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Correction of coherent interference in wave-resolving nearshore models and validation with experimental data

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Abstract

Here we address the problem of coherent interference that arises in double-sum wavemakers of wave-resolving models. Identified as a key problem for experimental and numerical simulations since the late 1970s, this problem induces spurious persistent longshore variability and affects nearshore dynamics. To overcome this problem, we present the implementation of a single-sum wavemaker in the 3D wave-resolving model CROCO. The new wavemaker, which assigns only one pair of direction and frequency values to each component of the wave spectrum, definitively prevents coherent interference, unlike a conventional double-sum wavemaker that allows waves of different direction to share the same frequency. Each wave component must also strictly comply with the periodicity rules, to avoid any spurious boundary dynamics. We validate the single-sum wavemaker with experimental data collected in a wave basin with longshore-uniform bathymetry and compare results with the double-sum wavemaker simulations. We show that the new wavemaker produces transient rips devoid of any coherent interference effect and that, consequently, the model statistics closely match the experimental data. The new wavemaker therefore guarantees statistical integrity while reducing computational costs, a necessary step for realistic wave-resolving studies of nearshore dynamics.

Keywords: Coherent interference, Wave-resolving model, Wavemaker, Wave basin, Directional spread

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1. Introduction

The nearshore region, consisting of the surf zone (from shoreline to breaking point) and the inner shelf (up to approximately 20 meter depth), is a turbulent area, with various time and space scales interacting and coexisting with each other. Understanding the processes that govern transport and circulation in this region is of critical importance for many reasons: health issues associated with coastal pollutants (Boehm et al., 2005), safety of users exposed to drowning due to rip currents (Woodward et al., 2013), ecosystem issues associated with coastal retention or dispersal of plankton or larvae (Moulton et al., 2023; Shanks et al., 2017), and sediment transport and morphological changes (Marchesiello et al., 2022).

One of the most important processes for cross-shore exchange between the surf and shelf are rip currents. They are narrow offshore directed flow of time scale from $\mathcal{O}(1 \text{ min})$ to much longer $\mathcal{O}(1 \text{ hr})$ and cross-shore spatial scale $\mathcal{O}(100 \text{ m})$. Rip currents are particularly important for cross-shore exchanges between the beach and the continental shelf, as they can extend seaward over a width 2 to 3 times that of the surfzone (Kumar and Feddersen, 2017). Recent studies also underline the importance of rip currents in the shelf circulation of $\mathcal{O}(1 \text{ km})$ (Wu et al., 2021). Rip currents are referred to as channeled (bathymetric) rip currents when driven by longshore variability in the bathymetry (Castelle, 2016), or transient rip currents (flash rips) when resulting from discontinuous breaking due to short crested waves (Peregrine, 1998; Clark et al., 2012; Johnson and Pattiaratchi, 2004). While channeled rip currents are relatively well understood (e.g., Marchesiello et al. 2015), flash rips are a more recent topic and are still incompletely assessed, even though they are thought to represent a large part of nearshore activity (Tang and Dalrymple, 1989).

The simulation of transient rip currents requires wave-resolving (or phase-resolving) models, which have the unambiguous ability to represent short-crested waves and associated vorticity injection into the surfzone. A necessary step in wave-resolving simulation is finding a way to force the wave field at the offshore boundary. There are three main options to do this: a wave generator at a source point inside the domain (Wei et al., 1999); a wave generator at a fixed offshore boundary point (Marchesiello et al., 2021); or a moving boundary simulating a

29 pad (Higuera et al., 2015), but this technique is only used to generate long waves. CROCO,
30 the Coastal and Regional Ocean Community model used in the present study, focuses on the
31 second method. More importantly here, regardless of the wave imposition technique, most
32 wave-resolving models use double summation to represent a wave spectrum that distributes
33 wave energy as a function of frequency and direction.

34 Double-sum wavemakers have been used extensively and helped improve our under-
35 standing of nearshore dynamics (Hally-Rosendahl et al., 2014; Suanda and Feddersen, 2015;
36 Spydell et al., 2019). However, they suffer from a phase-locking or coherent interference phe-
37 nomenon. This can be understood by considering two wave trains propagating towards the
38 beach from different directions. These waves interfere, generating a longshore modulation of
39 their amplitude (short-crested waves) which migrates along the beach at a speed increasing
40 with their frequency difference (Fowler and Dalrymple, 1990). For waves of same frequency,
41 the migration speed is zero, leaving a permanent pattern of short-crested waves (coherent
42 interference) that always break at the same point on the beach, generating persistent rip
43 currents in deterministic locations via more similar mechanisms to bathymetrically-driven
44 rip currents. Coherent interference from intersecting ocean wave trains can be found in
45 nature, e.g., resulting from reflection on a breakwater (Dalrymple, 1975; Smit and Janssen,
46 2013; Zhang et al., 2022). However, they tend to arise in models for nonphysical reasons,
47 simply because of the deterministic nature of discretized wave generators. This can affect the
48 model results in ways that are not necessarily noticed by modelers, as spurious rip currents
49 are mixed among other rip current events.

50 This problem was reported long ago (Jefferys, 1987; Miles and Funke, 1989), noting the
51 paradox of simulating a random sea state with a deterministic wavemaker. Early recommen-
52 dations were to use stochastic implementations, but these models require a lot of computing
53 time to be statistically reliable. Deterministic wavemakers therefore offer advantages, pro-
54 vided that wave coherence and associated stationary interference can be dealt with. A
55 common solution is to increase the number of frequencies in the wavemaker spectrum, but
56 this only reduces the probability of coherent interference, and is also computationally ex-
57 pensive. Building on previous work (Pascal and Bryden, 2011; Salatin et al., 2021), here

58 we implement a single-sum wavemaker that is both computationally efficient and definitely
59 devoid of coherent interference. To confirm that this is desirable in a numerical model,
60 we validate the single-sum method and compare with the double-sum method for the first
61 time with data from a directional wave basin experiment (Baker et al., 2023b). In addition,
62 attention to energy conservation ensures that the wavemaker correction does not affect the
63 integrity of the physical solution, and that it accurately represents reality. We hope that our
64 work will increase the modeling community’s awareness of the coherent interference problem,
65 and offer a simple and computationally efficient solution to resolve it.

66 **2. Methods**

67 *2.1. The 3D wave-resolving model CROCO*

68 CROCO is a non-hydrostatic, free-surface, terrain-following model developed around the
69 regional oceanic modeling system (Shchepetkin and McWilliams, 2005; Debreu et al., 2012).
70 Its capabilities include high-performance computation of high-order discretized equations
71 and coupling with atmospheric, wave, biogeochemical, sediment and turbulence models.
72 It has been applied to a variety of configurations, from regional and shelf circulations to
73 very fine-scale processes, such as wave-induced nearshore circulation (Marchesiello et al.,
74 2015, 2021, 2022). In its non-hydrostatic version, CROCO is able to resolve individual
75 wave propagation, shoaling and breaker-induced circulation. Breaking waves are treated
76 as bores with a shock-capturing advection scheme (WENO5), which transfers steep wave
77 energy to the mean currents, while part of the breaking wave energy is transferred to subgrid-
78 scale turbulence via a $k-\omega$ turbulence closure model. The latter corrects for an overmixing
79 problem posed in the potential (irrotational) flow region of non-breaking waves (Marchesiello
80 and Treillou, 2023), allowing stratification to be correctly included in our studies. CROCO
81 is therefore well suited to the study of 3D nearshore dynamics and surf-shelf exchange in
82 a rotating, stratified framework. Nonetheless, the wavemaker corrections proposed in the
83 present study are relevant for all wave-resolving models, including the classical Boussinesq
84 type.

