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# On the Influence of Collinear Surface Waves on Turbulence in Smooth-Bed Open-Channel Flows

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1 This work investigates how turbulence in open-channel flows is altered by the passage  
 2 of collinear surface waves by using experimental data collected with laboratory tests in  
 3 a large-scale flume facility, wherein waves followed a current. Flow velocity data were  
 4 measured with a Laser Doppler Anemometer and used to compute profiles of mean  
 5 velocity and Reynolds stresses, and pre-multiplied spectra. The velocity signal containing  
 6 contributions from the mean flow, wave motion and turbulence was decomposed using  
 7 the Empirical Mode Decomposition (EMD), which is considered a promising tool for  
 8 the analysis of velocity time-series from complex flows. A novel outer-length scale  $h_0$   
 9 proposed which separates the flow into two regions depending on the competition between  
 10 the vertical velocities associated with the wave motion and the turbulent velocities  
 11 imposed by the current. This outer-length scale allows for the identification of a genuine  
 12 overlap layer and an insightful scaling of turbulent statistics in the current-dominated  
 13 flow region (i.e.  $y/h_0 < 1$ ). As the wave contribution to the vertical velocity increases, the  
 14 pre-multiplied spectra reveal two intriguing features: (i) in the current-dominated flow  
 15 region, the very large-scale motions (VLSM) are progressively weakened but attached  
 16 eddies are still present; and (ii) in the wave-dominated flow region (i.e.  $y/h_0 > 1$ ), a  
 17 new spectral signature associated with long turbulent structures (approximately 6 and  
 18 25 times the flow depth  $h$ ) appears. These longitudinal structures present in the wave-  
 19 dominated flow region seem to share many features with Langmuir-type cells.

20 **Key words:**

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## 21 1. Introduction

22 Many flows occurring in marine, coastal and estuarine environments result from the  
 23 superposition of surface waves and currents, the latter often driven by either tidal forcing  
 24 or other long-range hydraulic-head differences. Turbulence features that emerge from  
 25 wave-current interaction (WCI) influence a variety of environmentally- and ecologically-  
 26 relevant processes such as sediment transport (e.g. Madsen & Grant 1976; Dyer & Soulsby

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27 1988; Blondeaux 2001; Green & Coco 2014; Fagherazzi *et al.* 2015), microbiota dynamics  
28 (Guasto *et al.* 2012), transport of nutrients and contaminants (De Souza Machado *et al.*  
29 2016) and evolution of saltmarshes (Fagherazzi *et al.* 2012; Francalanci *et al.* 2013).  
30 For what concerns engineering applications, wave-current turbulence plays a key role in  
31 dictating the power-output, the mechanical loads and wake dynamics of hydro-kinetic  
32 marine turbines (Gaurier *et al.* 2013; De Jesus Henriques *et al.* 2014; Noble *et al.* 2020)  
33 and the scour around marine and coastal structures (Sumer *et al.* 2013; Sumer 2014).

34 While its relevance is not in dispute, the study of turbulence in wave-current flows  
35 is still in its infancy. The majority of existing experimental works focus on the analysis  
36 of mean velocity and shear stress profiles, due to their importance for the modelling of  
37 sediment transport (Soulsby *et al.* 1993). Only sporadically, the attention has turned  
38 to investigating the structure of turbulence, in a broader sense, which results from the  
39 interaction between currents and either opposed (e.g. Kemp & Simons 1983; Klopman  
40 1994; Umeyama 2005, 2009b; Yuan & Madsen 2015; Roy *et al.* 2018) or following waves  
41 (e.g. Van Hoften & Karaki 1976; Kemp & Simons 1982; Klopman 1994; Umeyama 2005,  
42 2009b; Carstensen *et al.* 2010; Yuan & Madsen 2015; Singh & Debnath 2016; Roy *et al.*  
43 2017; Zhang & Simons 2019). All these studies agree on the fact that wave-current  
44 interaction is strongly non-linear, namely that the mean flow properties of the combined  
45 flow does not match those resulting from the linear superimposition of the current-alone  
46 and wave-alone flows. For example, compared to current-alone flows, combined flows in  
47 which waves follow a current display mean velocity higher near the bed and lower in the  
48 upper part of the water column, and dampened Reynolds stresses (e.g. Umeyama 2005,  
49 2009b; Singh & Debnath 2016).

50 However, there is no clear understanding of how and why different velocity statistics  
51 respond to different combinations of waves and currents. Most experimental results are  
52 presented dimensionally because there is no general agreement on the correct scaling  
53 that should be employed to compare velocity statistics as measured in different flow  
54 conditions. Further, the characterization of turbulence in terms of dominant eddies (i.e.  
55 the eddies bearing the largest contribution to different turbulent kinetic energy compo-  
56 nents) resulting from the non-linear interaction between waves and currents remains  
57 largely unexplored. This knowledge-gap represents a bottleneck for the development of  
58 appropriate and physically-based modelling strategies and it is not surprising that past  
59 attempts to model combined wave-current flows obtained fair but limited success (see e.g.  
60 Grant & Madsen 1979; Myrhaug 1984; Davies *et al.* 1988; Huang & Mei 2003; Olabarrieta  
61 *et al.* 2010; Tambroni *et al.* 2015).

62 Much of the literature devoted to the study of combined wave-current flows at a  
63 fundamental level relates to experimental studies carried out in laboratory settings. The  
64 commonly employed approach involves exploring how the mean and turbulence flow  
65 properties of a current-alone flow (i.e. the benchmark flow) are altered by the passage  
66 of waves with different frequency and amplitude. In this respect, the present paper is  
67 no different. However, with respect to past studies, it overcomes some experimental  
68 shortcomings that are now presented and discussed to highlight some of the novelties  
69 introduced herein.

70 Most previous laboratory studies were carried out by establishing flows with aspect  
71 ratios (i.e. the ratio between the channel width and the flow depth) lower than five,  
72 value that Nezu & Nakagawa (1993) indicated as the threshold below which lateral walls  
73 affect turbulent properties in the mid cross-section of current-alone flows. For combined  
74 wave-current flows, such lateral-wall effects have never been systematically investigated  
75 and are largely unknown hence, when comparing combined with current-alone flows, low

76 aspect ratios make it difficult to discern whether the observed differences in turbulence  
 77 properties are due to lateral walls' or waves' effects.

78 The aspect ratio is also known to significantly affect the scaling of energetic large eddies  
 79 populating current-alone flows (often referred to as Very-Large Scale Motions, VLSMs,  
 80 see [Peruzzi et al. 2020](#); [Zampiron et al. 2020](#)). In an attempt to shed light on the size and  
 81 scaling of dominant eddies emerging from the interaction between waves and currents,  
 82 this is an issue that should be taken into account when interpreting experimental data  
 83 but, so far, it has been ignored probably because the interlinks between VLSMs and  
 84 aspect ratio in open-channel flows have been identified only very recently.

85 Another shortcoming of past studies relates to the fact that benchmark flows (i.e.  
 86 current-alone) were never established with boundary layers covering the entire water  
 87 column. This, besides not being representative of flow conditions normally encountered in  
 88 the field ([Sellar et al. 2018](#)), implies that waves were superimposed to "hybrid" shear flows  
 89 displaying boundary layer properties up to some elevations from the bed and not well-  
 90 defined (and difficult to replicate) features further above where, presumably, residual inlet  
 91 turbulence persists. Such residual turbulence is facility-dependent and hence prevents  
 92 experimental data to display flow features of general validity.

93 To advance the comprehension of turbulence in combined wave-current flows, the  
 94 present study reports results obtained from novel experiments involving waves that follow  
 95 a steady current generated in a laboratory smooth-bed open-channel flume. Turbulence  
 96 statistics obtained from an unperturbed open-channel flow were used as benchmark to  
 97 study the alterations caused by the passage of waves in combined wave-current flows  
 98 involving a range of wave amplitudes and frequencies. The water surface level was  
 99 monitored using five ultrasonic gauges positioned along the flume and the 2-D flow  
 100 velocity field was measured using a Laser Doppler Anemometer (LDA). Much of the  
 101 aforementioned experimental limitations are here overcome because: (i) the aspect ratio  
 102 was kept above five to minimise lateral walls effects on turbulence statistics in the  
 103 centreline of the flume where the measurements were collected; (ii) the benchmark (i.e.  
 104 current-alone) experiment displayed a boundary layer thickness coinciding with the water  
 105 depth and well defined turbulence properties as per self-similar turbulent open-channel  
 106 flows over smooth beds; (iii) and VLSMs properties in the benchmark experiment were  
 107 well documented and classified.

108 The experimental procedure and the employed laboratory equipment used to carry  
 109 out the experiments are described in the next section (Section 2). Section 3 is then  
 110 dedicated to the description of the signal-decomposition technique (the Empirical Mode  
 111 Decomposition, EMD) that was employed to extract the turbulent signal from velocity  
 112 measurements and hence to compute some of the velocity statistics used to interpret  
 113 turbulence in combined wave-current flows. In Section 4 results are presented and  
 114 discussed starting from the analysis of mean velocity profiles (Section 4.1) where we  
 115 identify a novel length scale  $h_0$ , which we prove key for the analysis and interpretation  
 116 of turbulence in combined flows. This was explored through the analysis of second-  
 117 order moments of velocity turbulent fluctuations (Section 4.2) and spectral analysis  
 118 (Sections 4.3–4.4). The latter was successfully employed to investigate the fate of VLSMs  
 119 in combined flows as well as to identify, for the first time, other large-scale structures  
 120 that we speculate being induced by wave motion in ways that are somewhat similar to  
 121 those responsible for the generation of Langmuir turbulence in ocean flows. In Section 5  
 122 we present some discussions to interpret our results while Section 6 is finally devoted to  
 123 some conclusions where we summarise the main results of the present paper.

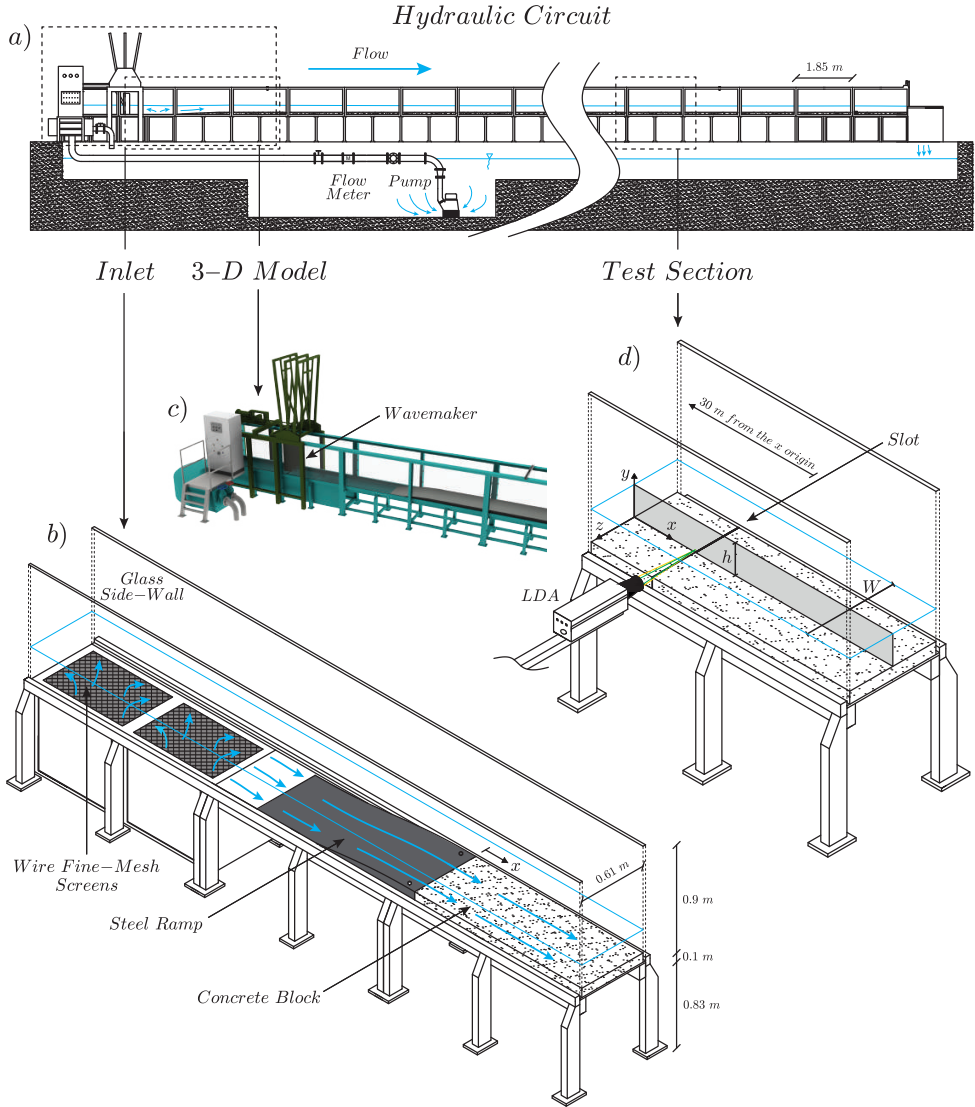


FIGURE 1. Overview of the flume: (a) sketch of the whole hydraulic circuit; (b) detail of the inlet configuration; (c) 3-D model of the inlet configuration and wavemaker; (d) detail of the test section. Panel (d) also shows the system of coordinate axes used in the present study (i.e. the longitudinal  $x$ , vertical  $y$  and spanwise  $z$  directions), the flow depth  $h$  and the channel width  $W$ . The origin of the longitudinal coordinate  $x$  is located at the downstream end of the steel ramp, as indicated in panel (b).

## 2. Methodology

### 2.1. Equipment

The experiments were carried out in the same flume facility and with the same setup and instrumentation as those described in [Peruzzi \*et al.\* \(2020\)](#). For this reason, in the text that follows we provide only a brief description of the equipment; for further details we encourage the reader to refer to [Peruzzi \*et al.\* \(2020\)](#).

The experiments were conducted in a non-tilting, recirculating open-channel flume at the Giorgio Bidone Hydraulics Laboratory of Politecnico di Torino (figure 1a). The flume

has glass sidewalls and is 50 m long with a rectangular cross-section 0.61 m wide and 1 m deep. To allow for near-wall LDA measurements (described below), the flume bottom was raised with smooth concrete blocks over the original bed. Close to the inlet section, the original bed and the concrete blocks were gently connected by a stainless-steel ramp (figure 1b–c), which was designed to prevent boundary layer separation (Bell & Mehta 1988) and hence the shedding of undesirable large scale eddies in the developing flow. To reduce the incoming turbulence generated by the hydraulic circuit, a series of wire fine-mesh screens were located in the sump underlying the flume inlet (figure 1b). For all the experiments, the test section was located at  $x = 30$  m (the longitudinal, vertical and spanwise coordinates are indicated with  $x$ ,  $y$  and  $z$ , respectively, and defined as indicated in figure 1d) from the origin (see figure 1b). As discussed in Peruzzi *et al.* (2020), at this distance, current-alone flows lose memory of inlet conditions and display self-similar vertical profiles of velocity statistics (as measured in the mid cross-section) that are in line with past literature on smooth-wall open-channel flows.

The flume used for the experiments allows for the generation of progressive surface waves by means of a piston-type wavemaker placed in proximity of the flume inlet (figure 1c). Three types of experiments were carried out involving, wave alone (WA), current-alone (CA) and combined wave-current (WC) flows. The channel outlet for the WA experiments was sealed with a steel cap downstream of a passive porous steel wave-absorber that absorbed about 91–94% of the wave total energy (estimated involving a simplified version of the two fixed probes method; Isaacson 1991) and hence prevented to a large extent wave reflections. The channel outlet for CA and WC flows was made of a rectangular sharp-crested weir, which was used to regulate the water depth  $h$ .

For all the experiments, water depths were measured with five ultrasonic gauges (sampling frequency  $f_s$  equal to 100 Hz) that were displaced along the flume, specifically at  $x = 3.1, 21.1, 27.1, 30.8$  and  $39.8$  m, respectively. The nominal accuracy of the ultrasonic gauges is  $\pm 1$  mm and their performance in the measurement of the wave surface characteristics is comparable to that of classical instrumentations such as resistive or pressure sensors (Marino *et al.* 2018).

The near-wall LDA measurements were made by adopting the technique developed by Poggi *et al.* (2002) and subsequently used in other studies (Poggi *et al.* 2003; Escudier *et al.* 2009; Manes *et al.* 2011; Peruzzi *et al.* 2020). It consists in leaving a thin vertical slot (3 mm wide in this application) between two adjacent concrete blocks at the test section (figure 1d) so that the vertical laser beams can pass undisturbed and measurements near the wall can be taken with negligible alterations to the overlying flow (Peruzzi *et al.* 2020 reported that the effect of the slot on the flow was negligible). The 2-D LDA system used for the experiments is a Dantec Dynamics Flow Explorer DPSS working in backscatter configuration, the signal processing and acquisition were performed with two Dantec Dynamics Burst Spectrum Analyzers (BSA F600-2D) and a dedicated software (BSA Flow Software v6.5).

## 2.2. Experimental procedure and hydraulic conditions

### 2.2.1. Waves alone experiments

Prior to conducting experiments with waves following a current (WC), experiments with waves alone (WA) were carried out to study the characteristics of the waves generated with the adopted setup (figure 1b–c) and to determine the transfer function of the wavemaker, namely the relation between wave-amplitude and frequency imposed by the wavemaker and those of the waves actually propagating in the flume at various distances from the inlet. Table 1 reports the experimental hydraulic conditions for the WA

Run	$h$ [cm]	$f_w$ [Hz]	$T$ [s]	$a$ [cm]	$H$ [cm]	$L$ [cm]	$A_b \dagger$ [cm]	$U_w \dagger$ [cm/s]	$h/L$ [-]	$H/h$ [-]	$\epsilon$ [-]	$U_R$ [-]
WA-T1	12.0	0.50	2.00	0.4	0.8	225.3	1.1	3.5	0.05	0.07	0.01	23.5
WA-T2	12.0	0.75	1.33	0.5	1.0	139.5	0.9	4.1	0.09	0.08	0.02	11.3
WA-T3	12.0	1.00	1.00	0.5	1.0	100.6	0.6	3.7	0.12	0.08	0.03	5.8
WA-T4	12.0	1.00	1.00	1.0	2.0	100.7	1.2	7.7	0.12	0.17	0.06	11.7
WA-T5	12.0	1.00	1.00	1.4	2.8	99.9	1.7	10.9	0.12	0.23	0.09	16.2

TABLE 1. Summary of the hydraulic conditions for the waves alone (WA) cases. The columns indicate: the mean water depth  $h$ ; the wave frequency  $f_w$ ; the wave period  $T = 1/f_w$ ; the mean wave amplitude  $a$ ; the mean wave height  $H = 2a$ ; the mean wave length  $L$ ; the longitudinal water particle semi-excursion due to the orbital motion at the bottom  $A_b$ ; the maximum longitudinal wave orbital velocity at the bottom  $U_w$ ; the relative depth  $h/L$ ; the relative height  $H/h$ ; the wave steepness  $\epsilon = ak$ , where  $k$  is the wave number  $k = 2\pi/L$ ; and the Ursell number  $U_R = HL^2/h^3$ . Note that the symbol  $\dagger$  denotes values calculated by using the Airy linear wave theory (Dean & Dalrymple 1991).

