

## Spatial and temporal distributions of turbulence under bichromatic breaking waves

Preprint of manuscript published in Coastal Engineering

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**Keywords:** Turbulence, breaking waves, surf zone, wave groups, bichromatic waves, wave flume experiment

### Abstract

The present study aims to extend insights of surf zone turbulence dynamics to wave groups. In a large-scale wave flume, bichromatic wave groups were produced with 31.5 s group period, 4.2 s mean wave period, and a 0.58 m maximum wave height near the paddle. This condition resulted in plunging-type wave breaking over a fixed, gravel-bed, barred profile. Optic, acoustic and electromagnetic instruments were used to measure the flow and the spatial and temporal distributions of turbulent kinetic energy (TKE). The measurements showed that turbulence in the shoaling region is primarily bed-generated and decays almost fully within one wave cycle, leading to TKE variations at the short wave frequency. The wave breaking-generated turbulence, in contrast, decays over multiple wave cycles, leading to a gradual increase and decay of TKE during a wave group cycle. In the wave breaking region, TKE dynamics are driven by the production and subsequent downward transport of turbulence under the successive breaking waves in the group. Consequently, the maximum near-bed TKE in the breaking region can lag the highest breaking wave by up to 2.5 wave cycles. The net cross-shore transport of TKE is in the shoaling region primarily driven by short-wave velocities and is shoreward-directed; in the wave breaking region, the TKE transport is seaward-directed by the undertow and the long-wave velocities. Downward transport of TKE is driven by the vertical component of the time-averaged flow. The cross-shore and vertical diffusive transport rates are small relative to the advective transport rates.

## 1 **1. Introduction**

2 Over the last decades, turbulence under breaking waves has been of vast scientific interest because of  
3 its effects on near-shore morphodynamics. Several studies have reported the entrainment of significant  
4 amounts of sediments by breaking waves (Nielsen, 1984; Yu *et al.*, 1993; Beach & Sternberg, 1996),  
5 and recent studies have attributed this to wave breaking turbulence that reaches the bed (Scott *et al.*,  
6 2009; Aagaard & Hughes, 2010; Sumer *et al.*, 2013; Otsuka *et al.*, 2017). The timing of wave breaking  
7 turbulence arrival at the bed has significant implications for the phase-dependent pickup of sediment  
8 (Yoon & Cox, 2012; Brinkkemper *et al.*, 2017), and the advection of suspended grains is closely related  
9 to the transport of TKE (LeClaire & Ting, 2017; van der Zanden *et al.*, 2017). Consequently, in order to  
10 assess the effects of wave breaking on near-shore morphodynamics, knowledge of the spatial and the  
11 temporal distribution of wave breaking turbulence is considered important.

12 The present study considers plunging breaking waves, which are characterized by the forward curling  
13 front of the overturning wave. The flow field under plunging waves has been extensively documented  
14 (e.g. Peregrine, 1983; Okayasu *et al.*, 1986; Battjes, 1988; Lin & Hwung, 1992). These studies showed  
15 that the curling wave front transforms into a jet that impinges the water surface and invades the water  
16 column. Upon wave breaking, part of the irrotational wave motion is transformed into a rotational vortex  
17 motion. The shear around the plunging jet and the breakup of the organized vortex leads to the  
18 production of turbulence in the water column. It should be noted that different types of wave breaking  
19 exist, with plunging and spilling being the predominant types. Under plunging breakers, breaking-  
20 generated turbulence is transported more quickly down to the bed and mixing rates are higher than for  
21 spilling breakers (Ting and Kirby, 1995, 1996). For these reasons, plunging breaking waves may be  
22 expected to have a stronger and more direct effect on surf zone sediment transport than spilling breakers  
23 and are therefore selected for the present study.

24 The spatial and temporal distributions of turbulence under plunging waves have been measured  
25 extensively in laboratory wave flumes at small scale, mostly over plane-sloping beds (Nadaoka &  
26 Kondoh, 1982; Ting & Kirby, 1995; Chang & Liu, 1999; Stansby & Feng, 2005; De Serio & Mossa,  
27 2006; Lara *et al.*, 2006; Govender *et al.*, 2011) with the exception of the barred bed study by Boers  
28 (2005), and at large scale over barred bed profiles (Scott *et al.*, 2005; Yoon & Cox, 2010; Brinkkemper  
29 *et al.*, 2016; van der Zanden *et al.*, 2016; van der A *et al.*, 2017). These studies revealed strong spatial  
30 variation with highest turbulent kinetic energy (TKE) in the breaking region near the water surface.  
31 From here, turbulence spreads vertically and horizontally. The vertical transport is downward due to  
32 diffusion by large eddies (Ting & Kirby, 1995) and as a result of advection by the vertical component  
33 of the mean flow in the breaking region (van der A *et al.*, 2017). The magnitude and direction of the  
34 cross-shore transport of TKE depends strongly on breaking characteristics and the responsible transport  
35 mechanism, which can be diffusion (Ting & Kirby, 1995), wave-related advection (De Serio & Mossa,  
36 2006) or current-related advection by the undertow (van der A *et al.*, 2017).

37 The flow in the surf zone is horizontally and vertically non-uniform, which in the presence of wave  
38 breaking turbulence enhances turbulence production in the water column (van der Zanden *et al.*, 2018).  
39 The time-dependent transport and production rates lead to a strong temporal variation in TKE. Studies  
40 involving waves breaking over a plane-sloping bed have revealed a sharp increase in TKE directly under  
41 the wave front, followed by a nearly complete decay within one wave cycle (Okayasu *et al.*, 1986; Ting  
42 & Kirby, 1995; De Serio & Mossa, 2006). However, turbulence under plunging waves at deep water  
43 (Melville *et al.*, 2002) and over a breaker bar trough (van der A *et al.*, 2017) can take over a few wave  
44 cycles to dissipate fully. TKE can be maximum during the wave crest (Okayasu *et al.*, 1986; Ting &

45 Kirby, 1995; De Serio & Mossa, 2006; Brinkkemper *et al.*, 2016) or wave trough half-cycle (Boers,  
46 2005; van der A *et al.*, 2017), depending on cross-shore location, breaking process, and bed geometry.

47 With the increase of computational power, advanced numerical models have been used to simulate wave  
48 breaking in recent years. Numerous studies have applied Reynolds-Averaged Navier-Stokes (RANS)  
49 models to reproduce time-varying TKE (Lin & Liu, 1998) as well as spatial distributions of time-  
50 averaged TKE at outer flow levels (Bradford, 2000; Xie, 2013; Jacobsen *et al.*, 2014; Brown *et al.*, 2016)  
51 and inside the wave bottom boundary layer (Fernandez-Mora *et al.*, 2016). Large Eddy Simulations  
52 (LES) have become increasingly important and are capable to reproduce the formation and transport of  
53 coherent structures during the breaking process (Christensen & Deigaard, 2001; Watanabe *et al.*, 2005;  
54 Zhou *et al.*, 2017). Although qualitatively successful, both approaches report a consistent overestimation  
55 of the modelled TKE in the pre-breaking and the wave breaking regions. This is due to the problem  
56 being physically challenging and requiring an appropriate model set-up for both the small-scale, bed-  
57 generated turbulence, as well as for the large-scale, breaking-generated turbulence. Although LES  
58 models are expected to resolve the large scales, the modeling of sub-grid processes often relies on similar  
59 parameterizations as in RANS models.

60 A recent study by Larsen and Fuhrman (2018) shows how the overestimation of turbulence pre-breaking  
61 comes from an instability problem for RANS models when applied to free-surface waves. An improved  
62 model that eliminates the problem was analytically derived and numerically tested, showing significant  
63 improvements in modelled turbulence levels as well as in undertow profiles in the pre-breaking and  
64 initial breaking regions (Larsen & Fuhrman, 2018). Zheng *et al.* (2017) revealed that the spatial  
65 distributions of TKE across the breaking region can be produced by turbulence closure models, if a  
66 cross-shore varying dissipation factor is applied. Though advances in numerical modelling of breaking  
67 waves have been made recently, these models can still be improved and the work towards better  
68 numerical models will benefit from high-resolution validation measurements of turbulence in various  
69 breaking wave conditions.

70 The majority of the aforementioned experimental studies involved regular breaking waves. Although  
71 such waves allow a detailed examination of intra-wave TKE, the continuous injection of turbulence into  
72 the water column by each passing wave and the steep cross-shore undertow gradients that develop are  
73 not fully representative for waves at natural beaches. On the other hand, studying the temporal variability  
74 of TKE under random breaking waves requires phase-averaging over a range of different waves (e.g.  
75 Brinkkemper *et al.*, 2016; Christensen *et al.*, 2018), which makes the results susceptible to relatively  
76 high measurement uncertainty. Furthermore, while waves at natural beaches tend to arrive in groups,  
77 this grouping nature of waves has not been considered in most previous studies. Therefore, the present  
78 study aims to shed more insights in the dynamics of surf zone turbulence under wave groups. The  
79 specific research objective is to quantify the spatial and temporal distributions and the dominant  
80 transport mechanisms of TKE under breaking wave groups. This is achieved by measuring the flow and  
81 turbulence under repeating bichromatic wave groups in a large-scale wave flume. Here the flow at the  
82 bed, in contrast to many small scale experiments, can be considered fully turbulent, but generated waves  
83 are still smaller than at field scale.

84 The wave flume experiments, measurements and data treatment are described in Section 2. The water  
85 surface elevation and flow velocity measurements are discussed in Sections 3 and 4, respectively.  
86 Section 5 presents measurements of the spatial and temporal turbulence distributions and of the net  
87 cross-shore and vertical transport of TKE. Section 6 discusses the results and the conclusions are  
88 summarized in Section 7.

## 89 2. Experiments

### 90 2.1 Experimental setup and test conditions

91 The experiments were conducted in the 100 m long, 3 m wide and 5 m deep wave flume at the  
92 Polytechnic University in Barcelona. The primary motivation for conducting the experiments at large  
93 scale was to establish a wave bottom boundary layer (WBL) flow that is in the same turbulent regime as  
94 on natural beaches. Detailed measurements of the WBL flow were obtained but are not considered in  
95 the present manuscript.

96 Figure 1 shows the experimental set-up. The cross-shore coordinate  $x$  is defined positively towards the  
97 beach with its origin at the toe of the wave paddle in rest position; the transverse coordinate  $y$  is defined  
98 positively towards the center of the flume with its origin at the right-hand flume wall when facing the  
99 beach; the vertical coordinate  $z$  is defined positively upward from the still water level (swl). The water  
100 depth  $h$  in the deeper part of the flume is 2.65 m. The bed profile consisted of a 1:12 offshore slope,  
101 followed by a breaker bar and trough, a 10 m long gently sloping (1:125) section, terminated by a 1:7  
102 sloping beach. The breaker bar is 0.6 m high (measured from crest to trough). This bed profile resulted  
103 from a preceding experiment and was formed by running regular waves over an initially horizontal,  
104 mobile, medium-sand test section for 3 hours (van der Zanden *et al.*, 2016). The bed profile was then  
105 fixed by replacing the top layer of sand by a 0.20 m thick layer of concrete, as described by Van der A  
106 *et al.* (2017). In the resulting bed profile, the breaker bar and trough are well separated from the beach,  
107 which isolates the wave-breaking-related processes from the processes occurring around the shoreline  
108 and in the swash zone. It should be noted that the bed profile was formed by regular waves rather than  
109 bichromatic waves and therefore cannot be considered the equilibrium bed profile of the present  
110 experiment. The profile was chosen for convenience, as the concrete bed was already present in the  
111 flume, and to facilitate comparison with wave breaking turbulence observations over the same bed  
112 profile for regular waves (van der A *et al.*, 2017; van der Zanden *et al.*, 2018).

113 Prior to the present experiment, in order to increase the WBL thickness and therefore increase the spatial  
114 resolution of measurements in the WBL, the bed roughness was increased by gluing a single layer of  
115 gravel to the concrete bed surface. This commercial gravel mixture had a median diameter  $D_{50} = 9.0$   
116 mm, with  $D_{10} = 7$  mm and  $D_{90} = 13$  mm, and was classified as 'well-sorted, medium gravel' (following  
117 Folk & Ward, 1957; Blott & Pye, 2001). The gravel was uniformly spread over the profile and was glued  
118 firmly to the concrete using epoxy resin.

119 The wave condition was a bichromatic wave which leads to well-defined repeating wave groups that  
120 induce velocity oscillations at short- and wave-group time scales. In addition, the repeating wave  
121 conditions allow velocity decomposition based on ensemble-averaging at the wave group time scale.  
122 The bichromatic wave had frequency components  $f_1 = 0.25$  Hz and  $f_2 = 0.22$  Hz, resulting in a wave  
123 group with group period  $T_{gr} = 31.5$  s that consisted of 7.5 short waves with mean period  $T_m = 4.2$  s. The  
124 measured maximum wave height near the wave paddle (at  $x = 11.8$  m) was  $H_{max} = 0.58$  m. Steering  
125 signals for the wave paddle were based on first-order wave generation theory. The wave paddle did not  
126 have absorption and flume seiching effects were corrected for in the data processing (see Section 2.4).  
127 To ensure sufficient convergence of phase-averaged quantities, each experimental "run" involved 58  
128 minutes of wave generation. Wave conditions across the flume and the wave breaking process are  
129 described in detail in Section 3.

130

## 131 2.2 Measurements

132 The water surface elevation was measured at a sampling frequency  $f_s = 40$  Hz with resistive wave gauges  
133 (RWGs) at 12 cross-shore locations and with acoustic wave gauges (AWGs) at 52 locations (Figure 1a).  
134 In addition, pressure transducer (PT) measurements of the dynamic pressure at 28 cross-shore locations  
135 were used to retrieve the water surface level by applying the non-linear weakly dispersive approach by  
136 Bonneton *et al.* (2018). For the present experiment, this approach yielded a better agreement with the  
137 AWG and WG recordings compared to the linear approach by Guza & Thornton (1980). The approach  
138 by Bonneton *et al.* (2018) involves taking second order time derivatives of the pressure, and therefore a  
139 cut-off frequency of 1 Hz was used in the reconstruction to limit spurious oscillations in the  
140 reconstruction (similar to Bonneton *et al.*, 2018). The PTs were primarily applied in the breaking region,  
141 where the RWGs and AWGs suffer from spurious measurements due to bubbles and splash-up of water.

142 Velocities were measured using two laser Doppler anemometers (LDAs), two acoustic Doppler  
143 velocimeters (ADV), and two electromagnetic current meters (ECMs), deployed from a measurement  
144 frame attached to a carriage atop of the flume (Figure 2). This “mobile frame” could be repositioned at  
145 any elevation (with mm accuracy) and cross-shore location (with cm accuracy); detailed specifications  
146 are provided by Ribberink *et al.* (2014). Velocities in cross-shore, transverse and vertical direction are  
147 defined  $u$ ,  $v$  and  $w$ , respectively.

148 The LDAs were two Dantec two-component backscatter LDA systems, each consisting of a 14 mm  
149 diameter submersible transducer probe with 50 mm focal length and powered by a 300 mW Ar-Ion air-  
150 cooled laser. The LDAs measured the  $u$  and  $w$  components in ellipsoidal-shaped measurement volumes  
151 of 115  $\mu\text{m}$  maximum diameter and approximately 2 mm length in the  $y$  direction. The LDA sampling  
152 frequency depends on seeding particle density and flow velocity and varied between  $f_s = 150$  Hz and  
153 670 Hz, with  $f_s = 332$  Hz on average, for the present experiment.

154 The two ADVs measured the three-component velocity at  $f_s = 100$  Hz. The lower ADV (“ADV1” in  
155 what follows) was a side-looking Nortek Vectrino, while the upper ADV (“ADV2” in what follows)  
156 was a downward-looking Nortek Vectrino+ (Figure 2). The cylindrical shaped measurement volumes of  
157 the ADVs was 6 mm in diameter and 2.8 mm in the  $y$ -direction. The two disc-shaped ECMs, custom-  
158 built by Deltares, measured the  $u$  and  $w$  component at  $f_s = 40$  Hz over a cylindrical shaped measurement  
159 volume of approximately 1 cm diameter.