85 *2.2. Default double-sum wavemaker*

86 The double-sum wavemaker implemented in CROCO (Marchesiello et al., 2021) forces
 87 a spectrum of 3D linear waves at the offshore boundary, much like SWASH (Zijlema et al.,
 88 2011), while Funwave (Wei et al., 1999) typically uses similar forcing but with an interior
 89 source function¹. In all cases, the frequency and directional distribution of wave energy is
 90 discretized via a double summation (Feddersen et al., 2011). The free surface and velocities
 91 at the offshore boundary are then, respectively, given by:

$$\eta_{bc}(y, t) = \sum_i^N a_i \sum_j^M d_j \cos(k_{y,i,j}y - \omega_i t - \phi_{i,j}) \quad (1)$$

$$u_{bc}(x, y, t) = \eta_{bc}(y, t) \omega_p \cos(\theta_m) \frac{\cosh(k_p(z+h))}{\sinh(k_p h)} \quad (2)$$

$$v_{bc}(x, y, t) = \eta_{bc}(y, t) \omega_p \sin(\theta_m) \frac{\cosh(k_p(z+h))}{\sinh(k_p h)} \quad (3)$$

92 where (x, y, z) are cross-shore, alongshore and vertical directions; a_i is the wave amplitude
 93 at each angular frequency ω_i from a given statistical distribution $S(\omega)$; d_j is the directional
 94 weight for wave angle θ_j from the given statistical distribution $D(\theta)$; $k_{y,i,j} = k_i \sin \theta_j$ is
 95 the alongshore wavenumber where k_i is the linear theory wavenumber: $\omega_i^2 = g k_i \tanh(k_i h)$
 96 with h the water depth; θ_m is the mean wave angle; ω_p and k_p are peak frequency and
 97 wavenumber; $\phi_{i,j}$ is a uniformly distributed random phase; and N and M are respectively
 98 the number of frequencies and directions.

99 As described by Marchesiello et al. (2021), w_{bc} is here set to zero rather than the lin-
 100 ear solution for w as only weak sensitivity to this choice was found. The depth-averaged
 101 (barotropic) velocities (\bar{u}, \bar{v}) are provided in the wavemaker because they are prognostic vari-
 102 ables in our split-explicit model, advanced at the same time as the fast acoustic mode (see
 103 Marchesiello et al., 2021). The depth-averaged normal velocity \bar{u} is supplemented at the

¹FUNWAVE-TVD now has the option of a single-sum wavemaker following the study conducted by (Salatin et al., 2021)

104 boundary by an Eulerian anti-Stokes current, opposed to the Stokes drift and thus closing
 105 the mass balance. We do not directly impose the depth-averaged value of u_{bc} but the value
 106 of the incoming characteristic of the shallow water system as in Flather-type conditions
 107 (Marchesiello et al., 2001; Blayo and Debreu, 2005):

$$\bar{u} = \bar{u}_{bc} - \sqrt{\frac{g}{h}}(\eta - \eta_{bc}) \quad (4)$$

108 This allows infragravity waves generated inside the domain to propagate out as long waves,
 109 while ensuring a near conservation of mass and energy through the open boundary. Likewise,
 110 the baroclinic components (u_{bc}, v_{bc}, w_{bc}) are applied via an adaptive radiation condition which
 111 helps short waves and 3D flow perturbations to leave the domain with only a small effect
 112 on the interior solution (Marchesiello et al., 2001).

113 In this study, the spectrum distributions is the product of a JONSWAP frequency spec-
 114 trum $S(\omega)$ (Goda, 2000) and a Gaussian-type directional spectrum $D(\theta)$ (Feddersen et al.,
 115 2011): $S(\omega, \theta) = S(\omega) \times D(\theta)$. The JONSWAP spectrum is formulated as follows:

$$S(\omega) = H_s^2 \beta_J \omega_p^4 \omega^{-5} \exp[-1.25\omega^{-4}\omega_p^4] \gamma^r \quad (5)$$

116 H_s is the significant wave height, ω_p , the peak wave frequency, and γ^r , the peak enhancement
 117 factor, with:

$$r = \exp \left[-\frac{1}{2} \left(\frac{\omega - \omega_p}{\sigma_\omega \omega_p} \right)^2 \right] \quad (6)$$

$$\sigma_\omega = \begin{cases} 0.07, & \text{if } \omega \leq \omega_p \\ 0.09, & \text{if } \omega > \omega_p \end{cases} \quad (7)$$

$$\beta_J = \frac{0.06238(1.094 - 0.01915 \log \gamma)}{0.23 + 0.0336\gamma - 0.185(1.9 + \gamma)^{-1}} \quad (8)$$

120 The directional spectrum around the mean direction θ_m , with directional spread σ_θ , is:

$$D(\theta) = \exp \left[-\left(\frac{\theta - \theta_m}{1.5\sigma_\theta} \right)^2 \right] \quad (9)$$

121 with $\int_{\theta_{min}}^{\theta_{max}} D(\theta) d\theta = 1$ to ensure that the directional spread (σ_θ) around the mean wave
 122 angle does not affect wave energy.

123 *2.3. Coherent interference principle*

124 We illustrate here the principle behind coherent interference by reproducing the solution
 125 given by Fowler and Dalrymple (1990) for two wave trains propagating towards the beach
 126 with different wavenumbers and frequencies. For simplicity (and without modifying the
 127 general idea), we consider waves of same amplitude a propagating at an angle θ around
 128 the x axis normal to the coast (θ is the directional spread in this case and $\theta_m = 0$). The
 129 mean wavenumber k is along the x axis, while the difference between the wavenumbers
 130 $\Delta k = 2k \sin \theta \sim 2k\theta$ lies along the y longshore axis. Similarly, we consider that the mean
 131 frequency is ω and the frequency difference between the two wave trains is $\Delta\omega$. In this case,
 132 the wave interference solution for the free surface η is :

$$\eta(x, y, t) = 2a \sin(kx - \omega t) \cos[0.5(\Delta k y - \Delta\omega t)] \quad (10)$$

133 The total surface elevation consists of a carrier wave (k, ω) modulated by a time-dependent
 134 envelope propagating along the coast at speed $\Delta\omega/\Delta k$. The envelope produces short crested
 135 waves of length $\lambda_c = 2\pi/\Delta k = \pi/k\theta$ — as first suggested by Longuet-Higgins 1956 and
 136 shown to apply to the more general case by comparison with experimental data (Baker
 137 et al., 2023b). Longshore envelope migration occurs when $\Delta\omega \neq 0$, i.e. the envelope is
 138 phase-shifted. In this case, waves have no persistent longshore variations (illustrated with
 139 H_s in Fig. 1). However, if the wave trains share the same frequency ($\Delta\omega = 0$), the envelope
 140 phase is locked and the propagation speed is zero. In this case, H_s shows a pattern of nodes
 141 and antinodes along the beach (Fig. 1), i.e. short-crested waves constantly travel towards
 142 the same location on the beach, thus creating stationary rip currents as they break.

143 This phenomenon is at the root of the coherent interference problem of discrete double-
 144 sum wavemakers. In the real ocean, with a continuous frequency spectrum of random waves,
 145 the probability of phase-locking is minimal, over smooth topography at least, and generally
 146 only occurs in focal zones due to refraction, diffraction or reflection of monochromatic waves
 147 around obstacles such as breakwaters or headlands (Smit and Janssen, 2013). We will see
 148 that wave basin experiments also tend to show little coherent interference. We therefore
 149 consider the coherent interference generated by discretized double-sum wavemakers as spu-

150 rious, and seek a definitive solution to avoid it by preventing the generated wave trains from
 151 sharing the same frequency. This is made possible by simple summation, presented below.