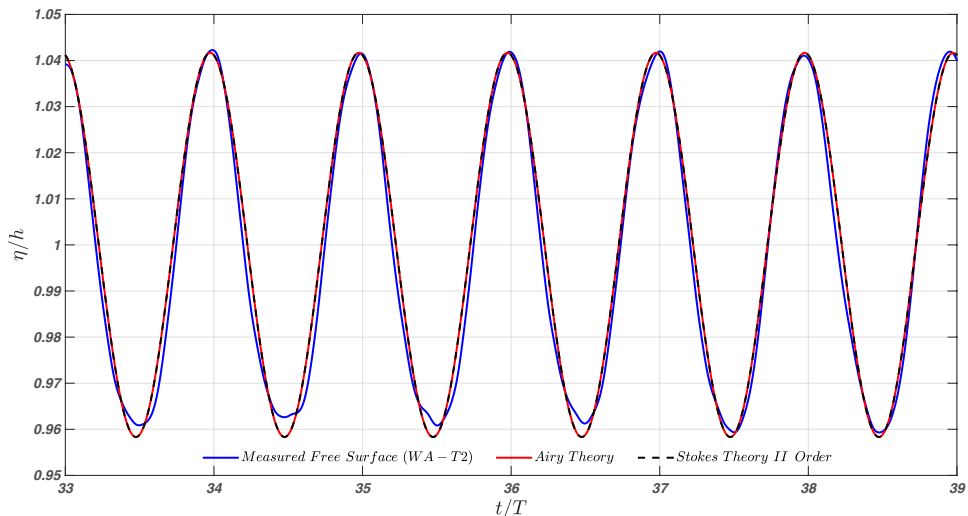


FIGURE 2. Temporal evolution of the normalized surface wave profile for the case WA-T2. The blue solid line represents the free-surface measured with the ultrasonic gauge in proximity to the LDA location ( $x/h = 256$ ). The red solid and black dashed lines refer to the Airy linear theory and Stokes II order theory, respectively.

180 cases. The parameters  $h$ ,  $a$  and  $T$  were determined from the water-surface measurements  
 181 provided by the ultrasonic gauge placed in proximity to the LDA system (i.e. gauge  
 182 number 4 at  $x = 30.8$  m). The measurements lasted approximately 160 s so that it was  
 183 possible to monitor 80–160 wave cycles, depending on the wave properties (table 1),  
 184 with low reflection effects from the wave absorber placed at the channel end.

185 Based on the key wave parameters reported in table 1, it can be inferred that waves  
 186 considered in the present study are in the intermediate water conditions and do not break  
 187 ( $0.05 < h/L < 0.5$ ,  $\epsilon < 0.442$  and  $H/h < 0.8$ ; Dean & Dalrymple 1991). According to  
 188 Hedges (1995), the Airy or Stokes' II order wave theories are suitable to describe the  
 189 waves generated in our experiments because both the Ursell number ( $U_R = HL^2/h^3$ )  
 190 and the wave steepness have low values ( $U_R \lesssim 40$  and  $\epsilon \lesssim 0.125$ ). Focusing on the Airy



191 linear wave theory, the water particle longitudinal semi-excursion  $A_b$  and the maximum  
 192 wave orbital longitudinal velocity  $U_w$  at the bed are defined as:

$$A_b = \frac{a}{\sinh(kh)} \quad (2.1)$$

$$U_w = \omega A_b \quad (2.2)$$

193 where  $k = 2\pi/L$  is the wave number and  $\omega = 2\pi/T$  is the wave angular frequency (Dean  
 194 & Dalrymple 1991). Indeed, from the analysis of the temporal evolution of the free-surface  
 195 profile  $\eta$ , reported in figure 2 for the representative test WA–T2, no substantial difference  
 196 between the Airy (or Stokes’ II order) theory and the measurements is evidenced. The  
 197 slight discrepancy in the wave troughs is approximately of the same order of magnitude  
 198 as the ultrasonic gauge measurement uncertainty ( $\pm\eta/h = 0.008$ ).

199 The wave attenuation along the flume was evaluated by comparing the wave heights  
 200 measured by the ultrasonic gauges placed along the channel with the analytical results of  
 201 Hunt’s wave attenuation theory (Hunt 1952). Even though the theory underestimates  
 202 the wave attenuation, as already reported in previous studies (Grosch *et al.* 1960;  
 203 Van Hoften & Karaki 1976), the general trend is well captured (not shown here). Overall,  
 204 experimental data suggest that the waves generated in the flume facility (figure 1a) can  
 205 be characterised with classical wave theories satisfactorily.

206 During the WA experiments, the wave-induced mass transport was not experimentally  
 207 studied because it is extremely challenging to accurately quantify (Monismith 2020) and,  
 208 above all, because the outlet boundary condition of the flume facility is different with  
 209 respect to WC experiments (i.e. in the WA tests, the channel outlet was sealed with a steel  
 210 cap and the wave-absorber is present, whereas in the WC test, the outlet was regulated  
 211 with a tailgate and the wave-absorber was removed). This causes different return flow  
 212 conditions between the two configurations, which make the comparison between the two  
 213 sets of experiments very difficult.

### 214 2.2.2. *Combined wave-current experiments*

215 A comparative analysis of combined wave-current (WC) flows was carried out using  
 216 a current-alone (CA) experiment as benchmark (see table 2). In WC experiments, the  
 217 wave absorber was removed to prevent obstruction of the current outflow and both the  
 218 pump and the wavemaker operated simultaneously. When the steady conditions for the  
 219 CA case were set, the wavemaker was activated using the same input as for the WA  
 220 cases (table 1) to generate the desired waves superimposed on the current. The hydraulic  
 221 conditions for the WC cases are reported in table 2.

222 In the WC experiments the flow velocity was measured with the LDA in coincidence  
 223 and non-coincidence mode. The former in order to have simultaneous longitudinal ( $u$ ) and  
 224 vertical ( $v$ ) velocity measurements and therefore to estimate the Reynolds shear stress  
 225 component, the latter to better resolve the turbulent spectrum at some elevations above  
 226 the bed, as it allows for higher sampling frequencies of individual velocity components.  
 227 In coincidence mode, the measurements were taken over 15 positions along the vertical  
 228 coordinate for each run and 1000 wave cycles were measured at each position with a  
 229 sampling frequency  $f_s$  ranging between 50 and 100 Hz. In non-coincidence mode, the  
 230 velocity was measured at six selected positions for both the longitudinal and vertical  
 231 components, with  $f_s$  of 150–300 Hz and sampling duration over 45 minutes. It is  
 232 important to highlight that, due to the water surface level variation associated with  
 233 the wave profile, the LDA velocity measurements were collected up to  $y/h \approx 0.83$ .



Run	$h$	$u_\tau$	$U_b \ddagger$	$f_w$	$a$	$H$	$Re_b \ddagger$	$Re_\tau \ddagger$	$Fr \ddagger$	$RE \uparrow$	$U_b/U_w$	$a f_w/u_{\tau_c}$
	[cm]	[cm/s]	[cm/s]	[Hz]	[cm]	[cm]	[–]	[–]	[–]	[–]	[–]	[–]
CA	12.0	0.755	15.17	–	–	–	14400	1000	0.14	–	–	–
WC–T1	12.0	0.776	15.17	0.50	0.4	0.8	14400	1000	0.14	440	4.3	0.26
WC–T2	12.0	0.821	15.17	0.75	0.5	1.0	14400	1000	0.14	390	3.7	0.50
WC–T3	12.0	0.849	15.17	1.00	0.5	1.0	14400	1000	0.14	250	4.0	0.66
WC–T4	12.0	0.822	15.17	1.00	1.0	2.0	14400	1000	0.14	1050	2.0	1.32
WC–T5	12.0	0.794	15.17	1.00	1.4	2.8	14400	1000	0.14	2090	1.4	1.85

TABLE 2. Summary of the hydraulic conditions for the current-alone (CA) and waves following a current (WC) cases. The columns indicate: the mean water depth  $h$ ; the shear velocity  $u_\tau$ ; the current bulk velocity  $U_b$ ; the wave frequency  $f_w$ ; the mean wave amplitude  $a$ ; the mean wave height  $H$ ; the current bulk Reynolds number  $Re_b = R_h U_b / \nu$ , where  $R_h$  is the hydraulic radius and  $\nu$  is the kinematic viscosity of the water (equal to  $0.907 \cdot 10^{-6}$  m<sup>2</sup>/s); the von Kármán number  $Re_\tau = u_\tau h / \nu$ ; the Froude number  $Fr = U_b / \sqrt{g h}$ , where  $g$  is the gravitational acceleration; the wave Reynolds number  $RE = A_b^2 \omega / \nu$ , where  $\omega = 2\pi f_w$  is the angular frequency;  $U_b / U_w$  is the ratio of current bulk velocity to longitudinal wave orbital velocity at the bottom and  $a f_w / u_{\tau_c}$  is a parameter whose meaning will be better explained in the following. Note that the symbol  $\ddagger$  denotes values determined in the current-alone case (CA) and the symbol  $\uparrow$  denotes values determined in the waves alone case (WA).

234 Furthermore, 30-minutes long time-series of the free water surface were recorded by  
 235 means of the ultrasonic gauges.

236 For all the experiments, the Froude number  $Fr = U_b / \sqrt{g h}$  (where  $g$  is the gravitational  
 237 acceleration) and the von Kármán number  $Re_\tau = u_\tau h / \nu$  of the current were 0.14 and  
 238 1000, respectively. The aspect ratio  $W/h$  was equal to 5.08 so that flow conditions at  
 239 the mid cross-section of the channel could be considered unaffected by lateral walls  
 240 (Nezu & Nakagawa 1993). The shear velocities  $u_\tau$  reported in table 2 include the shear  
 241 velocity for the CA case ( $u_{\tau_c}$ ; for more details see Peruzzi *et al.* 2020) and the shear  
 242 velocities for the WC cases ( $u_{\tau_{wc}}$ ); both were estimated using the classical Clauser method  
 243 (Clauser 1956), assuming the occurrence of a logarithmic layer in the near-wall region  
 244 (details on the existence of a logarithmic layer will be found in Section 4.1) and using  
 245 a von Kármán coefficient  $\kappa = 0.41$  and constant  $B = 5.5$  (values found for the CA  
 246 case). The values of  $u_{\tau_{wc}}$  are slightly higher than those of  $u_{\tau_c}$  and this agrees with  
 247 the detected increase in the gradient of the time-averaged free surface height,  $S_w =$   
 248  $dh/dx$ , in the presence of waves. Indeed, the free surface slope  $S_w$  between the two  
 249 ultrasonic gauges (i.e. gauges 3 and 4) adjacent to the LDA system is higher for the  
 250 WC cases ( $S_w$  ranging from  $-0.954 \cdot 10^{-4}$  to  $-1.361 \cdot 10^{-4}$ ) compared to the CA case  
 251 ( $S_w = -0.815 \cdot 10^{-4}$ ). This seems reasonable because an increase in the shear velocity  
 252 values in waves plus current experiments was already reported in the literature (Kemp  
 253 & Simons 1982; Zhang & Simons 2019).

254 Based on the values of the current Reynolds number  $Re_b$ , the wave Reynolds number  
 255  $RE$  and the ratio  $U_b / U_w$  (table 2), the resulting combined boundary layers were turbulent  
 256 for all the cases investigated (Lodahl *et al.* 1998), even though the wave boundary layers  
 257 for the WA cases were laminar or transitional (Blondeaux 1987).

258 It should be noted that the difference in the mean values of the wave heights  $H$   
 259 between the WA and WC experiments, reported in table 1 and table 2, is almost  
 260 negligible. However, experimental data obtained from the ultrasonic gauges indicate  
 261 that WC experiments are somehow affected by the presence of the current. To evaluate  
 262 these effects, figure 3(a–b) reports the coefficients of variation of the wave period

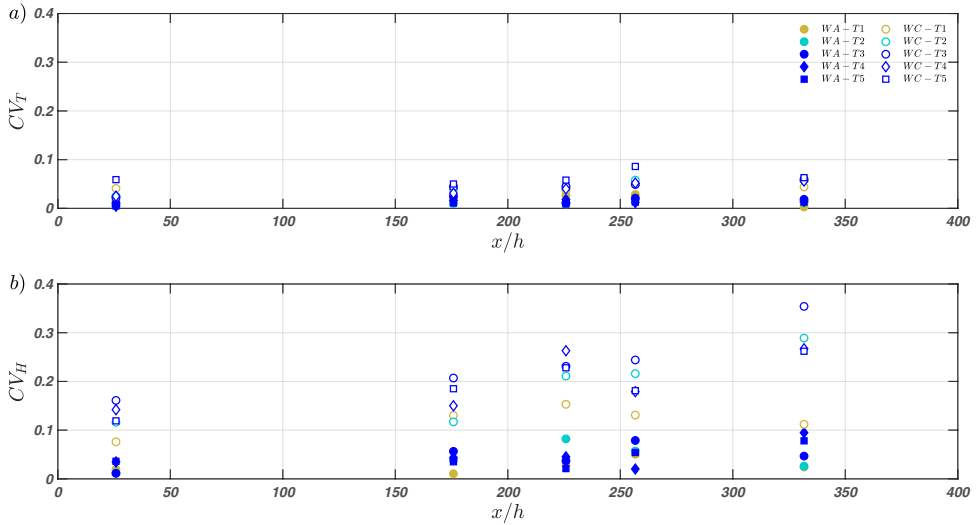


FIGURE 3. Coefficients of variation of (a) the wave period, and (b) the wave height for the WA (filled markers) and WC (hollow markers) experiments.

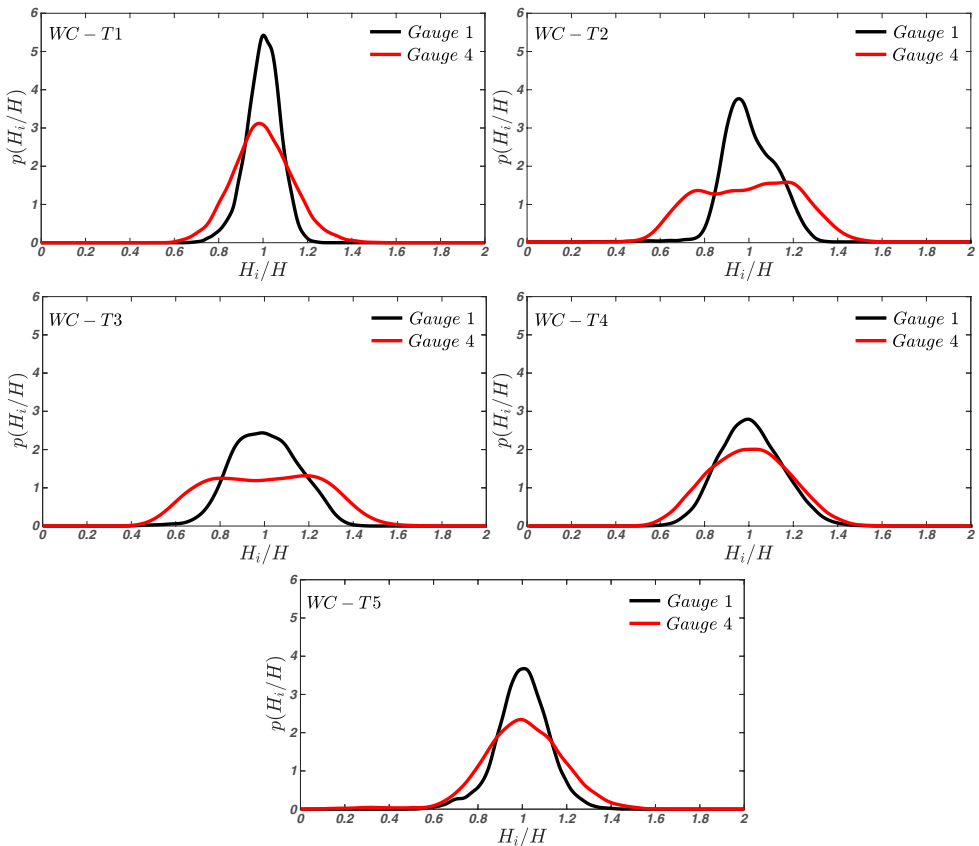


FIGURE 4. Data-estimated probability density functions (PDF) of wave heights for all the WC experiments recorded at gauge 1 (3.1 m from the origin, black) and gauge 4 (30.8 m from the origin, red).

263  $CV_T = T_{std}/T$  and wave height  $CV_H = H_{std}/H$ , where  $T_{std}$  and  $H_{std}$  are the wave  
 264 period and height standard deviations while  $T$  and  $H$  are the mean values (table 1 and  
 265 table 2), recorded at each ultrasonic gauge along the flume. While the values of  $CV_T$   
 266 are bounded between 0 and 0.1 for all the experiments with no obvious trend, indicating  
 267 low variability around the mean, the values of  $CV_H$  for the WA and WC experiments  
 268 display a different behaviour: the former show a negligible variation along the channel  
 269 ( $0 < CV_H < 0.1$ ), while the latter are spread across a wider range and show an increase as  
 270 the waves move along the channel. A considerable increase in variability associated with  
 271 the presence of the current is evident when comparing the same case with and without  
 272 current (figure 3b).