160 By repositioning the frame to a different location and elevation for each 58-min run, a high spatial  
161 coverage of velocity measurements was obtained (Figure 1b). After discarding spurious data (see next  
162 Section), the remaining velocity measurements covered 201  $x$ ,  $z$  locations. These measurements were  
163 collected during 48 runs, covering 22 cross-shore locations and involving one to three elevations of the  
164 mobile frame per location. At each cross-shore location, velocity profiles were measured with  
165 approximately 0.1 m vertical increments and with the lowest measurement (LDA) at 0.025 m above the  
166 local bed level  $z_{\text{bed}}$ . The latter was accomplished by lowering the frame while manually measuring the  
167 distance between the LDA probe and  $z_{\text{bed}}$ , where  $z_{\text{bed}}$  is defined as the top of the roughness elements over  
168 a  $0.3 \times 0.3 \text{ m}^2$  area. Measurements of the WBL velocity profile indicated that the lowest LDA  
169 measurement at  $z - z_{\text{bed}} = 0.025$  m is located approximately at the WBL overshoot elevation.

170

## 171 2.3 Data processing

172 The AWG measurements of the water surface elevation were despiked using a phase-space algorithm  
173 that was originally developed for despiking of ADV data (Goring & Nikora, 2002; Mori *et al.*, 2007).



174 Spurious velocity recordings by the ADV, for instance due to air bubble presence, were identified as  
175 having a signal-to-noise (SNR) ratio below 7 or a correlation value below 50%. In addition,  
176 measurements that deviated from more than five times the phase-averaged root-mean-square velocity  
177 were identified as outliers. These spurious measurements and outliers were discarded and not replaced.  
178 The EMCs provide erroneous measurements when the probe is emerged or close to the water surface.  
179 Therefore, EMC data were discarded when the probe was above, or within 0.35 m below, the locally  
180 measured instantaneous water surface elevation. The LDA data are SNR-validated instantaneously  
181 during acquisition and suffered from less spurious measurements than the ADVs and EMCs. The water  
182 surface and velocity recordings were decomposed into a long-wave and short-wave component using an  
183 8<sup>th</sup>-order zero phase Butterworth filter with cut-off frequency  $f=0.1$  Hz. The low-frequency ( $f < 0.1$  Hz)  
184 and high-frequency ( $f > 0.1$  Hz) components are annotated with subscripts “lf” and “hf”, respectively.  
185 In what follows, the low- and high-frequency components denote oscillations at time scales of the wave  
186 group and of the short waves, respectively.

187 The velocity time series showed that the undertow, defined as the cross-shore velocity time-averaged  
188 over a wave group, required approximately three wave group cycles to develop to an equilibrium  
189 magnitude. Data corresponding to the first 5 min (approximately 10 wave groups) were discarded and  
190 the remaining data, i.e. approximately 100 wave groups corresponding to a hydrodynamic equilibrium,  
191 were used for phase-averaging. Although the wave paddle steering signal was the same for all generated  
192 wave groups, it should be noted that the wave groups and short waves arriving at the test section did not  
193 all have the exact same wave (group) period, due to slight differences in wave generation at the paddle  
194 and in propagation speeds due to flume seiching. In order to obtain optimum phase correspondence of  
195 all wave repeats, phase-averaged quantities were evaluated for each of the seven short waves that form  
196 the group individually. Phase-averaged velocities over  $N$  wave groups are annotated with angular  
197 brackets and were computed following a conditional averaging method (e.g. Petti & Longo, 2001):

198

$$\langle u(t) \rangle_i = \frac{1}{N} \sum_{n=0}^{N-1} u(t + t_{n,i}) \quad 0 \leq t < T_i \quad (1)$$

199

200 Here,  $\langle u(t) \rangle_i$  is the phase-averaged velocity for short wave  $i$  (with  $i = 1, 2, \dots, 7$ );  $t_{n,i}$  is the start of the  $n^{\text{th}}$   
201 repeat of the  $i^{\text{th}}$  short wave, which was calculated as the upward zero crossing of the measured water  
202 surface elevation at  $x = 50.9$  m. The seven phase-averaged velocities  $\langle u(t) \rangle_i$  for the short waves were  
203 then combined into one phase-averaged velocity  $\langle u(t) \rangle$  for the wave group. Due to the irregular sampling,  
204 the LDA data were phase-averaged over small intervals  $\Delta t = 0.01$  s, while accounting for particle  
205 residence time, corresponding to a same sampling frequency similar to the ADVs. All phase-averaged  
206 data were time-referenced such that  $t/T_{\text{gr}} = 0$  corresponds to the passage of the front of the wave group  
207 at the most offshore mobile frame location,  $x = 49.0$  m (unless stated differently).

208 The velocity time series  $u$  was then decomposed into a time-averaged component  $\bar{u}$  and a periodic  
209 component  $\tilde{u} = \langle u \rangle - \bar{u}$ , that is further decomposed into long-wave and short-wave components  $\tilde{u}_{\text{lf}}$  and  
210  $\tilde{u}_{\text{hf}}$ . For elevations above wave trough level,  $\bar{u}$  is calculated over the ‘wet’ fraction of the wave cycle.  
211 The turbulent velocity  $u'$  was obtained using a Reynolds decomposition based on the phase-averaged  
212 velocity, which is arguably the most well-defined method for separating the turbulent velocity from the  
213 mean (Svendsen, 1987). In the present study,  $u'$  is calculated using the high-pass-filtered velocity time  
214 series as  $u' = u_{\text{hf}} - \langle u_{\text{hf}} \rangle$ . By using  $u_{\text{hf}}$  instead of  $u$ , velocity fluctuations at frequencies lower than 0.1 Hz

215 (e.g. due to flume seiching and variability between wave groups) do not contribute to the turbulence  
216 time series.

217 The contribution of wave bias (also termed 'pseudo-turbulence', e.g. Scott *et al.*, 2005) to the turbulent  
218 velocity can be assessed through Figure 3, which shows the power spectral densities of a velocity  
219 measurement by the LDA. PSDs are shown of the untreated velocity  $u$  (blue line) and of the turbulent  
220 velocity  $u'$  obtained after data cleaning, filtering, and decomposition (black line). The PSD of  $u$  reveals  
221 significant energy at  $f = 0.03$  Hz ( $= 1/T_{gr}$ ) and at  $f = 0.2$  to  $1.2$  Hz, which corresponds to the frequencies  
222 of the short waves and their higher harmonics. After filtering and decomposition, the energy at the wave  
223 group and at the short wave frequencies is almost entirely removed. This is illustrated by the PSD of  $u'$ ,  
224 which follows a well-established  $-5/3$  slope at a double log axis, consistent with energy-transferring  
225 turbulent vortices in the inertial subrange (Pope, 2000).

226 A slight peak in the PSD of  $u'$  is still observed around  $f = 0.5$  Hz, which likely indicates that some energy  
227 of the short waves is still present in  $u'$  (i.e., wave bias). The wave bias contribution to  $u'$  was estimated  
228 from the PSD in two steps. Firstly, the variance of  $u'$  was obtained by trapezoidal integration of the PSD  
229 over the full frequency range. Secondly, the peak around  $f = 0.5$  Hz in the spectrum was removed, the  
230 spectrum was linearly interpolated (at double log axes), and the variance was estimated once more. The  
231 quantified wave bias contribution to the total variance was 3%, which is considered acceptable.

232 The same decomposition was applied to  $v$  and  $w$ . Turbulence intensities  $u'_{rms}$ ,  $v'_{rms}$  and  $w'_{rms}$  were then  
233 calculated as the root-mean-square (rms) value at a phase instant, and were used to calculate the turbulent  
234 kinetic energy  $k$  as:

$$\langle k \rangle = \frac{1}{2} (\langle u'_{rms} \rangle^2 + \langle v'_{rms} \rangle^2 + \langle w'_{rms} \rangle^2) \quad (2)$$

235

236 For the two-component LDA measurements,  $k$  was calculated instead as

$$\langle k \rangle = \frac{1.33}{2} (\langle u'_{rms} \rangle^2 + \langle w'_{rms} \rangle^2) \quad (3)$$

237

238 where the factor 1.33 was proposed by Stive and Wind (1982) and Svendsen (1987) for surf zone  
239 turbulence. The use of this factor is supported by ADV measurements in the present study that indicate  
240 a mean factor of 1.32 (+/- 0.05) in the breaking region. Finally, the turbulent Reynolds shear stress was  
241 calculated as  $-\langle u'w' \rangle$ .

242 The EMC measurements could not provide accurate turbulence estimates in the present conditions, due  
243 to their relatively low sampling frequency and their large measurement volume. In addition, by  
244 comparing the turbulence intensities measured by LDA and ADV, it was found that the vertical velocity  
245 measured by ADV1, due to its sideward-looking orientation, suffered from high contributions of  
246 acoustic Doppler noise. These noise contributions, which could not be removed, led to an overestimation  
247 of  $k$ . Therefore, the TKE measurements by ADV1 were discarded, leaving the measurements by LDA1,  
248 LDA2 and ADV2 for the analysis of turbulence.

### 249 3. Water surface elevation

250 Time series of the phase-averaged water surface elevation  $\eta$  at three cross-shore locations are shown in  
251 Figure 4a-c. To facilitate a good inter-comparison, the time series in the present representation were  
252 time-referenced such that  $t/T_{gr} = 0$  corresponds to the passage of the front of the group at each location.  
253 The grey contour around the lines marks +/- one standard deviation. This contour is barely visible, which

254 indicates the excellent repeatability of the wave groups. The mean variability of  $\langle \eta \rangle$  over all  
255 measurements is less than 0.01 m.

256 Figure 4a shows that after generation, the short waves forming the wave group are slightly skewed  
257 (crests higher than troughs) and approximately symmetric. As the wave group propagates over the slope,  
258 the short waves become higher, more skewed, and more asymmetric ('sawtooth-shaped'). At  $x = 50.9$   
259 m (Figure 4b), which is in the shoaling region before wave breaking, the wave group consists of seven  
260 well-defined short waves. Visual observations and video recordings reveal that the five highest short  
261 waves broke over the bar as plunging-type breakers. These visual observations were used to detect the  
262 "plunge point", i.e. the location where the plunging jet first strikes the water surface (Peregrine, 1983),  
263 with approximately 0.5 m accuracy. Waves two to six were found to break at  $x = 58.5, 57.5, 56.5, 57.5$   
264 and  $57.5$  m, respectively, while the first and seventh short waves broke at the shoreline. The "break  
265 point" (where the wave starts to overturn) of the most offshore breaking wave was measured at  $x = 54.0$   
266 m, while the "splash point" (where the bounced jet strikes the water surface a second time) of wave two  
267 was located at  $x = 60.0$  m. Based on these visual observations and following terminology by Smith and  
268 Kraus (1991), we define the shoaling region ( $x < 54$  m), breaking region ( $54 \text{ m} < x < 60$  m), and inner  
269 surf zone ( $x > 60$  m). Hence, Figure 4c ( $x = 66.0$  m) corresponds to the inner surf zone where waves two  
270 to six have broken and have transformed into surf bores. These five surf bores have similar wave heights,  
271 are highly skewed, and are significantly lower in wave height than at  $x = 50.9$  m.

272 Figure 4d shows the cross-shore distribution of the maximum wave height  $H_{\max} = \langle \eta \rangle_{\max} - \langle \eta \rangle_{\min}$ . The  
273 three instruments yield generally consistent results, although the PTs tend to underestimate the wave  
274 height in the breaking region, where waves are strongly skewed and asymmetric, due to strong pressure  
275 attenuation of the higher harmonics of the wave. The wave heights are approximately constant over the  
276 horizontal, deeper part of the flume ( $x < 34$  m), except for some modulations that are attributed to wave  
277 reflection at the beach and at the offshore slope. As waves shoal over the offshore slope, the wave height  
278 increases up to  $H_{\max} = 0.90$  m at  $x = 52.8$  m. It should be noted that the wave height in the breaking  
279 region may be underestimated as a result of the de-spiking routine applied to the AWG data, which  
280 smoothens the wave crests slightly. The maximum wave height decreases by about 50% between  $x =$   
281  $53.8$  m and  $59.6$  m due to wave breaking. Between  $x = 60$  and  $70$  m the wave height remains  
282 approximately constant, while over the sloping beach ( $x > 70$  m) the waves shoal and break a second  
283 time.

284 As explained in Section 2.3, the water surface elevation was decomposed into a high-frequency and low-  
285 frequency component. Figure 4e shows the cross-shore distribution of  $\langle \eta \rangle_{\text{rms}}$  for both components. It can  
286 be seen that  $\langle \eta_{\text{hf}} \rangle_{\text{rms}}$  is approximately uniform over the offshore slope, which indicates that the increase  
287 in  $H_{\max}$  (Figure 4b) is primarily due to an increasing skewness of the waves. The low-frequency  
288 component  $\langle \eta_{\text{lf}} \rangle_{\text{rms}}$  gradually increases between the wave paddle and the bar crest. This relates to  
289 shoaling of the long wave and to energy transfer from the short waves to the wave group, as explored in  
290 several detailed studies (Baldock *et al.*, 2000; Janssen *et al.*, 2003; Lara *et al.*, 2011; de Bakker *et al.*,  
291 2015; Padilla & Alsina, 2017). Both  $\langle \eta_{\text{lf}} \rangle_{\text{rms}}$  and  $\langle \eta_{\text{hf}} \rangle_{\text{rms}}$  decrease in the wave breaking region around the  
292 bar crest ( $x \approx 55.0$  m). Such decrease at both high and low frequencies near the break point is consistent  
293 with several other laboratory studies (see Baldock, 2012, for an overview). The low-frequency wave  
294 energy increases across the inner surf zone towards the shoreline ( $x = 55$  to  $75$  m) as the wave groups  
295 shoal for the second time.



#### 296 4. Flow velocities

297 Time series of the phase-averaged cross-shore and vertical velocities  $\langle u \rangle$  and  $\langle w \rangle$  at eight cross-shore  
298 locations at a free-stream elevation  $z - z_{\text{bed}} \approx 0.4$  m are shown in Figure 5. The time series reveal the  
299 strongly skewed-asymmetric shape of the short-wave-induced velocity at all locations. The orbital  
300 amplitude increases from  $x = 49.0$  to  $54.0$  m (shoaling region to bar crest). At  $x = 54.0$  m, the highest  
301 velocities in both onshore (1.3 m/s) and offshore (-1.1 m/s) direction occur. The orbital amplitude  
302 decreases strongly between  $x = 54.0$  and  $58.0$  m (bar crest to trough) due to a combination of wave  
303 energy dissipation and an increasing water depth. At the same time the magnitude of the undertow  
304 increases, leading to increasing durations of the negative (seaward-directed) flow half cycles. Towards  
305  $x = 60.0$  to  $64.0$  m the undertow weakens and the duration of the positive (shoreward-directed) flow half  
306 cycles increases again.