152 *2.4. Corrected single-sum wavemaker*

153 In order to avoid coherent waves, i.e., waves of different directions having same fre-
 154 quencies, a solution is presented by Salatin et al. (2021). Double-sum is converted into a
 155 single-sum wavemaker where each wave component has specific frequency and direction. Sin-
 156 gle summation was proposed before with variations in the distribution of wave components
 157 (Jefferys, 1987; Miles and Funke, 1989; Pascal and Bryden, 2011), and a useful schematic
 158 view was given in Pascal (2012). Based on this previous work, we rewrite the free-surface
 159 wave boundary condition :

$$\eta_{bc}(y, t) = \sum_i^{N \times M} a_i \cos(k_{y,i}y - \omega_i t - \phi_i) \quad (11)$$

160 where a_i is now the amplitude of the i -th wave component taken as:

$$a_i = \sqrt{\frac{H_s^2 \overline{D(\theta_i)} S(\omega_i) d\omega}{8 \sum_i S(\omega_i) d\omega}} \quad (12)$$

161 which is the product of the wave amplitude $A = \sqrt{H_s^2/8}$ with $H_s = 4\sqrt{\int S(\omega) d\omega}$, the square
 162 root of the normalized frequency spectrum $S(\omega) d\omega / \sum_i S(\omega_i) d\omega$ (with frequency resolution
 163 $d\omega$), and the square root of the normalized directional spectrum $\overline{D(\theta)}$:

$$\overline{D(\theta)} = \frac{D(\theta) \sum_i S(\omega_i) d\omega}{\sum_i D(\theta_i) S(\omega_i) d\omega} \quad (13)$$

164 The wave angles around the mean direction are:

$$\theta_i = (-1)^i \left(-\frac{\pi}{2} + \frac{\pi}{2} \frac{i-1}{N-1} \right) + \theta_m, \quad (14)$$

165 ensuring that all wave angles are included between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$.

166 *2.5. Periodic boundary conditions*

167 Most nearshore circulation studies use periodic alongshore boundary conditions, to allow
 168 longshore drift to develop and surfzone eddies to propagate freely. It is therefore essential

169 that waves entering the domain satisfy these periodic conditions. Following the suggestion
 170 of Johnson and Pattiaratchi (2006), we impose that each i -th wave component satisfies the
 171 following equation:

$$k_{y,i} = k_i \sin \theta_i = \frac{2\pi p}{L_y} \quad (15)$$

172 where L_y is the domain longshore length and p an integer. This relationship guarantees that
 173 for each wave train component i (with given frequency and direction), there is an integer
 174 number of these waves projected in the longshore direction, as schematized in Fig. 2. This
 175 is sufficient to ensure periodicity. Otherwise, shadow zones can form, where strong wave
 176 height gradients can develop, generate parasite rip currents near the boundaries and affect
 177 longshore drift.

178 Periodization can be obtained by modifying the angle θ_i to satisfy Eq. 15 :

$$\theta_i = \arcsin \left(\frac{2\pi p}{k_i L_y} \right) \quad (16)$$

179 In CROCO, the directional spectrum and associated unrestricted wave angles are first calcu-
 180 lated. Then, all wave angles are corrected according to Eq. 16, ensuring that the mean wave
 181 angle θ_m remains unchanged. The correction is made by selecting the integer p that pro-
 182 duces the smallest change in θ_i (for the double-sum wavemaker, the correction is applied to
 183 all angles at each frequency). In practice, the differences between the original and corrected
 184 wave angles are relatively small and do not significantly impact the directional spectrum. All
 185 simulations presented in this article are therefore expected to respect boundary periodicity.

186 **3. Validation with laboratory wave basin**

187 *3.1. Laboratory experiments*

188 The data used to validate the new wavemaker comes from an experiment conducted in the
 189 Directional Wave Basin at the Oregon State University O.H. Hinsdale Wave Research Labo-
 190 ratory (Baker et al., 2023b). The goal of this experiment was to gain a better understanding
 191 of the processes involved in the generation of flash rips and surfzone eddies, by investigat-
 192 ing the effect of directional spread on breaking crest length. For this purpose, a barred

Case	H_s (m)	T_p (s)	θ_m ($^\circ$)	σ_θ ($^\circ$)
G1a	0.28	2.1	-0.1	2.4
G1d	0.27	2.0	-3.3	26.1

Table 1: Significant wave height H_s , peak period T_p , mean wave angle θ_m and directional spread σ_θ for cases used in this study. H_s , T_p , θ_m and σ_θ were estimated at the offshore wave gauges and are used as wavemaker forcing conditions in the model.

193 beach was recreated in the wave basin, respecting the surf similarity number (ratio of wave
194 steepness to slope) of real scale beaches. A 29-board piston-type wavemaker could simulate
195 a continuous distribution of multidirectional waves with JONSWAP frequency spectrum of
196 width $\gamma = 3.3$. Several experiments were run for a range of different significant wave heights,
197 peak periods and directional spreads. These experiments are of high interest to validate our
198 wavemaker as the wave basin is large enough (48.8 m long, 26.5 m wide) to investigate
199 longshore variation of the wave field. Each run lasted 45 minutes (~ 1350 wave periods),
200 providing sufficiently long time series to study coherent wave interference. The free surface
201 and velocities were measured with in situ sensors (pressure gauges, ADVs, and resistance
202 gauges). The in-situ sensors were deployed as longshore arrays: two offshore arrays, one on
203 the inner shelf and two in the surfzone (Fig. 3). The in-situ sensors had a frequency of 100
204 Hz. We refer the reader to Baker et al. (2023b) for more details about the experiment.

205 We focus on two experiments with low (G1a) and high (G1d) directional spread and
206 otherwise similar bulk wave statistics (Table 1). We use the wave conditions recorded onshore
207 of the wavemaker rather than those theoretically imposed at the wavemaker, partly because
208 directional errors affects the intended wave spectrum and do not, for example, allow G1a
209 to be a truly unidirectional experiment (Baker et al., 2023b). We have verified that the
210 two types of discretized wavemakers in the model give very similar results when directional
211 spread is exactly zero (case G1a with $\sigma_\theta=0^\circ$ gives H_s RMSE < 1 mm), and that the differences
212 in model results between the two wavemakers are due solely to directional spread.

213 Free surface model spectra ($S_{\eta\eta}$) are computed similarly to Baker et al. (2023b), using
214 a Hanning window period of 256 s with an overlap period of 128 s and correcting for depth

	Single sum (50 freq.)	Double sum (50 freq.)	Double sum (300 freq.)	Random-phase (50 freq.)
$\langle \sigma_{\omega_z} \rangle_{SZ} (s^{-1})$	0.03	0.16	0.08	0.03
$\langle \sigma_v \rangle_{SZ} (m.s^{-1})$	0.01	0.05	0.02	0.01
$\langle \sigma_{H_s} \rangle (m)$	0.02	0.04	0.03	0.02
H_s RMSE (m)	0.010	0.047	0.020	0.015

Table 2: Longshore standard deviation of 20-min time-averaged surface vertical vorticity (σ_{ω_z}), longshore velocity (v) and significant wave height (H_s) (see Fig. 5) for the model running case G1d with various wavemaker methods. RMSE between in-situ and simulations H_s for $t = 10 - 30$ min (see Fig. 6). σ_{ω_z} and σ_v are averaged in the surfzone ($27 < x < 31$ m) while σ_{H_s} is averaged on the whole domain. The RMSE of H_s indicating the error between model and data over the whole domain is also reported.

