529 SS waves propagate across the reef flat, setup decreases, and IG waves control runup elevation.

530 At high tide, wave runup is driven by a combination of SS and IG waves, with a small
531 contribution from wave setup.

532 **6.4 Island exposure to wave processes**

533 The beach face on Fatato Island is located 0.39 m above MSL. Using field measurements, tide
534 level exceeded the beach toe elevation for 22.4% of the experiment. Tide station data from the
535 atoll lagoon also shows that tides above +0.39 m occur for 23% of the year. Mean water depth
536 at the shoreline (tide + setup) exceeded beach toe elevation for 25% of the experiment. These
537 results suggest the beach face was directly exposed to wave activity for a quarter of the
538 experimental period. However, model analysis of maximum runup as a function of SS waves,
539 IG waves, setup and tide level reveal that waves actually impacted at or above the beach toe
540 for 70.8% of the deployment, with wave activity on the mid beach face for 57.4% of the
541 experiment.

542 Modeled R_{max} results show that islands on the south-eastern rim of Funafuti are much more
543 connected to ocean processes than topographic and tide measurements suggest. Geomorphic
544 change on atoll islands is limited to the temporal window of island exposure to wave activity
545 [Kench and Brander, 2006]. By measuring depth controls on SS wave propagation across
546 different reef flats Kench and Brander [2006] show that interaction between wave processes
547 and island shorelines is limited to a small temporal window at high tide. Results from Funafuti
548 highlight the importance of accounting for water level oscillations at all surf-zone frequencies
549 when assessing wave impacts at the shoreline. Accounting for R_{max} significantly increases the
550 temporal window of connectivity between wave processes and island sediment on Funafuti.
551 Under typical wave conditions, sediment transport between the reef flat and island beach can
552 occur for the majority of the tide cycle (71%). However, when exposed to higher wave energy,
553 the island can be connected to wave activity for the entire tide cycle. The enhanced interaction
554 between waves and the island is attributed to the large setup at low tide that results in IG wave
555 activity on the reef flat at all tide stages. The narrow reef flat also results in IG waves impacting
556 the island without any dissipation or tidal forcing being observed in field or model data. Results
557 suggest that even a small rise in sea level may result in 100% interaction between wave
558 processes and island shorelines, significantly increasing the period of time when geomorphic
559 change can occur on the beach face.

560 **7. Summary**

561 Field data collected from a 62 day deployment were examined to understand wave
562 transformation on Funafuti Atoll and evaluate a numerical models capability of simulating SS
563 wave attenuation, IG wave behaviour and wave setup. Research from Funafuti indicates that
564 the island shoreline is highly connected to wave processes, despite sitting 0.39 m above MSL
565 and only being submerged for 23% of the tide cycle. Tidal level has a strong control on SS
566 waves and wave setup at the shoreline on Fatato Island. Therefore, SS waves have the primary
567 influence on runup elevation at high tide and wave setup largely determines runup elevation at
568 low tide. Field and model results indicate that infragravity wave activity is not tidally
569 modulated on Funafuti, and runup analysis show IG waves are capable of elevating shoreline
570 water level throughout the tide cycle. Tide level and setup, combined with runup from SS and
571 IG waves result in island sediment being impacted by wave activity for 71% of the time, on
572 average. The increase in setup and IG wave activity during swell events mean that waves can
573 interact with the beach face for a complete spring tide cycle. These results imply that any rise
574 in sea level will further increase the temporal window of interaction between waves and island
575 sediment, with SS and IG waves becoming the dominant processes influencing shoreline water
576 level.

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589

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703 Tables

704 **Table 1:** Percentage of R_{max} associated with SS waves, IG waves and setup at different tide stages.

	High tide	Mid tide	Low tide	All tides
SS (%)	48.7	29.2	14.9	31.6
IG (%)	39.3	44.7	38.8	41.0
Setup (%)	12.0	26.1	46.3	27.4

705

706 Figure captions

707 **Figure 1.** a) Location of Funafuti Atoll in the Pacific Ocean. b) Funafuti Atoll with -100 m and -2 m contour lines,
708 islands are black and the reef flat ($h > 3$ m) is grey. c) Bathymetry around Fatato Island with field instrument
709 positions and contours at -100 m, -20 m and -2 m. d) Profile of the reef flat and Fatato Island, highlighting
710 geomorphic features and instrument locations.

