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1 **Numerical modelling of three-dimensional**  
2 **wave-current interactions in complex**  
3 **environment : application to Alderney Race**

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16 Modelling three-dimensional wave-current-turbulence interactions in extreme tidal environ-  
17 ments is still challenging and necessary for the development of the tidal industry, particularly  
18 for the dimensioning of tidal converters. Following this objective, we focus our study on the  
19 most energetic tidal site in Western Europe, the Alderney Race (France). Due to the strong  
20 tidal current at this location, wave-current interactions were poorly studied by the past and  
21 often neglected. We propose to assess how they impact the Alderney Race hydrodynamic by  
22 the use of numerical modelling and in-situ measurements. In this study, the following wave-  
23 current interactions were observed : i) Stokes drift effects inducing an increase/decrease in  
24 the current depending on the angle between waves and current, with a maximum influence  
25 near the surface, ii) wave enhancement of the bottom friction reducing the tidal current,  
26 iii) refraction of waves by the current, generating changes in waves directions, and iv) wave  
27 breaking ascribed to tidal current, increasing the turbulent mixing. A non-stationary time  
28 delay, varying within a same tidal cycle, was noted, which is reduced by including the local  
29 wind effects and by adjusting the bottom stress formulation. This study shows that wave-  
30 current interactions play a non-negligible role in Alderney Race although the strong tidal  
31 current and that they need to consider by the tidal industry.

# 1. Introduction

Marine renewable energies represent an alternative to fossil energies, which contribute to climate change. Ocean energy from tidal currents has a great potential throughout the world, because the currents are reliable and predictable and could be strong enough for industrial exploitation (e.g. Lynn 2013). In addition, the visual impact of tidal stream devices are limited in comparison to offshore wind farms or some wave energy converters. However, installation and maintenance of tidal converters are more complex than for other technologies due to the particular hydrodynamic conditions of tidal sites. Ocean tidal energy is considered economically feasible for water depths shallower than 50 meters and a flow velocity larger than 2.5 m/s (e.g. Lewis et al. 2015). A key point for the development of tidal energy is resource characterisation, which includes tidal site selection, possible modifications of the hydro-sedimentary environment induced by turbines and the impact of sediment transport on devices.

The most energetic tidal site in Western Europe is the Alderney Race, located in France, between La Hague Cape and Alderney Island, with tidal current reaching 5 m/s during spring tide (e.g. Bahaj and Myers 2004). Field measurements by velocity profilers were conducted in the past to estimate the hydrodynamic resources of the Alderney Race (e.g. Thiebault et al. 2019), but complex conditions generally led to loss or breakage of scientific devices making it very difficult to complete the measurements. Radio-oceanography, with High Frequency (HF) or/and Very High Frequency (VHF) and/or X-band radars, is a relevant option to obtain real-time spatialised measurements of flow velocity and ocean wave characteristics (e.g. Lopez et al. 2019). Numerical modelling is a useful alternative to estimate tidal resources. Because the circulation is primarily driven by astronomical tides, it can be computed with a barotropic model forced by tidal components at its open boundaries (Thiebot et al. 2015). The design of tidal energy converters, however, requires knowledge of the vertical structure of flow velocity in order to assess material fatigue issues and correct assessment of the energy production. Vertical profile depends on tide, as well as on ocean waves, marine turbulence and hydrodynamic interactions. A three-dimensional (3D) fully-coupled wave-current model with an accurate modelling of turbulent mixing is therefore required.

Most of sites that are suitable for tidal converters, including Alderney Race in Normandy (France) and Fromveur in Brittany (France), are influenced by surface waves, that modify the vertical shear of ocean velocity. Major modifications occur near the surface and up to a depth of about one half wavelength, but also near the bottom mainly within the wave and current bottom boundary layers (e.g. Nielsen 1992). Near-surface, ocean velocity may be reduced or accelerated depending on the angle between wave direction and tidal current due to Stokes drift effects (e.g. Kemp and Simons 1983, 1982; Groeneweg and Klopman 1998). Ocean waves also change the vertical shear of the turbulent quantities because of wave-enhancement of

69 turbulence in the bottom boundary layer and near the surface (e.g Grant and Madsen 1979;  
70 Burchard 2001). Grant and Madsen (1979) proposed a time-invariant two-layer turbulent  
71 model to take into account the wave effects on the turbulence level near and beyond the  
72 bottom. Following the same idea, many studies have proposed different formulations for the  
73 time-invariant turbulent eddy viscosity (e.g. Christoffersen and Jonsson 1985; Sleath 1991).  
74 In the upper ocean, changes in turbulence levels due to waves are mainly caused by wave  
75 breaking and Langmuirs circulations (e.g. Agrawal et al. 1992; Craik and Leibovich 1976).