215 attenuation (frequency cutoff = 1.2 Hz) over a 20-minute time series ($t = 10-30$ minutes,
216 with 10 min of spin-up). The significant wave height (H_s) is calculated as $4\sqrt{\int_{0.3}^{1.2} S_{\eta\eta}(f)df}$.
217 Velocity spectra are computed using a Hanning window period of 256 s with an overlap
218 period of 128 s over the same 20-minute time series. Reducing the time series by half did
219 not significantly affect the results.

220 3.2. Model configuration

221 The alongshore-uniform bathymetry in the model is identical to the experiment (Fig. 3),
222 without smoothing. The position of the shoreline is time-dependent, owing to a wetting-
223 drying scheme (Warner et al., 2013). The cross-shore and longshore domain lengths are
224 respectively 20 m and 30 m. The horizontal resolution is $\Delta x = 0.1$ m and there are 10 vertical
225 levels. The model time step is 0.003 s and total computed time is ~ 30 min (~ 900 wave
226 periods were enough for significant results). The bottom stress is modeled as a quadratic
227 friction using the law of the wall with roughness $z_{0,b} = 1 \times 10^{-5}$ m. Turbulent kinetic energy
228 is solved via a $k - \omega$ turbulent closure model (Marchesiello and Treillou, 2023).

229 The wavemaker has a resolution of $N = 50$ frequencies (between 0.1 Hz and 2 Hz, i.e.
230 between 0.2 and 2 times the peak frequency) and $M = 31$ directions, corresponding to default
231 settings in FUNWAVE-TVD (Salatin et al., 2021). However, to be comparable with studies

232 using a larger number of frequencies, we have added an experiment with 300 frequencies for
233 the double-sum wavemaker. This is 7% more expensive than the double-sum case with 50
234 frequencies, which is itself 20% more expensive than the single-sum wavemaker simulation
235 (also with 50 frequencies). Unlike the laboratory experiment, the model’s northern and
236 southern boundaries are periodic, and the western (offshore) boundary is open to long waves.
237 Wave-averaged and instantaneous fields are output every 12 s (corresponding to 6 peak
238 periods) on the entire domain, while model results at specific grid points corresponding to
239 the experimental stations are extracted at a frequency of ~ 6 Hz.

240 *3.3. Comparison of double and single sum wavemaker cases*

241 Directional spreading produces short-crested waves, which can generate flash rips when
242 they break in the surf zone. The G1d experiment, with its fairly large directional spread
243 ($\sigma_\theta=26.1^\circ$), is particularly effective at generating surfzone eddies and flash rips, as illustrated
244 by snapshots of vertical surface vorticity from the model solutions with double (50 freq.) or
245 single-sum wavemakers (Fig. 4). In both cases, flash rips and smaller-scale rib structures,
246 referred to as mini-rips (Marchesiello et al., 2021), can be observed in the surf zone. These
247 rib structures with longshore scale of ~ 1 m and frequencies in the infragravity band are
248 associated with 3D shear instability of the undertow.

249 From the snapshots alone, the difference between the two simulations could be accounted
250 for by the stochastic nature of the eddy field rather than coherent interference, but the 20-min
251 time-averaged fields are unambiguous (Fig. 5 and Table 2). No stationary vorticity pattern
252 is present in the case of the single-sum wavemaker, as might be expected if random waves
253 were breaking on uniform longshore bathymetry (Fig. 5, left). Only a residual stochastic
254 variability remains, due to the finite number of flash rip events during the experiment.
255 However, in the case of the double-sum wavemaker, the time-averaged vorticity shows strong
256 stationary rip currents, reminiscent of the patterns observed in the vorticity snapshot. In
257 the case where 50 frequencies are used, the longshore standard deviation of time-averaged
258 surfzone vorticity is 0.16 s^{-1} (see Table 2), whereas the single-sum wavemaker gives a lower
259 value by an order of magnitude of 0.03 s^{-1} . With 300 frequencies, the double-sum wavemaker

260 is improved as it produces a lower longshore standard deviation of surfzone vorticity (0.08
261 s^{-1}), but it remains higher than that produced by the single-sum wavemaker, at a higher
262 computational cost.

263 Stationary rip currents are also apparent on the longshore velocity field (Fig. 5, middle).
264 With the double-sum wavemaker, the weak longshore drift expected from the mean wave
265 angle ($\theta_m = -3.3^\circ$) is hidden by a series of strong converging flows. These patterns are
266 somewhat improved by the addition of wavemaker frequencies, but are much better corrected
267 by the single-sum method, which produces a smooth mean longshore drift as expected. Note
268 that the effect of double summation remains visible in case of weak directional spread (G1a,
269 not shown), with coherent wave-induced stationary rips that remain prominent.

270 Finally, we compare the significant wave height fields in Figure 5 (right). Interestingly,
271 the comparison between double and single wavemaker solutions has similar characteristics
272 to the idealized case presented in Section 2.3 of two wave trains with or without frequency
273 difference. The wave height band pattern in the double-sum wavemaker simulations, and
274 the absence of this pattern in the single-sum wavemaker simulation, are reminiscent of the
275 idealized solutions in Figure 1. In both idealized and realistic cases, the coherent interference
276 associated with waves of different angles but same frequencies produces high and low H_s
277 bands, correlating perfectly with the persistent rip currents appearing in the vorticity and
278 velocity fields. The single-sum wavemaker, by avoiding interference from waves of the same
279 frequency, presents a homogeneous H_s field.

280 *3.4. Comparison with data*

281 A comparison between double and single wavemakers has already been carried out
282 (Salatin et al., 2021), but no direct comparison has been made with data, and it is not
283 clear how realistic is the idea of eliminating all coherent interference in models. In partic-
284 ular, we wondered whether the uncertainty inherent in the forcing frequencies of the basin
285 experiment was sufficient to preclude coherent interference. To answer this question, we
286 present here a comparison between the model and the experimental data.

287 We showed in the last section that coherent interference patterns result in an alongshore-

288 varying H_s field, that manifest as elongated cross-shore bands of highs and lows. We there-
 289 fore first assess whether these signs of coherent interference are present in the data by
 290 examining H_s longshore variability. Figure 6 shows H_s along the offshore gauges (at $x = 19$
 291 m) in the G1d case, calculated from 20-minute time series. The experimental data show
 292 little longshore variability around the mean H_s value of 0.28 m, and present a good match
 293 with the single-sum wavemaker simulation. In contrast, the default double-sum wavemaker
 294 (with 50 frequencies) produces high longshore variability, with H_s as low as 0.19 m at some
 295 locations ($y = 9$ m), i.e. a third lower than the forcing value. The standard deviation of H_s
 296 reaches around 4 cm, compared with 2 cm for the single-sum wavemaker (in G1a, with low
 297 directional spread, the standard deviation is 0.8 cm and 0.04 cm for the double-sum and
 298 single-sum wavemakers, respectively). With 300 frequencies in G1d, the standard deviation
 299 reduces to 1.7 cm but coherent interference is still clearly present. The RMSE between
 300 the data and the single-sum wavemaker is around 1.0 cm, while it is around 4.7 cm for
 301 the 50-freq. double-sum wavemaker (with 2.0 cm with 300 freq.). It is important to note
 302 that, while laboratory experiments are prone to reflection and associated interference due
 303 to non-periodic boundaries, there is no evidence here of physical interference on the scale
 304 of that of the double-sum discretized wavemaker. The alongshore standard deviation of
 305 H_s in CROCO simulations are similar to FUNWAVE-TVD simulations with a single-sum
 306 wavemaker (Salatin et al., 2021; Nuss et al., in review).