711 **Figure 2.** Summary wave conditions from the offshore instrument (blue), reef flat instrument (green) and
712 shoreline instrument (red) from the 62 day deployment in 2013. H_{ss} and H_{ig} are significant wave heights in the SS
713 and IG band, respectively. $\bar{\eta}$ is wave setup.

714 **Figure 3.** Tidal controls on wave processes on the reef flat (left) and at the shoreline (right) from field
715 measurements. Tide is relative to MSL = 0, $\bar{\eta}$ is wave setup and \bar{h} is mean depth (tide + setup). j) Points outside
716 the small box show that mean depth is above the beach toe (MSL + 0.39m).

717 **Figure 4.** Sensitivity of modeled H_{ss} (top), H_{ig} (middle) and $\bar{\eta}$ (bottom) at the shoreline, to variations in B and
718 C_f . Model performance is quantified using R^2 (left), MAE (left) and skill (right).

719 **Figure 5.** a-g) Model outputs (red) compared to field measurements (black) for the 62 day experiment. a) Incident
720 H_s . d-b) H_{ss} , H_{ig} and $\bar{\eta}$ at the outer reef and e-g) at the shoreline. The same data from each time-series comparison
721 is also presented as a scatter (h-n), on the same line.

722 **Figure 6.** Field wave spectra (left) from the offshore instrument (a), outer reef flat (b) and shoreline (c) compared
723 to wave spectra calculated using model outputs (right) at the offshore location (d), outer reef flat (e) and shoreline
724 (f).

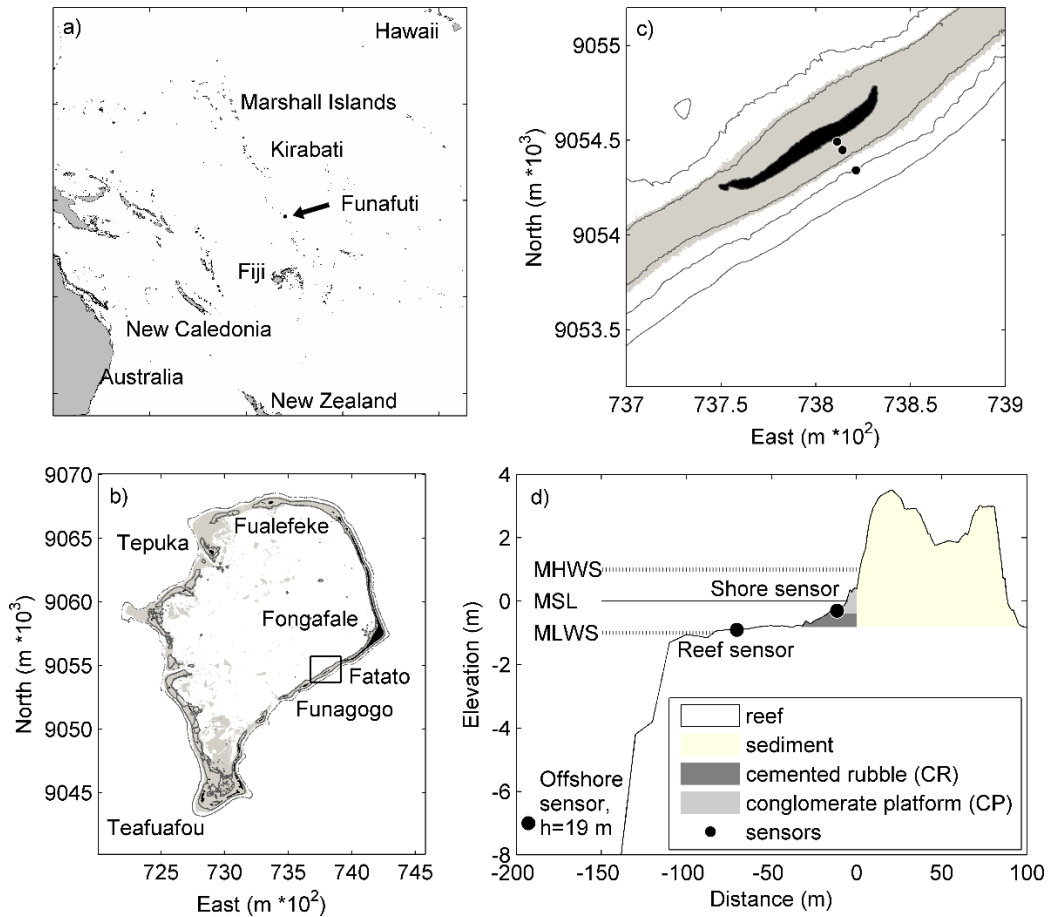
725 **Figure 7.** R_{max} analysis using model data. a) R_{max} location from each burst, highlighting the toe of beach (TOB)
726 threshold for wave interaction with island sediment. b) Tidal controls on R_{max} above MSL under different incident