273 To further characterise the variability of the wave heights in the WC experiments,  
 274 figure 4 displays the probability density functions (PDF) of the wave heights estimated  
 275 for each run at the gauges close to the flume inlet (gauge 1) and to the LDA system  
 276 (gauge 4), respectively. The PDFs were computed directly from the data by using a  
 277 non-parametric kernel distribution, that is often used with raw dataset in order to avoid  
 278 making assumptions about the data distribution. In figure 4, the PDF is indicated as  
 279  $p(H_i/H)$ , where  $H_i$  is the  $i$ -th measured wave height,  $H$  is the mean wave height (table 2).  
 280 Moving from the first to the fourth gauge, all cases show a flattening of the distribution  
 281 that is particularly marked in WC-T2 and WC-T3.

282 This important alteration of the wave surface characteristics in the WC experiments  
 283 was likely caused by multiple mechanisms, which require to be briefly discussed. Figure  
 284 3(b) indicates that, with respect to the WA case, WC experiments display increased  
 285 wave irregularity since the beginning of the flume. This suggests that, as observed by  
 286 [Robinson et al. \(2015\)](#), the upwelling configuration of the inlet might induce free surface  
 287 perturbations, which affect the generation of regular waves. More interestingly, figure 3(b)  
 288 and figure 4 also show that, for all the experiments but mostly for WC conditions,  
 289 waves' irregularity increases with increasing longitudinal distance from the inlet. Such  
 290 an increase in WA experiments (for deep and intermediate waters) is likely to be caused  
 291 by mechanisms akin to Benjamin-Feir instabilities ([Benjamin & Feir 1967](#)), which have  
 292 been experimentally documented since [Benjamin \(1967\)](#). It is therefore likely that a  
 293 similar instability mechanism makes the waves more irregular as they travel along the  
 294 flume also in the WC experiments. However, the reason why a current could exacerbate  
 295 such irregularity with respect to the WA experiments (see figure 3b) is not clear and is  
 296 not further commented herein as it requires a dedicated study, which goes beyond the  
 297 scope of the present paper. It is important to point out, though, that due to the observed  
 298 non-uniform distribution of waves' characteristics along  $x$ , the investigated flows cannot,  
 299 strictly speaking, be considered as "equilibrium (i.e. self-similar) boundary layers" (note  
 300 that the CA alone experiment was identified by [Peruzzi et al. \(2020\)](#) to be in equilibrium  
 301 to a very good approximation, so the source of non equilibrium can only come from  
 302 waves' evolution along the flume). This means that at each location along the flume, it is  
 303 not clear whether the WC boundary layers are either fully developed or not. However, to  
 304 the authors' opinion, in combined wave-current flows this difficulty has to be embraced  
 305 mainly because it is experimentally very challenging to generate well developed turbulent  
 306 currents over distances that are short enough to consider wave properties reasonably  
 307 uniform. Moreover (but this is a weaker justification) irregular and developing waves  
 308 are the rule rather than the exception in the field ([Draycott et al. 2019](#)). Despite the  
 309 non-uniform conditions and wave variability reported, we believe that the data analysis  
 310 and interpretation reported herein lead to results that are fairly robust and supported  
 311 by sound physical arguments.

312 Besides dealing with non-equilibrium conditions, the interpretation of experimental

313 results is made difficult by waves' irregularity, which makes it challenging to isolate the  
 314 turbulence component of the signal and hence infer turbulence properties and structure.  
 315 This problem is dealt with in the next section.

### 316 **3. Signal decomposition**

317 One of the challenges of studying turbulence in combined wave-current flows is the need  
 318 for extracting and separating the turbulent and wave components of the raw velocity  
 319 signal. Unsteady turbulent velocity signals can be decomposed according to the so-  
 320 called triple decomposition (Hussain & Reynolds 1970). For instance, the longitudinal  
 321 instantaneous velocity component can be decomposed as:

$$u = U + \tilde{u} + u' \quad (3.1)$$

322 where  $U$  is the time-averaged velocity,  $\tilde{u}$  is the periodic component (e.g. the periodicity  
 323 imposed by the passage of waves) and  $u'$  is the turbulent component. The periodic  
 324 component  $\tilde{u}$  can be determined with  $\tilde{u} = \langle u \rangle - U$ , where  $\langle u \rangle$  is the phase-averaged  
 325 velocity determined by averaging over an ensemble of samples taken at a fixed phase in  
 326 the imposed oscillation and it is expressed as:

$$\langle u \rangle = \frac{1}{N} \sum_{i=1}^N u(t + iT) \quad (3.2)$$

327 where  $T$  is the period of the oscillation and  $N$  is the total number of cycles.

328 This signal analysis procedure is referred to as the phase-averaging method (Franca &  
 329 Brocchini 2015) and is the most common employed technique in the study of combined  
 330 wave-current flows (Kemp & Simons 1982; Umeyama 2005, 2009a; Singh & Debnath  
 331 2016; Roy *et al.* 2017; Zhang & Simons 2019).

332 This technique is very sensitive to the regularity of the waves and if the waves  
 333 are not perfectly monochromatic or do not present a repetitive pattern over time,  
 334 it becomes very difficult to obtain reliable estimates of conditional statistics because  
 335 there are mutual leakages between the wave and turbulent component of the signal.  
 336 An alternative two-point measurement technique for separating turbulent and wave  
 337 components was developed by Shaw & Trowbridge (2001). This technique utilises the  
 338 velocity signals collected simultaneously by two sensors spatially separated so that the  
 339 correlation between the two signals is associated with the wave motion only; namely,  
 340 the sensors are located at a distance much larger than the turbulence integral scale, but  
 341 much smaller than the wavelength of the surface waves (Hackett *et al.* 2011; Nayak *et al.*  
 342 2015). This latter technique is not affected by irregular waves but it requires two-point  
 343 measurements that are often available in laboratory settings but rarely in the field. This  
 344 makes direct comparison of results difficult, due to the lack of a common protocol in  
 345 data analysis procedures. Note that, to the authors' opinion, within the context of wave-  
 346 turbulence interaction, results will be always partially dependent on the chosen signal  
 347 decomposition technique so working on common grounds, namely widely accepted data  
 348 analysis techniques, would be desirable in future studies.

349 In light of the limitations of the phase-averaging method in dealing with not perfectly  
 350 monochromatic waves (see Section 2.2), in the current study we separated the turbulent  
 351 and wave components employing the so-called Empirical Mode Decomposition (EMD).  
 352 This technique was chosen because, besides working well for irregular signals resulting

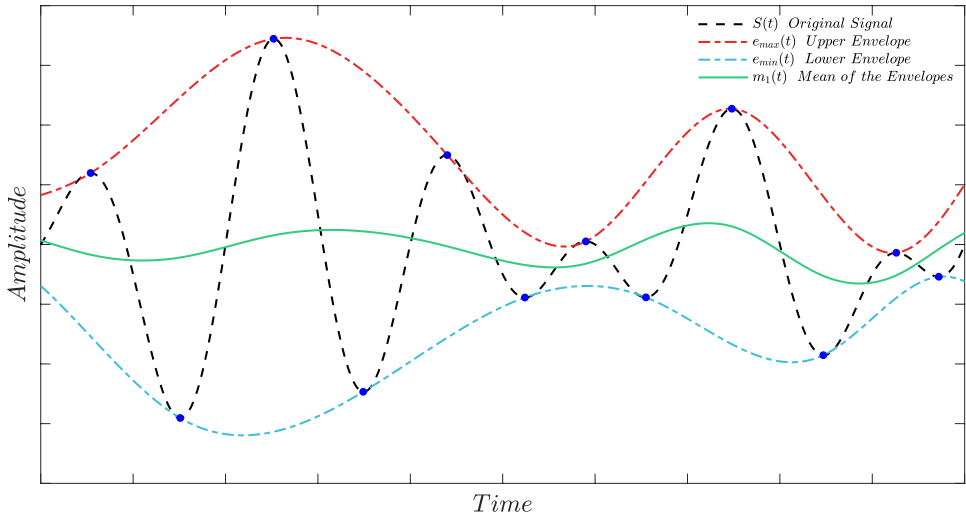


FIGURE 5. Identification of the signal extrema (blue dots), construction of the upper (red) and lower (blue) envelopes and computation of the mean envelope (green).

353 from non-linear interaction processes (such as wave-turbulence interactions), it does not  
 354 require simultaneous multipoint measurements.

355

### 3.1. Empirical mode decomposition

356

The Empirical Mode Decomposition (EMD) was firstly proposed by Huang *et al.* (1998, 1999, 2003) for the analysis of non-stationary time series and has been used in numerous fields since then. Some successful applications in fluid mechanics are: the analysis of turbulent scales in fully developed homogeneous turbulence (Huang *et al.* 2008, 2010), the quantification of the amplitude modulation effects in wall turbulence (Dogan *et al.* 2019) and the study of wave-turbulence properties in the surf zone (Schmitt *et al.* 2009) or ocean-surface (Qiao *et al.* 2016).

362

Differently from most other methods (e.g. spectrogram or wavelet), the basic functions of the EMD are directly inferred from the data themselves and no signal features are assumed *a priori*. The main drawback of the EMD is that it is fully empirical and no rigorous mathematical foundations have been yet derived, although some theoretical justifications have been proposed (see, Flandrin *et al.* 2004). Nevertheless, the EMD procedure satisfies the perfect reconstruction property, namely the original signal can be reconstructed completely by summing all the functions that have been inferred from it. Such functions are referred to as Intrinsic Mode Functions (IMFs) and represent the natural oscillatory modes that are embedded in the signal. Any IMF must satisfy two conditions: (i) “in the whole dataset, the number of extrema (maxima and minima) and the number of zero-crossings must either be equal or differ at most by one”; and (ii) “at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero” (Huang *et al.* 1998, 1999). Hence, the IMF represents an ideal zero-mean amplitude and frequency modulation function.

377

The IMFs are extracted from the signal by means of the so-called sifting process (Huang *et al.* 1998, 1999, 2003), which has two main purposes: (i) to eliminate riding waves, i.e. the presence of a local minimum (maximum) greater (lesser) than zero between two successive local maxima (minima); and (ii) to make the oscillatory profiles more symmetric with respect to zero.

381

382 The first step of the sifting process is the localization of the maxima and minima in the  
 383 original signal  $S(t)$ . Then, the upper envelope  $e_{max}(t)$  and the lower envelope  $e_{min}(t)$  are  
 384 reconstructed and the mean envelope can be calculated as  $m_1(t) = (e_{max}(t) + e_{min}(t))/2$   
 385 (figure 5). The envelopes are reconstructed by means of an interpolating function. The  
 386 function involved in the interpolation of the maxima/minima varies according to the  
 387 changes and improvements to the algorithm proposed by various authors (Lei *et al.* 2013),  
 388 nevertheless the most used is the cubic spline interpolator. At this point, the function  
 389 generated by the first round of sifting of the signal is determined as  $h_1(t) = S(t) - m_1(t)$ .  
 390 However,  $h_1(t)$  is rarely a true IMF and must be further processed to eliminate any riding  
 391 waves until it respects the two IMF conditions. Therefore, the generated  $h_1(t)$  is set as  
 392 the new input time-series and the sifting process is repeated  $j$  times until the first IMF  
 393 from  $h_{1j}(t) = h_{1(j-1)}(t) - m_{1j}(t)$  is obtained. From the first IMF  $C_1(t) = h_{1j}(t)$ , the  
 394 first residual is obtained by subtraction from the original signal, i.e.  $r_1(t) = S(t) - C_1(t)$ .  
 395 If the residual  $r_1(t)$  is either a constant, a monotonic function or a function with at  
 396 most one local extreme point, the sifting process ends, otherwise  $r_1(t)$  is used as the new  
 397 input signal and the sifting is repeated from the first step. When no more IMFs can  
 398 be extracted, the sifting ends with  $(n - 1)$  IMFs and a residual  $r_n(t)$ . At this point the  
 399 original signal  $S(t)$  can be expressed as:

$$S(t) = \sum_{i=1}^{n-1} C_i(t) + r_n(t) \quad (3.3)$$

400 where  $C_i(t)$  is the  $i$ th IMF following the order of extraction from the signal. Due to the  
 401 nature of the EMD,  $C_1(t)$  is the IMF with the highest characteristic frequency oscillation,  
 402 while  $C_{n-1}(t)$  has the lowest.

403 If too many sifting iterations are performed, the IMF reduces to a constant-amplitude  
 404 frequency-modulated function, annihilating the intrinsic amplitude variations and mak-  
 405 ing the results physically meaningless (Huang *et al.* 2003). To prevent this, the sifting  
 406 iterations must be limited by means of a stopping criterion (e.g. Huang *et al.* 1998;  
 407 Rato *et al.* 2008; Tabrizi *et al.* 2014). The sifting stopping criterion we employed is the  
 408 Resolution Factor (Rato *et al.* 2008), which is based on the ratio between the energy  
 409 of the original signal  $S(t)$  and the energy of the average of envelopes  $m_i(t)$  at the  $i$ th  
 410 iteration, i.e.:

$$RF = 10 \log_{10} \left( \frac{S(t)^2}{m_i(t)^2} \right) \quad (3.4)$$

411 In particular, we used a threshold value of 45 dB as recommended by Rato *et al.* (2008).

### 3.2. Adopted procedure

413 In this work we implemented the EMD algorithm proposed by Rato *et al.* (2008),  
 414 who improved the original procedure introduced by Huang *et al.* (1998) to minimise  
 415 the impact of sensitive factors, such as: the extrema localisation, the method used to  
 416 interpolate the extrema and calculate the envelopes, the handling of the end-points at  
 417 the boundaries and the decomposition stopping criterion. The following procedure was  
 418 adopted to separate the periodic (wave) and turbulent components of the original signal  
 419 obtained from the WC experiments:

- 420 **Step I** obtain the IMFs and the residual from the signal by using the EMD algorithm;
- 421 **Step II** compute the spectrum of the IMFs;

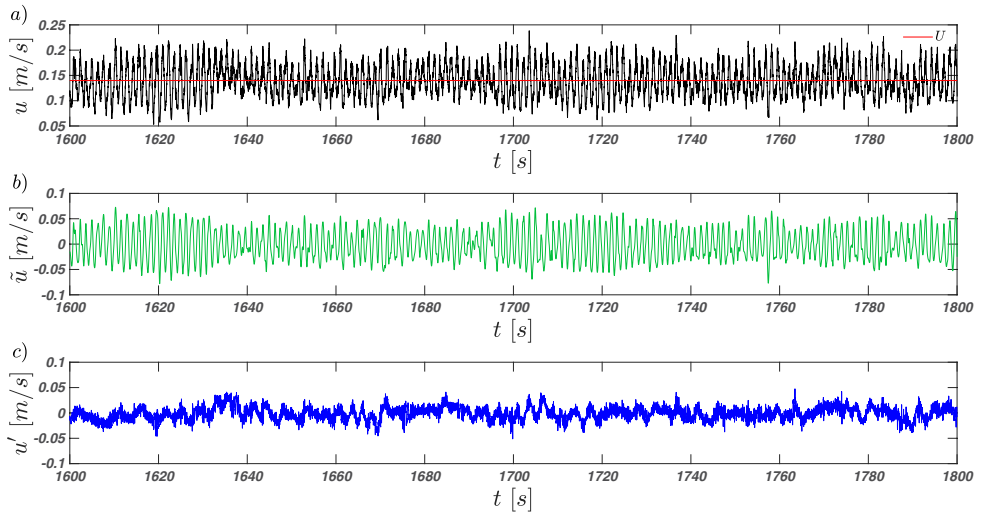


FIGURE 6. (a) Original signal (black) and mean velocity (red); (b) wave component (green) and (c) turbulent component (blue). Test WC-T2,  $y/h = 0.1$ , longitudinal velocity component.

422 **Step III** identify the IMFs that contain the wave signal based on the shape of the  
 423 spectrum (i.e. the dominant peak/peaks associated with the wave motion);

424 **Step IV** obtain the wave component by summing up all the IMFs that contain the wave  
 425 signal, the remaining components are summed up to obtain the turbulent component.  
 426 This way the original signal is decomposed into wave and turbulent component;

427 **Step V** perform a visual check of the wave and turbulent components against the original  
 428 signal to qualitatively assess whether all the wave oscillations have been separated from  
 429 the signal. The features considered are the difference between the amplitude of the wave  
 430 motion and the turbulent fluctuations together with wave-shaped patterns having the  
 431 wave frequency inside the turbulent component;

432 **Step VI** if the quality check shows that some wave oscillations are still present in the  
 433 turbulent component, then additional IMFs must be classified as wave components and  
 434 handled accordingly. This step must be repeated until the turbulent component shows  
 435 no obvious periodicity.

436 At the end of the process, the original signal (figure 6a) is decomposed in the wave  
 437 (figure 6b) and turbulent (figure 6c) components. In the current study, for all the exper-  
 438 imental conditions, the wave component was entirely embedded in 2–5 well-recognisable  
 439 IMFs at most.

440 As clearly visible in the example displayed in figure 7, the adopted procedure creates  
 441 an artificial valley in the power spectral density of the turbulent signal whose physical  
 442 meaning is questionable. This happens because part of the turbulent energy with fre-  
 443 quency bandwidth around the frequency of the wave motion results to be associated  
 444 with the wave component instead of the turbulent component, creating a sort of spectral  
 445 loss. Despite numerous attempts, we could not find any tuning of the EMD procedure  
 446 that allowed for the removal of this valley and the associated loss. Therefore, it was  
 447 decided to quantify its effects using a standardised procedure as follows.