307 Figure 5 further includes the low-frequency velocity  $\langle \tilde{u}_{\text{lf}} \rangle$  (dashed lines). The amplitude of the low-  
308 frequency velocity shows a clear variation with cross-shore location. This is better illustrated through  
309 Figure 6, which shows the cross-shore variations of free-stream  $\langle \tilde{u}_{\text{hf}} \rangle_{\text{rms}}$  and  $\langle \tilde{u}_{\text{lf}} \rangle_{\text{rms}}$  around the bar. The  
310 amplitude of  $\langle \tilde{u}_{\text{lf}} \rangle$  is small in the shoaling region (e.g.  $x = 49.0$  m), but its magnitude increases in the  
311 breaking region at the bar crest ( $x = 54.0$  m) and reaches a maximum at  $x = 58.5$  m, which corresponds  
312 to the bar trough and is located about 1 m shoreward from the plunge point of the largest breaking waves.  
313 Further shoreward ( $x > 58.5$  m), the amplitude of  $\langle \tilde{u}_{\text{lf}} \rangle$  decreases. This cross-shore variation of  $\langle \tilde{u}_{\text{lf}} \rangle_{\text{rms}}(x)$   
314 differs from the variation of  $\langle \eta_{\text{lf}} \rangle_{\text{rms}}(x)$  (Figure 4e), which indicates that the low-frequency velocity  
315 variations are not directly driven by the water surface level variations at the wave group frequency.  
316 Instead, the large  $\langle \tilde{u}_{\text{lf}} \rangle$  values for  $x=57-59.5$  m are explained by time variations in the return flow induced  
317 by the successive breaking waves: the return flow, averaged over a short wave cycle, is relatively low  
318 under the non-breaking waves and relatively high under the highest breaking waves, hence yielding a  
319 periodic velocity oscillation at the wave group time scale (see also, e.g., Holmes *et al.*, 1997; Alsina and  
320 Caceres, 2011). The  $\langle \tilde{u}_{\text{lf}} \rangle$  oscillations in the surf zone can thus be interpreted as a wave to wave variation  
321 in “undertow” velocity, although it should be stressed that the term “undertow” is used in the present  
322 study for the longer-term (i.e., wave-group-averaged), and not for the short-wave-averaged, cross-shore  
323 velocity. Therefore, the  $\langle \tilde{u}_{\text{lf}} \rangle$  oscillations will simply be addressed as “low-frequency” or “long-wave”  
324 fluctuations, following, e.g., Alsina and Caceres (2011).

325 The spatial distribution of the time-averaged cross-shore velocity  $\bar{u}$  is shown in Figure 7. The time-  
326 averaged cross-shore velocity magnitude increases from -0.05 m/s in the shoaling region to a maximum  
327 of -0.3 m/s in the breaking region over the bar trough, followed by a decrease to -0.2 m/s in the inner  
328 surf zone. Mass continuity requires these cross-shore variations in time-averaged cross-shore velocity  
329 to be balanced by a time-averaged velocity in vertical direction ( $d\bar{u}/dx = -d\bar{w}/dz$ ). The measurements  
330 (not shown for brevity) do indeed confirm a downward  $\bar{w}$  between  $x = 58$  and  $60$  m and an upward  $\bar{w}$   
331 between  $x = 56$  and  $58$  m with magnitudes between 0 and 0.1 m/s. Such clockwise (in the present  $x, z$   
332 view) mean flow circulations have been discussed in several surf zone studies (e.g. Dyhr-Nielsen &  
333 Sorensen, 1970; Svendsen, 1984; Greenwood & Osborne, 1990).

334 Note that  $\bar{u}(x)$  follows a similar cross-shore variation as  $\langle \tilde{u}_{\text{lf}} \rangle_{\text{rms}}(x)$  (Figure 6). This may be expected, as  
335 both velocity components are driven by the same processes, i.e., the effects of wave breaking on the  
336 mass and continuity balances. The location with strongest undertow magnitudes ( $x = 58.5$  m) is located  
337 between 0 and 2 m shoreward from the plunge points of the five highest waves. This spatial lag is  
338 consistent with observations by Van der A *et al.* (2017) for regular plunging waves.

339 The undertow profiles in Figure 7 differ strongly in shape: around the bar crest ( $x = 53$  to  $56$  m, i.e.  
340 under wave break points)  $\bar{u}(z)$  distributions tend to convex shapes, while  $\bar{u}(z)$  over the bar trough ( $x =$

341 58 to 61 m, i.e. under splash points) increases strongly within the first few cm above the bed and tends  
342 to a concave shape at higher elevations. The variation of these undertow shapes, and their spatial  
343 occurrence relative to break and splash points, is consistent with previous observations of regular (e.g.  
344 Govender *et al.*, 2011; van der A *et al.*, 2017) and irregular (Boers, 2005) breaking waves over a bar.

## 345 5. Turbulence

346 This section provides insights into the spatial and temporal distributions of wave breaking turbulence.  
347 This is done by firstly examining the spatial distributions of the time-averaged TKE and Reynolds stress  
348 (Section 5.1). Subsequently, measurements of the time-dependent TKE are presented in Section 5.2 and  
349 are analyzed in more detail in Section 5.3. The net cross-shore and vertical transport of TKE is studied  
350 in Section 5.4.

### 351 5.1 Time-averaged TKE and turbulent Reynolds stress

352 The spatial distribution of the time-averaged turbulent kinetic energy  $\bar{k}$  is shown in Figure 8a. For  
353 reference, the arrows mark the plunge points of the breaking waves, i.e. waves two to six in the wave  
354 group sequence as described in Section 3.

355 Similar to earlier observations of surf zone turbulence (see Introduction),  $\bar{k}$  is strongly non-uniform,  
356 with values in the wave breaking region that are over an order of magnitude higher than those measured  
357 in the shoaling and inner surf zones. The region with highest  $\bar{k}$  in the upper half of the water column ( $x$   
358 = 56 – 59 m) corresponds to the plunge points of the breaking waves and to the region with the strongest  
359 decrease in short-wave energy. Hence, the increase in TKE is attributed to a transformation of wave  
360 energy to turbulent kinetic energy.

361 Close to the bed in the shoaling region up to the bar crest ( $x = 49$  to 55.5 m), the relatively high  $\bar{k}$  near  
362 the bed represents contributions by bed-shear generated turbulence. However, despite the gravel bed  
363 being hydraulically (very) rough (following the classification of Jonsson, 1980), this bed-shear produced  
364 TKE is small compared to the TKE produced in the breaking region near the water surface. Maximum  
365  $\bar{k}$  at  $z = -0.5$  m is measured at  $x = 58$  m, which is about 0.5 to 1.5 m shoreward from the plunge points  
366 of the highest breaking waves in the group. A similar spatial lag was observed by Van der A *et al.* (2017)  
367 for regular waves. The measurements also reveal a high penetration depth of wave breaking turbulence  
368 into the water column, with wave breaking TKE that appears to stretch downward all the way to the bed  
369 ( $x = 56$  to 60 m). This is again consistent with observations for regular breaking waves (e.g. Cox &  
370 Kobayashi, 2000; Scott *et al.*, 2005; van der Zanden *et al.*, 2016). The Froude-scaled TKE, defined as  
371  $\sqrt{\bar{k}/gh}$  where  $g$  is the gravitational acceleration and  $h$  the local water depth, varied between 0.015 and  
372 0.03 in the wave breaking region. These non-dimensional TKE measurements are quantitatively  
373 compared with other studies in Section 6.

374 Figure 8b shows the time-averaged turbulent Reynolds stress  $-\overline{u'w'}$ . In the shoaling region up to the  
375 bar crest ( $x = 49$  to 55.5 m),  $-\overline{u'w'}$  values are small but negative. Negative  $-\overline{u'w'}$  can be expected  
376 based on the velocity shear by the time-averaged cross-shore velocity ( $d\bar{u}/dz < 0$ , see Figure 7), hence  
377 suggesting that the time-averaged turbulent Reynolds stress in the shoaling region is produced by the  
378 undertow. Such negative  $-\overline{u'w'}$  has also been measured under shoaling laboratory waves by e.g. De  
379 Serio and Mossa (2013). The Reynolds stress changes sign and increases in magnitude in the wave  
380 breaking region, especially near the water surface between  $x = 57$  and 60 m. The positive Reynolds stress  
381 in this region is associated with wave breaking turbulence, as follows from comparison with the  
382 distribution of  $\bar{k}$  (Figure 8a), and is consistent with previous measurements of positive  $-\overline{u'w'}$  in the

383 wave breaking region (Stansby & Feng, 2005; De Serio & Mossa, 2006; Ruessink, 2010; van der Werf  
384 *et al.*, 2017). Despite the high positive Reynolds stresses high in the water column between  $x = 57$  and  
385 60 m, the stresses close to the bed are negative and are likely associated with bed-shear generated  
386 turbulence by the undertow. This is consistent with the observations by Van der Zanden *et al.* (2018),  
387 who found that  $-\overline{u'w'}$  inside the WBL may be negative despite strong positive  $-\overline{u'w'}$  at outer-flow  
388 elevations in wave the breaking region.

389

## 390 5.2 Time-dependent TKE

391 Figure 9 shows time series of phase-averaged TKE,  $\langle k \rangle$ , at four cross-shore locations and at two  
392 elevations:  $z - z_{\text{bed}} = 0.40$  m and 0.025 m. The latter corresponds roughly to the elevation of the velocity  
393 overshoot in the WBL.

394 In the shoaling region at  $x = 49.0$  m and at  $z - z_{\text{bed}} = 0.025$  m  $\langle k \rangle$  shows pairs of short-duration peaks  
395 (Figure 9b, grey line) that lag the maximum offshore- and onshore-directed velocity by approximately  
396  $0.2T_m$  (Figure 9a). These TKE peaks relate to turbulence that is produced at the bed during each half-  
397 cycle and that subsequently spreads upward. During the relatively long interval between the maximum  
398 onshore and maximum offshore velocity, i.e. under the rear side of the wave,  $\langle k \rangle$  decays to nearly zero  
399 until the maximum velocity in offshore direction is reached and the process repeats as described. Hence,  
400 the transfer of TKE to the subsequent wave cycle is low and  $\langle k \rangle$  is instead controlled by turbulence  
401 production and dissipation at the short-wave time scale. This is consistent with observations of negligible  
402 “time-history effects” of WBL turbulence in irregular flows in oscillatory flow tunnels (Bhawanin *et al.*,  
403 2014; Yuan & Dash, 2017).

404 At the bar crest ( $x = 55.0$  m), near-bed  $\langle k \rangle$  shows six well-defined peaks that are approximately in phase  
405 with the maximum onshore free-stream velocity (Figure 9c,d). The fact that only one peak in  $\langle k \rangle$  appears  
406 per wave cycle, instead of two peaks such as at  $x = 49.0$  m, can be explained as follows. Firstly,  
407 maximum velocity magnitudes during the offshore half-cycles are substantially larger at  $x = 55.0$  m than  
408 at 49.0 m and consequently, the TKE produced during the offshore half-cycle is greater and requires  
409 more time to dissipate. Secondly, the waves are much more asymmetric at  $x = 55.0$  m, leading to a  
410 shorter time interval between the maximum offshore and maximum onshore velocity, and thereby more  
411 “accumulation” of turbulence during the successive offshore and onshore half cycles. Similar to  $x = 49.0$   
412 m,  $\langle k \rangle$  decreases rapidly under the wave rear (offshore-to-onshore flow half cycles) and TKE has  
413 dissipated almost fully before a new production stage during the subsequent offshore half-cycle  
414 commences.

415 At the same location at  $z - z_{\text{bed}} = 0.40$  m (Figure 9d, black line),  $\langle k \rangle$  is substantially higher than at  $x =$   
416 49.0 m (same elevation) which can be explained by wave breaking turbulence that is advected in offshore  
417 direction to this location (see also Figure 8a). Furthermore,  $\langle k \rangle$  shows short-duration peaks during the  
418 upward zero crossings of the free-stream horizontal velocity. These peaks may be explained by the  
419 strong velocity shear that occurs during the offshore-to-onshore reversal under strongly asymmetric  
420 waves, contributing to a sudden and high local production of turbulence (van der Zanden *et al.*, 2018).

421 Figure 9f shows  $\langle k \rangle$  over the bar trough ( $x = 59.0$  m). At this location  $\langle k \rangle$  is continuously higher at  $z -$   
422  $z_{\text{bed}} = 0.40$  m than at 0.025 m, due to the injection of turbulence from the breaking waves. The TKE  
423 does not dissipate within one wave cycle, leading to a gradual build-up of TKE during the wave group  
424 cycle ( $t/T_{\text{gr}} = 0.50$  to 0.80). Consequently,  $\langle k \rangle$  shows a pronounced asymmetry at wave group time scale,  
425 with substantially higher TKE under the last three waves in the group ( $t/T_{\text{gr}} = 0.75$  to 0.05) than under  
426 the first three waves ( $t/T_{\text{gr}} = 0.20$  to 0.50). Three evident peaks in  $\langle k \rangle$  are observed at  $t/T_{\text{gr}} \approx 0.65, 0.80,$

427 and 0.90. These peaks occur consistently under the rear of the short waves, i.e. around crest to trough  
428 reversal, when orbital velocities are downward-directed. Therefore, the occurrence of the peaks in  $\langle k \rangle$   
429 likely relates to an advective influx of TKE by the combined downward-directed time-averaged and  
430 periodic velocity (c.f. Figure 5d).  $\langle k \rangle$  is maximum at  $t/T_{gr} \approx 0.8$ , shortly after the fifth short wave in the  
431 wave group has passed. Note that the highest wave upon breaking is the fourth wave (passing  $x = 59.0$   
432 m at  $t/T_{gr} = 0.6$ ) and the maximum  $\langle k \rangle$  thus lags this wave by about 1.5 short wave cycle. Near the bed  
433 (grey line)  $\langle k \rangle$  shows a similar time variation at wave group scale, although less pronounced than at 0.40  
434 m.

435 Figure 9h finally shows the time series of  $\langle k \rangle$  in the inner surf zone ( $x = 64.0$  m). It follows that TKE at  
436 both elevations is continuously small with minor temporal variation at short-wave and wave-group time  
437 scales. These low turbulence levels occur despite the passage of the turbulent surface roller at this  
438 position, hence suggesting limited downward transfer from the roller to the flow at these elevations.

439 The temporal variation of TKE at wave group time scale is further explored in Figure 10, which shows  
440 the spatial distribution of  $\langle k \rangle$  for seven instants of the wave group cycle. These instants match in terms  
441 of the phase of the short wave: from top to bottom, the seven panels correspond to the instant at which  
442 the crest of the seven short waves arrives at  $x = 62.0$  m. It is recalled that the first and last wave (top and  
443 bottom panels) passed the bar without breaking and that the fourth wave (middle panel) is the highest  
444 wave upon breaking. By inter-comparing the TKE distributions for each panel, the build-up and decay  
445 of TKE at wave group time scale under the successive breaking waves can be studied. The maximum  
446  $\langle k \rangle$  in the upper half of the water column in the breaking region ( $x = 54$  to  $60$  m) is observed at  $t/T_{gr} =$   
447  $0.78$ . In the lower half of the water column,  $\langle k \rangle$  is maximum at  $t/T_{gr} = 0.92$ . This shows that maximum  
448  $\langle k \rangle$  may lag the highest breaking wave by one to two wave periods  $T_m$ , depending on cross-shore location  
449 and elevation. A similar time lag follows from analysing the minimum in  $\langle k \rangle$  in the breaking region,  
450 which occurs during  $t/T_{gr} = 0.38$ . This corresponds to the passage of the second wave in the group and  
451 to a time lag of approximately  $1.5T_m$  relative to the minimum of the wave group envelope. The cross-  
452 shore variation of this time lag is explored in more detail in the next section.

453

### 454 5.3 Temporal variability and time lagging of TKE

455 The time series in the previous section show that TKE varies at time scales of the short wave and of the  
456 wave group. The aim of the present section is firstly to assess at which locations the highest temporal  
457 variability occurs, and whether TKE varies predominantly at the short-wave or at the wave-group time  
458 scale. Secondly, the time lag of near-bed TKE with respect to the wave group forcing is analyzed.