76 Lewis et al. (2017) and Thiebault and Sentchev (2017) explain that the vertical shear  
77 of the ocean velocity in tidal areas follows a power law in some cases. However, Lewis  
78 et al. (2017) highlight high variability in vertical shear, showing the necessity to improve  
79 our understanding of the hydrodynamic processes that cause this variability. Togneri et al.  
80 (2017) explain that the well-known turbulent closure  $k - \epsilon$  without modifications to include  
81 wave effects fails to reproduce the vertical structure of turbulent quantities. They observe  
82 an underestimate of turbulent kinetic energy while turbulent dissipation is overestimated.  
83 Guillou et al. (2016), Lewis et al. (2014) and Hashemi et al. (2015) have studied the influence  
84 of surface waves on the tidal energy estimate. On the whole, they found 10 – 20% variation  
85 due to waves, depending on the angle between the tidal current and surface waves. However,  
86 these earlier studies are idealised : Guillou et al. (2016) used three-dimensional radiation  
87 stresses that are constant over the depth, because they were in shallow waters. In addition,  
88 in the latter study, the real case of the Iroise Sea is treated but vertical shear of the ocean flow  
89 is not discussed. Lewis et al. (2014) employ the COASWT model (Warner et al. 2010) with  
90 three-dimensional radiation stresses of Mellor (2015), which are debated by Arduin et al.  
91 (2017) and Mellor (2017), and study an idealised case of a 3D wave-induced flow propagating  
92 over a seamount. Hashemi et al. (2015) simulate the real case of the tidal site off the north-  
93 western coast of Anglesey Island (Wales, UK), with the inclusion of wave effects, but these  
94 simulations are two-dimensional (depth-integrated). Therefore, 3D effects were not taken  
95 into account.

96 Ocean waves also influence the bottom friction because they modify the turbulence level  
97 near the bottom, particularly inside the wave bottom boundary layer. Grant and Madsen  
98 (1979) have conceptualised these processes by a large apparent roughness. Many laboratory  
99 and in-situ measurements (e.g Mathisen and Madsen 1996b,a) have supported this concept.  
100 Mathisen and Madsen (1999) added the streaming effects to the original form of the apparent  
101 roughness model established by Grant and Madsen (1979). Parameterised approaches based  
102 on the outputs of these studies have also been developed to formulate the bottom shear  
103 stress under waves and current action (e.g. Soulsby et al. 1993; Holmedal et al. 2000) and  
104 are widely used by the scientific community when numerical models are not able to explicitly  
105 resolve these interactions.

106 We propose to extend the existing studies by performing realistic 3D simulations with a  
107 fully-coupled wave-current model (Bennis et al. 2011, 2014, 2016, 2018) in order to unders-  
108 tand, how ocean waves and tidal current interact in Alderney Race. The data and methods  
109 are described in Section 2 as follows : 2a. Study site and in-situ data, 2b. Numerical mo-  
110 delling, 2c. Details on coupling procedure and set-up, and 2d. Description of the numerical  
111 experiments. Results are shown and discussed in Section 3 which is divided into four parts :  
112 3a. Tidal elevation, 3b. Sea states, 3c. Time series of the tidal stream velocity, and 3d.  
113 Vertical structure of the tidal stream velocity. Conclusions are drawn in Section 4.

## 114 2. Data and Methods

### 115 a. Study Site and Data Collection

116 Alderney Race is located inside the English Channel (hereinafter EC) between the Al-  
117 derney Island and La Hague Cape along the French coast, with a depth of 25-65 m (see  
118 Figure 1a). Due to the proximity of the Cherbourg harbour and its facilities, that facilitates  
119 marine operations, companies are interested in installing of marine currents turbines (MCTs)  
120 to produce electricity from tidal current. Alderney Race is a mega-tidal environment (e.g.  
121 Dauvin 2015), with a mean spring tidal range varying from 6 to 11 m from the north to the  
122 south of La Hague Cape (about 5 km between Anse de Saint Martin :  $49^{\circ}42'30''$  N/ $1^{\circ}53'0''$  W  
123 and Herqueville :  $49^{\circ}40'06''$  N/ $1^{\circ}52'34''$  W) and with a strong tidal asymmetry due to the  
124 interactions between tidal flow and bathymetry (see Figure 1b). The particular geometry of  
125 the Alderney Race, with the short distance, around 12 kms, between Alderney Island and  
126 La Hague Cape, generates a channel effect that accelerates the tidal flow up to 5 m/s during  
127 spring tides. The maximum mean potential power is estimated to be 5.1 GW (Coles et al.  
128 2017). For comparison, this represents half of the French tidal resource (Bahaj and Myers  
129 2004) and is 35% higher than the potential power of Pentland Firth, the best tidal site in  
130 United Kingdom.

131 Swells from the Atlantic Ocean propagate through the EC, mainly in the western part  
132 because they are often stopped by the Cotentin peninsula. Alderney Race, located west of  
133 this peninsula, though protected by the Alderney Island, is influenced by swells (e.g. Lopez  
134 et al. 2018). The dominant winds in La Hague Cape are south-west or west, with wind velo-  
135 city stronger than 16 m/s about 130 days per year according to the French Weather Service  
136 (Météo-France). Thus, Alderney Race sea states are often complex, with superposition of  
137 swells and wind-seas. Maisondieu (2016) performed statistical analyses based on the HO-  
138 MERE database (Boudiere et al. 2013) for the period between 2003 and 2012. The results  
139 were : i) about 40% of sea states had at least 3 swells, ii) about 30% of sea states had at  
140 least 2 swells and 1 wind-sea, and iii) about 20% of sea states have at least 1 swell and 1

141 wind-sea. Furthermore, a chaotic sea was observed when the tidal current and wind direc-  
142 tions were opposite, with wave heights of about 4 m and wavelengths shorter than 50 metres.  
143 Complex sea states also occurred and were recorded during the HYD2M experiments, with  
144 significant wave heights of about 8 m. Wave breaking is often observed in Alderney Race  
145 due to the interactions between waves and the tidal current, leading to the French name  
146 'Raz Blanchard' (In English : 'White Race', named for the frequent white caps in this area).  
147 High energy marine turbulent structures are present in Alderney Race because of the very  
148 rough nature of the seabed, which leads to the ejection of turbulent cells from the bottom  
149 to the surface (Mercier 2019). These structures, a few tens of meters in length, are 3D and  
150 visible to the naked eye. They interact with the tidal current and ocean waves. Moreover, the  
151 bathymetry is very uneven with features and faults acting as several metre height barriers  
152 to the flow (Furgerot et al. 2019). The bottom sedimentology is strongly heterogeneous with  
153 sand, pebbles and large rocks (e.g. Larsonneur et al. 1982; Foveau et al. 2017; Furgerot et al.  
154 2019).