448 Similarly to what was done by [Banerjee \*et al.\* \(2015\)](#) and [Vettori \(2016\)](#), this spectral  
 449 loss was quantified as the area bounded between a power law (line of constant slope in  
 450 log-log coordinates) and the artificial valley. The edges of the valley were chosen as the  
 451 last/first spectral point after/before which an evident change in the trend identified by



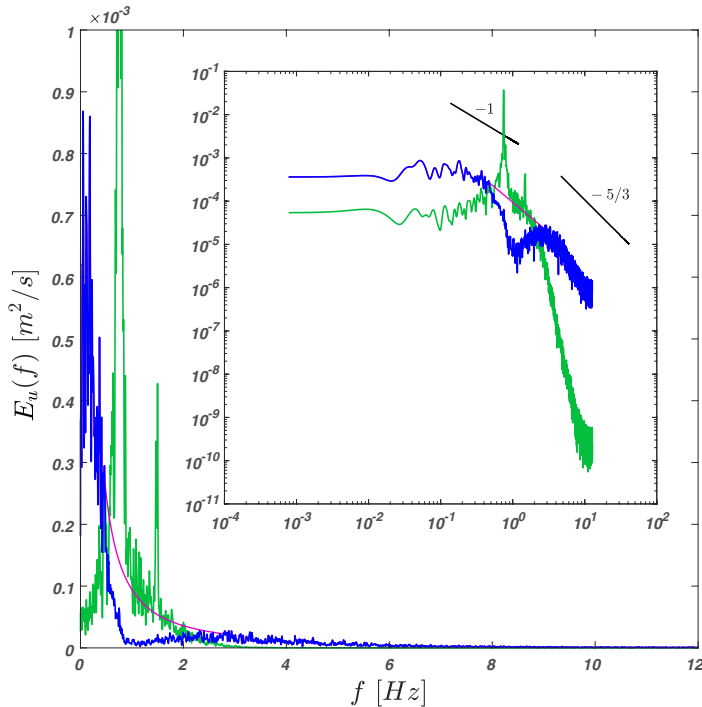


FIGURE 7. Spectra of the longitudinal velocity measured at  $y/h = 0.03$  for the test WC-T2. Blue and green lines indicate the turbulent and wave component. The magenta line shows an example of how the artificial valley in the turbulent signal spectrum was bridged. The main and sub-plot show spectra in linear and log-scale, respectively. The straight black lines in the sub-plot represent power laws with exponents  $-1$  and  $-5/3$ .

452 the previous/following ten spectral estimates was detected. Following this method, the  
 453 loss resulted to be as 20%–30% of the total spectral energy for the longitudinal velocity  
 454 and 10%–20% for the vertical velocity. Note that, after a careful sensitivity analysis, this  
 455 estimates resulted to be weakly dependent on the exact location of the aforementioned  
 456 edges of the power law, which we realise, is identified with a level of arbitrariness. Equally  
 457 arbitrary is the choice of using a power law because the exact shape of the spectra in  
 458 proximity of the valley is unknown. Despite these obvious shortcomings, the analysis  
 459 above revealed that the relative magnitude of the spectral loss is roughly constant and  
 460 independent of flow conditions. This indicates that the turbulent velocity variances are  
 461 probably underestimated by the EMD procedure (note that  $\sigma_v^2 = \int E_u(f) df$ , e.g. Bendat  
 462 & Piersol 2011), however their behaviour in response to different wave forcing (i.e. the  
 463 response in terms of trends instead of actual values) is likely to be preserved and captured.  
 464 Finally, it is worth noting that the spectral analysis presented in Sections 4.3–4.4 was  
 465 conducted on the complete velocity signal to avoid potential impact on the estimated  
 466 scales of VLSMs.

## 467 4. Results

### 468 4.1. Mean velocity profiles

469 The vertical profiles of the time-averaged longitudinal velocity for the waves following  
 470 a current (WC) and current-alone (CA) cases (table 2) are reported in figure 8(a). With

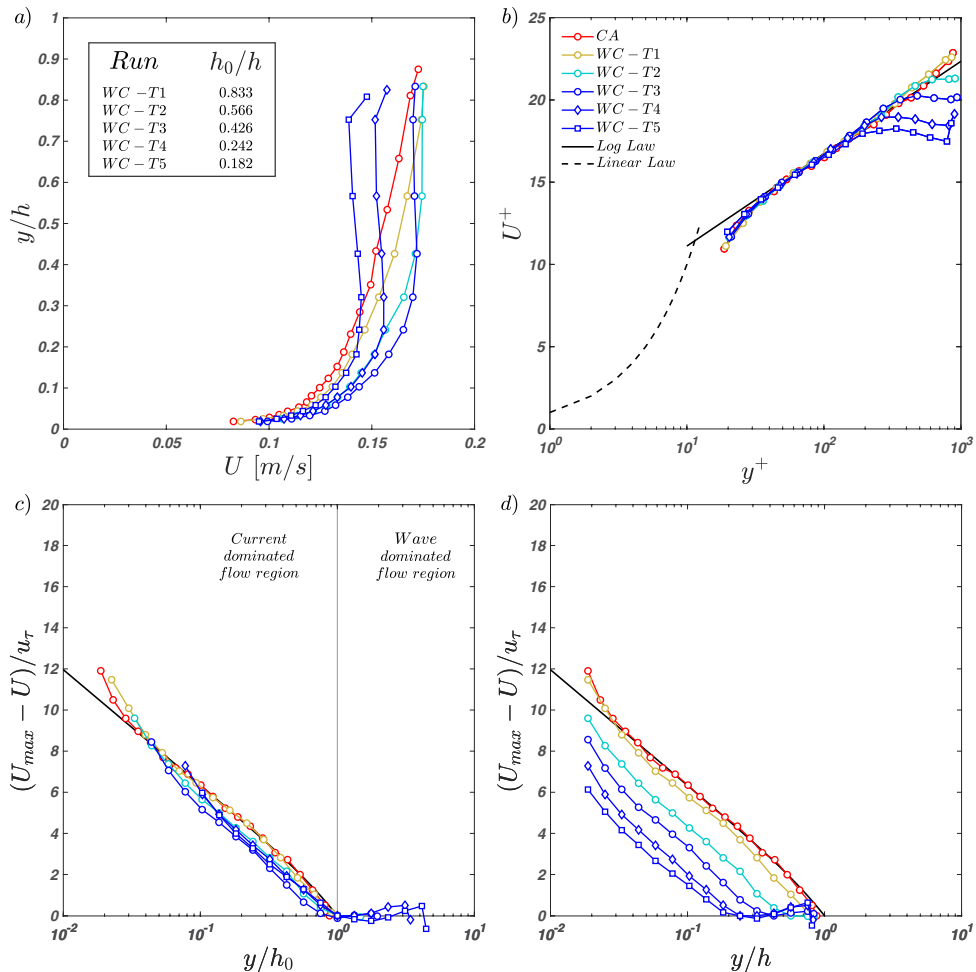


FIGURE 8. Panel (a) shows the vertical profiles of the mean longitudinal velocity for the CA and WC experiments (complete waves plus current signal). In the inset, the normalised values of the proposed outer-length scale  $h_0$  are reported. Panels (b) and (c) show the normalised profiles of the mean longitudinal velocity in inner and outer scaling, respectively. Finally, panel (d) reports the outer-scaled profiles of the mean longitudinal velocity by using the flow depth  $h$  as outer scale.

471 respect to the CA case, the vertical profiles pertaining to the WC cases are significantly  
 472 different and indicate that waves are responsible for a redistribution of time-averaged  
 473 momentum and global shear. In what follows we show that such a redistribution can  
 474 be interpreted as the result of waves generating two distinct flow regions in the water  
 475 column. The discussion about the existence, scaling and turbulence features of these two  
 476 flow regions is at the heart of the whole paper.

477 We begin the analysis by plotting mean velocity profiles following the approach nor-  
 478 mally taken in wall turbulence studies, namely in inner and outer scaling (figure 8b–c).  
 479 In the following, the superscript ‘+’ refers to the usual inner normalisation  $y^+ = yu_\tau/\nu$   
 480 and  $U^+ = U/u_\tau$ , where the  $u_\tau$  values are listed in table 2. By applying the inner scaling,  
 481 the velocity profiles collapse within a narrow interval (figure 8b). Note that the so-  
 482 called two-log-profile structure proposed by Grant & Madsen (1979) and experimentally  
 483 validated by Fredsøe *et al.* (1999) and Yuan & Madsen (2015) in hydraulically rough-bed

484 conditions, is not detectable in figure 8(b). This may be attributable to the fact that  
 485 the Stokes length  $l_S = \sqrt{2\nu/\omega}$  - which to some extent quantifies the wave boundary  
 486 layer thickness  $\delta_w$  in smooth-bed flows (i.e.  $\delta_w = 2 - 4l_S$ , Nielsen 1992) - ranges from  
 487  $5.4 \cdot 10^{-4}$  to  $7.6 \cdot 10^{-4}$  m, corresponding to 4.7–6.5 wall units, and therefore it is fully  
 488 buried within the buffer/viscous layer. Consequently, it is not surprising that the two-log-  
 489 profile structure was evidenced only for combined wave-current flows over rough-beds, in  
 490 which case the  $\delta_w$  is magnified by the bed roughness. Furthermore, it is worth pointing  
 491 out that the logarithmic region in figure 8(b) is shortened in tests WC–T2 to WC–T5  
 492 with respect to the CA case. This result is similar to the finding obtained by Deng *et al.*  
 493 (2019) when Langmuir cells are present in the water column. This could be connected to  
 494 the results discussed later in Sections 4.3–4.4.

495 In the outer scaling there is a reasonably-good collapse of the mean velocity profiles  
 496 for the CA case and the WC cases if  $h_0$  and  $U_{max} - U$  are used as the outer length scale  
 497 and velocity defect, respectively (see the difference between figure 8c and figure 8d).  
 498 The quantity  $h_0$  is here defined as the distance from the wall where the mean velocity  
 499 profile reaches its maximum  $U_{max}$  and beyond which it decreases or maintains a constant  
 500 value (figure 8a). It is also import to highlight that the uppermost measured point  
 501 in the velocity profiles of tests WC–T4 and WC–T5 were not considered during the  
 502 determination of  $h_0$  and  $U_{max}$  since these points present a sudden increasing in the  
 503 mean longitudinal velocity probably induced by near surface effects (figure 8a). Given  
 504 the small number of data points available across the water column, to obtain velocity  
 505 profiles with higher resolution we interpolated the data using spline functions. Since the  
 506 maxima locations identified by the cubic spline functions were very close to the maxima in  
 507 the data points, we estimated the locations of  $h_0$  using the point measurements available  
 508 (normalised values of  $h_0$  are reported in figure 8a).

509 Figure 8(b–c) shows that, for each experimental condition, there is a range of elevations  
 510 where mean velocity profiles nearly collapse both in inner and outer scaling over the  
 511 log law of the wall (solid lines). Besides CA, data collapse is particularly good for  
 512 case WC–T1, whereas cases WC–T2, –T3, –T4 and –T5 seem to be shifted slightly  
 513 downwards. Despite this shift the collapse is satisfactory and suggests the existence of  
 514 a logarithmic-overlap layer as defined within the remit of asymptotic matching theories  
 515 (Yaglom 1979). Clearly, the collapse of the data is strongly dependent on the exact  
 516 location of  $h_0$  (and consequently also the estimation of  $U_{max}$ ). More refined measurements  
 517 of velocity profiles are required to further substantiate these results, but the improvement  
 518 with respect to figure 8(d) is tangible. Another possible explanation for the not perfectly  
 519 collapse between test WC–T1 and the other WC tests is that a change of the von Kármán  
 520 coefficient  $\kappa$  occurs. As it is widely recognised (Nagib & Chauhan 2008; Marusic *et al.*  
 521 2010),  $\kappa$  varies between different canonical flows (e.g.  $\kappa \approx 0.37$  in closed-channel flows,  
 522  $\kappa \approx 0.384$  in zero-pressure gradient turbulent boundary layers and  $\kappa \approx 0.41$  in pipe flows)  
 523 and it is plausible that, when the effects of the wave motion become relevant,  $\kappa$  change  
 524 its value from that one observed for the open-channel flow case CA. This observation  
 525 seems consistent with the results that we show in the following, but, to better elucidate  
 526 this aspect and remove any doubt a dedicated study should be addressed.

527 However, the inner-outer scaling of the vertical profiles of the mean longitudinal  
 528 velocity is noteworthy because: (i) to the best of the authors' knowledge, this is the first  
 529 time that the existence of a logarithmic layer (which has a profound physical meaning  
 530 and is very relevant for modelling purposes) in wave-current flows is supported on the  
 531 basis of arguments that go beyond the simple identification of a log-type shape in the  
 532 profile of  $U$ ; and (ii) the existence of a log profile justifies the use of the Clauser method  
 533 to estimate the shear velocity in WC experiments. Further support for the existence of a

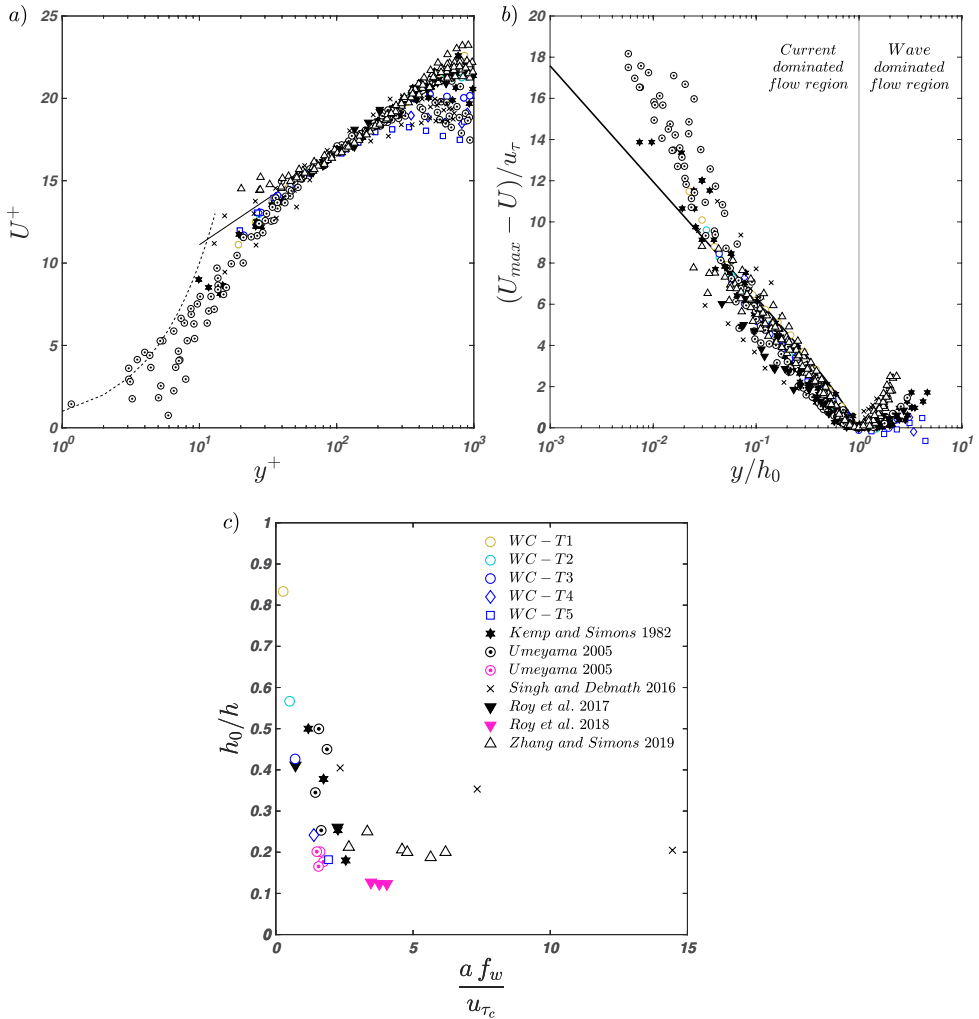


FIGURE 9. Panels (a) and (b) report the normalised profiles of the mean longitudinal velocity of the present results together with data taken from the literature (Kemp & Simons 1982; Umeyama 2005; Singh & Debnath 2016; Roy *et al.* 2017; Zhang & Simons 2019) in inner and outer scaling, respectively. Panel (c) shows the normalised outer-length scale  $h_0/h$  as a function of the dimensionless parameter  $a f_w/u_{\tau c}$  for waves following a current (black markers) and waves against a current (magenta markers). The dataset for this latter case were taken from Umeyama (2005) and Roy *et al.* (2018).

534 logarithmic-type layer in the WC experiments will be provided when discussing second  
 535 order velocity statistics and spectral analysis.

536 The proposed inner-outer scaling was also employed to available literature data relating  
 537 to mean velocity profiles measured in combined wave-current flows with waves following a  
 538 current (Kemp & Simons 1982; Umeyama 2005; Singh & Debnath 2016; Roy *et al.* 2017;  
 539 Zhang & Simons 2019) to test its universality (figure 9a–b). The value of  $u_\tau$  and  $h_0$  where  
 540 estimated as per the dataset presented herein using the mean velocity profiles extracted  
 541 from each referenced paper. As shown in figure 9(a), the velocity profiles collapse very well  
 542 in inner scaling but this is somewhat imposed by using the Clauser method to estimate  
 543 the friction velocity. In outer scaling, the scatter of data is significant but the velocity

544 profiles seem to cluster around our data (figure 9b). The reasons explaining the observed  
 545 scatter can be deduced after interpreting the physical meaning of  $h_0$  as follows.

546 It is herein introduced the concept (further substantiated in the next sections) that the  
 547 height  $h_0$  represents a crossover between two different flow regions: (i) the first, between  
 548 the bed and  $h_0$ , where the flow is influenced by the presence of waves but retains, to  
 549 a good extent, the character of a current (the current-dominated flow region); (ii) the  
 550 second, between  $h_0$  and the free-surface, where the flow is mainly controlled by the wave  
 551 motion (the wave-dominated flow region; note that also Umeyama (2005) introduced an  
 552 inner layer depth included between  $y = 0$  and  $y = h$  in his work, but without giving  
 553 any physical meaning to it). Bearing in mind the nature of the combined wave-current  
 554 flows considered in the present study, we propose that  $h_0$  could be dictated by a trade-  
 555 off between two competing mechanisms: wave-induced velocities, which, according to  
 556 classical wave theories, scale as  $a f_w$  and the turbulent velocities imposed by the current,  
 557 which notoriously scale with the friction velocity,  $u_{\tau_c}$ . Therefore, we argue that:

$$\frac{h_0}{h} = F\left(\frac{a f_w}{u_{\tau_c}}; \frac{h}{L}; \frac{\delta_c}{h}\right) \quad (4.1)$$

558 where  $F$  is an unknown functional relation and  $\delta_c$  is the thickness of the current  
 559 boundary layer. It is important to recall that in the present work,  $a f_w/u_{\tau_c}$  and  $h/L$  vary  
 560 in the range 0.26 to 1.85 and 0.05 to 0.12 (see table 1 and table 2), respectively, while  
 561  $\delta_c/h = 1$  (see Peruzzi *et al.* 2020), hence the validity of Eq. 4.1 is currently limited to  
 562 these conditions. From a physical point of view, the shift between the two regions cannot  
 563 be as sharp as conceptualised above and it is expected that a sizeable transition zone  
 564 exists. However, our reasoning is similar to that of the boundary layer concept, where the  
 565 distinction between the turbulent and irrotational flow is set where the mean streamwise  
 566 velocity  $U$  equals 95–99% of the edge velocity  $U_e$  imposed by the potential flow.