459 The temporal variability of TKE is quantified for each measurement through the coefficient of variation,  
460  $\langle \tilde{k} \rangle_{rms}/\bar{k}$ . High  $\langle \tilde{k} \rangle_{rms}/\bar{k}$  indicates large temporal variability, while  $\langle \tilde{k} \rangle_{rms}/\bar{k} = 0$  corresponds to constant  
461  $\langle k \rangle$ . Figure 11a shows the cross-shore and vertical distribution of  $\langle \tilde{k} \rangle_{rms}/\bar{k}$ . Note that some data near the  
462 water surface were discarded when  $\langle k \rangle$  time series were discontinuous because of emergence of the ADV  
463 probe or significant signal attenuation by bubbles. It follows from Figure 11a that the highest temporal  
464 variability in  $\langle k \rangle$  occurs over the shoaling region up to the bar crest ( $x = 49$  to  $55.5$  m) within 0.20 to  
465 0.30 m from the bed. Over the shoreward slope of the bar ( $x = 55.5$  to  $57.5$  m), TKE is relatively steady.  
466 Between  $x = 57.5$  and  $59.5$  m, the temporal variability of TKE increases again over the whole water  
467 column. TKE variations here are attributed to the injection and downward transfer by the successive  
468 breaking waves. The inner surf zone ( $x > 60$  m) is characterized by a minor temporal variability in  $\langle k \rangle$ .

469 Important for our understanding of the temporal behavior of surf zone turbulence is whether the  
470 variations occur primarily at short- or at long-wave (wave group) frequencies. This is especially relevant

471 near the bed, where the time-varying TKE can have important implications for suspended sand transport.  
472 For that reason,  $\langle \tilde{k} \rangle$  is decomposed into short-wave (high-frequency) and long-wave (low-frequency)  
473 components  $\langle \tilde{k}_{\text{hf}} \rangle$  and  $\langle \tilde{k}_{\text{lf}} \rangle$ , similar to the decomposition for water surface and velocity measurements  
474 (see Section 2.3). Figure 11b shows the coefficients of variation of  $\langle \tilde{k} \rangle$ ,  $\langle \tilde{k}_{\text{hf}} \rangle$  and  $\langle \tilde{k}_{\text{lf}} \rangle$  at  $z - z_{\text{bed}} = 0.025$   
475 m along the profile. It follows that the high variability in near-bed  $\langle k \rangle$  between  $x = 49.0$  to  $55.5$  m is  
476 primarily explained by high-frequency variations, i.e. at short wave time scales. This corresponds to the  
477 time series at these locations, which suggested turbulence production and subsequent rapid dissipation  
478 during each wave cycle (see Section 5.2). Between  $x = 55.5$  and  $57.0$  m the temporal variability of  $\langle \tilde{k}_{\text{hf}} \rangle$   
479 decreases, which relates directly to the decreasing orbital velocity amplitude over this region, hence  
480 leading to a reduction in bed shear stress and in the associated turbulence production. Between  $x = 57.0$   
481 and  $59.5$  m, the variability in  $\langle k \rangle$  increases, especially due to variations at the wave group time scale as  
482 indicated by the increase in  $\langle \tilde{k}_{\text{lf}} \rangle_{\text{rms}} / \bar{k}$ . This suggests an increased buildup of TKE during the wave group,  
483 attributed to the wave breaking turbulent vortices that do not dissipate entirely within one wave cycle.  
484 This is again consistent with the time series of  $\langle k \rangle$  discussed in Section 5.2. The measurements at  $z - z_{\text{bed}}$   
485  $= 0.025$  m show that the buildup of TKE during the wave group is not restricted to outer-flow elevations,  
486 but also occurs close to the bed, inside the WBL.

487 The TKE time series in Section 5.2 suggested a time lag of maximum TKE relative to the passage of the  
488 maximum wave. The timing of the maximum TKE within the group is relevant for time-varying  
489 sediment suspension, and consequently, for net sand transport and surf zone morphodynamics. For that  
490 reason, the time lag  $\tau$  of near-bed TKE with  $\eta$  was quantified by cross-correlating  $\langle \tilde{k} \rangle$  at  $z - z_{\text{bed}} = 0.025$   
491 m with the wave group envelope, which is defined as the vertical distance between the cubic interpolated  
492 crest and trough levels of the short waves (see Figure 4b). To prevent a bias due to the changing wave  
493 shape across the test section, all measured  $\langle \tilde{k} \rangle$  time series were cross-correlated with the wave group  
494 envelope at  $x = 50.9$  m. The obtained  $\tau$ , which is the time lag at which the cross-correlation is maximum,  
495 was subsequently corrected for the changing phase of the wave group with cross-shore location by using  
496 the crest of the highest short wave as phase reference.

497 The time lag  $\tau$  at  $z - z_{\text{bed}} = 0.025$  m, normalized by the short wave period  $T_m$ , is shown in Figure 12a.  
498 The time-averaged TKE (Figure 12b) and the measurement positions over the bed (Figure 12c) are also  
499 shown for reference. In the shoaling region,  $\tau$  varies between 0 and  $1 \cdot T_m$ , indicating that  $\langle k \rangle$  is  
500 approximately in phase with the wave group envelope. This is consistent with small-scale bed-generated  
501 turbulence that responds almost instantaneously to velocity forcing and has a high turnover rate, i.e. with  
502 limited buildup over the wave group. The time lag increases gradually over the breaking region, which  
503 is attributed to the arrival of external, wave-breaking-generated turbulence at the bed. Time lags of  $\tau$  up  
504 to  $2.5T_m$  are consistent with descriptions in Section 5.2 that also indicated that wave breaking turbulence  
505 requires a few wave cycles to arrive at the bed. The increasing  $\tau$  from bar crest to trough ( $x = 55$  to  $58$   
506 m) suggests that the local water depth has an important effect on the time lag. However, the time lag is  
507 not only explained by the vertical distance to be covered, but also to other processes such as the vertical  
508 transport rate of TKE (next section) and the interaction of wave breaking turbulence with the flow. In  
509 the inner surf zone,  $\tau$  reduces slightly. It should be noted that the time-averaged TKE and the variations  
510 of  $\langle k \rangle$  are much smaller in the inner surf zone than in the breaking region, which makes the method more  
511 susceptible to measurement uncertainties.

512



## 513 5.4 TKE transport

514 The net (i.e. time-averaged) local transport rate of TKE in horizontal and vertical directions are shown  
515 in Figure 13a ( $\overline{uk}$ ) and Figure 13b ( $\overline{wk}$ ). The transport over the shoaling region up to the bar crest is  
516 shoreward near the bed, and seaward at higher elevations. In the wave breaking region, the net transport  
517 of TKE is of higher magnitude and is negative over the whole water column. Cross-shore transport rates  
518 decrease in the inner surf zone where turbulence levels are much lower. The vertical transport is  
519 downward over  $x = 58$  to  $60$  m and upward between  $x = 54$  and  $58$  m. The cross-shore and vertical  
520 transport rates in Figure 13a-b indicate a clockwise circulation of TKE in the wave breaking region,  
521 much alike the circulation observed by Van der A *et al.* (2017) for regular waves.

522 These observed net transport patterns can be further explained by decomposing the flux as

$$\overline{uk} = \overline{uk} + \overline{\tilde{u}_{hf}\tilde{k}_{hf}} + \overline{\tilde{u}_{lf}\tilde{k}_{lf}} + \overline{u'k'} \quad (4)$$

523 where the right-hand terms denote, respectively, the transport contribution by the current, the short wave,  
524 the long wave, and by turbulent diffusion. Figure 14 shows the cross-shore transport rates by each of  
525 these four components. The current-related component (Figure 14a) is controlled by the undertow and  
526 is consequently seaward at nearly all locations. Highest magnitudes of  $\overline{uk}$  occur over the bar trough,  
527 where concurrent strong undertow velocities and high  $\bar{k}$  are measured. The transport by short waves  
528 ( $\overline{\tilde{u}_{hf}\tilde{k}_{hf}}$ ) is significant, relative to the current-related contributions, only near the bed and between  $x = 49$   
529 and  $55.5$  m (Figure 14b). This transport is shoreward-directed as the near-bed TKE is higher during the  
530 onshore-flow half-cycles (crest stage) than during the offshore-flow half-cycles (trough phase) of the  
531 short waves. Note that the total net TKE transport between  $x = 49$  and  $55.5$  m is shoreward-directed  
532 since the shoreward short-wave-related transport exceeds the seaward transport by the mean current (c.f.  
533 Figure 14a-b). The TKE transport by the long wave is significant only in the wave breaking region  
534 (Figure 14c). Here,  $\overline{\tilde{u}_{lf}\tilde{k}_{lf}}$  is directed seaward because TKE is relatively high under the highest waves in  
535 the group, when the long-wave velocity is negative (as shown previously). The diffusive transport  $\overline{u'k'}$   
536 is at most locations shoreward (Figure 14d), but magnitudes are small relative to the advective transport  
537 rates.

538 The decomposition in Eq. (4) was also applied to the vertical transport of TKE, results of which are  
539 shown in Figure 15. It follows that the net vertical transport is primarily explained by the time-averaged  
540 vertical flow component  $\bar{w}$ , driving a net transport  $\overline{wk}$  (Figure 15a). These velocities  $\bar{w}$  are part of the  
541 clockwise mean flow circulation (discussed in Section 4), and are directed upward over  $x = 55$  to  $58$  m  
542 and downward over  $x = 58$  to  $60$  m. The short-waves contribute to downward transport in the breaking  
543 region around  $x = 59$  m (Figure 15b). This downward transport is explained by relatively high TKE  
544 under the rear of the wave, i.e. during the crest-to-trough transition of the water surface. The long-wave-  
545 driven vertical transport is negligible (Figure 15c). The diffusive transport (Figure 15d) is downward  
546 but it forms a minor contribution to the total net vertical transport.

547

## 548 6. Discussion

549 Similar to previous regular wave studies, the TKE time series and time lags show that TKE at  $z - z_{bed} =$   
550  $0.025$  m is controlled by bed shear only in the shoaling region,. In the breaking and inner surf zones,  
551 breaking-generated turbulence appears to control the TKE even at close distance ( $0.025$  m) from the  
552 bed. This is consistent with Van der Zanden *et al.* (2018), where a smaller roughness was used, and it

553 implies that most of the turbulence dynamics in the present study are independent of the applied bed  
554 roughness.

555 The non-dimensional (Froude-scaled) TKE in the wave breaking region varied between  $\sqrt{\bar{k}/gh} = 0.015$   
556 and 0.03 in the present study. These values are about a factor 3 smaller than values of  $\sqrt{\bar{k}/gh} = 0.05$  to  
557 0.10 measured under regular plunging waves over plane sloping beaches (see several studies reported  
558 by Govender *et al.*, 2002) and a barred bed (van der A *et al.*, 2017). It should be noted that these studies  
559 differed not only in terms of water depth but also in terms of wave heights. However, the use of  $H_{\max}$  or  
560  $\eta_{\text{rms}}$  as Froude length scale still results in Froude-scaled  $\bar{k}$  values that are over a factor 2 lower in the  
561 present study than in Van der A *et al.* (2017). Note that although values are presented here for time-  
562 averaged TKE only, a similar difference between the present experiment and the experiment by Van der  
563 A *et al.* (2017) was observed for the Froude-scaled maximum TKE,  $\sqrt{\langle k \rangle_{\max}/gh}$ .

564 The relatively low  $\sqrt{\bar{k}/gh}$  values in the present study relate likely to the fact that the waves are not regular  
565 (non-monochromatic). This would be qualitatively consistent with observations by Scott *et al.* (2005),  
566 who reported TKE under irregular waves to be up to five times lower than under regular waves with  
567 similar wave heights. This can physically be understood because the waves in the present study do not  
568 all break at the exact same location. Consequently, the injection of turbulence for the present bichromatic  
569 waves is more spatially distributed over the surf zone, and the wave-group-averaged production of  
570 turbulence by wave breaking is likely of lower magnitude, because some waves pass the bar without  
571 breaking. In addition, as shown by Van der Zanden *et al.* (2018), a significant fraction of TKE in the  
572 surf zone originates from local turbulence production in the water column, due to the combination of  
573 high turbulent stresses and velocity shear. It is expected that the irregularity of the waves leads to reduced  
574 undertow velocity gradients and, consequently, to lower turbulence production rates in the water column  
575 compared to regular waves.

576 The time-dependent TKE differs clearly between the shoaling region, where turbulence is primarily bed-  
577 shear generated, and the breaking region, where turbulence is generated by wave breaking. The bed-  
578 generated turbulence dissipates quickly, i.e. within one wave cycle after being produced, leading to  $\langle k \rangle$   
579 variations at the frequency of a wave cycle and/or wave half-cycle. Turbulence in the wave breaking  
580 region, in contrast, decays over multiple wave cycles, and the turbulence production by successive  
581 breaking waves in a group leads to a rise and fall of  $\langle k \rangle$  at the wave group time scale. The observation  
582 of wave breaking turbulence requiring multiple wave cycles to decay, is consistent with observations by  
583 Van der A *et al.* (2017) in a study that involved regular plunging waves (deep-water wave height  $H_0 =$   
584 0.82 m,  $T = 4$  s) over the same barred bed profile as in the present study. Some studies over plane-sloping  
585 beds found that wave breaking TKE dissipates almost fully within one wave cycle (Ting & Kirby, 1994;  
586 De Serio & Mossa, 2006). Van der A *et al.* (2017) attributed this difference in relative decay rate to the  
587 barred bed profile, since vortices with larger length and time scales can develop under waves plunging  
588 into a bar trough relative to those breaking at shallower water over a plane-sloping bed.

589 In the present study the net cross-shore TKE transport is the balance between an offshore-directed  
590 current-related transport by the undertow and an onshore-directed contribution by the short waves, which  
591 reaffirms preceding studies (Ting & Kirby, 1994; van der A *et al.*, 2017). Compared to the study by Van  
592 der A *et al.* (2017) over the same barred bed but with regular plunging waves, the present study indicates  
593 a much higher relative magnitude of the wave-related transport compared to the current-related transport.  
594 This is largely attributed to the wave (ir)regularity: regular waves produce stronger undertow currents  
595 which leads to a higher dominance of the current-related transport of TKE. Another difference with Van  
596 der A *et al.* (2017) is the gravel-bed roughness in the present study, leading to higher bed-shear generated

597 TKE which contributes to the onshore-directed wave-related transport of TKE over the offshore slope  
598 and bar crest.

599 Another difference with regular-wave studies is the low-frequency transport, driven by the long wave  
600 (also called infragravity wave) induced velocities and the phase-coupling of TKE at the wave group time  
601 scale  $T_{gr}$ . The present study indicates that in particular between the break and splash point of the wave,  
602 concurrently high amplitudes of the long-wave velocity and strong variations of TKE at the wave group  
603 time scale can occur, leading to a net transport of TKE by the long wave component. TKE is generally  
604 higher when the long-wave velocity is directed offshore, hence the long wave contributes to the seaward  
605 transport of TKE. This reaffirms laboratory observations of Brinkkemper *et al.* (2016) who found highest  
606 TKE during negative  $u_{lf}$  under predominantly plunging waves. The results are also consistent with  
607 measurements by Ting (2001, 2002), who measured predominantly offshore-directed net transport of  
608 TKE by the low-frequency velocities, although these experiments involved spilling breakers. Several  
609 studies have shown that the transport of TKE shows strong similarities with the transport of suspended  
610 sediment (Brinkkemper *et al.*, 2017; LeClaire & Ting, 2017; van der Zanden *et al.*, 2017). Consequently,  
611 the present study's results on turbulence dynamics at the wave group time scale can contribute to  
612 understanding sand resuspension and net sand fluxes at infragravity wave time scales in the surf zone,  
613 as observed in several studies (Beach & Sternberg, 1991; Osborne & Greenwood, 1992; Ruessink *et al.*,  
614 1998; de Bakker *et al.*, 2016).