155 ADCP data were collected by the HYD2M consortium (ADCP) in 2017 (see Figure 1a,  
156 yellow cross), using a bottom-mounted 500 kHz Teledyne RDI Sentinel V50. ADCP was  
157 located at  $49^{\circ}40'50.00''\text{N}/2^{\circ}01'46.44''\text{W}$ . The estimated mean depth was about 35 m. The  
158 bin size was 1 m and the lowest cell was 2 m above the seabed. ADCP data were collec-  
159 ted from 14 October 2017 to 26 February 2018, but only days in the period of 21 to 25  
160 November 2017 are considered here. ADCP recorded ocean wave characteristics in addi-  
161 tion to measurements of vertical profile of the three components of the flow velocity. All  
162 ADCP data were 15 min-averaged. This means that high frequency variations, particularly  
163 due to turbulence, were not taken into account in this study, but were presented in Furgerot  
164 et al. (2018). Data from Met-Office wave buoys (62103 and 62027), available on EMOD-  
165 net platform (<http://www.emodnet.eu>), were also used to validate the wave model, but  
166 comparison plots are not shown here. The simulated mean sea level was tested against mea-  
167 surements of Shom tidal gauges installed in Cherbourg (TG1, recordings from 1943 to now)  
168 and Dièlette (TG2, recordings from 2015 to now). Data are downloadable via the datas-  
169 hom portal (<https://data.shom.fr>). Tidal gauge locations are marked in black on Figure 1a.  
170 Wind data were collected by Gourey Semaphore, that is located 7 km apart ADCP point, at  
171 10 meters above ground level.

172 The studied time period is representative of typical conditions in Alderney Race, except  
173 for extreme events. The met-oceanic conditions were : i) a tidal range between 4 and 7 m,  
174 ii) a tidal current varying from 0.2 m/s to 3 m/s, iii) a significant wave height ranging from  
175 0.5 m - 4.5 m (with wind-waves and swells), and iv) a wind speed less than 18 m/s.

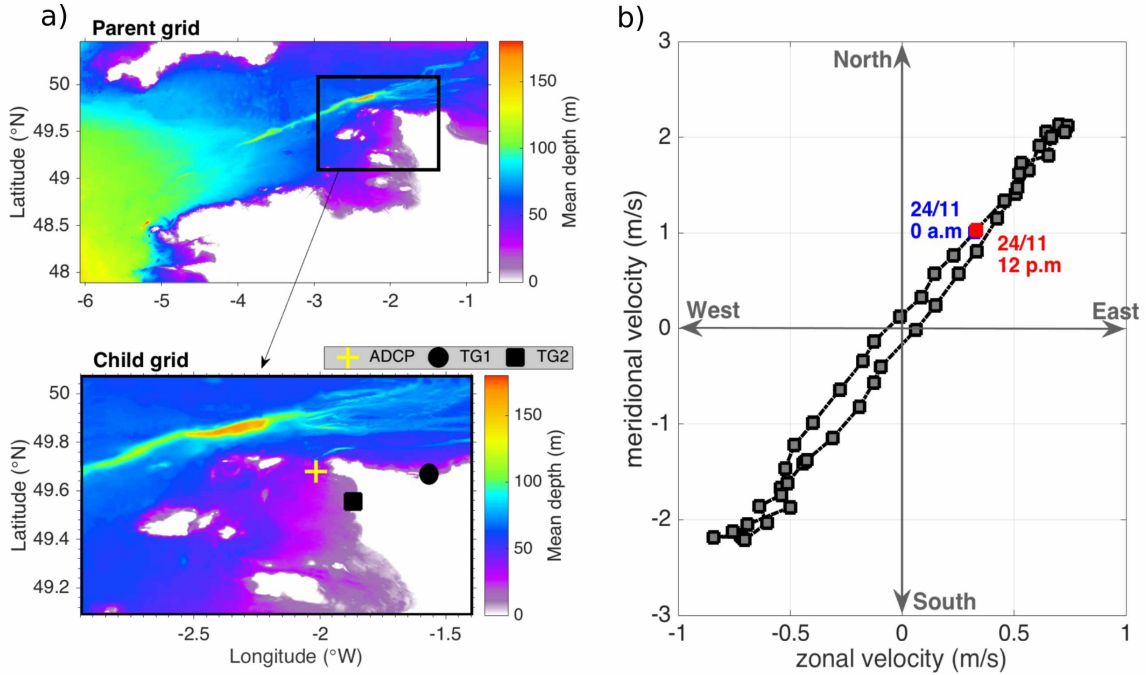


FIGURE 1: (a) ADCP (yellow cross) and tidal gauges (TG1 and TG2 in black circle and square, respectively) over the mean depth (colour scale). (b) Current hodograph for a 12-hour time period on 24 November 2017 between 0 a.m. (blue square) and 12 p.m. (red square).