307 The double-sum method not only affects longshore variability, but also the average wave
 308 energy in the domain. Figure 7 presents a cross-shore profile of H_s averaged in the longshore
 309 direction from all sensors. Here also, the single-sum wavemaker shows an excellent match
 310 with the data over the whole profile. For the double-sum wave maker, the coherent wave-
 311 induced H_s bands tend to cancel out when averaged alongshore, giving fairly similar cross-
 312 shore H_s profiles, but still leaving a negative bias of up to 2-3 cm (offshore stations), reduced
 313 by around half when the number of frequencies is increased to 300 (Fig. 5).

314 The effect of wavemaker types on nearshore dynamics can also be assessed using power
 315 spectra (Fig. 8 and 9). Model and data free surface spectra $S_{\eta\eta}$ at points offshore ($x = 19$ m,
 316 $-9 < y < 9$ m) and in the outer surf zone ($x = 28.4$ m, $-8 < y < 3$ m) are shown in Figure 8.

317 The longshore mean and standard deviation of $S_{\eta\eta}$ are closer to the data for the single-sum
318 wavemaker at almost all frequencies. Specifically, the spurious longshore variability for the
319 double-sum wavemaker is far too high (the double-sum wavemaker here is with 300 freq.,
320 and the variability is even greater with 50 freq.), particularly in the low-frequency range,
321 but also in the swell band ($0.3 < f < 1.2$ Hz) (Salatin et al., 2021).

322 The S_{uu} cross-shore velocity spectra on the innershelf (Fig. 9) show similar differences to
323 the free-surface spectra, with an even greater longshore standard deviation at low frequency
324 for the double-sum wavemaker. Both wavemakers show a good match with the data in the
325 longshore mean, and the difference lies mainly in the standard deviation. Consequently, the
326 surfzone eddies are affected by persistent spurious rip currents, but the effect tends to cancel
327 out over the domain.

328 4. Conclusion

329 Over the past decade, studies has been carried out to find a suitable way of forcing a
330 random sea state into wave-resolving models. Here, we build on the work of Salatin et al.
331 (2021) and others to define a wavemaker devoid of spurious coherent interference, apply it
332 to the 3D wave-resolving model CROCO and validate it with experimental data. We show
333 that a single-sum wavemaker that assigns only a pair direction and frequency values to each
334 component of a wave spectrum definitively prevents coherent interference, in contrast to a
335 conventional double-sum wavemaker that allows waves of different direction to share the
336 same frequency. This method also saves a great deal of computing time — over 25% of the
337 cost of the simulation, depending on the number of frequencies used in the first method
338 to mitigate coherent interference. Another correction made to the wavemaker consists in
339 periodizing each wave component by slightly modifying its direction. Similar correction is
340 present in FUNWAVE-TVD (Salatin et al., 2021). The new wavemaker is then applied to a
341 model setup of the laboratory wave basin experiment presented in Baker et al. (2023b).

342 In the double-sum wavemaker simulation, the generation of stationary rip currents from
343 coherent interference is clearly visible in the mean vorticity field. The mean longshore
344 drift also changes sign despite the longshore uniform bathymetry, and the significant wave

345 height shows bands of high and low values oriented in the shore-normal direction (creating
346 longshore pressure gradients). Increasing the number of frequencies in the classical double-
347 sum wavemaker reduces the observed biases, but they remain significant and affect the
348 production of transient rip and surf zone eddies, as can be seen in the velocity power spectra.
349 The single-sum wavemaker has none of these characteristics, and consistently reproduces
350 the experimental data with regard to the magnitude and variation of surface elevation and
351 velocities, therefore, likely more realistically representing the transient rip current behaviors.

352 While the classical double-sum method cannot compete with the single-sum method in
353 terms of accuracy and cost, we have more successfully tested (see Table 2) the double-sum
354 method of Johnson and Pattiaratchi (2006), which added a time-dependent random phase
355 shift to mitigate the phase-locking effect (similar to the effect of random errors in the forcing
356 frequencies of the laboratory experiment). Yet even in this case, the computational cost
357 remains prohibitive compared with the single-sum method (in addition, the added random
358 phase shift modifies, albeit slightly, the dispersion relation; Johnson and Pattiaratchi 2006).

359 On the basis of a validation which, for the first time, uses experimental data, we con-
360 clude that a single-sum wavemaker gives better results than the double-sum wavemaker
361 at low computational cost. We expect that our study will increase confidence in future
362 wave-resolving simulations, and provide a necessary step towards a more comprehensive in-
363 vestigation of rip currents, tracer dispersion or morphological evolution using this type of
364 model.

365 **CRedit authorship contribution statement**

366 **Simon Treillou:** Conceptualization, Methodology, Software, Validation, Writing – origi-
367 nal draft. **Patrick Marchesiello:** Methodology, Software, Validation, Supervision, Writing
368 – review & editing. **Christine M. Baker:** Validation, Data Curation, Writing – review &
369 editing.

370 Declaration of competing interest

371 The authors declare that they have no known competing financial interests or personal
372 relationships that influenced the work reported in this paper.

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378 available at www.croco-ocean.org. The laboratory measurements are available at Design
379 Safe (Baker et al., 2023a). Modeling data are available upon request.

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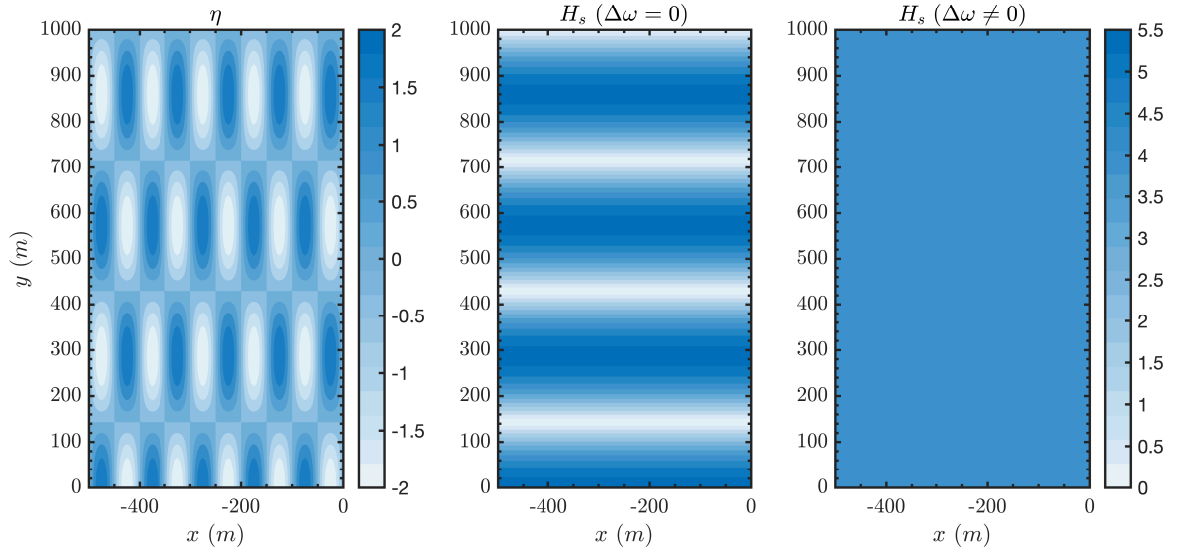


Figure 1: Illustration of the coherent interference of two deep water wave trains propagating to the right at an angle of ± 10 degrees to the x axis (amplitude 1 m, wavelength 100 m, period 10 s). The left panel shows a snapshot of surface elevation η featuring short-crested waves ~ 286 m long, migrating along the y axis with a speed varying with the frequency difference $\Delta\omega$ between wave trains; the central panel shows H_s for $\Delta\omega = 0$, i.e. with no longshore migration. The right-hand panel shows the significant wave height H_s in the case where $\Delta\omega \neq 0$. In the first case, coherent interference produces a persistent H_s pattern that should create stationary rip currents as they break on the beach. In the second case, no pattern is produced and no persistent rip currents are expected.