615 Time lags up to 2.5 wave cycles between near-bed TKE and the wave group envelope were observed.  
616 This time lag could be interpreted as the combination of a travel time and an "accumulation time",  
617 although the latter term, which expresses the build-up of TKE during the wave group cycle, may not be  
618 entirely appropriate because TKE is not a mass-conserving quantity: production and dissipation rates  
619 are of similar significance in the TKE balance as advection and diffusion rates (e.g., Van der Zanden *et al.*,  
620 2018). The net TKE transport rates in Section 5.4 show that the downward transport is primarily  
621 advective, with minor turbulent diffusive contributions, and driven by the vertical component of the  
622 time-averaged flow circulation. The time-averaged downward velocities in the breaking region reach  
623 values of -0.05 to -0.10 m/s, corresponding to TKE travel lags toward the bed of approximately 10 to 20  
624 wave cycles if TKE were only to be spread downward by advection. This does not match the  
625 observations of TKE spreading and the quantified time lags which both indicate a lag of about two wave  
626 cycles. The explanation is that much of the apparent "TKE spreading" is not due to already existing TKE  
627 being advected and/or diffused, but instead, because turbulent vorticity in a shear flow leads to  
628 additional, local production of turbulence. Hence, although the periodic velocity leads to minor net  
629 downward advection of TKE (see Section 5.4), the orbital motion may contribute to intra-wave vertical  
630 spreading of TKE and thus to enhancing TKE production at successive lower elevations.

631 Morphodynamic models require a high skill in terms of simulating turbulence in order to accurately  
632 reproduce the mean flow, sand transport, and morphodynamics in the surf zone. The present study offers  
633 new insights that may benefit the advancing of numerical models for surf zone morphodynamics. Firstly,  
634 the present study shows that turbulence under wave groups spreads gradually and that TKE time series  
635 at the bed may lag wave breaking by a few wave cycles. Depth-averaged models may not be able to  
636 reproduce such phase lagging, unless empirical factors are introduced to account for delays in turbulence  
637 spreading. A second issue relates to the application of wave-averaged models, in which turbulence is  
638 primarily controlled by the mean flow and the short-wave-related transport of TKE is largely neglected.  
639 Uncertainty is therefore particularly expected in terms of the significant cross-shore transport of TKE  
640 from the shoaling to breaking region. This transport, which is primarily driven by the short waves  
641 ( $\overline{\tilde{u}_{hf} \tilde{k}_{hf}}$ ), is against the direction of the undertow and towards a region with higher TKE and is thus in  
642 opposite direction of what would be predicted by a conventional wave-averaged  $k$ - $\epsilon$  model, for example.

643 On the other hand, it is expected that an intra-wave, depth-resolving hydrodynamic model is able to  
644 reproduce the main processes driving the spatiotemporal distributions of TKE in the surf zone (Lin &  
645 Liu, 1998; Brown *et al.*, 2016). Given their high computational demands, the latter type of models could  
646 be used to derive parameterizations for the vertical time lagging of TKE and for the short-wave-related  
647 transport of TKE for implementation in wave-averaged and depth-averaged morphodynamic models.

648

## 649 **7. Conclusions**

650 The spatial and temporal distributions of turbulent kinetic energy (TKE) under bichromatic, plunging  
651 breaking waves were studied in a large-scale wave flume. The flow velocities and turbulence were  
652 measured with high temporal resolution and spatial coverage across a fixed, gravel-bed breaker bar,  
653 covering part of the shoaling region, the full wave breaking region, and part of the inner surf zone. The  
654 bichromatic wave produced a wave group with seven incident short waves, of which the highest five  
655 waves were plunging breaking over the bar.

656 The temporal dynamics of TKE vary strongly across the profile. In the shoaling region, where turbulence  
657 is primarily bed-shear generated, turbulence decays within one wave cycle, leading to time-varying TKE  
658 at the short wave frequency. In contrast, the wave breaking-generated turbulence between plunge and  
659 splash points requires multiple wave cycles to decay fully, leading to a gradual increase in TKE during  
660 the group and to variations of TKE at the wave group frequency.

661 As TKE builds up and is gradually transported downward under the train of successive breaking waves,  
662 maximum TKE does not occur directly under the largest wave in the group. Instead, maximum TKE  
663 near the bed may lag the passage of the highest breaking wave by more than two wave cycles. This time  
664 lag depends on the local water depth, with relatively higher time lags over the bar trough relative to the  
665 bar crest. Such time lags are virtually absent in the shoaling region, where near-bed turbulence responds  
666 almost instantaneously to the local velocity forcing and TKE is maximum under the highest wave in the  
667 group.

668 The cross-shore transport of TKE is shoreward in the shoaling region and seaward in the wave breaking  
669 region. The shoreward transport in the shoaling region is explained by a positive phase coupling between  
670 velocity and TKE at the short-wave frequency, i.e. TKE is relatively high during the onshore flow half-  
671 cycles. The seaward transport of TKE is largely driven by the undertow, with an additional contribution  
672 by the long-wave (infragravity) velocity due to a negative phase coupling between TKE and velocity at  
673 the wave group frequency. The vertical transport of breaking-generated TKE is primarily driven by the  
674 mean flow circulation.

675 The results in this study contribute to the understanding of surf zone turbulence dynamics at short-wave  
676 and wave group time scales. Future studies may focus on further developing numerical models for surf  
677 zone TKE and on quantifying the grouped-nature and time lag effects of surf zone turbulence on  
678 sediment transport and morphology.

679

## 680 **Acknowledgments**

681 We gratefully acknowledge the suggestions by the three reviewers that helped to improve the  
682 manuscript. The work described in this publication was supported by the European Community's  
683 Horizon 2020 Programme through the grant to the budget of the Integrated Infrastructure Initiative  
684 HYDRALAB+, Contract no. 654110, and was conducted as part of the transnational access project

685 HYBRID. BEL acknowledges financial support from the Independent Research Fund Denmark project  
686 SWASH: Simulating WAVE Surf-zone Hydrodynamics and sea bed morphology, Grant no. 8022-  
687 00137B. For their contributions to the experiments, we thank fellow HYBRID researchers and the  
688 CIEMLAB staff (Oscar Galego, Andrea Marzeddu, and Joaquim Sospedra). We are grateful to Deltares  
689 for lending out their ECMs and to dr Jose Alsina for his contributions to the generation of the wave  
690 paddle steering signals.



## References

- Aagaard, T., & Hughes, M. G. (2010). Breaker turbulence and sediment suspension in the surf zone. *Marine Geology*, 271(3-4), 250-259. doi:10.1016/j.margeo.2010.02.019
- Alsina, J. M., & Caceres, I. (2011). Sediment suspension events in the inner surf and swash zone. Measurements in large-scale and high-energy wave conditions. *Coastal Engineering*, 58(8), 657-670. doi:DOI 10.1016/j.coastaleng.2011.03.002
- Baldock, T. E., Huntley, D. A., Bird, P. A. D., O'Hare, T., & Bullock, G. N. (2000). Breakpoint generated surf beat induced by bichromatic wave groups. *Coastal Engineering*, 39(2-4), 213-242. doi:10.1016/S0378-3839(99)00061-7
- Baldock, T. E. (2012). Dissipation of incident forced long waves in the surf zone—Implications for the concept of “bound” wave release at short wave breaking. *Coastal Engineering*, 60, 276-285. doi:10.1016/j.coastaleng.2011.11.002
- Battjes, J. A. (1988). Surf-Zone Dynamics. *Annual Review of Fluid Mechanics*, 20, 257-293.
- Beach, R. A., & Sternberg, R. W. (1991). *Infragravity-driven suspended sediment transport in the swash, inner and outer-surf zone*. Proc. Coastal Sediments.
- Beach, R. A., & Sternberg, R. W. (1996). Suspended-sediment transport in the surf zone: Response to breaking waves. *Continental Shelf Research*, 16(15), 1989-2003.
- Bhawanin, M., O'Donoghue, T., Van der A, D. A., & Ribberink, J. S. (2014). *Effect of flow irregularity on oscillatory boundary layer flow*. Proc. Int. Conf. on Coastal Engineering (ICCE).
- Blott, S. J., & Pye, K. (2001). GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26(11), 1237-1248. doi:10.1002/esp.261
- Boers, M. (2005). *Surf zone turbulence*. (PhD Thesis), TU Delft, The Netherlands, Delft.
- Bonneton, P., Lannes, D., Martins, K., & Michallet, H. (2018). A nonlinear weakly dispersive method for recovering the elevation of irrotational surface waves from pressure measurements. *Coastal Engineering*, 138, 1-8. doi:10.1016/j.coastaleng.2018.04.005
- Bradford, S. F. (2000). Numerical Simulation of Surf Zone Dynamics. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 126(1), 1-13. doi:10.1061/(asce)0733-950x(2000)126:1(1)
- Brinkkemper, J. A., Lanckriet, T., Grasso, F., Puleo, J. A., & Ruessink, B. G. (2016). Observations of turbulence within the surf and swash zone of a field-scale sandy laboratory beach. *Coastal Engineering*, 113, 62-72. doi:10.1016/j.coastaleng.2015.07.006
- Brinkkemper, J. A., de Bakker, A. T. M., & Ruessink, B. G. (2017). Intrawave sand suspension in the shoaling and surf zone of a field-scale laboratory beach. *Journal of Geophysical Research: Earth Surface*, 122(1), 356-370. doi:10.1002/2016jef004061
- Brown, S. A., Greaves, D. M., Magar, V., & Conley, D. C. (2016). Evaluation of turbulence closure models under spilling and plunging breakers in the surf zone. *Coastal Engineering*, 114, 177-193. doi:10.1016/j.coastaleng.2016.04.002
- Chang, K. A., & Liu, P. L. F. (1999). Experimental investigation of turbulence generated by breaking waves in water of intermediate depth. *Physics of Fluids*, 11(11), 3390-3400.
- Christensen, E. D., & Deigaard, R. (2001). Large eddy simulation of breaking waves. *Coastal Engineering*, 42(1), 53-86. doi:10.1016/S0378-3839(00)00049-1
- Christensen, D. F., Brinkkemper, J., Ruessink, G., & Aagaard, T. (2018). Field observations of turbulence in the intertidal and shallow subtidal zones. *Continental Shelf Research*, 170, 21-32. doi:10.1016/j.csr.2018.10.002
- Cox, D. T., & Kobayashi, N. (2000). Identification of intense, intermittent coherent motions under shoaling and breaking waves. *Journal of Geophysical Research-Oceans*, 105(C6), 14223-14236. doi:10.1029/2000JC900048
- de Bakker, A. T. M., Herbers, T. H. C., Smit, P. B., Tissier, M. F. S., & Ruessink, B. G. (2015). Nonlinear Infragravity-Wave Interactions on a Gently Sloping Laboratory Beach. *Journal of Physical Oceanography*, 45(2), 589-605. doi:10.1175/jpo-d-14-0186.1
- de Bakker, A. T. M., Brinkkemper, J. A., van der Steen, F., Tissier, M. F. S., & Ruessink, B. G. (2016). Cross-shore sand transport by infragravity waves as a function of beach steepness. *Journal of Geophysical Research: Earth Surface*, 121(10), 1786-1799. doi:10.1002/2016jef003878

- De Serio, F., & Mossa, M. (2006). Experimental study on the hydrodynamics of regular breaking waves. *Coastal Engineering*, 53(1), 99-113. doi:10.1016/j.coastaleng.2005.09.021
- De Serio, F., & Mossa, M. (2013). A laboratory study of irregular shoaling waves. *Experiments in Fluids*, 54(6). doi:10.1007/s00348-013-1536-0
- Dyhr-Nielsen, M., & Sorensen, T. (1970). *Some sand transport phenomena on coasts with bars*. Proceedings of the 12th International Conference on Coastal Engineering, Washington, D.C.
- Fernandez-Mora, A., Ribberink, J. S., Van der Zanden, J., van der Werf, J. J., & Jacobsen, N. G. (2016). *RANS-VOF modeling of hydrodynamics and sand transport under full-scale non-breaking and breaking waves*. Proceedings of the 35th Conference on Coastal Engineering, Antalya, Turkey.
- Folk, R. L., & Ward, W. C. (1957). Brazos River bar [Texas]; a study in the significance of grain size parameters. *Journal of Sedimentary Research*, 27(1), 3-26. doi:10.1306/74d70646-2b21-11d7-8648000102c1865d
- Goring, D. G., & Nikora, V. I. (2002). Despiking Acoustic Doppler Velocimeter Data. *Journal of Hydraulic Engineering*, 128(1), 117-126. doi:10.1061/(asce)0733-9429(2002)128:1(117)
- Govender, K., Mocke, G. P., & Alport, M. J. (2002). Video-imaged surf zone wave and roller structures and flow fields. *Journal of Geophysical Research*, 107(C7). doi:10.1029/2000jc000755
- Govender, K., Michallet, H., & Alport, M. J. (2011). DCIV measurements of flow fields and turbulence in waves breaking over a bar. *European Journal of Mechanics B-Fluids*, 30(6), 616-623. doi:10.1016/j.euromechflu.2011.09.001
- Greenwood, B., & Osborne, P. D. (1990). Vertical and horizontal structure in cross-shore flows: An example of undertow and wave set-up on a barred beach. *Coastal Engineering*, 14(6), 543-580. doi:10.1016/0378-3839(90)90034-t
- Guza, R. T., & Thornton, E. B. (1980). Local and Shoaled Comparisons of Sea-Surface Elevations, Pressures, and Velocities. *Journal of Geophysical Research-Oceans*, 85(Nc3), 1524-1530. doi:DOI 10.1029/JC085iC03p01524
- Holmes, P., Baldock, T.E., Chan, R.T. and Neshaei, M.A.L., 1997. Beach evolution under random waves. *Proc. 25th Int. Conf. on Coastal Eng.*, pp. 3006-3019, doi 10.1061/9780784402429.233
- Jacobsen, N. G., Fredsøe, J., & Jensen, J. H. (2014). Formation and development of a breaker bar under regular waves. Part 1: Model description and hydrodynamics. *Coastal Engineering*, 88, 182-193. doi:10.1016/j.coastaleng.2013.12.008
- Janssen, T. T., Battjes, J. A., & van Dongeren, A. R. (2003). Long waves induced by short-wave groups over a sloping bottom. *Journal of Geophysical Research-Oceans*, 108(C8), 1-14. doi:10.1029/2002jc001515
- Jonsson, I. G. (1980). A new approach to oscillatory rough turbulent boundary layers. *Ocean Engineering*, 7(1), 109-152. doi:10.1016/0029-8018(80)90034-7
- Lara, J. L., Losada, I. J., & Liu, P. L. F. (2006). Breaking waves over a mild gravel slope: Experimental and numerical analysis. *Journal of Geophysical Research*, 111(C11). doi:10.1029/2005jc003374
- Lara, J. L., Ruju, A., & Losada, I. J. (2011). Reynolds averaged Navier-Stokes modelling of long waves induced by a transient wave group on a beach. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 467(2129), 1215-1242. doi:10.1098/rspa.2010.0331
- Larsen, B. E., & Fuhrman, D. R. (2018). On the over-production of turbulence beneath surface waves in Reynolds-averaged Navier-Stokes models. *Journal of Fluid Mechanics*, 853, 419-460. doi:10.1017/jfm.2018.577
- LeClaire, P. D., & Ting, F. C. K. (2017). Measurements of suspended sediment transport and turbulent coherent structures induced by breaking waves using two-phase volumetric three-component velocimetry. *Coastal Engineering*, 121, 56-76. doi:10.1016/j.coastaleng.2016.11.008
- Lin, C., & Hwung, H. H. (1992). External and Internal Flow-Fields of Plunging Breakers. *Experiments in Fluids*, 12(4-5), 229-237.
- Lin, P., & Liu, P. L. F. (1998). A numerical study of breaking waves in the surf zone. *Journal of Fluid Mechanics*, 359, 239-264. doi:10.1017/s002211209700846x
- Melville, W. K., Veron, F., & White, C. J. (2002). The velocity field under breaking waves: coherent structures and turbulence. *Journal of Fluid Mechanics*, 454, 203-233. doi:10.1017/s0022112001007078