567 The proposed scaling (Eq. 4.1) identifies a good trend in the data (listed in table 2  
 568 and from the literature) presented in figure 9(c): for increasing values of  $a f_w/u_{\tau_c}$ ,  
 569  $h_0/h$  decreases, meaning that the stronger the wave velocities the more the current-  
 570 dominated region shrinks towards the bed. Interestingly (and encouragingly), data taken  
 571 from the literature (Kemp & Simons 1982; Umeyama 2005; Singh & Debnath 2016; Roy  
 572 *et al.* 2017; Zhang & Simons 2019) for the case of waves following a current, while not  
 573 collapsing that well with the present data, do show more or less similar trends. The  
 574 scatter visible in figure 9(b), might be the result of two factors. First, as already pointed  
 575 out, combined wave-current flows are possibly non-equilibrium flows whose scaling is  
 576 implicitly not universal. Second, the literature data refer to flow conditions whereby waves  
 577 are superimposed to currents whose ratio between depth and boundary layer thickness  
 578 (equal to 1 for the experimental data pertaining to the present paper) is not the same  
 579 among different experiments, which are therefore not fully comparable. Furthermore,  
 580 in figure 9(c) are reported the data from Umeyama (2005) and Roy *et al.* (2018) for  
 581 waves against a current situation. The values of  $h_0/h$  were determined by using the more  
 582 general procedure for the identification of  $h_0$  explained in the last part of Section 4.2.  
 583 These new data seem consistent with our theoretical framework, although they display  
 584 a downward shift from the waves following a current data. It may be possible that in  
 585 the waves against current environment, the current-dominated region is further shrunken  
 586 but, at the moment, we do not have sufficient information to comment on this.

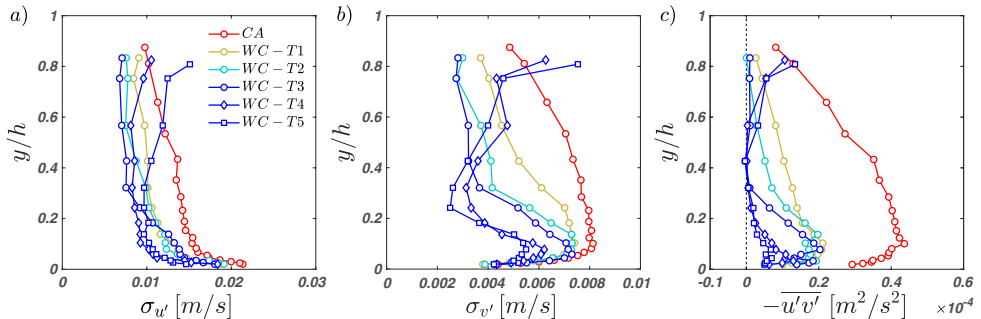


FIGURE 10. Profiles of the dimensional Reynolds stresses. In panel (a)  $\sigma_{u'}$  is the standard deviation of the turbulent longitudinal velocity component; in panel (b)  $\sigma_{v'}$  is the standard deviation of the turbulent vertical velocity component; in panel (c)  $-\overline{u'v'}$  is the covariance between the turbulent components of the longitudinal and vertical velocities.

587

#### 4.2. Reynolds stresses

588 Because we are mainly interested in the effect of waves on turbulence, in the following,  
 589 we focus our attention on the Reynolds stresses computed from the turbulent signal only,  
 590 we encourage the readers interested in the Reynolds stresses of the wave signal to read  
 591 [Peruzzi \(2020\)](#).

592 It is convenient to begin commenting the Reynolds stresses (as obtained from the  
 593 turbulence velocity signal extracted using the EMD) plotted in dimensional form as this  
 594 allows for comparisons with data previously presented in the literature. Figure 10(a–c)  
 595 indicates that the Reynolds stresses for the WC cases deviate considerably from the  
 596 benchmark CA case. In agreement with other experimental studies (e.g. [Umeyama 2005](#);  
 597 [Singh & Debnath 2016](#)), the normal ( $\sigma_{u'}$  and  $\sigma_{v'}$ ) and shear Reynolds stresses ( $-\overline{u'v'}$ )  
 598 are damped by the presence of the wave motion (in particular the shear component,  
 599 which shows a dramatic reduction in magnitude). In accordance with what observed from  
 600 previous studies, in the near bed region the profiles of normal and shear Reynolds stresses  
 601 retain a peak (not visible for  $\sigma_{u'}$  due to spatial resolution issues) as observed for the CA  
 602 flow. Away from the bed, the shape of the profiles is severely altered by the passage of  
 603 waves. As observed by [Umeyama \(2005, 2009a,b\)](#) and [Roy et al. \(2017\)](#), such profiles tend  
 604 to become flatter or, for the experiments WC–T4 and WC–T5, associated with a switch  
 605 in sign of their vertical gradient. Finally, the shear Reynolds stress  $-\overline{u'v'}$  is always positive  
 606 throughout the water column (indicating a downward turbulent momentum transport)  
 607 and for cases WC–T3 to WC–T5 becomes null at  $y/h \approx 0.4$ .

608 Clearly, it is extremely difficult to infer properties of turbulence by assessing dimension-  
 609 al quantities as reported in figure 10(a–c). As shown in the following text, the use  
 610 of an appropriate scaling is more revealing.

611 The second-order moments in inner and outer scaling are reported in figure 11(a–f).  
 612 On the one hand, the Reynolds stress profiles do not either collapse or stratify well when  
 613 plotted in inner scaling (figure 11a–c). On the other hand, the outer scaling unveils  
 614 interesting features when  $h_0$  is used as the outer length-scale (figure 11d–f): (i) for the  
 615 WC experiments,  $\sigma_{u'}/u_\tau$  are generally slightly lower with respect to the CA case but  
 616 collapse fairly well in the current dominate region and show no obvious dependence to  
 617 wave properties (figure 11d); (ii) the  $\sigma_{v'}/u_\tau$  profiles are damped significantly with respect  
 618 to the CA case but, contrary to  $\sigma_{u'}/u_\tau$ , show a clear dependence on the parameter  
 619  $a f_w/u_{\tau c}$  (figure 11e); and (iii) the  $-\overline{u'v'}/u_\tau^2$  profiles decrease with  $y/h_0$ , tending to zero  
 620 for  $y/h_0 \approx 1$  (figure 11f).

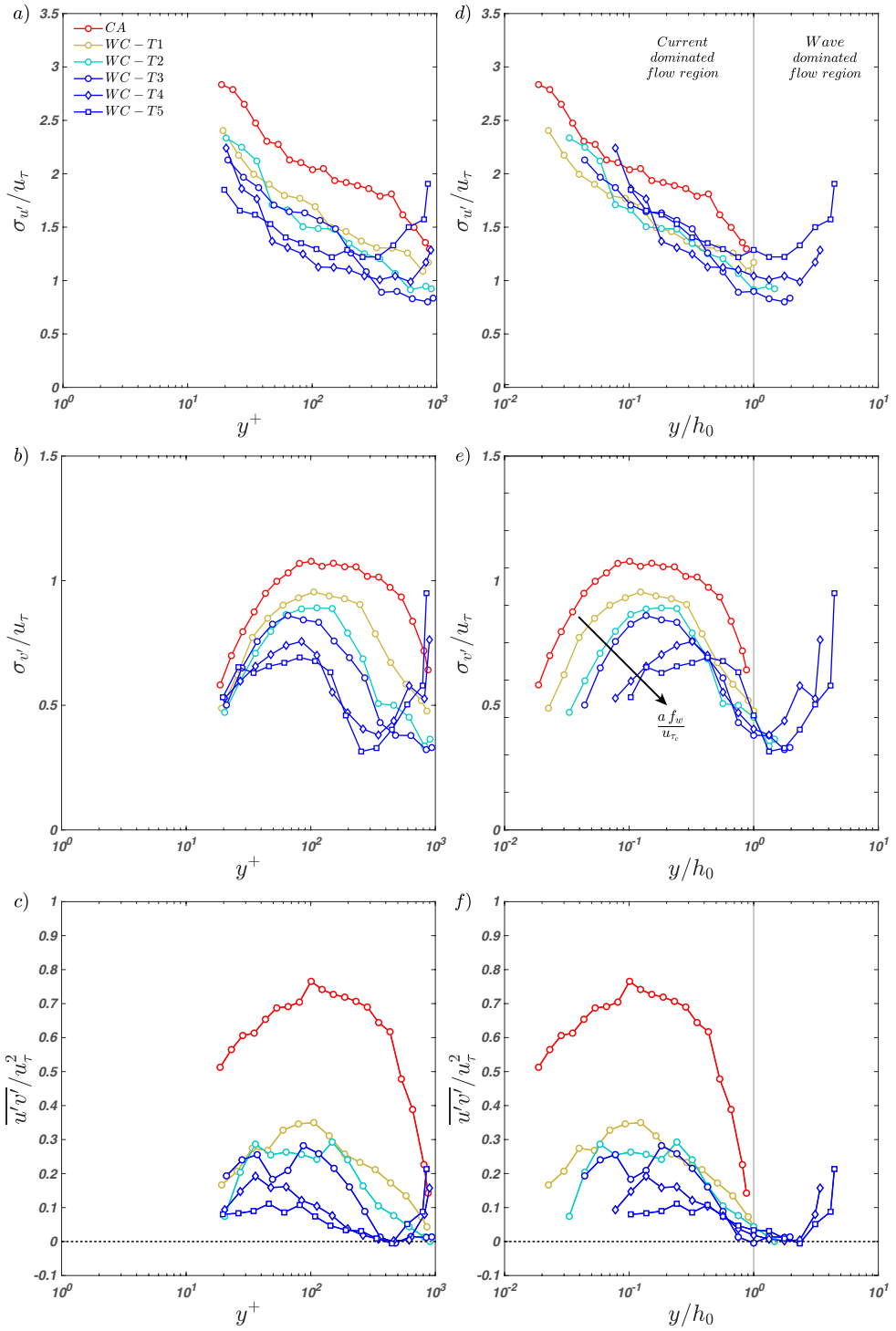


FIGURE 11. Profiles of non-dimensional Reynolds stresses. Panels (a)–(c), inner scaling; panels (d)–(f) outer scaling.



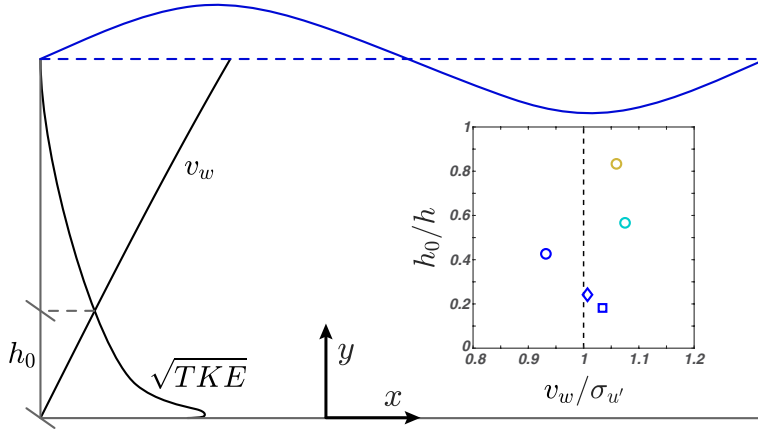


FIGURE 12. Representation of the vertical profiles of the maximum amplitude of the wave-induced vertical velocity  $v_w$ , according to the linear wave theory, and of the square root of TKE, where  $\text{TKE} = 0.5(\sigma_{u'}^2 + \sigma_{v'}^2 + \sigma_{w'}^2)$ . Phenomenologically, we expect that  $h_0$  is located at the elevation where these two quantities are comparable. The inset reports the normalised  $h_0$  (obtained as the maximum of the mean velocity profiles) as a function and of  $v_w/\sigma_{u'}$  for the five runs. Since the spanwise velocity  $w$  was not measured,  $\sqrt{\text{TKE}}$  was estimated as  $\sigma_{u'}$ , as commonly done in turbulence wall flows (Pope 2000).

621 Among the investigated Reynolds stress profiles, the one that seems to respond more  
 622 consistently to different wave forcing is  $\sigma_{v'}/u_\tau$ , which decreases with increasing  $a f_w/u_{\tau_c}$   
 623 (figure 11e). Moreover,  $\sigma_{v'}/u_\tau$  profiles display a plateau (as encountered in canonical  
 624 wall flows) whose extent reduces with increasing  $a f_w/u_{\tau_c}$ , probably because the whole  
 625 current-dominated flow region also shrinks in size (i.e.  $h_0/h$  reduces, see figure 9c). Inter-  
 626 estingly, in canonical wall flows this plateau is normally associated with the occurrence of  
 627 attached eddies (Nickels *et al.* 2007) and, as surmised from the analysis of mean velocity  
 628 profiles (figure 8b–c), of a logarithmic layer. The existence of attached eddies seems  
 629 therefore to be another feature of canonical wall-flows which resists to the perturbing  
 630 action of waves within the current-dominated flow region. This hypothesis will be further  
 631 corroborated by spectral analysis in Section 4.3.

632 The vertical profiles of the Reynolds stresses scaled with  $h_0$  all display a clear change  
 633 in behaviour at  $y/h_0 = 1$ , hence further substantiating that  $h_0$  is a crossover length scale  
 634 between two flow regions dominated by a significantly different physics. While there is  
 635 now reasonably good evidence supporting the hypothesis of  $h_0$  being a relevant length  
 636 scale in combined wave-current flows, its definition is admittedly unsatisfactory. As a  
 637 matter of fact, the elevation where mean velocity profiles display a maximum cannot be  
 638 considered a general definition for  $h_0$  because, for example, it would not be valid for the  
 639 analysis of waves opposing currents, where such a maximum does not appear (Kemp &  
 640 Simons 1983; Klopman 1994; Umeyama 2005; Roy *et al.* 2018). In an attempt to overcome  
 641 this shortcoming we provide a more general criterion as follows.

642 So far it has been argued, although fairly vaguely, that  $h_0$  is dictated by a competing  
 643 mechanism between wave motion and current-induced turbulence (see figure 9c). Let  
 644 us now consider wave and current flows individually. According to irrotational wave  
 645 theory, wave-induced motion progressively reduces with decreasing  $y$  mainly because of  
 646 the vertical velocity component dying off in response to the impermeability condition  
 647 imposed by the bed (figure 12). Conversely, the turbulent kinetic energy (TKE) of the  
 648 current, which can be taken as a good indicator of turbulent motion intensity, increases

with reducing distance from the bed. Hence, it is reasonable to assume that the aforementioned competing mechanism results into  $h_0$  corresponding to the elevation where the square root of current-induced TKE and the wave-induced vertical velocity become comparable (figure 12). Consistently with this hypothesis, we report that the values of  $h_0$  as identified from mean velocity profiles correspond to a very good approximation to the elevation where the maximum amplitude of the wave-induced vertical velocity component  $v_w = a\omega \sinh ky / \sinh kh$  (as estimated from linear wave theory and recalling the coordinate system shown in figure 1d) equals  $\sigma'_u$  of the current alone CA case that, in wall flows, is known to be a very good estimator of  $\sqrt{\text{TKE}}$  (see e.g. Pope 2000). Note that  $h_0$  relates equally well to the elevation where  $v_w/\sigma_{v'}$  is about 2 because of the scaling of velocity variances in the CA flow (i.e. in turbulent wall flows  $\sigma_{u'}/\sigma_{v'}$  is nearly equal to 2 over the entire outer region).

The trustworthiness of the criterion  $v_w/\sigma_{u'} = 1$  for the identification of  $h_0$  is supported by the results reported in figure 9(c), where the values for the waves against current were determined in this way. We believe that this criterion for the identification of  $h_0$  is of more general validity and more physically based than the one based on the maxima in mean velocity profiles; however, we do realise that more data pertaining to a wider range of flow conditions is required to verify its reliability.

### 4.3. Spectral analysis: on large-scale structures in the current-dominated flow region

It is now interesting to investigate how, with respect to the benchmark CA case, waves affect velocity spectra and hence how turbulent kinetic energy components distribute over different length scales in the WC experiments. By using the Taylor frozen-turbulence hypothesis (Taylor 1938), the 1-D power spectrum of the longitudinal velocity component  $E_{xx}(k_x)$  in the wavenumber domain  $k_x$  can be estimated from its frequency counterpart  $E_u(f)$  by using  $k_x = 2\pi f/U(y)$  and  $E_{xx}(k_x) = E_u(f)U(y)/2\pi$ , where  $U(y)$  is the local mean velocity. The 1-D power spectrum of the vertical velocity component  $E_{yy}(k_x)$  can be similarly estimated with the appropriate modifications. Since the spectral distortion induced by the Taylor frozen-turbulence hypothesis is stronger in the near-wall region and weaker above  $y/h = 0.1$  (Nikora & Goring 2000), in the following the results are mainly discussed for  $y/h \geq 0.1$ .

Figure 13(a–f) and figure 14(a–f) report 1-D pre-multiplied spectra of the complete signal (i.e. the original wave plus current signal) of the longitudinal and vertical velocity component, respectively. Note that the panels b–f in figure 13 and in figure 14 refer to the WC experiments where spectral peaks associated with characteristic wavenumbers of the imposed waves are much more energetic than the remaining part of spectral estimates. For convenience, in these figures such peaks are visually cut off (and neighbour spectral estimates plotted in light colour) to allow for a more comfortable analysis of the spectral estimates at turbulence-related energy levels. It is also important to highlight that the Taylor frozen-turbulence hypothesis used to plot figure 13(a–f) and figure 14(a–f) is valid for spectral estimates associated with turbulent eddies. Frequencies associated with waves' motion should be transformed into wavenumbers using the waves' celerity  $C = L/T$ . That is why there is a mismatch between wave-induced peaks in figure 13(a–f) and figure 14(a–f) and actual wavenumbers of the waves as reported in table 2.