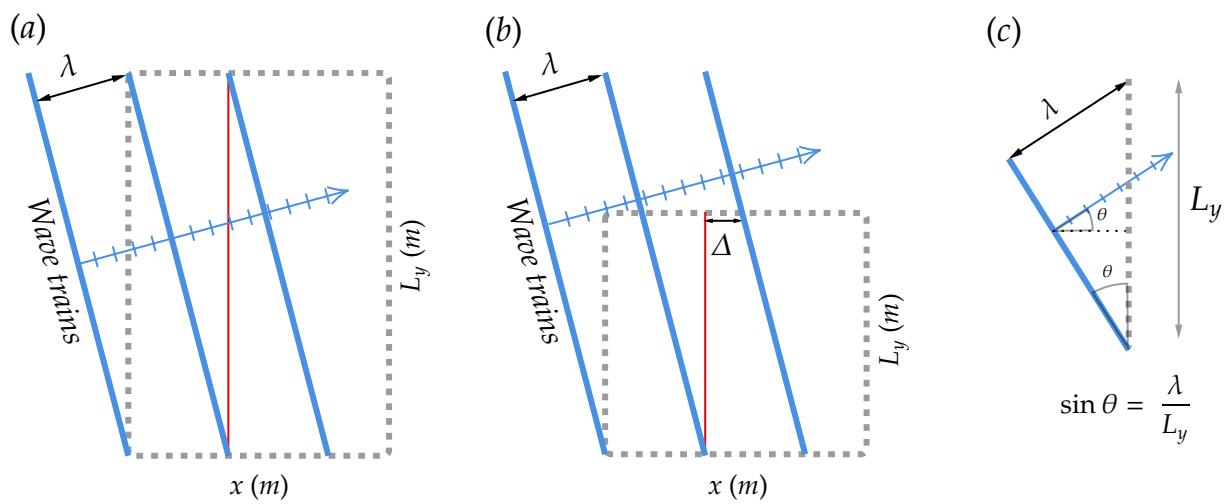


Figure 2: Schematic view of the periodicity condition for obliquely incident long-crested waves over a finite domain. (a) the periodicity is respected by the right combination of domain length L_y and wavelength λ ; (b) the domain size breaks periodicity by introducing a small gap Δ between wave crests at the northern and southern boundaries; (c) relationship linking wave direction to L_y and λ to ensure periodicity. Note that the scheme assumes only one periodic wavelength for simplicity but there can be an integer number p of smaller wavelength (the relation is then $\sin \theta = \frac{p\lambda}{L_y}$).

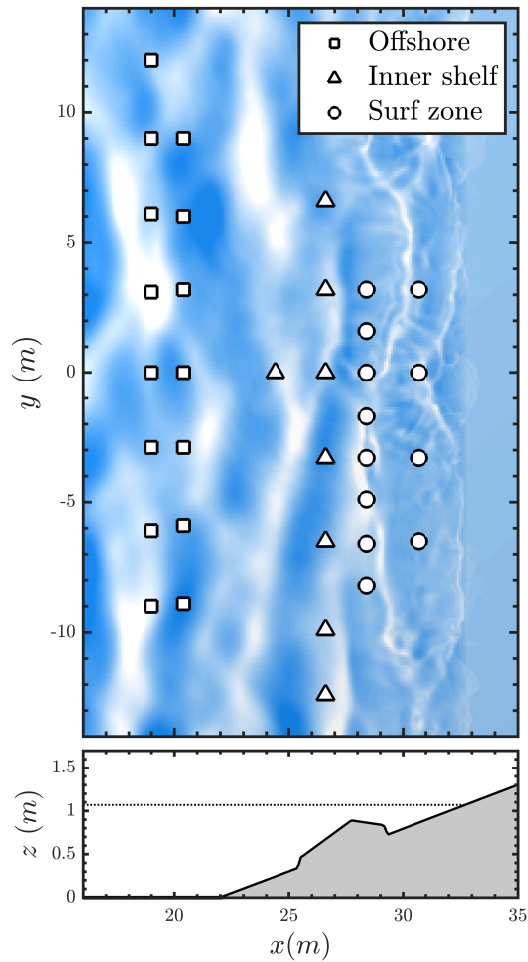


Figure 3: (Top) Snapshot of simulated free surface elevation in the case G1d ($\sigma_\theta = 26.1^\circ$) after 15 minutes. The stations where experimental data were collected are displayed. Squares represent offshore wire resistance gauges, triangles innershelf pressure gauges and circles surf zone pressure gauges. (Bottom) Cross-shore profile of the bathymetry (shaded) and still water level (dashed line, at 1.07 m).