- Mori, N., Suzuki, T., & Kakuno, S. (2007). Noise of Acoustic Doppler Velocimeter Data in Bubbly Flows. *Journal of Engineering Mechanics*, 133(1), 122-125. doi:10.1061/(asce)0733-9399(2007)133:1(122)
- Nadaoka, K., & Kondoh, T. (1982). Laboratory measurements of velocity field structure in the surf zone by LDV. *Coastal Engineering in Japan*, 25, 125-145.
- Nielsen, P. (1984). Field-Measurements of Time-Averaged Suspended Sediment Concentrations under Waves. *Coastal Engineering*, 8(1), 51-72. doi:10.1016/0378-3839(84)90022-X
- Okayasu, A., Shibayama, T., & Mimura, N. (1986). *Velocity Field under Plunging Waves*. Proceedings of the 20th International Conference on Coastal Engineering, Taipei, Taiwan.
- Osborne, P. D., & Greenwood, B. (1992). Frequency-Dependent Cross-Shore Suspended Sediment Transport .2. A Barred Shoreface. *Marine Geology*, 106(1-2), 25-51.
- Otsuka, J., Saruwatari, A., & Watanabe, Y. (2017). Vortex-induced suspension of sediment in the surf zone. *Advances in Water Resources*, 110, 59-76. doi:10.1016/j.advwatres.2017.08.021
- Padilla, E. M., & Alsina, J. M. (2017). Transfer and dissipation of energy during wave group propagation on a gentle beach slope. *Journal of Geophysical Research: Oceans*, 122(8), 6773-6794. doi:10.1002/2017jc012703
- Peregrine, D. H. (1983). Breaking waves on beaches. *Annual Review of Fluid Mechanics*, 15(1), 149-178. doi:10.1146/annurev.fl.15.010183.001053
- Petti, M., & Longo, S. (2001). Turbulence experiments in the swash zone. *Coastal Engineering*, 43(1), 1-24.
- Pope, S. B. (2000). *Turbulent Flows*, Cambridge University Press.
- Ribberink, J. S., van der A, D. A., van der Zanden, J., O'Donoghue, T., Hurther, D., Cáceres, I., & Thorne, P. D. (2014). *SandT-Pro: Sediment transport measurements under irregular and breaking waves*. Proceedings of the 34th International Conference on Coastal Engineering, Seoul, Korea, Seoul, Korea. 10.9753/icce.v34.sediment.1
- Ruessink, B. G., Houwman, K. T., & Hoekstra, P. (1998). The systematic contribution of transporting mechanisms to the cross-shore sediment transport in water depths of 3 to 9 m. *Marine Geology*, 152(4), 295-324. doi:10.1016/S0025-3227(98)00133-9
- Ruessink, B. G. (2010). Observations of Turbulence within a Natural Surf Zone. *Journal of Physical Oceanography*, 40(12), 2696-2712. doi:10.1175/2010jpo4466.1
- Scott, C. P., Cox, D. T., Maddux, T. B., & Long, J. W. (2005). Large-scale laboratory observations of turbulence on a fixed barred beach. *Measurement Science and Technology*, 16(10), 1903-1912. doi:10.1088/0957-0233/19/10/004
- Scott, N. V., Hsu, T. J., & Cox, D. (2009). Steep wave, turbulence, and sediment concentration statistics beneath a breaking wave field and their implications for sediment transport. *Continental Shelf Research*, 29(20), 2303-2317. doi:10.1016/j.csr.2009.09.008
- Smith, E. R., & Kraus, N. C. (1991). Laboratory study of wave-breaking over bars and artificial reefs. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 117(4), 307-325. doi:10.1061/(asce)0733-950x(1991)117:4(307)
- Stansby, P. K., & Feng, T. (2005). Kinematics and depth-integrated terms in surf zone waves from laboratory measurement. *Journal of Fluid Mechanics*, 529, 279-310. doi:10.1017/S0022112005003599
- Stive, M. J. F., & Wind, H. G. (1982). A Study of Radiation Stress and Set-up in the Nearshore Region. *Coastal Engineering*, 6(1), 1-25.
- Sumer, B. M., Guner, H. A. A., Hansen, N. M., Fuhrman, D. R., & Fredsoe, J. (2013). Laboratory observations of flow and sediment transport induced by plunging regular waves. *Journal of Geophysical Research-Oceans*, 118(11), 6161-6182. doi:10.1002/2013jc009324
- Svendsen, I. A. (1984). Mass flux and undertow in a surf zone. *Coastal Engineering*, 8, 347-365.
- Svendsen, I. A. (1987). Analysis of Surf Zone Turbulence. *Journal of Geophysical Research-Oceans*, 92(C5), 5115-5124. doi:10.1029/JC092iC05p05115
- Ting, F. C. K., & Kirby, J. T. (1994). Observation of Undertow and Turbulence in a Laboratory Surf Zone. *Coastal Engineering*, 24(1-2), 51-80. doi:10.1016/0378-3839(94)90026-4
- Ting, F. C. K., & Kirby, J. T. (1995). Dynamics of Surf-Zone Turbulence in a Strong Plunging Breaker. *Coastal Engineering*, 24(3-4), 177-204. doi:10.1016/0378-3839(94)00036-W

- Ting, F. C. K., & Kirby, J. T. (1996). Dynamics of surf-zone turbulence in a spilling breaker. *Coastal Engineering*, 27(3-4), 131-160. doi:10.1016/0378-3839(95)00037-2
- Ting, F. C. K. (2001). Laboratory study of wave and turbulence velocities in a broad-banded irregular wave surf zone. *Coastal Engineering*, 43(3-4), 183-208.
- Ting, F. C. K. (2002). Laboratory study of wave and turbulence characteristics in narrow-band irregular breaking waves. *Coastal Engineering*, 46(4), 291-313.
- van der A, D. A., van der Zanden, J., O'Donoghue, T., Hurther, D., Cáceres, I., McLelland, S. J., & Ribberink, J. S. (2017). Large-scale laboratory study of breaking wave hydrodynamics over a fixed bar. *Journal of Geophysical Research: Oceans*, 122(4), 3287-3310. doi:10.1002/2016jc012072
- van der Werf, J., Ribberink, J., Kranenburg, W., Neessen, K., & Boers, M. (2017). Contributions to the wave-mean momentum balance in the surf zone. *Coastal Engineering*, 121, 212-220. doi:10.1016/j.coastaleng.2016.12.007
- van der Zanden, J., van der A, D. A., Hurther, D., Cáceres, I., O'Donoghue, T., & Ribberink, J. S. (2016). Near-bed hydrodynamics and turbulence below a large-scale plunging breaking wave over a mobile barred bed profile. *Journal of Geophysical Research: Oceans*, 121(8), 6482-6506. doi:10.1002/2016jc011909
- van der Zanden, J., van der A, D. A., Hurther, D., Cáceres, I., O'Donoghue, T., & Ribberink, J. S. (2017). Suspended sediment transport around a large-scale laboratory breaker bar. *Coastal Engineering*, 125, 51-69. doi:10.1016/j.coastaleng.2017.03.007
- van der Zanden, J., van der A, D. A., Cáceres, I., Hurther, D., McLelland, S. J., Ribberink, J. S., & O'Donoghue, T. (2018). Near-Bed Turbulent Kinetic Energy Budget Under a Large-Scale Plunging Breaking Wave Over a Fixed Bar. *Journal of Geophysical Research: Oceans*, 123(2), 1429-1456. doi:10.1002/2017jc013411
- Watanabe, Y., Saeki, H., & Hosking, R. J. (2005). Three-dimensional vortex structures under breaking waves. *Journal of Fluid Mechanics*, 545(-1), 291. doi:10.1017/s0022112005006774
- Xie, Z. (2013). Two-phase flow modelling of spilling and plunging breaking waves. *Applied Mathematical Modelling*, 37(6), 3698-3713. doi:10.1016/j.apm.2012.07.057
- Yoon, H. D., & Cox, D. T. (2010). Large-scale laboratory observations of wave breaking turbulence over an evolving beach. *Journal of Geophysical Research-Oceans*, 115. doi:10.1029/2009jc005748
- Yoon, H. D., & Cox, D. T. (2012). Cross-shore variation of intermittent sediment suspension and turbulence induced by depth-limited wave breaking. *Continental Shelf Research*, 47, 93-106. doi:10.1016/j.csr.2012.07.001
- Yu, Y., Sternberg, R. W., & Beach, R. A. (1993). Kinematics of breaking waves and associated suspended sediment in the nearshore zone. *Continental Shelf Research*, 13(11), 1219-1242. doi:10.1016/0278-4343(93)90050-8
- Yuan, J., & Dash, S. M. (2017). Experimental investigation of turbulent wave boundary layers under irregular coastal waves. *Coastal Engineering*, 128, 22-36. doi:10.1016/j.coastaleng.2017.07.005
- Zheng, P., Li, M., van der A, D. A., van der Zanden, J., Wolf, J., Chen, X., & Wang, C. (2017). A 3D unstructured grid nearshore hydrodynamic model based on the vortex force formalism. *Ocean Modelling*, 116, 48-69. doi:10.1016/j.ocemod.2017.06.003
- Zhou, Z., Hsu, T.-J., Cox, D., & Liu, X. (2017). Large-eddy simulation of wave-breaking induced turbulent coherent structures and suspended sediment transport on a barred beach. *Journal of Geophysical Research: Oceans*, 122(1), 207-235. doi:10.1002/2016jc011884



## Figures

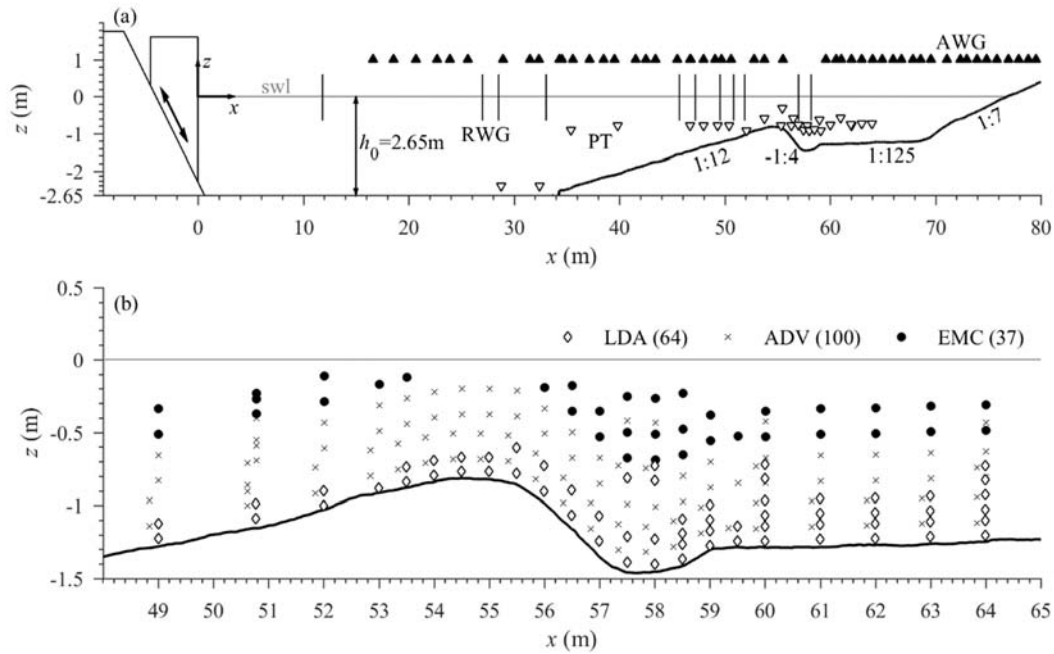


Figure 1. Experimental set-up including measurement locations by: (a) resistive wave gauges (RWG, solid vertical lines), pressure transducers (PT, white triangles), and acoustic wave gauges (AWG, black triangles); (b) laser Doppler anemometers (LDA, diamonds), acoustic Doppler velocimeters (ADVs, crosses), and electromagnetic current meters (EMC, circles), with numbers between brackets indicating the total number of measurement locations by each instrument.



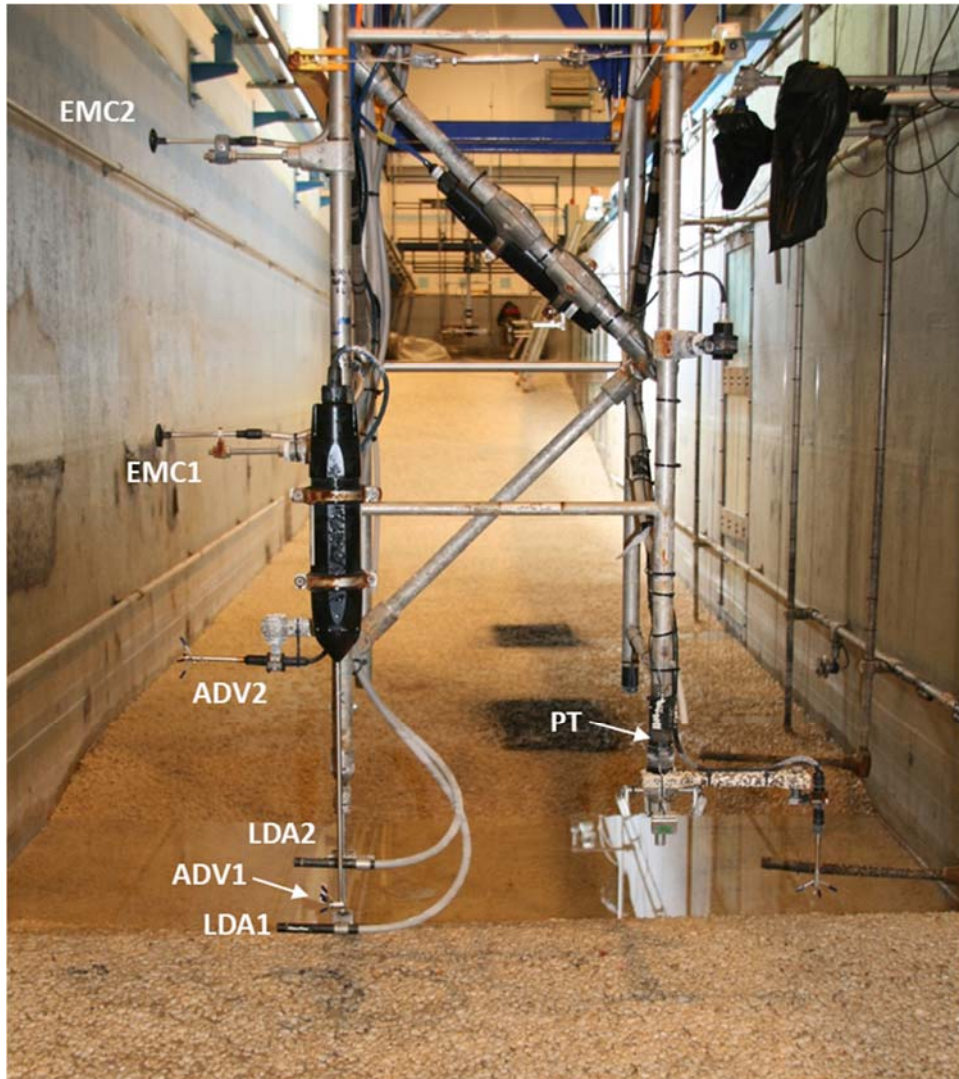


Figure 2. Photo of mobile frame positioned above the bar crest.

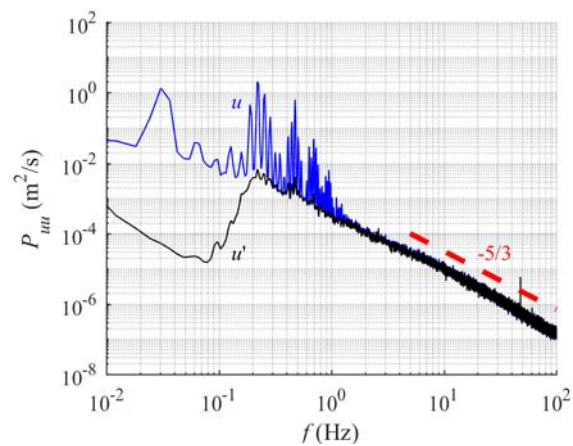


Figure 3. Power spectral density (PSD) of velocity measured by LDA at  $x = 59.5$  m and  $z - z_{\text{bed}} = 0.025$  m. PSD's are shown of the raw (untreated) velocity time series (blue) and of the cleaned turbulent time series  $u'$  (black).