727 wave conditions. c) R_{max} frequency at different elevations, relative to MSL=0. d) The contribution of wave setup
 728 (dots), IG waves (+) and SS waves (x) in R_{max} above tide level.

729 **Figure 8.** Model outputs for instant, mean and maximum water level (WL) on the reef and shoreline during the
 730 spring tide swell on June 23. a) Setup dominant R_{max} at low tide. b) IG dominant R_{max} at high tide. c) SS dominant
 731 R_{max} at high tide. Bar plots on the right highlight the contribution of tide level, setup, IG waves and SS waves in
 732 runup, relative to MSL = 0.

733 **Figures**

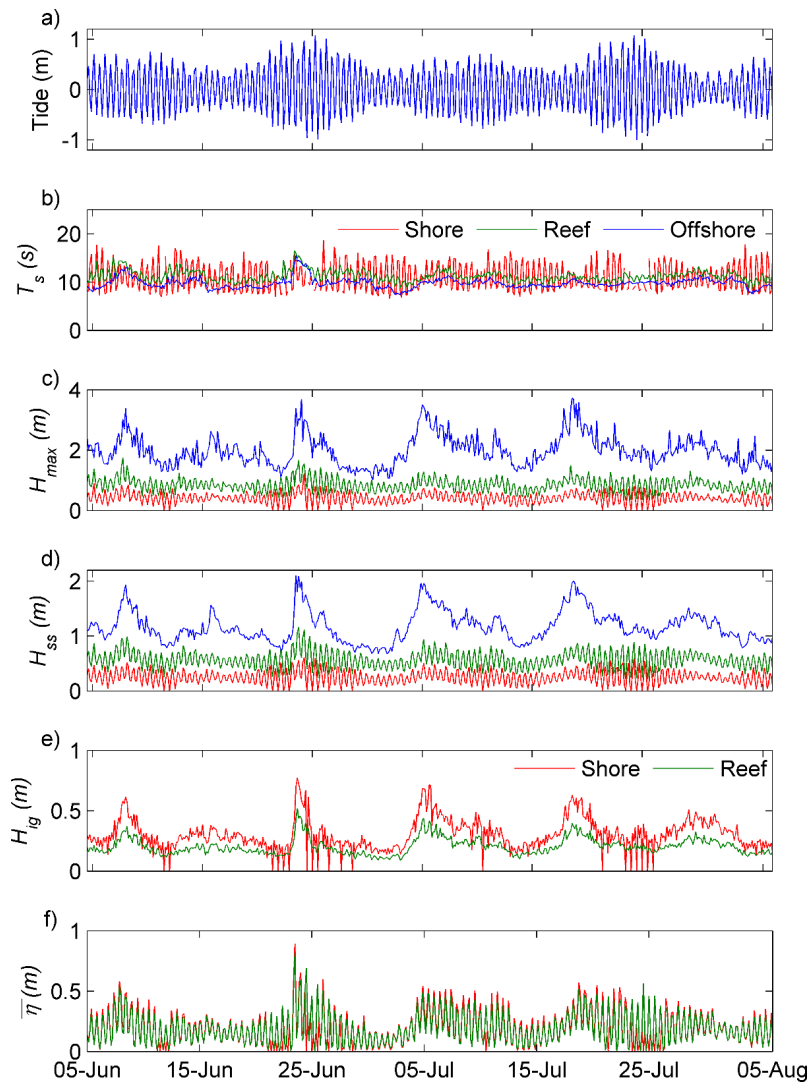
734 Figure 1.