The pre-multiplied spectra in the CA experiment display the characteristic double-peak shape (green and red arrows in figure 13a) that was detected both in smooth (Duan *et al.* 2020; Peruzzi *et al.* 2020) and rough-wall (Cameron *et al.* 2017) open-channel flows. The peak at the higher wavenumber is usually associated with the passage of so-called Large-Scale Motions (LSMs) whereas the peak at the lowest wavenumbers is associated with the occurrence of VLSMs. For experiment WC–T1, VLSM peaks can still be detected in the

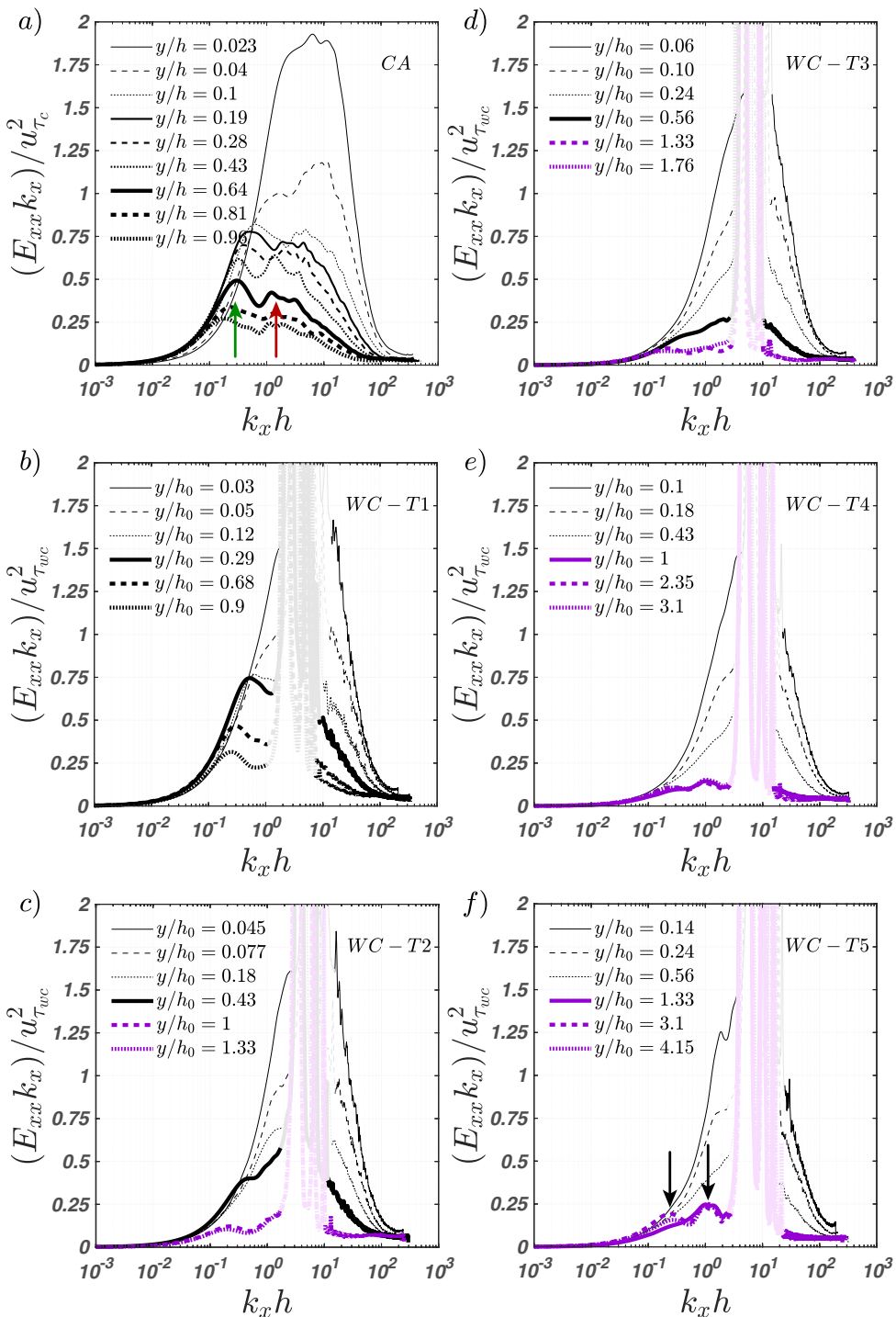


FIGURE 13. Outer-scaled pre-multiplied 1-D spectra of the longitudinal velocity component (complete wave plus current signal). Each panel reports spectra at different elevations for one experimental condition. Black lines identify vertical elevations below  $h_0$  (i.e. in the current-dominated flow region), whereas purple lines above it (i.e. in the wave-dominated flow region). Red and green arrows in panel (a) identify spectral peaks associated with LSMs and VLSMs, respectively. Black arrows in panel (f) identify spectral peaks presumably associated with Langmuir-type turbulence in WC experiments; peaks at similar wavenumbers are also observed in panels (c), (d) and (e). The 95% confidence interval for the pre-multiplied one-dimensional spectra is approximately 0.91 to 1.1 times  $(E_{xx}k_x)/u_{\tau_c}^2$ .

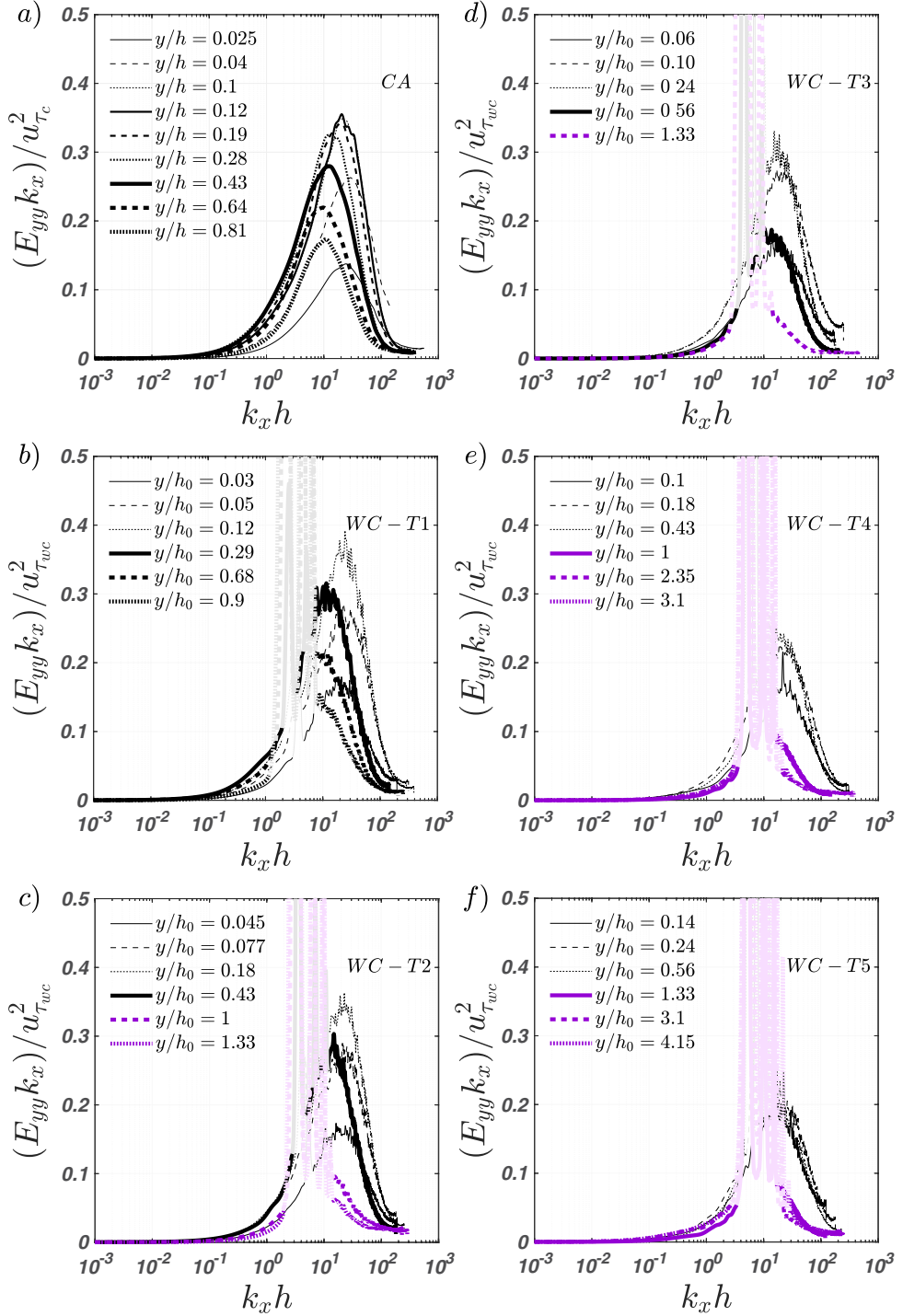


FIGURE 14. Outer-scaled pre-multiplied 1-D spectra of the vertical velocity component (complete wave plus current signal). Each panel reports spectra at different elevations for one experimental condition. Black lines identify vertical elevations below  $h_0$  (i.e. in the current-dominated flow region), whereas purple lines above it (i.e. in the wave-dominated flow region).

pre-multiplied spectra, probably because wave motion is significantly less intense than turbulence, i.e.  $a f_w/u_{\tau_c}$  is very small (figure 13b, table 2). For the remaining WC cases, instead, wave motion is strong enough (i.e.  $a f_w/u_{\tau_c}$  is large enough) to suppress VLSMs (figure 13c–f, table 2). It is possible to argue that the critical value for VLSMs suppression should be in between that of WC–T1 and WC–T2, i.e. 0.25 and 0.5 (see table 2). For what concerns LSMs, they cannot be distinguished in any of the WC experiments because spectral peaks due to waves occupy the wavenumbers where LSMs would be expected to display their peaks (compare e.g. figure 13a and figure 13b). It is therefore difficult to assess whether LSMs are suppressed or not by the passage of waves.

The reason why VLSMs (and possibly LSMs) are suppressed is difficult to identify with the data presented. However, it should be noted that, at the investigated CA flow-conditions, LSMs and VLSMs are associated with wavelengths of  $\approx 5h - 7h$  and  $\approx 20h - 25h$  respectively. These values are comparable with the spatial length scale imposed by the wave motion (the wave length  $L$ ), which is  $\approx 8h - 20h$  (depending on the run, see table 1), hence it is plausible that, provided  $a f_w/u_{\tau_c}$  is large enough, waves strongly interact and possibly suppress turbulence structures of similar length.

In the pre-multiplied spectra of the vertical velocity component, as measured in the current-dominated flow region (i.e.  $y/h_0 < 1$ ), there is a clear scale separation between peaks due to energetic turbulent structures and peaks imposed by waves (figure 14b–f), which allows for some interesting observations. For all WC experiments, the peaks caused by turbulence structures occur over the same range of wavenumbers as in the CA experiment, where, as per other canonical wall flows, they are usually considered as a characteristic trait of attached eddies (Baidya *et al.* 2017). This result further confirms what surmised from the analysis of the  $\sigma_{v'}/u_{\tau}$  profiles: attached eddies resist to waves' perturbations and continue to populate the current-dominated flow region. Conversely, in the wave-dominated flow region (i.e.  $y/h_0 > 1$ ) there is no scale separation between turbulence and waves (i.e. it is impossible to distinguish between peaks associated with turbulence and waves), which suggests that turbulent velocity fluctuations are associated with mechanisms possibly powered by waves.

#### 4.4. *Spectral analysis: on large-scale structures in the wave-dominated flow region*

The pre-multiplied spectra pertaining to the wave-dominated flow region (purple lines) also show some unexpected features (figure 13c–f). They display either one or two peaks (or bumps) at rather low wavenumbers (see black arrows in panel f), suggesting that the wave-dominated flow region hosts turbulence structures at scales comparable to LSMs and VLSMs (the wavelength  $\lambda_x$  of these structures is equal to about  $25h$  and  $6h$  for the peak at the lowest and highest wavenumber, respectively). This is rather counter-intuitive because in the current-dominated flow region such structures are suppressed by waves and it is surprising to see them in the wave-dominated region. With the data set presented, it is rather difficult to discuss the physical mechanisms underpinning the formation of such structures; however, for the sake of discussion and to identify future research directions, some hypotheses can be made.

Towards this end, it is worth recalling the study by Huang & Mei (2006), which reports a linear stability analysis of turbulent open-channel flows over smooth beds superimposed to waves, exactly as in the present study. Besides linearising the equation of motion and boundary conditions at the free surface and at the bed surface, Huang & Mei (2006) made the following assumptions: (i) the dimensionless water depth was set of order unity  $kh = \mathcal{O}(1)$ , (ii) the wave steepness  $\epsilon = ka$  was small, and (iii) the wave orbital velocity was set comparable to the current velocity; all these conditions are reasonably met in our experiments (table 2). Interestingly, and in line with our

747 experimental results, their stability analysis identified two large-scale unstable modes.  
 748 These modes were associated with cellular structures with longitudinal vorticity, akin  
 749 to Langmuir-type turbulent cells. Huang & Mei (2006) point out that, analogously to  
 750 Langmuir turbulence, the key requirements for the production of longitudinal vorticity,  
 751 and hence of the two observed unstable modes, are a source of vertical vorticity (e.g. any  
 752 spanwise perturbation of the longitudinal velocity) and a horizontal shear stress induced  
 753 by vertical gradients of longitudinal velocities. The vertical vorticity interacts with the  
 754 Stokes drift shear to generate longitudinal vorticity through vortex tilting and stretching.  
 755 The resulting spanwise gradient of the vertical velocity component interacts with the  
 756 mean shear imposed by the current to generate further vertical vorticity (presumably via  
 757 vortex stretching) to sustain the whole process of longitudinal vorticity generation.

758 The self-sustained process proposed by Huang & Mei (2006) might explain the two  
 759 peaks observed in figure 13(c–f). However, Huang & Mei (2006) did not estimate  
 760 the characteristic longitudinal wavenumber of the detected instabilities. This makes it  
 761 difficult to carry out a full and direct comparison between their theoretical results and  
 762 the present experimental data (i.e. the wavenumber at which spectral peaks occur in  
 763 figure 13c–f). The recent work by Xuan *et al.* (2019), though, indicates that Langmuir  
 764 turbulence (which is not the one discussed herein and by Huang & Mei (2006), but it does  
 765 share some similarities) occurs in the form of elongated eddies of length equal to eight  
 766 times their width. Assuming that the cells in the present experiments are circular and  
 767 filling the entire wave-dominated region, this implies that their width is about  $h - h_0$  and  
 768 hence about  $0.2-0.5h$  (see figure 12). This means that the estimates provided by Xuan  
 769 *et al.* (2019) are close to those of the peak observed at  $k_x h = \mathcal{O}(1)$  in figure 13(c–f).  
 770 Furthermore, Deng *et al.* (2020), through a wall-modelled Large Eddy Simulation (LES)  
 771 of shallow-water Langmuir turbulence with a very large computational domain ( $\approx 100h$ ),  
 772 reveal streamwise streaks induced by Langmuir cells that meander in the streamwise  
 773 direction with a wavelength of around  $25h$ , in accordance with the peak observed at  
 774  $k_x h = \mathcal{O}(0.1)$  in figure 13(c–f). As it is well known, one-dimensional velocity spectra  
 775 measure the spanwise meandering frequency rather than the actual wavelength of large-  
 776 scale turbulent structures (Hutchins & Marusic 2007), and the meandering configuration  
 777 reported in Deng *et al.* (2020) well support the spectral footprints herein reported. Also  
 778 in line with our experimental data is the fact that Huang & Mei (2006) observed that  
 779 the unstable modes occur only for wave steepness  $\epsilon$  greater than 0.02 and the larger  $\epsilon$  the  
 780 stronger their growth rate. In our experiments,  $\epsilon < 0.02$  only for the case WC–T1 and  
 781  $\epsilon$  increases from WC–T2 to WC–T5 (table 2). Remarkably, all the WC cases, excepts  
 782 for WC–T1, present evidence of instabilities in line with the modes reported by Huang  
 783 & Mei (2006) in the wave-dominated flow region (figure 13c–f). It is also worth noting  
 784 that WC–T5 is characterised by the highest value of  $\epsilon$  and the most pronounced spectral  
 785 peaks at low wavenumbers (see figure 13f).

786 To the authors' opinion, the experimental data presented herein combined with the  
 787 theoretical analysis proposed by Huang & Mei (2006) provide clues to support the idea  
 788 that, in the wave-dominated flow region, turbulence is organized in eddies similar to  
 789 Langmuir cells. These findings are also in line with the experimental results of Nepf &  
 790 Monismith (1991), who reported the presence of longitudinal vortices arising through  
 791 wave-current interaction.