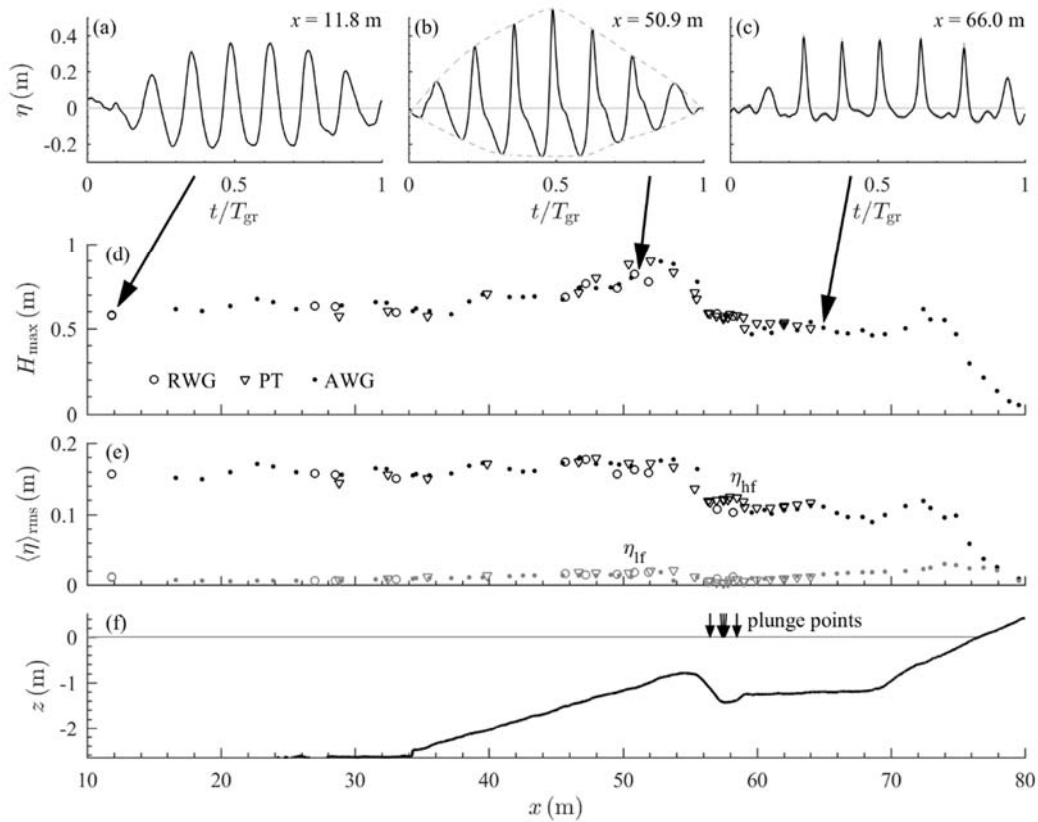


Figure 4. (a-c) Time series of phase-averaged water surface, measured by RWG (a, b) and AWG (c) (solid), with dashed lines in (b) marking the upper and lower bounds of the wave group envelope; (d) Maximum wave height  $H_{max} = \langle \eta \rangle_{max} - \langle \eta \rangle_{min}$ , measured by RWGs (circles), PTs (triangles) and AWGs (dots); (e) Root-mean-square water surface elevation, high-frequency (black symbols) and low-frequency (grey symbols) components; (f) bed profile including locations of the five plunge points.

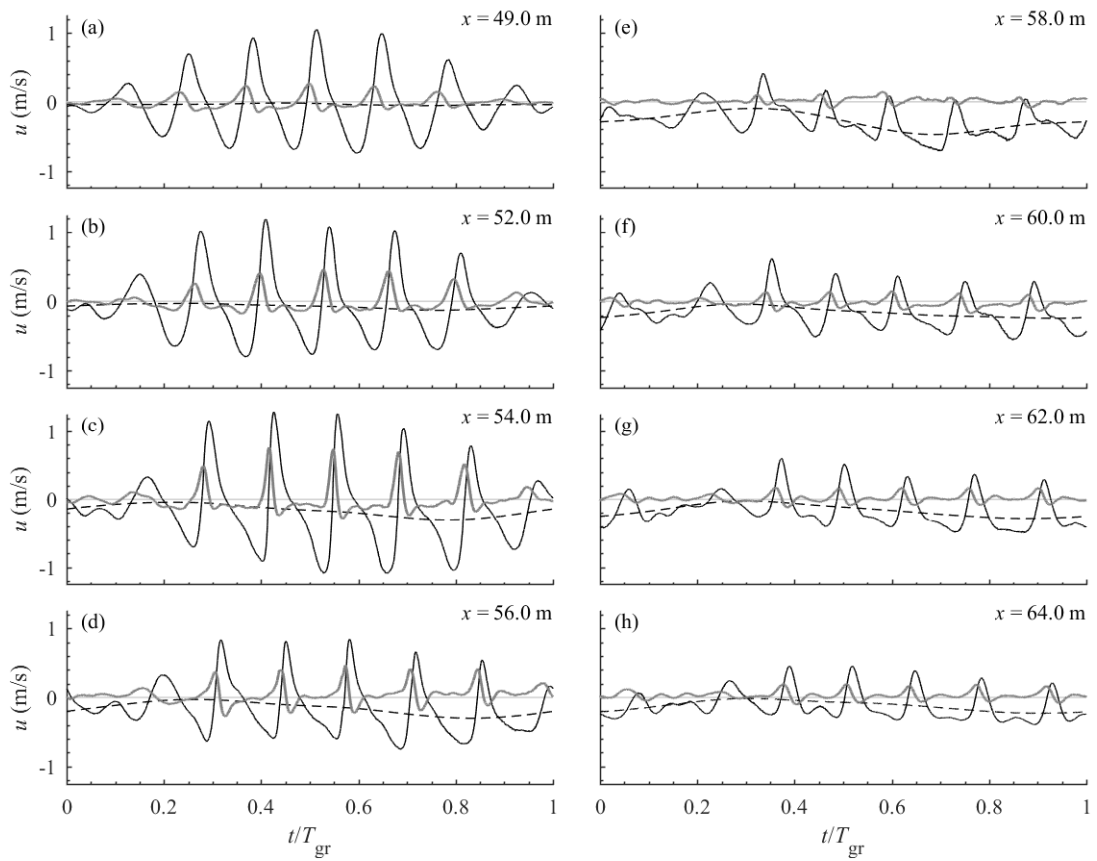


Figure 5. Time series of phase-averaged velocities  $\langle u \rangle$  (solid black),  $\langle \tilde{u}_{lf} \rangle + \bar{u}$  (dashed black), and  $\langle w \rangle$  (solid grey) at eight locations and at  $z - z_{bed} \approx 0.40$  m.

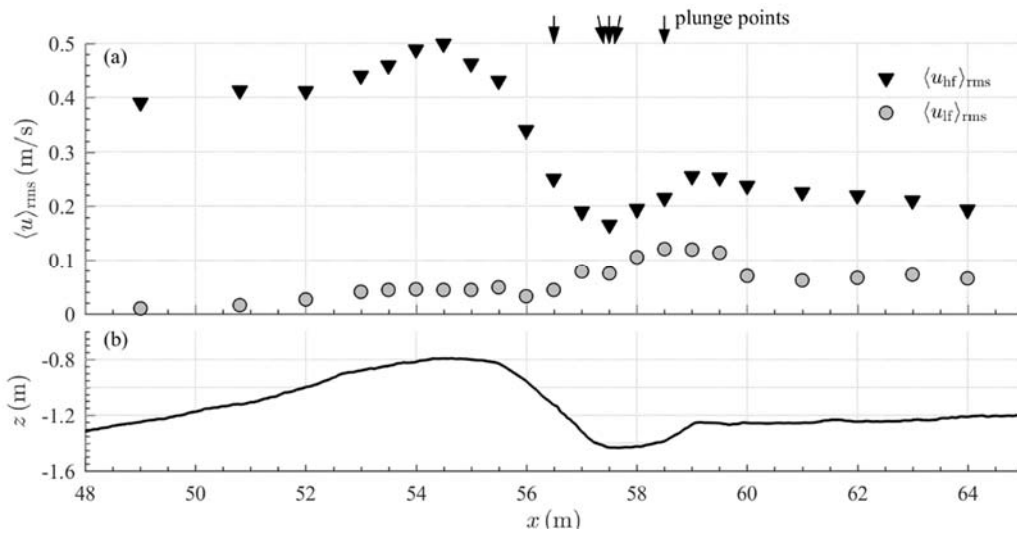


Figure 6. Spatial variation of root-mean-square high- and low-frequency cross-shore velocity at  $z - z_{bed} \approx 0.40$  m.

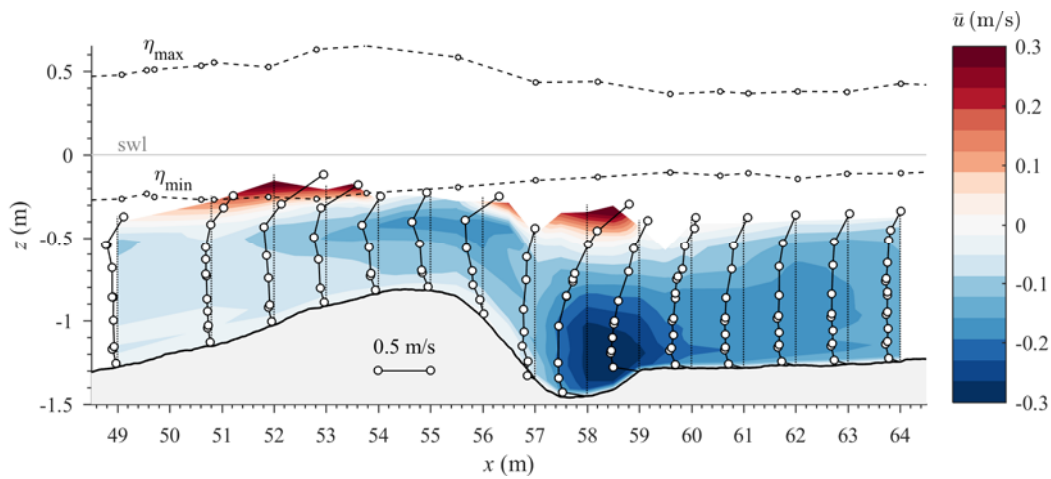


Figure 7. Spatial distribution of time-averaged cross-shore velocity  $\bar{u}$ .

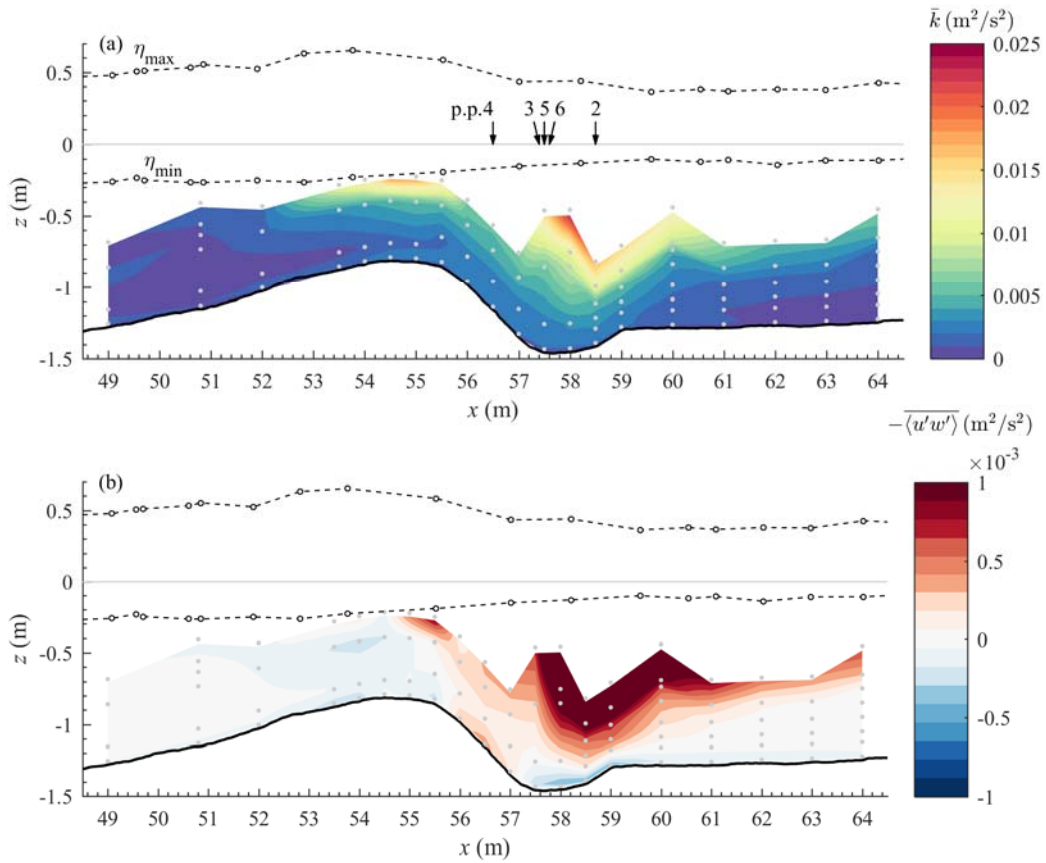


Figure 8. Time-averaged TKE (a) and turbulent Reynolds stress (b). Arrows in upper panel depict the plunge points of the second to sixth wave within the group, grey dots indicate the measurements positions.



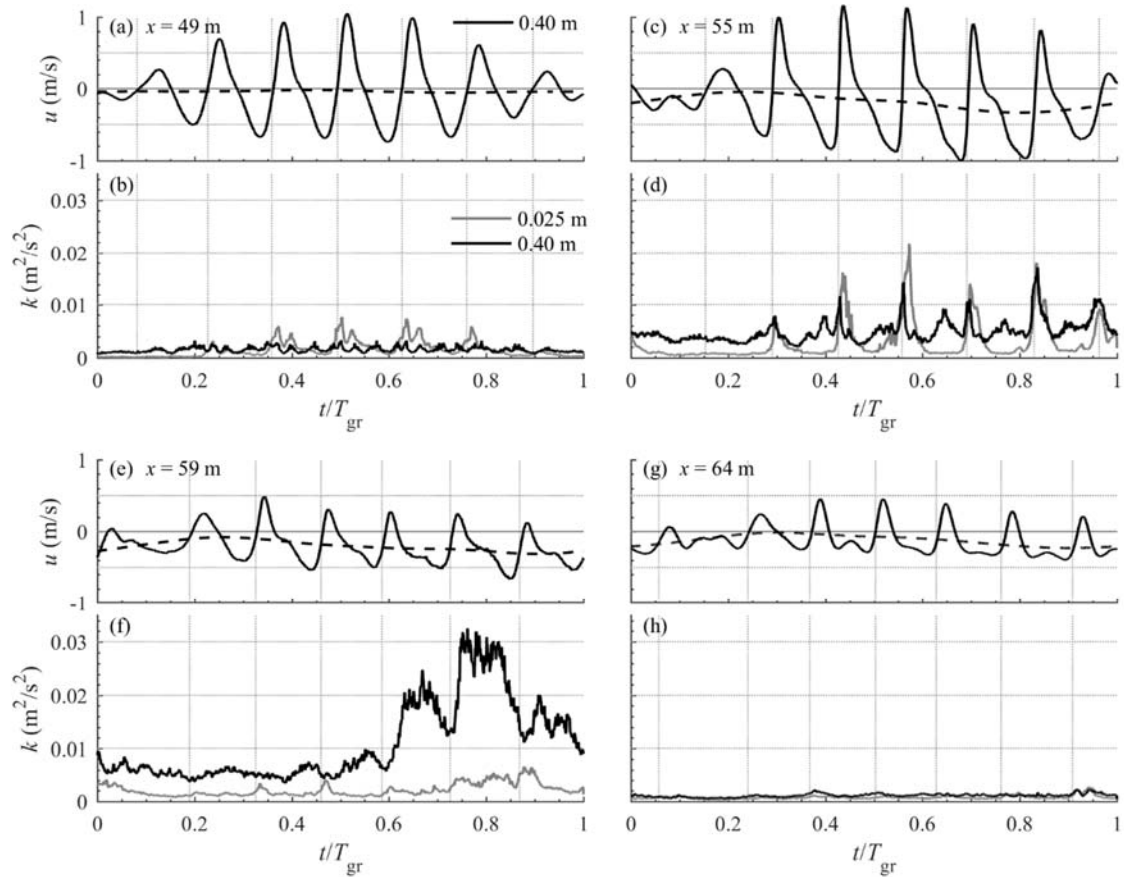


Figure 9. Time series of phase-averaged velocity and TKE at  $x = 49.0$  (shoaling region),  $55.0$  m (bar crest),  $59.0$  m (bar trough), and  $64.0$  m (inner surf zone). (a, c, e, g) Cross-shore velocity  $\langle u \rangle$  (solid) and  $\langle \tilde{u}_{hf} \rangle + \bar{u}$  (dashed) at  $z - z_{bed} \approx 0.40$  m; (b, d, f, h) TKE at  $z - z_{bed} \approx 0.40$  m (black) and at  $z - z_{bed} = 0.025$  m (grey). The vertical grid lines mark the zero-up crossings of  $\langle \tilde{u}_{hf} \rangle$  at  $z - z_{bed} = 0.40$  m at each location.