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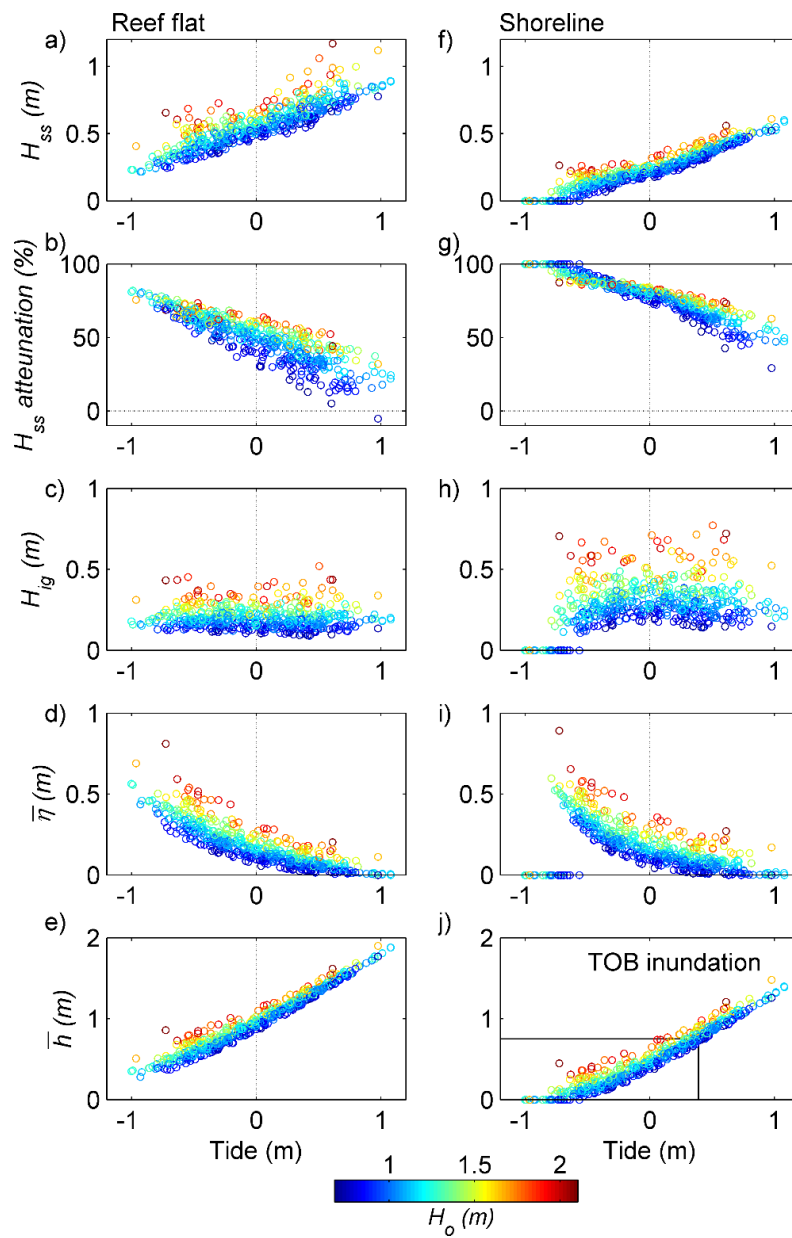
737 Figure 2.



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740 Figure 3.