## 792 5. Discussion

793 Note that in Section 4.3, we have argued that the suppression of VLMSs in the current-  
 794 dominated region is controlled by  $a f_w / u_{\tau_c}$  whose critical value lies between 0.26 and



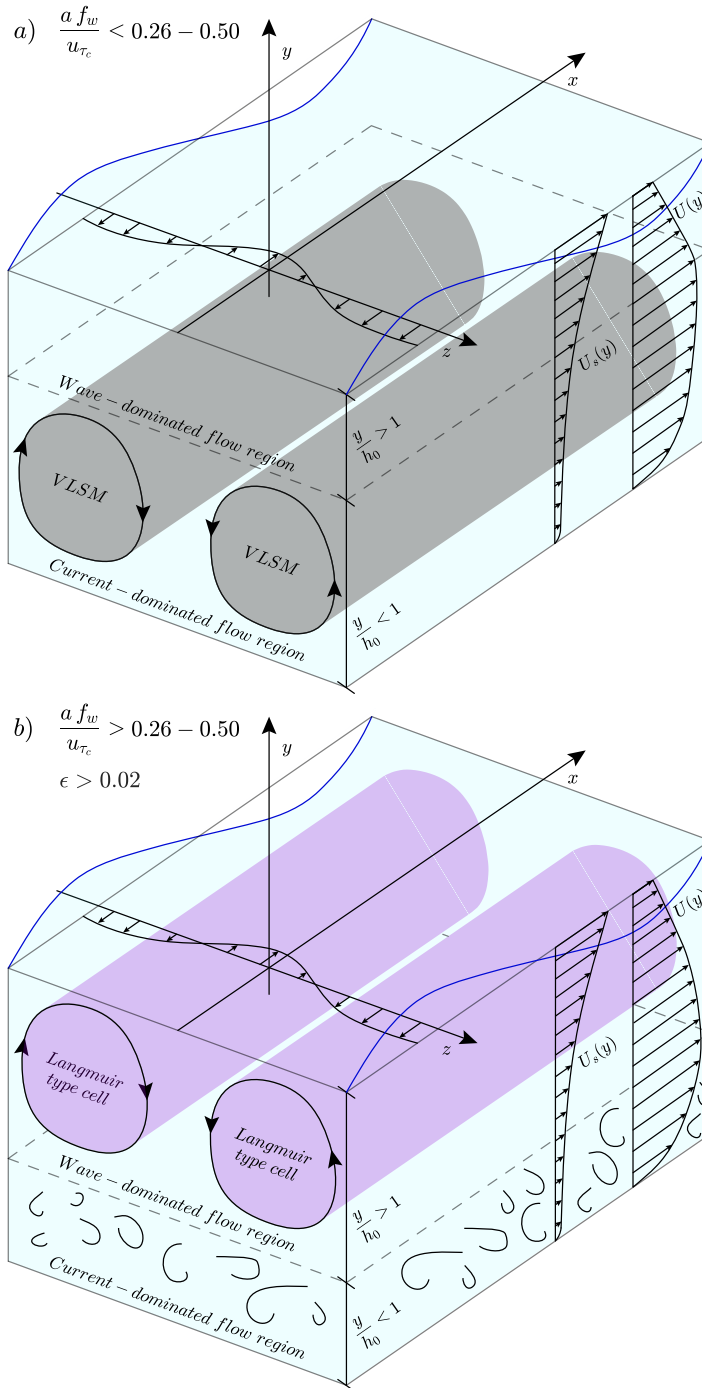


FIGURE 15. Representation of large-scale turbulence phenomenology in combined wave-current flows as observed in the present paper: (a) for cases where  $a f_w / u_{\tau_c} < 0.26 - 0.50$ ; (b) for cases where  $a f_w / u_{\tau_c} > 0.26 - 0.50$  and  $\epsilon > 0.02$ . The vertical profiles of the longitudinal mean velocity  $U$  and the Stokes drift  $U_s$  are not to scale.



795 0.50. Instead, according to Huang & Mei (2006), the presence of large-scale structures  
 796 in the wave-dominated region is controlled by wave steepness (i.e.  $\epsilon$  should exceed 0.02).  
 797 Nevertheless, for a wave-dominated region to exist also large values of  $a f_w/u_{\tau_c}$  are  
 798 required, so we expect that both non-dimensional parameters should be employed for  
 799 the diagnostics of Langmuir-type turbulence in combined wave-current flows. Figure 15  
 800 is a sketch where these concepts are graphically summarised. For low values of  $a f_w/u_{\tau_c}$   
 801 (panel a), the wave-dominated region is thin and VLSMs persist in the current-dominated  
 802 region. When  $a f_w/u_{\tau_c}$  attains higher values (panel b), VLSMs in the current-dominated  
 803 region vanish and, provided  $\epsilon > 0.02$ , Langmuir-type turbulence appears in the wave-  
 804 dominated region.

805 It is now worthy to recall some features pertaining to neutrally-stratified shallow-water  
 806 Langmuir turbulence, where Langmuir cells engulf the entire water column, impacting the  
 807 vertical mixing and the bottom boundary layer (Tejada-Martínez & Grosch 2007; Tejada-  
 808 Martínez *et al.* 2012; Sinha *et al.* 2015; Xuan *et al.* 2019; Deng *et al.* 2019, 2020). In this  
 809 circumstance, the current is wind-driven generated by surface stresses  $\tau_s$  (figure 16a). A  
 810 key dimensionless parameter to understand if the interaction between the wind-driven  
 811 shear current and the Stokes drift current induced by surface gravity waves is able to  
 812 generate Langmuir circulation (and the associated turbulence), is the turbulent Langmuir  
 813 number defined by McWilliams *et al.* (1997) as:

$$La_t = \sqrt{\frac{u_{\tau_{wind}}}{U_s(h)}} \quad (5.1)$$

814 i.e., it is the ratio between the friction velocity induced by the wind ( $u_{\tau_{wind}} = \sqrt{\tau_s/\rho}$ ,  
 815 where  $\rho$  is the water density) and the surface Stokes drift velocity  $U_s(h)$ . Following  
 816 Tejada-Martínez & Grosch (2007), the characteristic surface Stokes drift velocity is  
 817 defined as:

$$U_s(h) = \omega k a^2 = C \epsilon^2 \quad (5.2)$$

818 where  $C = \omega/k = L/T$  is the wave celerity. Considering the results coming from LES  
 819 simulations (Li *et al.* 2005; Sinha *et al.* 2015; Deng *et al.* 2019), the transition between  
 820 shear turbulence to Langmuir turbulence occurs for  $La_t < 1$ , i.e. when the wave motion  
 821 start to overcome the wind-induced current.

822 In our situation, Eq. 5.1 could not be straightforwardly used to verify the occurrence of  
 823 the Langmuir-type cells in the wave-dominate region since the shear turbulence is driven  
 824 by a different mechanism (figure 16b). In particular, since the turbulence is generated  
 825 at the bed, the shear velocity of the current is defined as  $u_{\tau_c} = \sqrt{\tau_0/\rho}$ , where  $\tau_0$  is  
 826 the bed shear stress. Thus, it is necessary to modify the  $La_t$  number with respect to  
 827 the type of current (wave-drive or pressure-driven) present in the flow. In the context  
 828 of pressure-driven currents, we introduce a slightly different turbulent Langmuir number  
 829  $La_t$  as:

$$La_t = \sqrt{\frac{u_{\tau_c}}{U_s(h)}} \quad (5.3)$$

830 To understand when the Langmuir-type cells represented in figure 15(a) start to occur,  
 831 we manipulate the two conditions previously identified, i.e.  $a f_w/u_{\tau_c} > 0.26 - 0.5$  and  
 832  $\epsilon > 0.02$ . Considering the term  $a f_w/u_{\tau_c}$ , it can be manipulated to obtain:

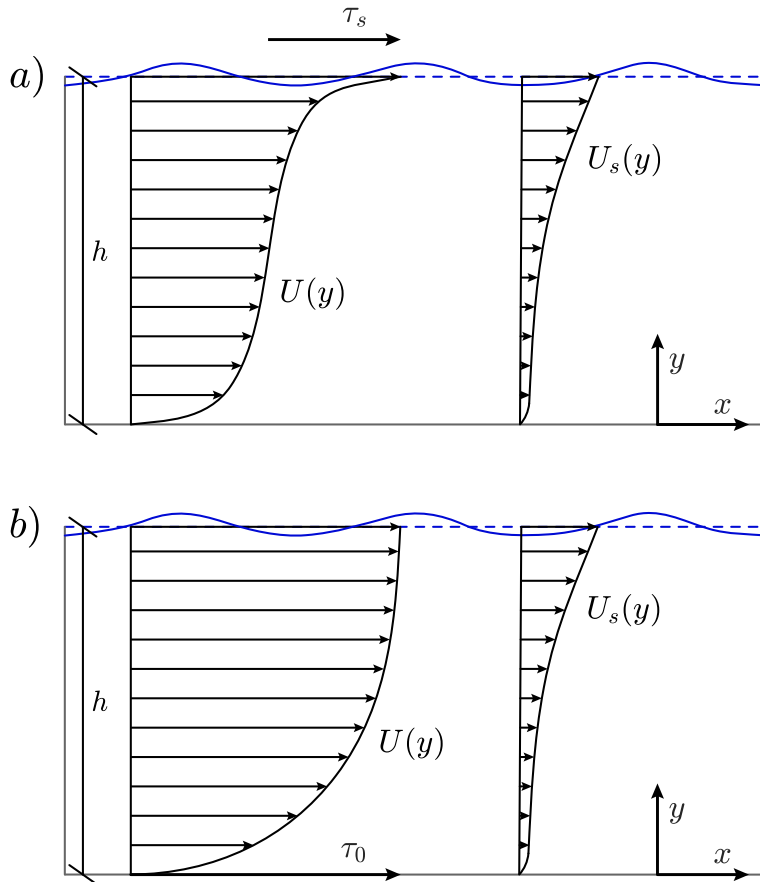


FIGURE 16. Surface gravity waves interacting with: (a) wind-driven current; (b) pressure-driven current. The vertical profiles of the longitudinal mean velocity  $U$  and the Stokes drift  $U_s$  are not to scale.

$$\frac{a f_w}{u_{\tau_c}} = \frac{a f_w C}{u_{\tau_c} C} = \frac{a C}{u_{\tau_c} L} = \frac{C \epsilon}{2\pi u_{\tau_c}} = \frac{C \epsilon^2}{2\pi \epsilon u_{\tau_c}} = \frac{1}{2\pi \epsilon La_t^2} \quad (5.4)$$

833 Introducing  $A = \begin{pmatrix} 0.26 \\ 0.50 \end{pmatrix}$ , the first condition can be rewritten as:

$$\frac{1}{\epsilon La_t^2} > 2\pi A \quad \longrightarrow \quad La_t < \sqrt{\frac{1}{2\pi \epsilon A}} \quad (5.5)$$

834 Assuming for simplicity  $\epsilon = 0.02$  (from the second condition), we finally obtain:

$$La_t < 4 - 5.53 \quad (5.6)$$

835 Interestingly, using the values reported in table 1 and table 2 to compute  $La_t$ , we obtain  
 836  $La_t = 8.18, 4.25, 2.88, 1.44, 0.96$  for cases from WC-T1 to WC-T5, respectively. It is  
 837 not surprisingly that the threshold range obtained in Eq. 5.6 is higher than 1 since  
 838  $u_{\tau_c}$  is evaluated at the wall and does not represent the actual balance of forces at the  
 839 free-surface between the wave motion and the current.

840 It is important to highlight that, in open-channel flume facilities the main source of  
 841 vertical vorticity is the boundary layers that develop at the sidewalls of the channel (Nepf

842 & Monismith 1991). Thus the formation of the Langmuir-type cells could be facilitated  
 843 with respect to a natural situation, where pressure-driven currents (e.g. tide currents)  
 844 interact with surface gravity waves in a less confined environment.

## 845 6. Conclusions

846 A new set of experiments featuring LDA velocity measurements was carried out in a  
 847 smooth-bed turbulent open-channel flow where surface waves with various frequency  $f_w$   
 848 and amplitude  $a$  were superimposed on a current.

849 Due to the irregularity of the wave motion generated within the experimental flume  
 850 facility, the separation of the turbulent and wave components from the original signal  
 851 was achieved by employing the Empirical Mode Decomposition (EMD), a data analysis  
 852 technique that is being increasingly used in coupled wave-currents flows and represents  
 853 a suitable technique for both laboratory and field applications (Schmitt *et al.* 2009; Qiao  
 854 *et al.* 2016), hence allowing for future data-set comparisons.

855 The experimental results presented in Section 4 provide an interesting picture about  
 856 turbulence in open-channel flows perturbed by following waves.

857 As surmised in the literature, but never really demonstrated, a genuine logarithmic-  
 858 overlap layer seems to occur in WC flows. This is corroborated by finding that, for a  
 859 range of elevations, mean velocity data collapse both in inner and outer scaling, provided  
 860 that the maximum velocity  $U_{max}$  of the profile and the elevation at which it occurs  
 861 ( $h_0$ ) are employed to define the velocity defect and the outer length-scale, respectively.  
 862 Interestingly,  $h_0$  also corresponds to the elevation where the Reynolds shear stress reduces  
 863 to zero, which endorses the hypothesis of  $h_0$  being a length-scale akin to a boundary layer  
 864 depth below which the flow scales similarly to canonical wall-flows. It follows that  $h_0$  can  
 865 be used to identify two flow regions: a current-dominated flow region in the lower part of  
 866 the water column ( $y/h_0 < 1$ ; figure 15), and a wave-dominated flow region in the upper  
 867 part ( $y/h_0 > 1$ ; figure 15).

868 The profiles of all Reynolds stresses in the current-dominated flow region display some  
 869 similarities with the profiles occurring in canonical wall flows even though they are not  
 870 free from wave effects. Similarities include the occurrence of a plateau in  $\sigma_{v'}/u_\tau$ , which  
 871 testifies the presence of attached eddies and, although indirectly, confirms the presence of  
 872 a genuine logarithmic layer as surmised from mean velocity profiles. Wave effects include  
 873 a reduction in Reynolds stress magnitude with respect to the CA case. The reduction  
 874 is more evident for  $\sigma_{v'}/u_\tau$  and  $-\overline{u'v'}/u_\tau^2$  than for  $\sigma_{u'}/u_\tau$ . Interestingly, the damping of  
 875  $\sigma_{v'}/u_\tau$  is found to be strongly correlated to the relative magnitude of wave velocities  
 876 with respect to turbulence, i.e. a parameter identified as  $a f_w/u_{\tau_c}$ , which therefore seems  
 877 to be a key non-dimensional parameter to characterise combined wave-current flows.  
 878 This is corroborated by the fact that the relative depth  $h_0/h$  correlates fairly well with  
 879  $a f_w/u_{\tau_c}$ . Indeed,  $h_0/h$  is found to reduce as  $a f_w/u_{\tau_c}$  increases, meaning that the current-  
 880 dominated flow region shrinks towards the bed, leaving space to an overlying region where  
 881 turbulence is controlled by wave motion, i.e. the wave-dominated flow region (figure 15).  
 882 A more in depth analysis of the data reveals that  $h_0$  corresponds to the elevation where  
 883 the vertical component of the waves' motion (as obtained from irrotational wave theories)  
 884 equals  $\sigma_{u'}$  of the CA case, which is a good proxy for the square root of the turbulent  
 885 kinetic energy (Pope 2000). The implication of this result is twofold: first, it suggests that  
 886 it is through vertical motion that waves compete with turbulence to dictate  $h_0$ ; second, it  
 887 provides a more general way to identify  $h_0$  which can be applicable also for flow conditions  
 888 displaying no maximum in the mean velocity profile (which was the criterion used herein)  
 889 as in the case of waves opposed to currents.

890 Spectral analysis provided important information about the structure of turbulence  
 891 in both current- and wave-dominated regions. Pre-multiplied spectra of the vertical  
 892 velocity component provided support for the existence of attached eddies in the current-  
 893 dominated region as inferred from the vertical profiles of  $\sigma_{v'}/u_{\tau}$ . The pre-multiplied  
 894 spectra related to the longitudinal velocity component reveal that, in the current-  
 895 dominated region, waves tend to suppress VLSMs, whereas in the wave-dominated region  
 896 low wavenumber peaks testifies the presence of large-scale structures akin to Langmuir  
 897 turbulence as theoretically derived by [Huang & Mei \(2006\)](#) and experimentally observed  
 898 by [Nepf & Monismith \(1991\)](#). It was also brought up a parallelism between Langmuir  
 899 turbulence, where the current is generated by the wind blowing on the free-surface and  
 900 our situation, where the current is generated by the presence of a pressure gradient.  
 901 In the latter case, a slightly modified turbulent Langmuir number  $La_t$  was introduced  
 902 to effectively discern when Langmuir-type cells start to populate the wave-dominated  
 903 region of the flow. Based on our data, the threshold was determined as  $La_t < 4 - 5.53$   
 904 (that is equivalent to the imposition of two conditions, i.e.  $af_w/u_{\tau_c} > 0.26 - 0.5$  and  
 905  $\epsilon > 0.02$ ). Ongoing work by the authors is currently dedicated to experimentally verify  
 906 this proposed pictorial view of turbulence in combined wave-current flows.

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## REFERENCES

- BAIDYA, R., PHILIP, J., HUTCHINS, N., MONTY, J. P. & MARUSIC, I. 2017 Distance-from-the-wall scaling of turbulent motions in wall-bounded flows. *Phys. Fluids* **29** (2), 020712.
- BANERJEE, T., MUSTE, M. & KATUL, G. 2015 Flume experiments on wind induced flow in static water bodies in the presence of protruding vegetation. *Adv. Water Resour.* **76**, 11–28.
- BELL, J. H. & MEHTA, R. D. 1988 Contraction design for small low-speed wind tunnels. *NASA STI/Recon Technical Report N* **89**, 13753.
- BENDAT, J. S. & PIERSOL, A. G. 2011 *Random data: Analysis and measurement procedures (IV Edition)*. John Wiley & Sons, New York City, New York, US.
- BENJAMIN, T. B. 1967 Instability of periodic wavetrains in nonlinear dispersive systems. *Proc. R. Soc. Lond. A* **299** (1456), 59–76.
- BENJAMIN, T. B. & FEIR, J. E. 1967 The disintegration of wave trains on deep water. Part 1. Theory. *J. Fluid. Mech.* **27** (3), 417–430.
- BLONDEAUX, P. 1987 Turbulent boundary layer at the bottom of gravity waves. *J. Hydraul. Res.* **25** (4), 447–464.
- BLONDEAUX, P. 2001 Mechanics of coastal forms. *Annu. Rev. Fluid Mech.* **33** (1), 339–370.
- CAMERON, S. M., NIKORA, V. I. & STEWART, M. T. 2017 Very-large-scale motions in rough-bed open-channel flow. *J. Fluid Mech.* **814**, 416–429.
- CARSTENSEN, S., SUMER, B. M. & FREDSE, J. 2010 Coherent structures in wave boundary layers. Part 1. oscillatory motion. *J. Fluid Mech.* **646**, 169–206.
- CLAUSER, F. H. 1956 The turbulent boundary layer. *Adv. Appl. Math.* **4**, 1–51.
- DAVIES, A. G., SOULSBY, R. L. & KING, H. L. 1988 A numerical model of the combined wave and current bottom boundary layer. *J. Geophys. Res.: Oceans* **93** (C1), 491–508.
- DE JESUS HENRIQUES, T. A., TEDDS, S. C., BOTSARI, A., NAJAFIAN, G., HEDGES, T. S.,