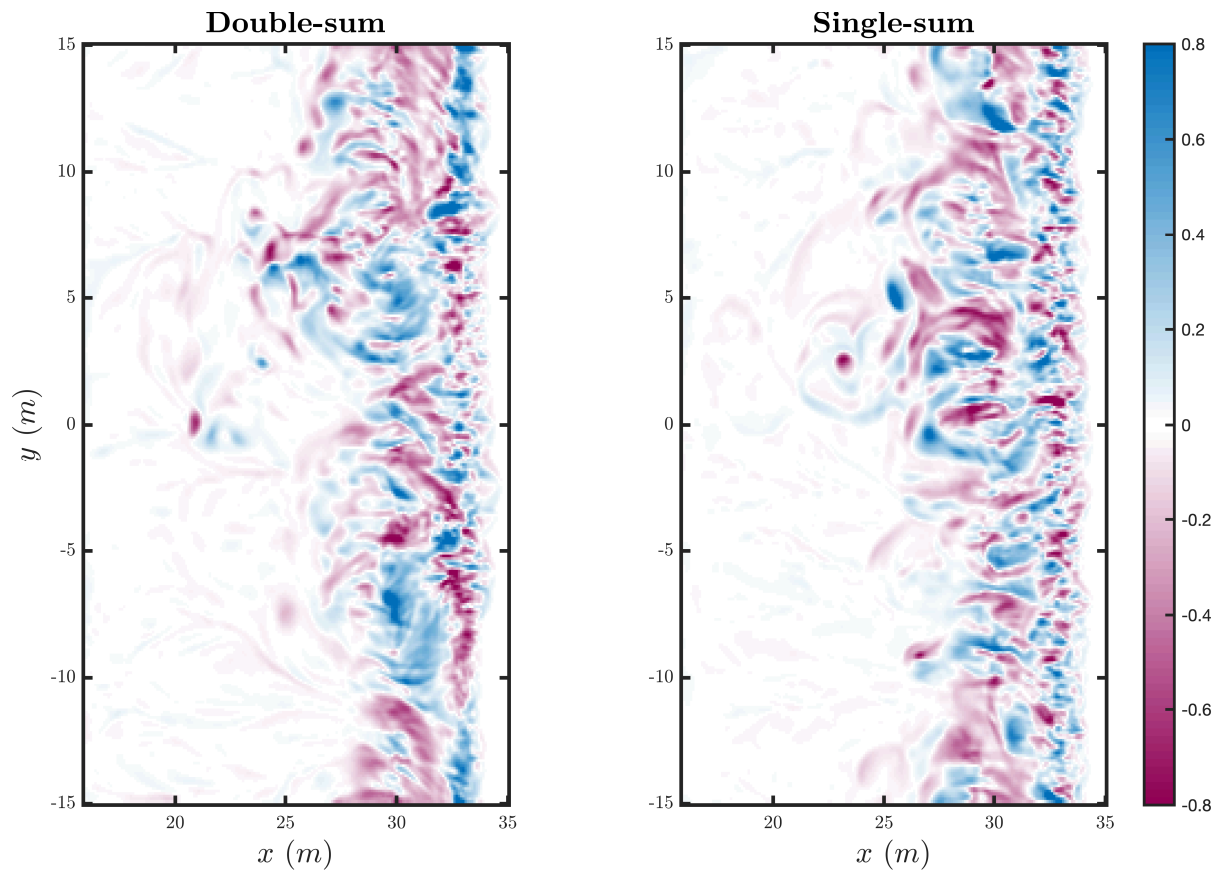


Figure 4: Snapshot of instantaneous surface vertical vorticity ω_z (s^{-1}) for the double-sum (left, 50 freq.) and single-sum (right) wavemakers in the G1d experiment ($\sigma_\theta = 26.1^\circ$).

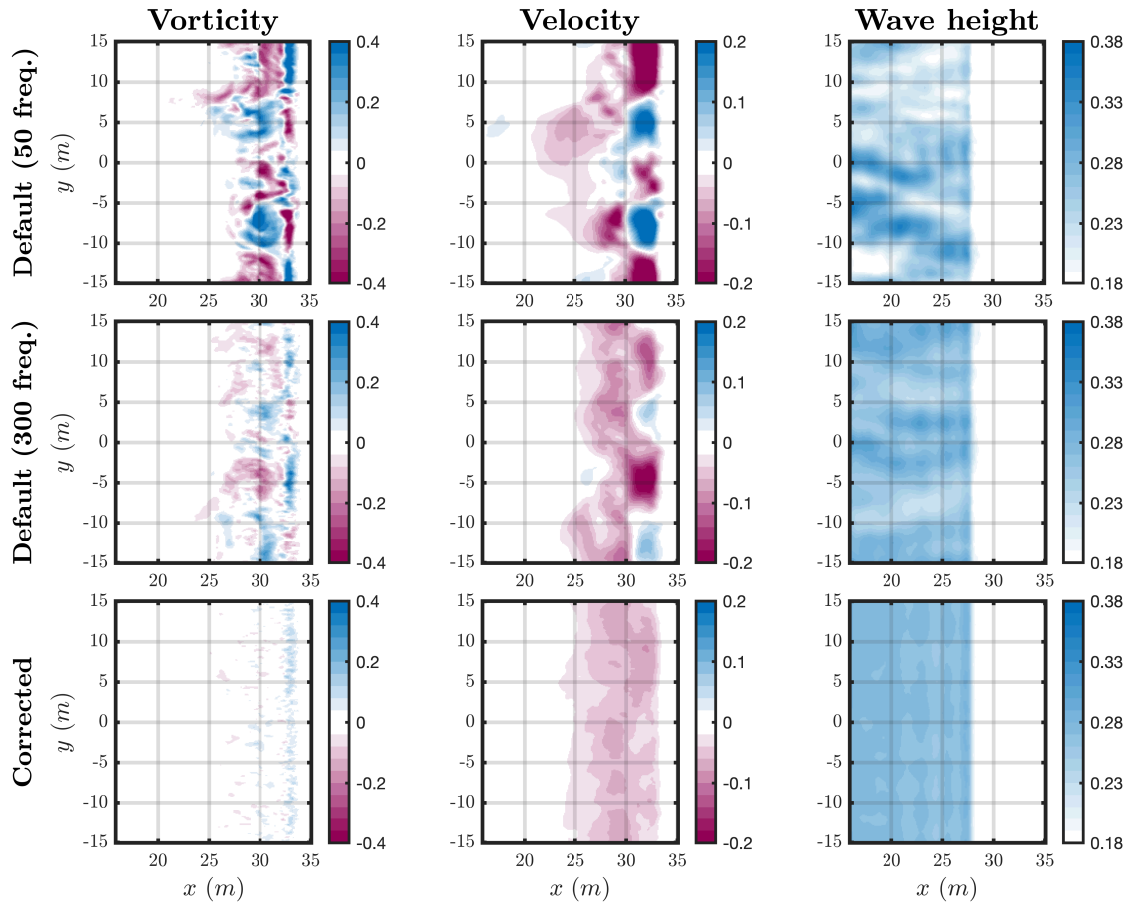


Figure 5: Time-averaged ($t = 10 - 30$ min) surface vertical vorticity ω_z (s^{-1} , left), alongshore velocity v ($\text{m}\cdot\text{s}^{-1}$, middle) and significant wave height H_s (m, right) for the double-sum (top: $N = 50$ freq., middle: $N = 300$ freq.) and single-sum (bottom: $N = 50$ freq.) wavemakers in the G1d case ($\sigma_\theta = 26.1^\circ$).

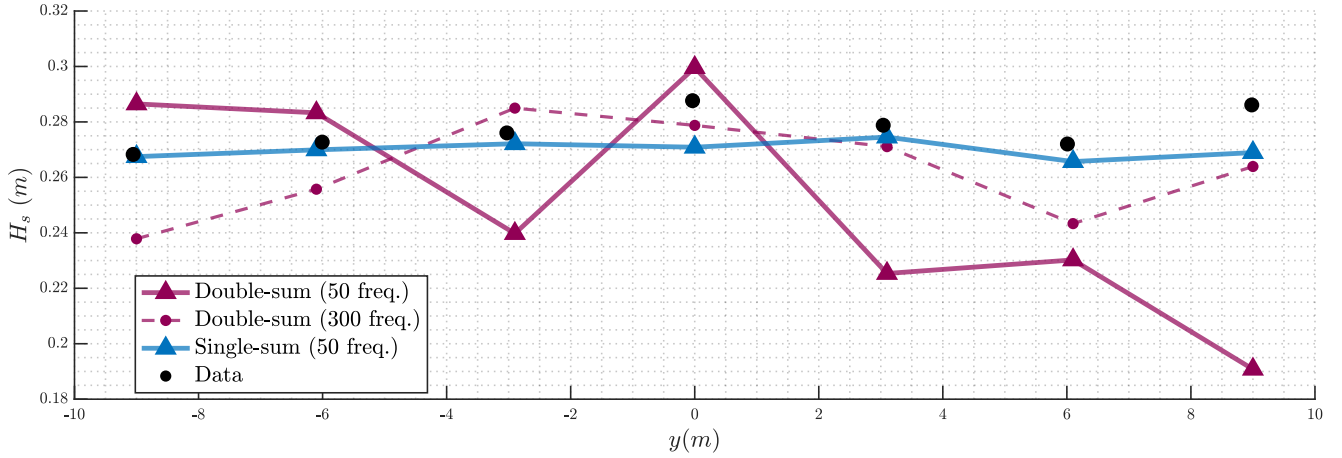


Figure 6: Significant wave height H_s (m) for G1d ($\sigma_\theta = 26.1^\circ$) at all offshore stations along the coast ($x = 19.0\text{m}$, $-9 < y < 9\text{m}$). The data (black circles) is from wave gauges and the model values from the double-sum (pink triangles for $N = 50$ freq. and pink dots for $N = 300$ freq.) and single-sum (blue triangles) wavemaker simulations computed at the same locations.