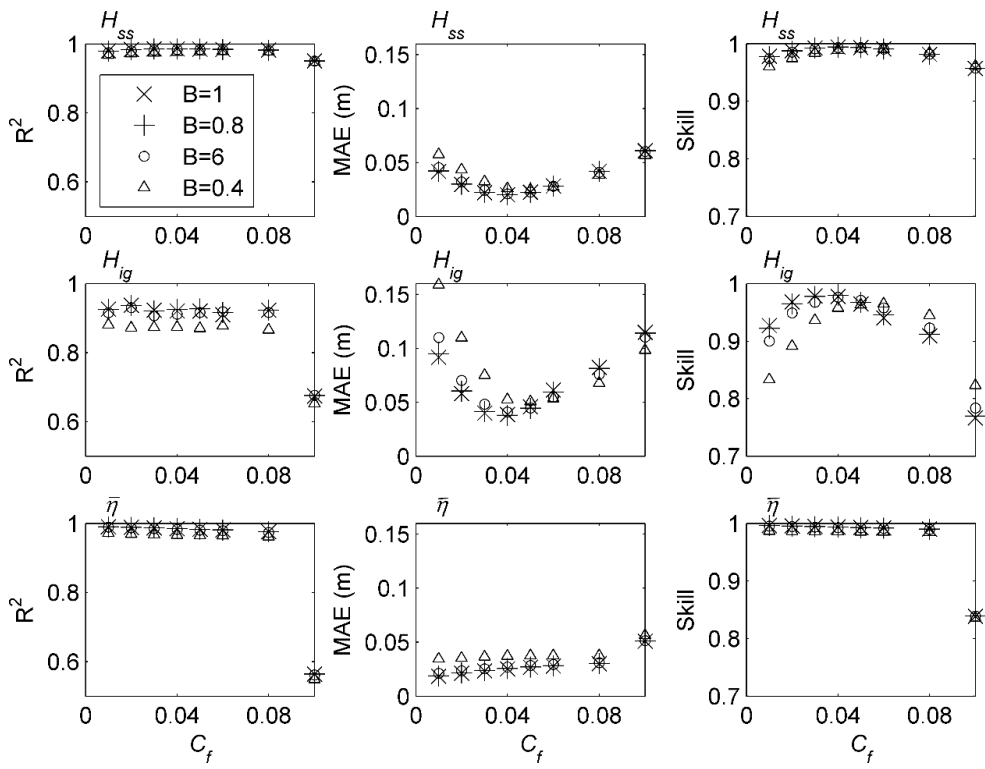


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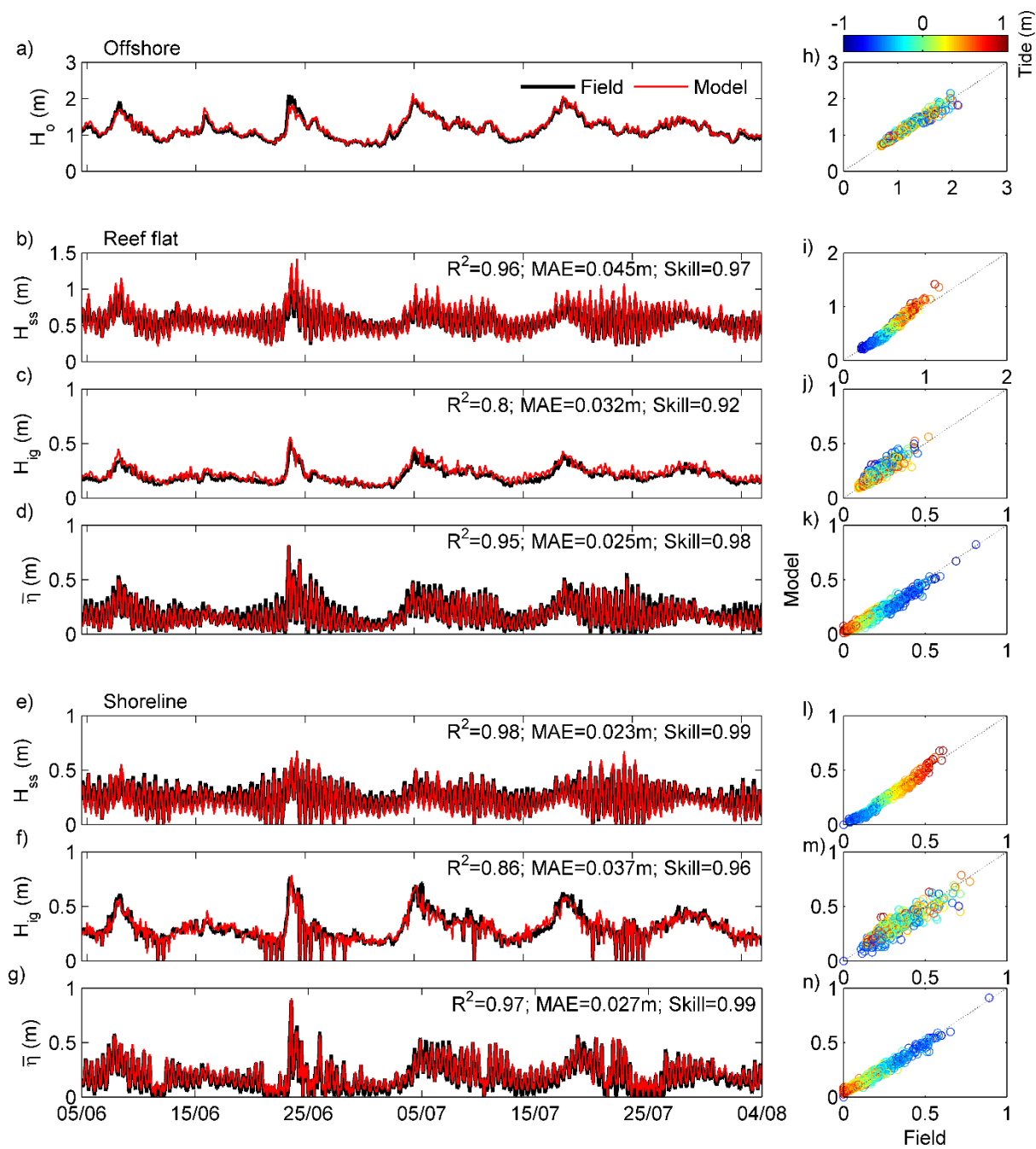
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