- SUTCLIFFE, C. J., OWEN, I. & POOLE, R. J. 2014 The effects of wave–current interaction on the performance of a model horizontal axis tidal turbine. *Int. J. Mar. Energy* **8**, 17–35.
- DE SOUZA MACHADO, A. A., SPENCER, K., KLOAS, W., TOFFOLON, M. & ZARFL, C. 2016 Metal fate and effects in estuaries: a review and conceptual model for better understanding of toxicity. *Sci. Total Environ.* **541**, 268–281.
- DEAN, R. G. & DALRYMPLE, R. A. 1991 *Water Wave Mechanics for Engineers and Scientists*. World Scientific, Singapore.
- DENG, B. Q., YANG, Z., XUAN, A. & SHEN, L. 2019 Influence of Langmuir circulations on turbulence in the bottom boundary layer of shallow water. *J. Fluid Mech.* **861**, 275–308.
- DENG, B. Q., YANG, Z., XUAN, A. & SHEN, L. 2020 Localizing effect of Langmuir circulations on small-scale turbulence in shallow water. *J. Fluid Mech.* **893**, A6.
- DOGAN, E., ÖRLÜ, R., GATTI, D., VINUESA, R. & SCHLATTER, P. 2019 Quantification of amplitude modulation in wall-bounded turbulence. *Fluid Dyn. Res.* **51** (1), 011408.
- DRAYCOTT, S., SELLAR, B., DAVEY, T., NOBLE, D. R., VENUGOPAL, V. & INGRAM, D. M. 2019 Capture and simulation of the ocean environment for offshore renewable energy. *Renew. Sust. Energ. Rev.* **104**, 15–29.
- DUAN, Y., CHEN, Q., LI, D. & ZHONG, Q. 2020 Contributions of very large-scale motions to turbulence statistics in open channel flows. *J. Fluid Mech.* **892**, A3.
- DYER, K. R. & SOULSBY, R. L. 1988 Sand transport on the continental shelf. *Annu. Rev. Fluid Mech.* **20** (1), 295–324.
- ESCUDIER, M. P., NICKSON, A. K. & POOLE, R. J. 2009 Turbulent flow of viscoelastic shear-thinning liquids through a rectangular duct: Quantification of turbulence anisotropy. *J. Nonnewton Fluid. Mech.* **160** (1), 2–10.
- FAGHERAZZI, S., EDMONDS, D. A., NARDIN, W., LEONARDI, N., CANESTRELLI, A., FALCINI, F., JEROLMACK, D. J., MARIOTTI, G., ROWLAND, J. C. & SLINGERLAND, R. L. 2015 Dynamics of river mouth deposits. *Rev. Geophys.* **53** (3), 642–672.
- FAGHERAZZI, S., KIRWAN, M. L., MUDD, S. M., GUNTENSPERGEN, G. R., TEMMERMAN, S., D’ALPAOS, A., VAN DE KOPPEL, J., RYBCZYK, J. M., REYES, E., CRAFT, C. & CLOUGH, J. 2012 Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Rev. Geophys.* **50** (1).
- FLANDRIN, P., RILLING, G. & GONCALVES, P. 2004 Empirical Mode Decomposition as a filter bank. *IEEE Signal Process. Lett.* **11** (2), 112–114.
- FRANCA, M. J. & BROCCINI, M. 2015 Turbulence in rivers. In *Rivers—Physical, Fluvial and Environmental Processes*, pp. 51–78. Springer-Verlag, Berlin/Heidelberg, Germany.
- FRANCALANCI, S., BENDONI, M., RINALDI, M. & SOLARI, L. 2013 Ecomorphodynamic evolution of salt marshes: Experimental observations of bank retreat processes. *Geomorphology* **195**, 53–65.
- FREDSØE, J., ANDERSEN, K. H. & SUMER, B. M. 1999 Wave plus current over a ripple-covered bed. *Coast. Eng.* **38** (4), 177–221.
- GAURIER, B., DAVIES, P., DEUFF, A. & GERMAIN, G. 2013 Flume tank characterization of marine current turbine blade behaviour under current and wave loading. *Renew. Energy* **59**, 1–12.
- GRANT, W. D. & MADSEN, O. S. 1979 Combined wave and current interaction with a rough bottom. *J. Geophys. Res.: Oceans* **84** (C4), 1797–1808.
- GREEN, M. O & COCO, G. 2014 Review of wave–driven sediment resuspension and transport in estuaries. *Rev. Geophys.* **52** (1), 77–117.
- GROSCH, C. E., WARD, L. W. & LUKASIK, S. J. 1960 Viscous dissipation of shallow water waves. *Phys. Fluids* **3** (3), 477–479.
- GUASTO, J. S., RUSCONI, R. & STOCKER, R. 2012 Fluid mechanics of planktonic microorganisms. *Annu. Rev. Fluid Mech.* **44**, 373–400.
- HACKETT, E. E., LUZNIK, L., NAYAK, A. R., KATZ, J. & OSBORN, T. R. 2011 Field measurements of turbulence at an unstable interface between current and wave bottom boundary layers. *J. Geophys. Res.: Oceans* **116** (C2).
- HEDGES, T. S. 1995 Regions of validity of analytical wave theories. In *Proc. of the Institution of Civil Engineers—Water, Maritime and Energy*, pp. 111–114.
- HUANG, N. E., SHEN, Z. & LONG, S. R. 1999 A new view of nonlinear water waves: the Hilbert spectrum. *Annu. Rev. Fluid Mech.* **31** (1), 417–457.

- HUANG, N. E., SHEN, Z., LONG, S. R., WU, M. C., SHIH, H. H., ZHENG, Q., YEN, N. C., TUNG, C. C. & LIU, H. H. 1998 The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc. R. Soc. Lond. A* **454** (1971), 903–995.
- HUANG, N. E., WU, M. C., LONG, S. R., SHEN, S. S. P., QU, W., GLOERSEN, P. & FAN, K. L. 2003 A confidence limit for the empirical mode decomposition and hilbert spectral analysis. *Proc. R. Soc. Lond. A* **459** (2037), 2317–2345.
- HUANG, Y. X., SCHMITT, F. G., LU, Z. M., FOUGAIROLLES, P., GAGNE, Y. & LIU, Y. L. 2010 Second-order structure function in fully developed turbulence. *Phys. Rev. E* **82** (2), 026319.
- HUANG, Y. X., SCHMITT, F. G., LU, Z. M. & LIU, Y. L. 2008 An amplitude-frequency study of turbulent scaling intermittency using empirical mode decomposition and Hilbert spectral analysis. *EPL* **84** (4), 40010.
- HUANG, Z. & MEI, C. C. 2003 Effects of surface waves on a turbulent current over a smooth or rough seabed. *J. Fluid Mech.* **497**, 253–287.
- HUANG, Z. & MEI, C. C. 2006 Wave-induced longitudinal vortices in a shallow current. *J. Fluid Mech.* **551**, 323–356.
- HUNT, J. N. 1952 Viscous damping of waves over an inclined bed in a channel of finite width. *Houille Blanche* pp. 836–842.
- HUSSAIN, A. K. M. F. & REYNOLDS, W. C. 1970 The mechanics of an organized wave in turbulent shear flow. *J. Fluid Mech.* **41** (2), 241–258.
- HUTCHINS, N. & MARUSIC, I. 2007 Evidence of very long meandering features in the logarithmic region of turbulent boundary layers. *J. Fluid Mech.* **579**, 1–28.
- ISAACSON, M. 1991 Measurement of regular wave reflection. *J. Waterw. Port, Coast. Ocean Eng.* **117** (6), 553–569.
- KEMP, P. H. & SIMONS, R. R. 1982 The interaction between waves and a turbulent current: waves propagating with the current. *J. Fluid Mech.* **116**, 227–250.
- KEMP, P. H. & SIMONS, R. R. 1983 The interaction of waves and a turbulent current: waves propagating against the current. *J. Fluid. Mech.* **130**, 73–89.
- KLOPMAN, G. 1994 Vertical structure of the flow due to waves and currents – Laser-Doppler flow measurements for waves following or opposing a current. *Progress Report No. H840-30, Part II, for Rijkswaterstaat (Tidal Hydraulic Division)* .
- LEI, Y., LIN, J., HE, Z. & ZUO, M. J. 2013 A review on empirical mode decomposition in fault diagnosis of rotating machinery. *Mech. Syst. Signal. Process.* **35** (1-2), 108–126.
- LI, M., GARRETT, C. & SKYLLINGSTAD, E. 2005 A regime diagram for classifying turbulent large eddies in the upper ocean. *Deep Sea Res. Part I Oceanogr. Res. Pap.* **52** (2), 259–278.
- LODAHL, C. R., SUMER, B. M. & FREDSSØE, J. 1998 Turbulent combined oscillatory flow and current in a pipe. *J. Fluid Mech.* **373**, 313–348.
- MADSEN, O. S. & GRANT, W. D. 1976 Quantitative description of sediment transport by waves. In *Proc. 15th Int. Conf. Coast. Eng.*, pp. 1092–1112.
- MANES, C., POGGI, D. & RIDOLFI, L. 2011 Turbulent boundary layers over permeable walls: scaling and near-wall structure. *J. Fluid Mech.* **687**, 141–170.
- MARINO, M., RABIONET, I. C., MUSUMECI, R. E. & FOTI, E. 2018 Reliability of pressure sensors to measure wave height in the shoaling region. *Proc. 36th Int. Conf. Coast. Eng.* (36), 10–10.
- MARUSIC, I., MCKEON, B. J., MONKEWITZ, P. A., NAGIB, H. M., SMITS, A. J. & SREENIVASAN, K. R. 2010 Wall-bounded turbulent flows at high reynolds numbers: recent advances and key issues. *Phys. Fluids* **22** (6), 065103.
- MCWILLIAMS, J. C., SULLIVAN, P. P. & MOENG, C. H. 1997 Langmuir turbulence in the ocean. *J. Fluid Mech.* **334**, 1–30.
- MONISMITH, S. G. 2020 Stokes drift: theory and experiments. *J. Fluid Mech.* **884**, F1.
- MYRHAUG, D. 1984 A theoretical model of combined wave and current boundary layers near a rough sea bottom. In *Proc. 3rd Offshore Mechanics and Arctic Eng.*, pp. 559–568.
- NAGIB, H. M. & CHAUHAN, K. A. 2008 Variations of von Kármán coefficient in canonical flows. *Phys. Fluids* **20** (10), 101518.
- NAYAK, A. R., LI, C., KIANI, B. T. & KATZ, J. 2015 On the wave and current interaction with

- a rippled seabed in the coastal ocean bottom boundary layer. *J. Geophys. Res.: Oceans* **120** (7), 4595–4624.
- NEPF, H. M. & MONISMITH, S. G. 1991 Experimental study of wave-induced longitudinal vortices. *J. Hydraul. Eng.* **117** (12), 1639–1649.
- NEZU, I. & NAKAGAWA, H. 1993 *Turbulence in Open-Channel Flows*. A. A. Balkema, Rotterdam, The Netherlands.
- NICKELS, T. B., MARUSIC, I., HAFEZ, S., HUTCHINS, N. & CHONG, M. S. 2007 Some predictions of the attached eddy model for a high reynolds number boundary layer. *Philos. Trans. R. Soc. A* **365** (1852), 807–822.
- NIELSEN, P. 1992 *Coastal Bottom Boundary Layers and Sediment Transport*. World Scientific, Singapore.
- NIKORA, V. I. & GORING, D. 2000 Eddy convection velocity and Taylor’s hypothesis of ‘frozen’ turbulence in a rough-bed open-channel flow. *J. Hydrosoci. Hydraul. Engng.* **18** (2), 75–91.
- NOBLE, D. R., DRAYCOTT, S., NAMBIAR, A., SELLAR, B. G., STEYNOR, J. & KIPRAKIS, A. 2020 Experimental assessment of flow, performance, and loads for tidal turbines in a closely-spaced array. *Energies* **13** (8), 1977.
- OLABARRIETA, M., MEDINA, R. & CASTANEDO, S. 2010 Effects of wave–current interaction on the current profile. *Coast. Eng.* **57** (7), 643–655.
- PERUZZI, C. 2020 Turbulence properties of smooth-bed open-channel flows with and without collinear gravity waves. PhD thesis, Politecnico di Torino.
- PERUZZI, C., POGGI, D., RIDOLFI, L. & MANES, C. 2020 On the scaling of large-scale structures in smooth-bed turbulent open-channel flows. *J. Fluid Mech.* **889**, A1.
- POGGI, D., PORPORATO, A. & RIDOLFI, L. 2002 An experimental contribution to near-wall measurements by means of a special Laser Doppler Anemometry technique. *Exp. Fluids* **32** (3), 366–375.
- POGGI, D., PORPORATO, A. & RIDOLFI, L. 2003 Analysis of the small-scale structure of turbulence on smooth and rough walls. *Phys. Fluids* **15** (1), 35–46.
- POPE, S. B. 2000 *Turbulent flows*. IOP Publishing, Bristol, UK.
- QIAO, F., YUAN, Y., DENG, J., DAI, D. & SONG, Z. 2016 Wave–turbulence interaction-induced vertical mixing and its effects in ocean and climate models. *Phil. Trans. R. Soc. Lond. A* **374** (2065), 20150201.
- RATO, R. T., ORTIGUEIRA, M. D. & BATISTA, A. G. 2008 On the HHT, its problems, and some solutions. *Mech. Syst. Signal. Process.* **22** (6), 1374–1394.
- ROBINSON, A., INGRAM, D., BRYDEN, I. & BRUCE, T. 2015 The effect of inlet design on the flow within a combined waves and current flumes, test tank and basins. *Coast. Eng.* **95**, 117–129.
- ROY, S., DEBNATH, K. & MAZUMDER, B. S. 2017 Distribution of eddy scales for wave current combined flow. *Appl. Ocean Res.* **63**, 170–183.
- ROY, S., SAMANTARAY, S. S. & DEBNATH, K. 2018 Study of turbulent eddies for wave against current. *Ocean Eng.* **150**, 176–193.
- SCHMITT, F. G., HUANG, Y. X., LU, Z. M., LIU, Y. L. & FERNANDEZ, N. 2009 Analysis of velocity fluctuations and their intermittency properties in the surf zone using empirical mode decomposition. *J. Mar. Syst.* **77** (4), 473–481.
- SELLAR, B. G., WAKELAM, G., SUTHERLAND, D. R. J., INGRAM, D. M. & VENUGOPAL, V. 2018 Characterisation of tidal flows at the european marine energy centre in the absence of ocean waves. *Energies* **11** (1), 176.
- SHAW, W. J. & TROWBRIDGE, J. H. 2001 The direct estimation of near-bottom turbulent fluxes in the presence of energetic wave motions. *J. Atmos. Ocean. Technol.* **18** (9), 1540–1557.
- SINGH, S. K. & DEBNATH, K. 2016 Combined effects of wave and current in free surface turbulent flow. *Ocean Eng.* **127**, 170–189.
- SINHA, N., TEJADA-MARTÍNEZ, A. E., AKAN, C. & GROSCH, C. E. 2015 Toward a K-profile parameterization of Langmuir turbulence in shallow coastal shelves. *J. Phys. Oceanogr.* **45** (12), 2869–2895.
- SOULSBY, R. L., HAMM, L., KLOPMAN, G., MYRHAUG, D., SIMONS, R. R. & THOMAS, G. P. 1993 Wave-current interaction within and outside the bottom boundary layer. *Coast. Eng.* **21** (1-3), 41–69.



- SUMER, B. M. 2014 Flow–structure–seabed interactions in coastal and marine environments. *J. Hydraul. Res.* **52** (1), 1–13.
- SUMER, B. M., PETERSEN, T. U., LOCATELLI, L., FREDSSØE, J., MUSUMECI, R. E. & FOTI, E. 2013 Backfilling of a scour hole around a pile in waves and current. *J. Waterw. Port Coast. Oc. Eng.* **139** (1), 9–23.
- TABRIZI, A. A., GARIBALDI, L., FASANA, A. & MARCHESIELLO, S. 2014 Influence of stopping criterion for sifting process of empirical mode decomposition (EMD) on roller bearing fault diagnosis. In *Advances in Condition Monitoring of Machinery in Non-Stationary Operations*, pp. 389–398. Springer-Verlag, Berlin/Heidelberg, Germany.
- TAMBRONI, N., BLONDEAUX, P. & VITTORI, G. 2015 A simple model of wave–current interaction. *J. Fluid Mech.* **775**, 328–348.
- TAYLOR, G. I. 1938 The spectrum of turbulence. *Proc. R. Soc. Lond. A* **164** (919), 476–490.
- TEJADA-MARTÍNEZ, A. E. & GROSCH, C. E. 2007 Langmuir turbulence in shallow water. Part 2. Large-eddy simulation. *J. Fluid Mech.* **576**, 63.
- TEJADA-MARTÍNEZ, A. E., GROSCH, C. E., SINHA, N., AKAN, C. & MARTINAT, G. 2012 Disruption of the bottom log layer in large-eddy simulations of full-depth Langmuir circulation. *J. Fluid Mech.* **699**, 79–93.
- UMEYAMA, M. 2005 Reynolds stresses and velocity distributions in a wave–current coexisting environment. *J. Waterw. Port Coast. Oc. Eng.* **131** (5), 203–212.
- UMEYAMA, M. 2009a Changes in turbulent flow structure under combined wave–current motions. *J. Waterw. Port Coast. Oc. Eng.* **135** (5), 213–227.
- UMEYAMA, M. 2009b Mean velocity changes due to interaction between bichromatic waves and a current. *J. Waterw. Port Coast. Oc. Eng.* **135** (1), 11–23.
- VAN HOF TEN, J. D. A. & KARAKI, S. 1976 Interaction of waves and a turbulent current. In *Proc. 15th Int. Conf. Coast. Eng.*, pp. 404–422.
- VETTORI, D. 2016 Hydrodynamic performance of seaweed farms: an experimental study at seaweed blade scale. PhD thesis, University of Aberdeen.
- XUAN, A., DENG, B. Q. & SHEN, L. 2019 Study of wave effect on vorticity in Langmuir turbulence using wave–phase–resolved large-eddy simulation. *J. Fluid Mech.* **875**, 173–224.
- YAGLOM, A. M. 1979 Similarity laws for constant–pressure and pressure–gradient turbulent wall flows. *Annu. Rev. Fluid Mech.* **11** (1), 505–540.
- YUAN, J. & MADSEN, O. S. 2015 Experimental and theoretical study of wave–current turbulent boundary layers. *J. Fluid Mech.* **765**, 480–523.
- ZAMPIRON, A., CAMERON, S. & NIKORA, V. I. 2020 Secondary currents and very–large–scale motions in open–channel flow over streamwise ridges. *J. Fluid Mech.* **887**, A17.
- ZHANG, X. & SIMONS, R. R. 2019 Experimental investigation on the structure of turbulence in the bottom wave–current boundary layers. *Coast. Eng.* **152**, 103511.