## 177 *b. Numerical Modelling Strategy*

178 Our modelling system couples a 3D ocean model, MARS3D v10 (Lazure and Dumas  
 179 2008), and the spectral wave model, WAVEWATCH III v4.08 (hereinafter WW3, Tolman  
 180 and al. 2014). The wave-driven circulation is computed according to Arduin et al. (2008b)  
 181 and Bennis et al. (2011). Wave forcing is based on the vortex force method which has been  
 182 mainly validated for surf zone and also at coastal scales (e.g. Michaud et al. 2012; Moghimi  
 183 et al. 2013; Bennis et al. 2014; Delpey et al. 2014; Bennis et al. 2016). This method consi-  
 184 ders the mean flow, represented by the quasi-Eulerian velocity (ie. the Lagrangian velocity  
 185 minus the Stokes drift), rather than the total momentum, which removes the tricky problem  
 186 of modelling the vertical flux of momentum (Arduin et al. 2008a). The generic formula-  
 187 tion of momentum equations for a wave-forced, three-dimensional, incompressible, unsteady,  
 188 hydrostatic, constant-density flow is :

$$189 \quad \frac{D\hat{\mathbf{U}}}{Dt} = \mathbf{S}_{\text{EPG}} + \mathbf{S}_{\text{VM}} + \mathbf{S}_{\text{HM}} + \mathbf{S}_{\text{WP}} + \mathbf{S}_{\text{BA}} + \mathbf{S}_{\text{BBL}} + \mathbf{S}_{\text{VF}}, \quad (1)$$

190 where  $\hat{\mathbf{U}} = (\hat{U}, \hat{V}, \hat{W})$  is the 3D quasi-Eulerian velocity. The source terms  $\mathbf{S}_{\text{EPG}}$ ,  $\mathbf{S}_{\text{VM}}$ ,



191  $\mathbf{S}_{HM}$ ,  $\mathbf{S}_{BA}$ ,  $\mathbf{S}_{BBL}$ ,  $\mathbf{S}_{VF}$ ,  $\mathbf{S}_{WP}$  are related to the external pressure gradient, the vertical  
 192 mixing, the horizontal mixing, the breaking acceleration, the streaming, the vortex force and  
 193 the wave-induced pressure gradient, respectively. Wave-induced forcing terms are mainly the  
 194 vortex force, the Bernoulli Head, the forces induced by the wave-to-ocean momentum flux,  
 195 the wave-induced mixing and the wave-bottom interactions when the wave bottom boundary  
 196 layer is solved. These terms influence source terms of (1) (more details in Bennis et al. 2011).  
 197 This set of equations is compatible with that of McWilliams et al. (2004) used in Uchiyama  
 198 et al. (2010) and Kumar et al. (2012).

199 Horizontal mixing is grid-spacing dependent as in Smagorinsky (1963) with horizontal  
 200 viscosity ( $\nu_H$ ) defined as  $\nu_H = f_{visc} \cdot 0.01 \cdot (\Delta_{xy})^{1.15}$ , where  $\Delta_{xy}$  is the horizontal grid spacing  
 201 and  $f_{visc}$  is a user defined parameter (Okubo 1971).

202 The well-known k- $\epsilon$  turbulent scheme, modified according to Walstra et al. (2000) to  
 203 include ocean wave effects, is used for the vertical mixing :

$$\frac{\partial k}{\partial t} = \frac{1}{D^2} \cdot \frac{\partial}{\partial \zeta} \left( \frac{\nu_V}{s_k} \cdot \frac{\partial k}{\partial \zeta} \right) - \frac{\partial k}{\partial \zeta} \cdot \frac{\partial \zeta}{\partial t} + \text{Prod} + \text{Buoy} - \epsilon + \mathcal{P}_k, \quad (2)$$

$$\frac{\partial \epsilon}{\partial t} = \frac{1}{D^2} \cdot \frac{\partial}{\partial \zeta} \left( \frac{\nu_V}{s_\epsilon} \cdot \frac{\partial \epsilon}{\partial \zeta} \right) - \frac{\partial \epsilon}{\partial \zeta} \cdot \frac{\partial \zeta}{\partial t} + \frac{\epsilon}{k} (c_1 \text{Prod} + c_3 \text{Buoy}) + \mathcal{P}_\epsilon. \quad (3)$$

204 where  $k$  is the turbulent kinetic energy and  $\epsilon$  is the turbulent dissipation.  $\nu_V$  is the vertical  
 205 viscosity and depends on both mixing length and turbulent kinetic energy. Coefficients  $c_1$ ,  
 206  $c_3$ ,  $s_k$  and  $s_\epsilon$  are set according to Warner et al. (2005). Prod and Buoy terms represent the  
 207 turbulent production by shear and buoyancy, respectively. Equations (2) and (3) differ from  
 208 the classic ones : two source terms ( $\mathcal{P}_k$  and  $\mathcal{P}_\epsilon$ ) were added to include the mixing effects  
 209 relating to the bottom friction and wave breaking. At the surface, we preferred to use the  
 210 Dirichlet boundary conditions of Kantha and Clayson (2004), because they are based on  
 211 friction velocity, rather than the conditions of Walstra et al. (2000). Turbulent source terms  
 212 depend on wave energy dissipated by bottom friction and wave breaking, near-bottom wave  
 213 orbital velocity and wave bottom boundary layer thickness. They are linearly distributed  
 214 over a characteristic depth, that is equal to the root mean square significant wave height  
 215 divided by two near the surface and to the bottom boundary layer thickness near the bed  
 216 (more details in Walstra et al. 2000). While other distributions, e.g. trigonometric functions,  
 217 have been tested, only marginal differences have been noted.