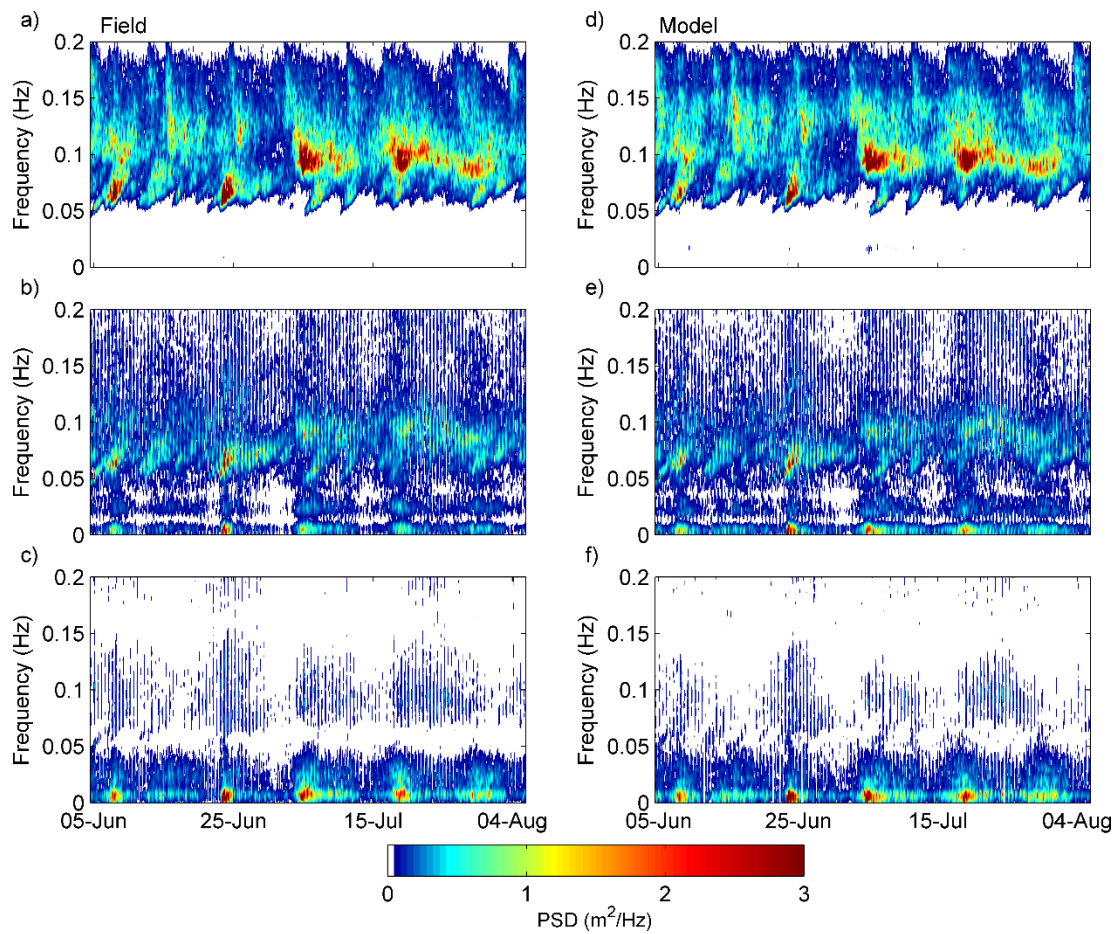
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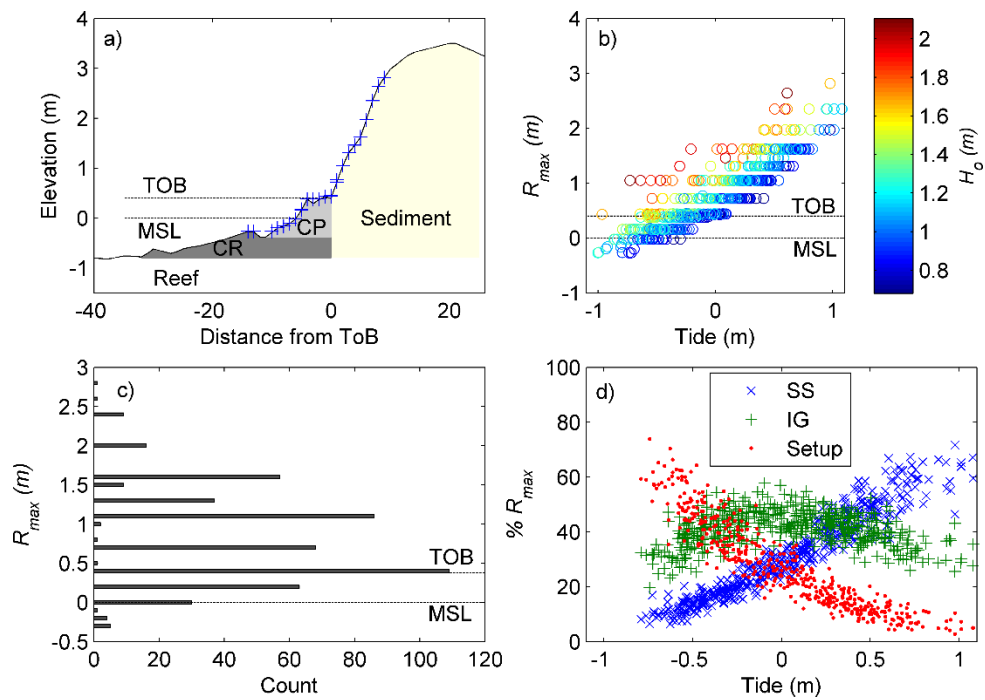
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750 Figure 6.