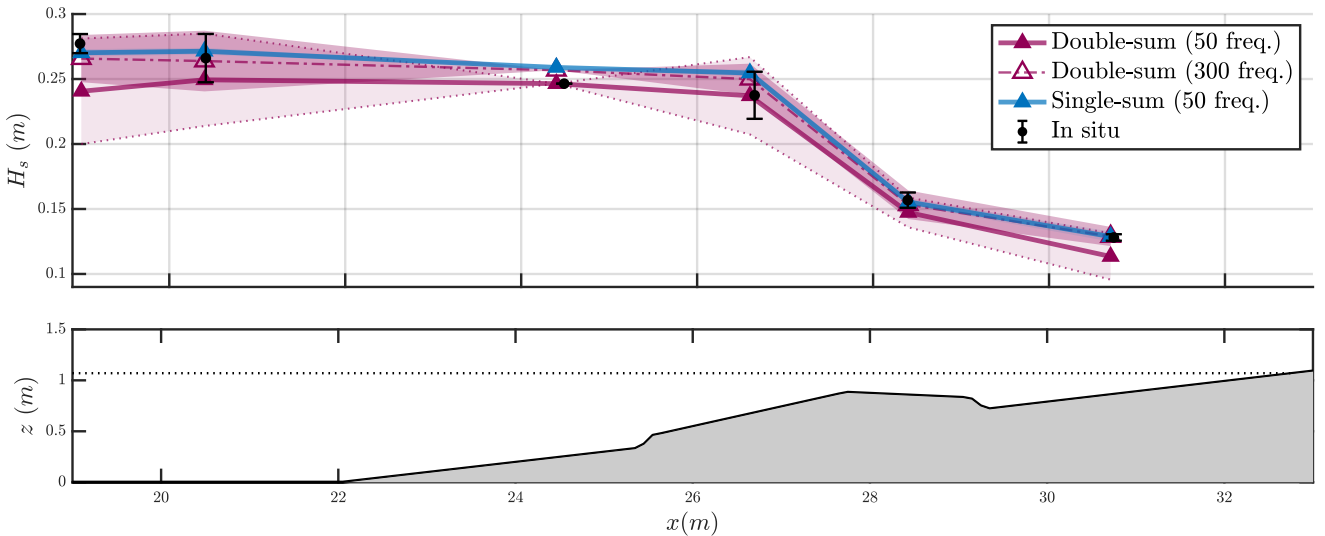


Figure 7: (Top) Cross-shore profile of longshore and time-averaged significant wave height H_s (m) for G1d ($\sigma_\theta = 26.1^\circ$). Comparison is made between experimental in-situ data (black dots) and the double-sum (pink solid line for $N = 50$ freq. and pink dashed line for $N = 300$ freq.) and single-sum (blue triangles) wavemaker simulations. The longshore standard deviation is shown as shaded areas for the model solutions, and as an error bar for the in-situ data. The longshore standard deviation for the double-sum (50 freq.) wavemaker simulation is enhanced with dashed fine pink line for readability. (Bottom) Cross-shore bathymetry profile (shaded) and still water level (dashed line, at 1.07 meters).

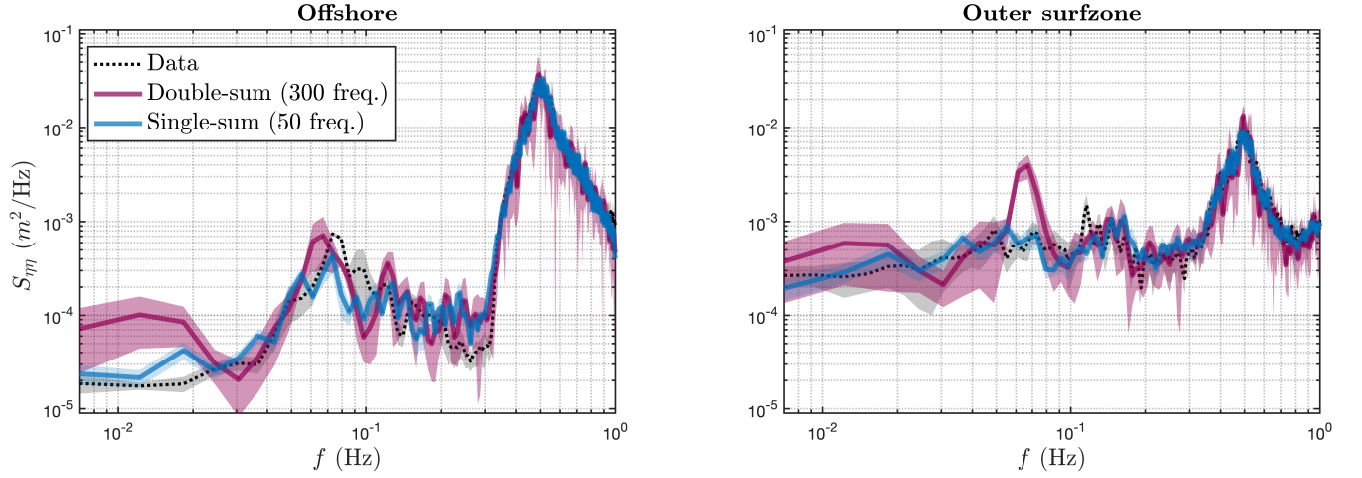


Figure 8: Longshore-averaged power spectra of free surface ($S_{\eta\eta}$) as a function of frequency (f) for stations located offshore (left, $x = 19.0\text{m}$, $-9 < y < 9\text{m}$) and in the outer surfzone (right, $x = 28.4\text{m}$, $-8 < y < 3\text{m}$). Spectra from experimental data are shown as black dots, while those from simulations with the double-sum (300 freq.) and single-sum wavemakers are shown as pink and blue lines, respectively. The longshore standard deviations of the model and data spectra are represented by shaded areas.

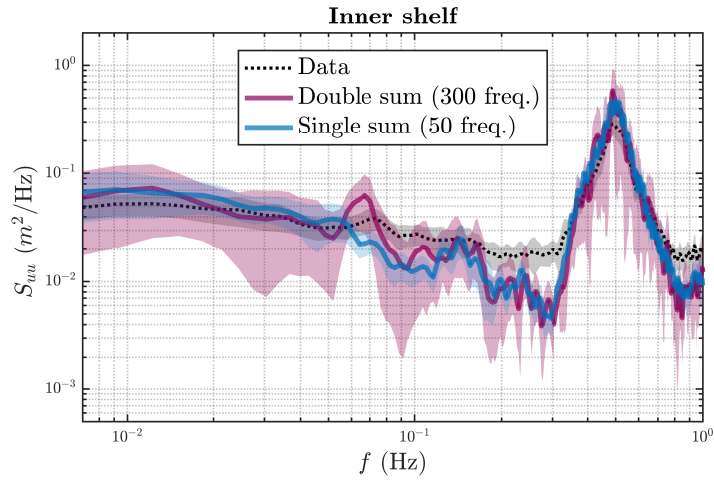


Figure 9: Longshore-average power spectra of the cross-shore velocity (S_{uu}) as a function of frequency (f) for station located in the innershelf (left, $x = 26.6\text{m}$, $-10 < y < 10\text{m}$). The spectrum from experimental data is shown as black dots, while those from simulations with the double-sum (300 freq.) and single-sum wavemakers are shown as pink and blue lines, respectively. The longshore standard deviations of the model and data spectra are represented by shaded areas.