Bottom friction and its enhancement by surface waves is parameterised with the formu-  
 lation of Soulsby (1995), such that the bottom stress ( $\tau_b$ ) is :

$$\tau_b = |\mathcal{T}_c| \cdot \left[ 1 + 1.2 \left( \frac{|\mathcal{T}_w|}{|\mathcal{T}_w| + |\mathcal{T}_c|} \right)^{3.2} \right], \quad (4)$$

218 where  $|\mathcal{T}_w|$  and  $|\mathcal{T}_c|$  are the shear stresses related to waves and current dynamic, such  
 219 that :

$$|\mathcal{T}_c| = \rho \left[ \frac{\kappa}{\ln\left(\frac{z_m}{z_0}\right)} \right]^2 \cdot |\mathbf{u}_b|^2, \quad (5)$$

220 and

$$|\mathcal{T}_w| = \frac{1}{2} \rho f_w |\mathbf{u}_{orb}|^2. \quad (6)$$

221 where  $z_0$  is the bottom roughness,  $\rho$  is water mass density,  $\mathbf{u}_b$  and  $\mathbf{u}_{orb}$  are the nearbed  
 222 ocean velocity and wave orbital velocity, respectively, and  $\kappa$  is Von-Karman's constant (set  
 223 to 0.4),  $f_w$  is the friction factor defined according to Soulsby (1995) and  $z_m$  is a reference  
 224 depth above the sea bed (where the flow velocity is assumed to follow a logarithmic law).  
 225 Simulations using two different definitions of  $z_m$  were carried out and their results were  
 226 compared to provide a sensitivity analysis :

227 (H1).  $z_m$  is the depth of the grid cell point nearest the bottom,

228 (H2).  $z_m$  is a fraction of the mean depth.

229 Wave forcing terms of equations (1), (2), (3) and (4) are calculated using the mean  
 230 wave parameters resulting from WW3. It solves the spectral wave action equation in space  
 231 and time, from which spectrum based wave parameters, atmosphere-waves and ocean-waves  
 232 parameters and many more parameters are derived. The main purpose of this model is to si-  
 233 mulate the wave generation by wind, dissipation and redistribution effects, their propagation  
 234 by solving :

$$\frac{DN}{Dt} = \frac{1}{\sigma} (\mathbf{S}_{ln} + \mathbf{S}_{in} + \mathbf{S}_{nl} + \mathbf{S}_{ds} + \mathbf{S}_{bot} + \mathbf{S}_{db} + \mathbf{S}_{tr} + \mathbf{S}_{sc} + \mathbf{S}_{ice} + \mathbf{S}_{ref} + \mathbf{S}_{mud}) \quad (7)$$

235 where  $\mathbf{N}(k, \theta; \mathbf{x}, t)$  is the wave action density spectrum which is a function of time ( $t$ ),  
 236 physical space ( $\mathbf{x}$ ), wave number ( $k$ ) and wave direction ( $\theta$ ).  $\sigma$  is the intrinsic wave radian  
 237 frequency. Source terms are  $\mathbf{S}_{ln}$ ,  $\mathbf{S}_{in}$ ,  $\mathbf{S}_{nl}$ ,  $\mathbf{S}_{ds}$ ,  $\mathbf{S}_{bot}$ ,  $\mathbf{S}_{db}$ ,  $\mathbf{S}_{tr}$ ,  $\mathbf{S}_{sc}$ ,  $\mathbf{S}_{ice}$ ,  $\mathbf{S}_{ref}$ ,  $\mathbf{S}_{mud}$ , respecti-  
 238 vely, for the linear wind input, exponential wind input, non-linear wind input, whitecapping  
 239 dissipation, dissipation by bottom friction over sandy and rocky beds, depth-induced wave  
 240 breaking dissipation, triad wave-wave interactions, bottom scattering, wave-ice interactions,  
 241 reflection by shoreline or by floating icebergs and dissipation by viscous mud (more details  
 242 can be found in Tolman and al. 2014).

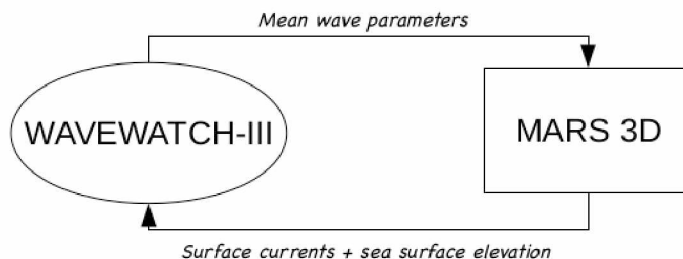
243 For  $\mathbf{S}_{in} + \mathbf{S}_{ds}$ , formulations of Ardhuin et al. (2010) and Filipot and Ardhuin (2012) (he-  
 244 reinafter ST4), and Zieger et al. (2015) (hereinafter ST6) have been tested. They aim to

245 modelise the wind input, the swell dissipation and the wave breaking. Please note that ST4  
 246 and ST6 do not use a parametric tail in  $f^{-5}$  at high frequencies. For  $\mathbf{S}_{\text{bot}}$ , two parame-  
 247 terisations (hereinafter BT1 and BT4) from the JONSWAP (Hasselmann et al. 1973) and  
 248 SHOWEX (Ardhuin et al. 2003) experiments were evaluated. However, the results obtained  
 249 with Hasselmann et al. (1973) were not shown here. For  $\mathbf{S}_{\text{db}}$ , the expression of Battjes and  
 250 Janssen (1978) was chosen with the Miche-style shallow water limiter for maximum energy.  
 251 For  $\mathbf{S}_{\text{nl}}$ , the Discrete Interaction Approximation method (Hasselmann et al. 1985) was turned  
 252 on. For  $\mathbf{S}_{\text{ref}}$ , the parameterisation of Ardhuin and Roland (2012) was activated.