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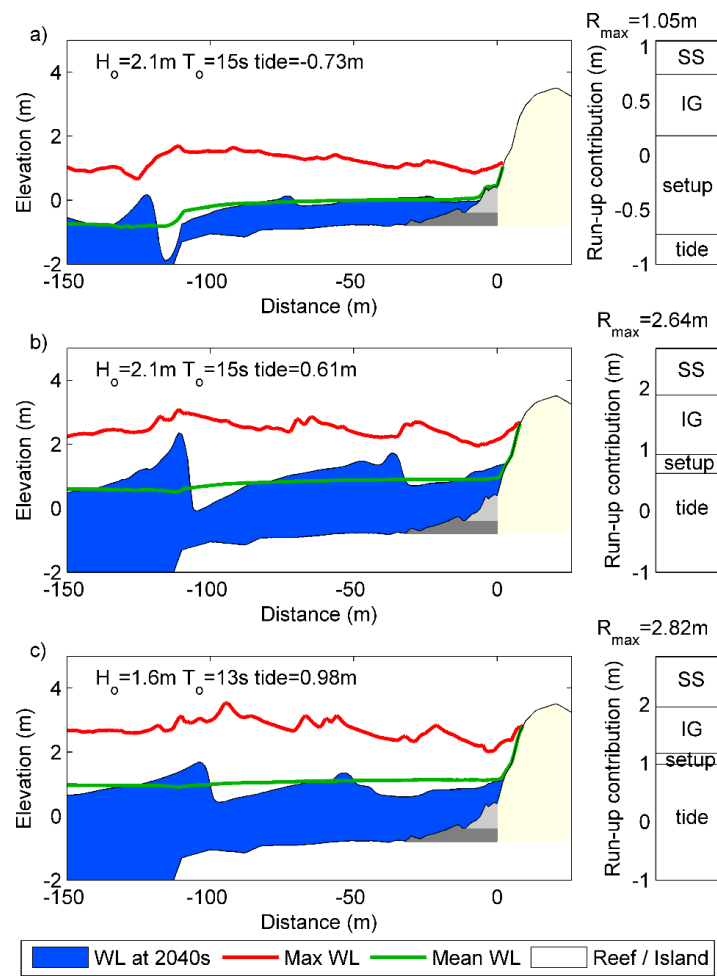
752 Figure 7.



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755 Figure 8.



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