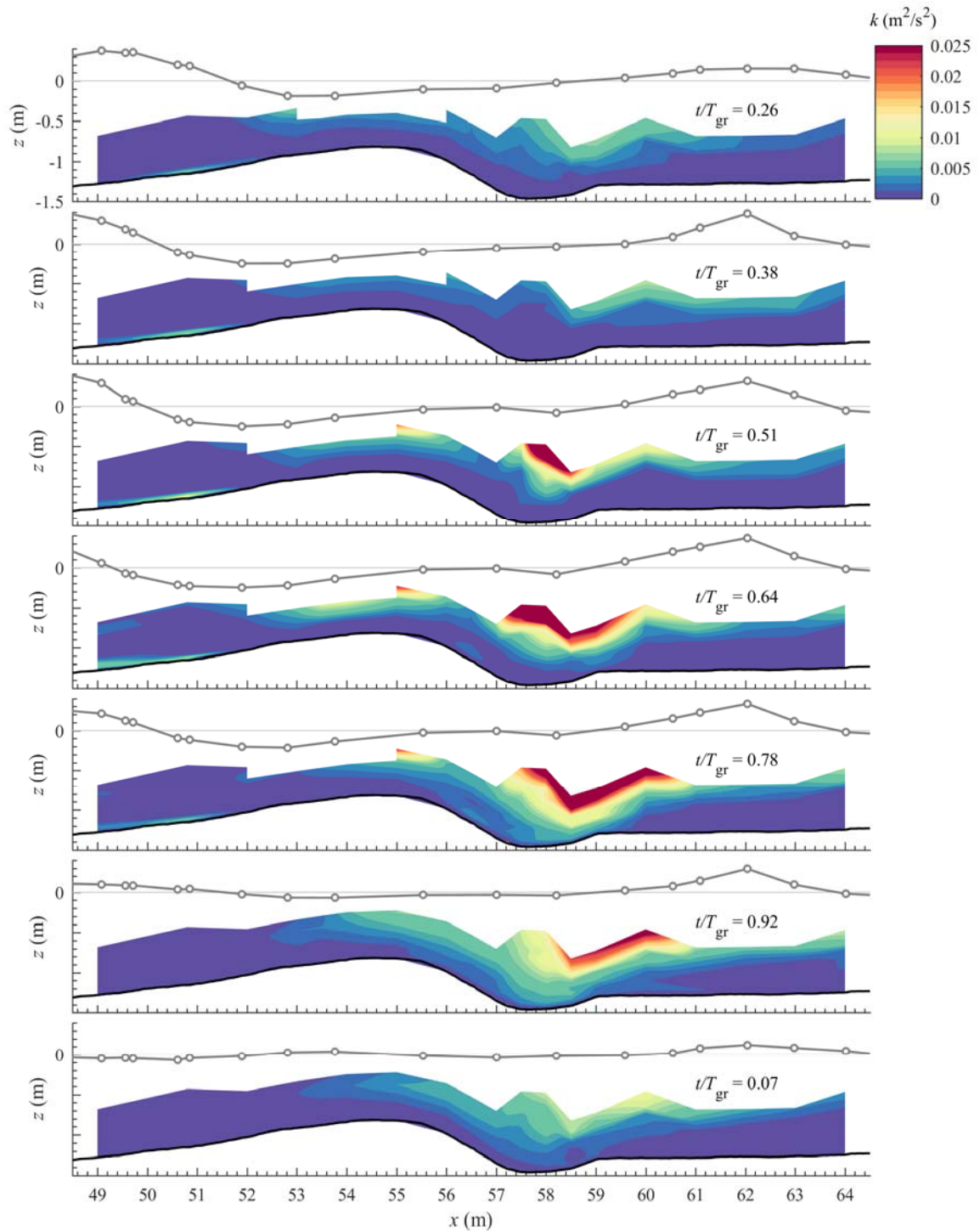


Figure 10. Spatial distributions of phase-averaged TKE at seven phases during the wave cycle, corresponding from top to bottom to the arrival of the seven short waves at  $x = 62.0$  m. The water surface elevation is depicted by the grey circles and line.

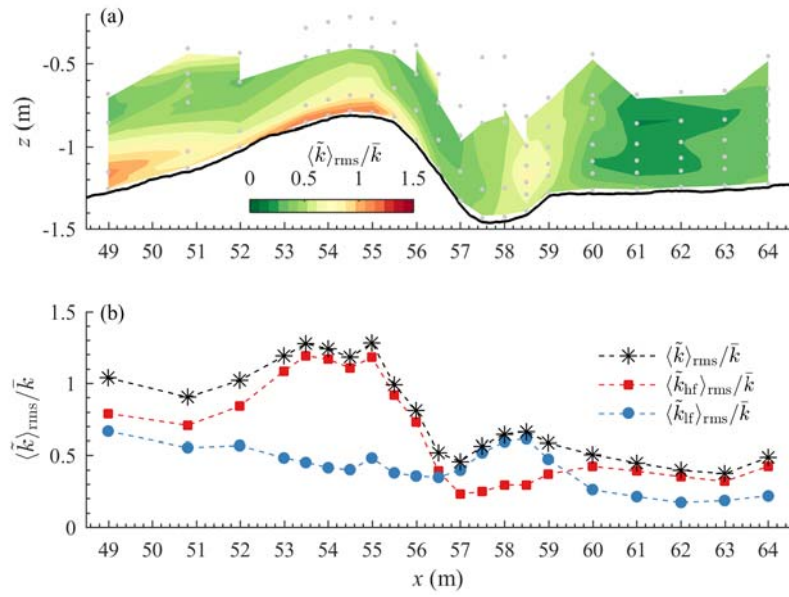


Figure 11. (a) Cross-shore and vertical distribution of the coefficient of variation of TKE,  $\langle \tilde{k} \rangle_{\text{rms}} / \bar{k}$ , with grey dots indicating measurement positions; (b) Cross-shore distribution of  $\langle \tilde{k} \rangle_{\text{rms}} / \bar{k}$  (stars),  $\langle \tilde{k}_{\text{hf}} \rangle_{\text{rms}} / \bar{k}$  (squares) and  $\langle \tilde{k}_{\text{lf}} \rangle_{\text{rms}} / \bar{k}$  (circles) at  $z - z_{\text{bed}} = 0.025$  m.

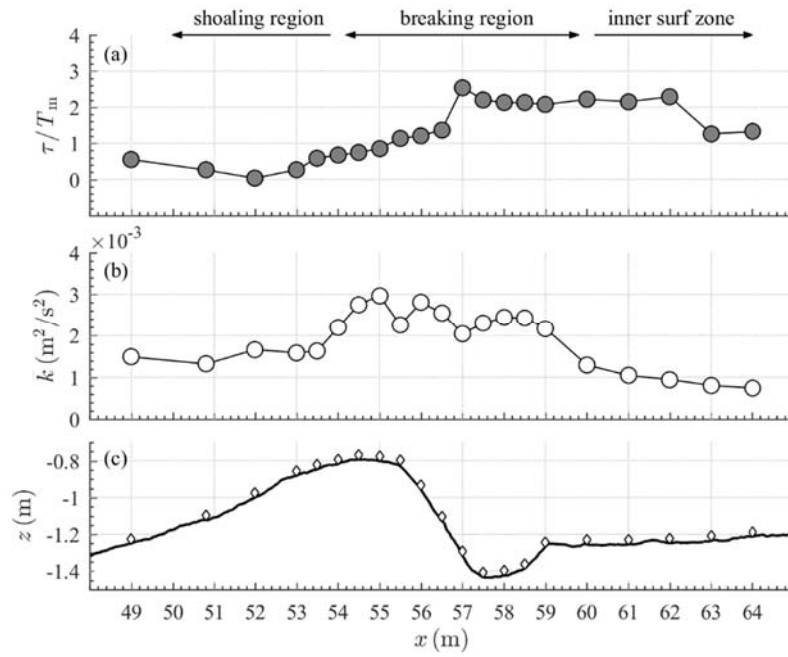


Figure 12. (a) Cross-shore distribution of time lag  $\tau$  of near-bed TKE ( $z - z_{bed} = 0.025$  m) w.r.t. center wave in the group; (b) Time-averaged TKE at  $z - z_{bed} = 0.025$  m; (c) Bed profile, with diamonds indicating measurement locations.

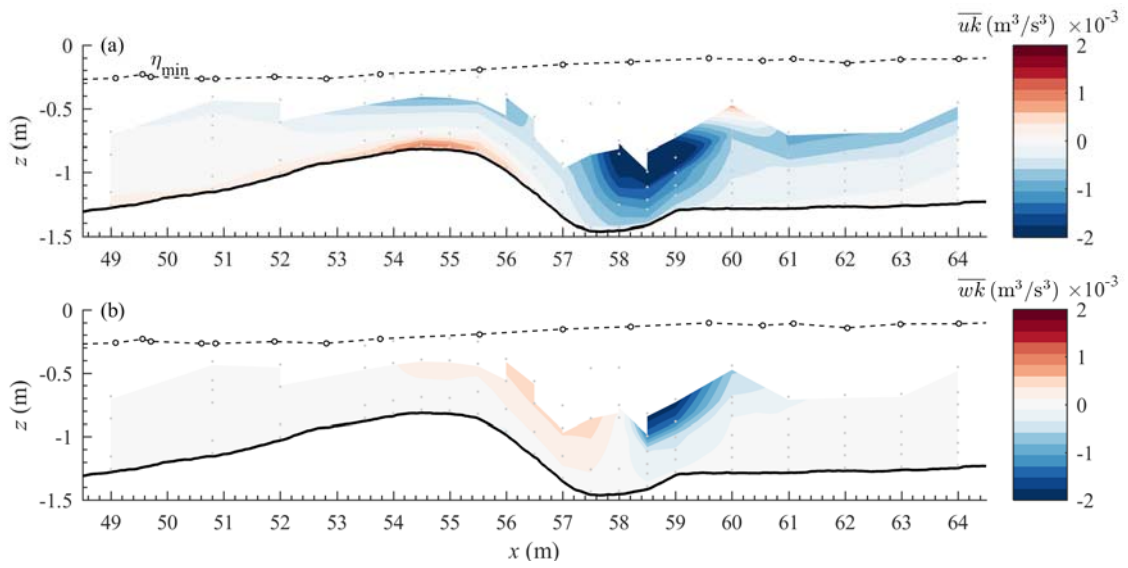


Figure 13. Net total transport of TKE in horizontal (a) and vertical (b) directions.



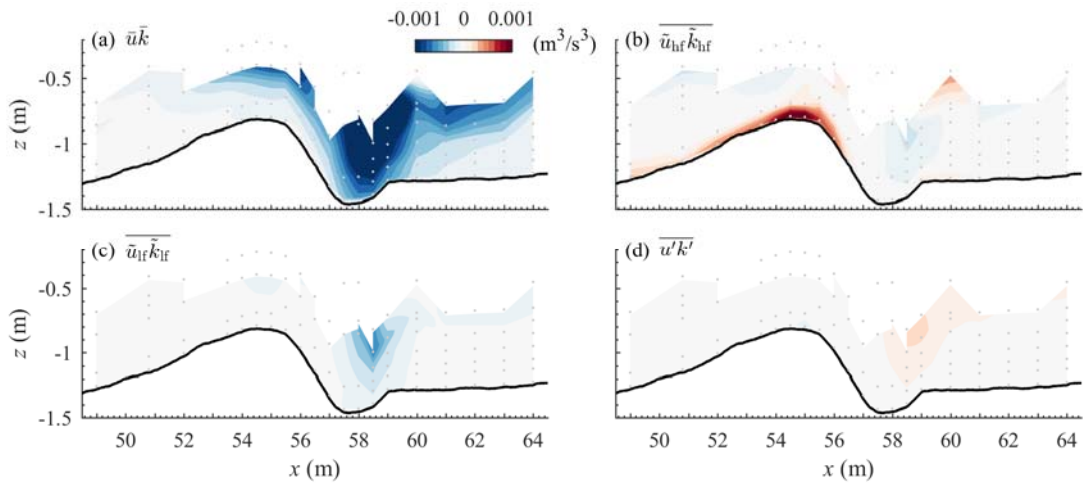


Figure 14. Net cross-shore transport of TKE, decomposed into current-related (a), short-wave-related (b), long-wave-related (c) and diffusive components (d). The same color scale applies to all panels.

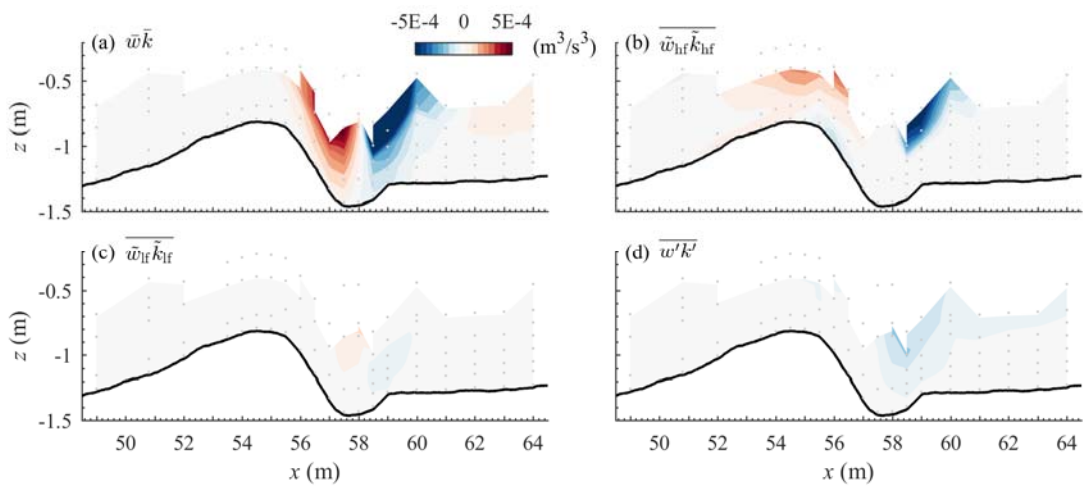


Figure 15. Net vertical transport of TKE, decomposed into current-related (a), short-wave-related (b), long-wave-related (c) and diffusive components (d). The same color scale applies to all panels.