253 *c. Coupling Procedure and Numerical Set-up*

254 The two-way coupling procedure was initially built by Bennis et al. (2011, 2013). Now,  
 255 exchanges between the two models are managed by the automatic coupler OASIS (Valcke  
 256 et al. 2015), instead of PALM (Buis et al. 2008). We defined a coupling time step that  
 257 was greater than the models time steps. For each coupling time step, OASIS exchanges  
 258 hydrodynamic variables among the two models, which will serve to calculate the forcing  
 259 terms, as explained below. MARS computes hydrodynamic fields and sends, through the  
 260 OASIS coupler, the surface flow velocities, as recommended by Banihashemi et al. (2017),  
 261 and sea surface elevation to WW3. After several integration times, corresponding to one  
 262 coupling time step, WW3 sends mean wave parameters, e.g. significant wave height and  
 263 Bernouilli head, to MARS. The terms used in Eq. (1), (2), (3), (4), (6) are then calculated  
 264 by MARS from these mean wave parameters and the MARS hydrodynamic is re-computed.  
 265 Subsequently, the surface sea elevation and surface currents are re-sent to WW3 (see Figure  
 266 2), and so on.

267 We define two different coupling modes : i) the one-way mode (hereinafter OW) when  
 268 WW3 forces MARS and ii) the two-way mode (hereinafter TW) where the feedback from  
 269 MARS to WW3 is included in addition to the forcing of MARS by WW3.



270

FIGURE 2: Coupling procedure. More details in Bennis et al. (2011).

271 Both models use two nested-grids (hereinafter parent and child grids), with similar  
 272 horizontal resolutions (600 m and 120 m), that are shown on Figure 1a. Their South-

273 West and North-East boundaries are : i) for parent grid : 47°53'60.0" N/6°03'32.4" W -  
274 50°27'0.0" N/0°43'12.0" W, and ii) for child grid : 49°04'48.0" N/2°56'56.4" W - 50°4'12.0" N/  
275 1°23'24.0" W. All MARS simulations are in three dimensions with 12 sigma levels over the  
276 vertical. The wave model employs 32 frequencies from 0.04 Hz to 0.7678 Hz and 24 directions  
277 leading to a directional step of 15 degrees. Open boundaries of MARS are forced with the  
278 Shom CST France atlas that uses 114 tidal components (Leroy and Simon 2003). WW3  
279 utilises wave spectra of the HOMERE and Ifremer databases (Boudiere et al. 2013) at its  
280 open boundaries. WW3 is forced by NCEP winds from CFSRR re-analysis. The deployment  
281 of child grids requires 2D-wave spectra, water levels and flow velocity from their parent grids  
282 at boundaries. All runs are coupled, with a one-way/two-way coupling for parent and child  
283 grids. The child grid coupling time step is 180 s and 20 s for one-way and two-way runs,  
284 respectively.

#### 285 *d. Numerical Experiments*

286 A sensitivity analysis on the influence of main formulations and parameters is necessary to  
287 ensure a proper validation. The behaviour of the coupled model is assessed through different  
288 parameterisations for wave energy dissipation (ST4, ST6) and bottom friction (BT1, BT4).  
289 Moreover, the impact of bottom roughness ( $z_0$ ) and of the size of the near-bottom logarithmic  
290 layer ( $z_m$ ) are evaluated. Bottom stress in MARS is parameterised according to Eqs. (4), (5),  
291 (6) with (H1) and (H2) hypothesis for  $z_m$ . Tests are also carried out for the two coupling  
292 modes (OW and TW) in order to ensure cross validation. All sensitivity tests are not shown to  
293 avoid cluttering. So, only the relevant experiments were presented and they are summarised  
294 in Table 1. Runs 3, 4 and 7 included wave effects but not local wind effects while Runs 5 and  
295 6 took into account the wave and local wind effects. The wave and wind effects were absent  
296 from Run 10 where the hydrodynamic was only driven by tides.

297 Model accuracy is evaluated through the root mean square error (RMSE), normalized  
298 root mean square error (NRMSE), BIAS, PBIAS, MAE and R-squared ( $R^2$ ), which are  
299 defined as follows (e.g. Allen et al. 2007b,a) :

$$\text{RMSE} = \frac{1}{N} \sqrt{\Sigma(X_{model} - X_{data})^2}, \quad (8)$$

$$\text{NRMSE} = \frac{\text{RMSE}}{\max(X_{data}) - \min(X_{data})}, \quad (9)$$

$$\text{BIAS} = \frac{\Sigma(X_{model} - X_{data})}{N}, \quad \text{PBIAS} = 100 \times \text{BIAS}, \quad (10)$$

300

$$\text{MAE} = \frac{\Sigma(|X_{model} - X_{data}|)}{N}, \quad (11)$$

$$R^2 = 1 - \frac{\Sigma(X_{data} - X_{model})^2}{\Sigma(X_{data})^2}, \quad (12)$$

301

302

303 where  $N$  is the total number of available samples,  $X_{model}$  and  $X_{data}$  are related to samples  
 304 coming from numerical simulations and in-situ data, respectively. PBIAS gives a measure of  
 305 whether the model is systematically underestimating or overestimating the measurements.  
 306 The closer the value is to zero the better the model. Performance levels regarding  $|PBIAS|$   
 307 are categorised as follows  $\leq 10$  excellent,  $10 - 20$  very good,  $20 - 40$  good,  $\geq 40$  poor  
 308 (Marechal 2004; Allen et al. 2007a).  $R^2$  is a statistical measure of how close the data to the  
 309 fitted regression line.  $R^2 = 1$  indicates that model results and data are similar. Performance  
 310 levels regarding  $R^2$  are categorised as :  $\geq 0.65$  excellent,  $0.65 - 0.5$  very good,  $0.5 - 0.2$  good,  
 311  $\leq 0.2$  poor (Marechal 2004). The choice of category boundary is subjective, these criteria  
 312 are not of the fail/pass type, but valuate the performance in four categories from excellent  
 313 to poor.

	<b>Year</b>	<b>Wave energy dissipation</b>	<b>Wave bottom friction</b>	<b>Coupling mode</b>	<b>Local wind effects</b>
<b>Run 3</b>	2017	ST6	BT4	TW	NO
<b>Run 4</b>	2017	ST6	BT4	OW	NO
<b>Run 5</b>	2017	ST4	BT4	OW	YES
<b>Run 6</b>	2017	ST4	BT4	TW	YES
<b>Run 7</b>	2017	ST4	BT4	TW	NO
<b><i>Run 10</i></b>	<i>2017</i>	—	—	—	NO

314

TABLE 1: List of numerical experiments according to date, wave energy dissipation formula-  
 tion, wave bottom friction parameterisation, coupling mode and the inclusion of local wind  
 315 effects. All runs include wave effects except for Run 10 in italics.

### 316 3. Results and Discussion

317 Model tests against ADCP, wave buoys and tidal gauge data are presented. Numerical  
 318 validations are related to tidal elevation, mean wave parameters, wave spectra, time series and

319 vertical profiles of the tidal stream velocity. We investigated how ocean waves interact with  
320 the tidal current in Alderney Race for different met-oceanic conditions. Effects of bottom  
321 friction, bottom roughness, direction of propagation of wave and current, and turbulence  
322 modelling are discussed.

### 323 *a. Tidal Elevation*

324 Tidal range varies between 4 and 7 m for the studied area and time period. Comparisons  
325 between measurements of tidal gauges (TG1 and TG2) and numerical simulations of MARS-  
326 WW3 are shown on Figure 3. Our coupled model produces mean sea surface elevation values  
327 with a terrestrial definition (IGN 69) for the vertical reference. As TG1 and TG2 measu-  
328 rements use the levels of the lowest tide, chart data as vertical references, we shifted the  
329 simulated water level with 3.88 m for TG1 and 5.55 m for TG2 as recommended by Shom  
330 (2017) to provide a commensurable comparison. This correction, based on the minimum  
331 BIAS, is consistent with the measured mean sea level of 3.87 m and 5.45 m in Cherbourg  
332 and Dièlette in 2017, respectively (Shom 2017).

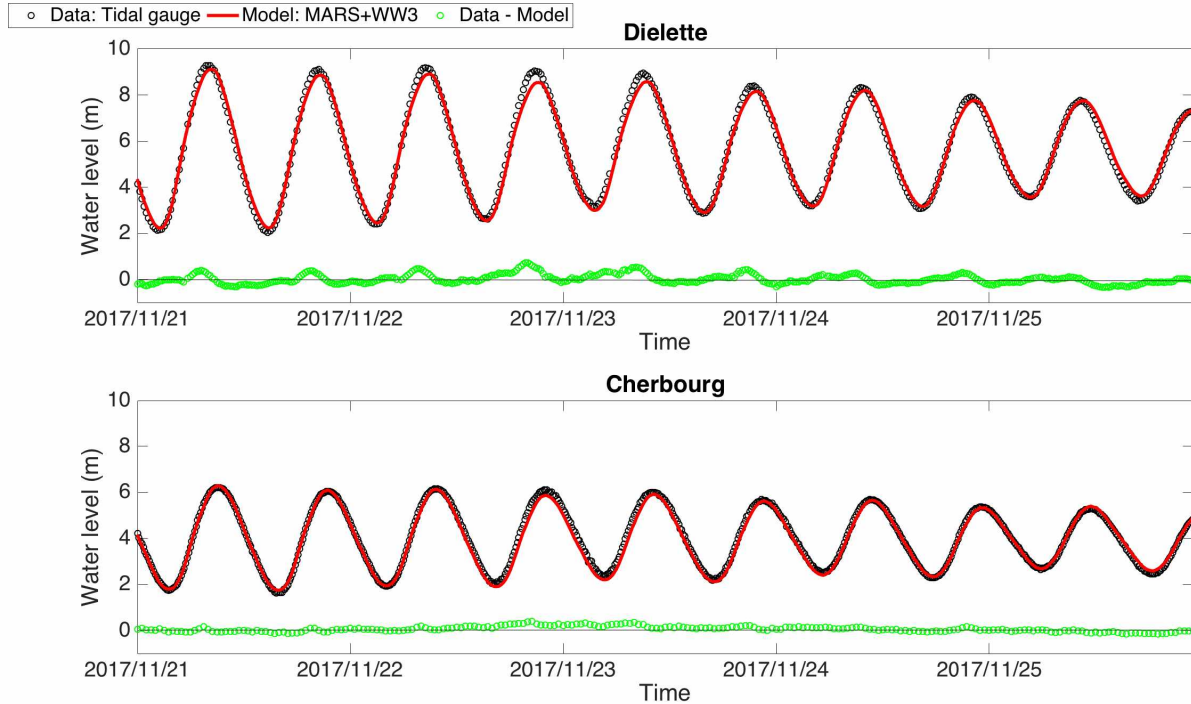
333 Model and data results were close at Cherbourg (TG1), with good fits in amplitude and  
334 time phasing (see Figure 3, black dots and red line). Absolute error (hereinafter AE) were  
335 around few tens of centimetres, with a maximum values of 0.39 m (see Table 2). RMSE  
336 was 0.13 m and  $R^2 = 0.98$ , that is excellent. Errors mainly occurred just before the high  
337 tide, showing that the tidal asymmetry was not well represented in some cases. At Dielette  
338 (TG2), numerical simulations were worse than in Cherbourg but they were acceptable, with  
339  $BIAS = 0.02$  m,  $RMSE = 0.44$  m and  $R^2 = 0.95$ . However, discrepancies were observed with  
340 a phase delay up to few minutes for some tidal cycles. In contrast, this problem was absent  
341 in Cherbourg (TG1). This illustrates the complexity of the tidal dynamic around La Hague  
342 Cape where the tidal range increases by 5 metres within a few kilometres, as shown in Bailly  
343 Du Bois et al. (2012). This could be ascribed to bathymetry errors and bottom stress that  
344 is strongly impacted by such errors (more details in Section 3c).

		21-25 Nov 2017
<b>TG1 (Cherbourg)</b>	max(AE)	0.39 m
	min(AE)	-0.16 m
	BIAS	0.06 m
	RMSE	0.13 m
<b>TG2 (Dièlette)</b>	max(AE)	0.73 m
	min(AE)	-0.34 m
	BIAS	0.02 m
	RMSE	0.44 m

345

TABLE 2: Maximum (max(AE)) and minimum (min(AE)) values of AE are presented as well as BIAS and RMSE for TG1 and TG2. Positive and negative signs denote under-estimation and over-estimation of water levels by the model, respectively.

346



347

FIGURE 3: Water level at Dielette (TG2, top row) and Cherbourg (TG1, bottom row) measured by Shom tidal gauge (black dots) and computed by the coupled model (red solid line) over 5 days from 21 to 25 November 2017. AE is represented in green dots at each time.

348 *b. Sea States*

349 Sea states in Alderney Race are often complex, with wind seas combined with swells  
 350 from the Atlantic Ocean (Maisondieu 2016). Comparisons between numerical simulations and

351 measurements were performed in order to investigate how wave-current interactions influence  
352 ocean waves in Alderney Race. Several parameterisations for the wave energy dissipation by  
353 whitecapping and bottom friction were evaluated. Moreover, water level and surface current  
354 effects on the wave field are presented and discussed as well as local wind effects.

355 Time series of the magnitude (hereinafter  $U_{10}$ ) and direction (hereinafter  $Udir_{10}$ ) of the  
356 wind at 10 metres above ground level (see Figure 4) showed high values for  $U_{10}$  during  
357 the night of 22-23 November, with a maximum value around 17.5 m/s, and for a North-  
358 North-East to South-South-West wind. The wind simulated by CFSRR, that have a spatial  
359 resolution of  $0.2^\circ$  of latitude and of  $0.1^\circ$  of longitude at the study site location, is used  
360 to force WW3. Wind forcing was in agreement with the wind measured at Goury by the  
361 semaphore (see Figure 4). NRMSE is around 0.11 (see Table 3) while PBIAS is positive  
362 for  $U_{10}$ , indicating that the CFSRR values were higher than the measured ones. However,  
363 PBIAS remains very good for  $U_{10}$  (around 14%) while MAE is excellent for  $Udir_{10}$  (around  
364 7%). The discrepandancies can be explained by the coarse resolution of the CFSRR model,  
365 the distance (around 7 km) between Goury and the ADCP point (Coelingh et al. 1996, 1998),  
366 and also because the semaphore data are recorded above ground level that influences the  
367 atmospheric boundary layer and the wind velocity (e.g. Bailly Du Bois and Dumas 2005).  
368 The significant wave height recorded by ADCP was highest on 23 November at 2 :13 a.m.  
369 and 3 :13 a.m., reaching 4 m and 3.6 m, respectively. During this time period, high winds  
370 were measured with  $U_{10}$  values greater than 15 m/s. As a result the inclusion of local wind  
371 effects has improved the simulated significant wave height (see Figures 5 and 6a, Run 3 vs  
372 Run 6, and Table 4), in particular between the 22 November at 12 a.m. and the 23 November  
373 at 12 p.m, where  $U_{10}$  was highest. NRSME has been reduced by 50% and now reached 0.08  
374 for Run 6. PBIAS were high for Run 3 (around 25%) and Run 4 (around 28%) and showed  
375 that the significant wave height was largely underestimated by the model. With local wind  
376 effects, PBIAS decreased substantially to 5.8% for Run 6 (see Table 4), that is excellent.  
377 R-squared values and scatter plots of Figure 5 well illustrated how the local wind effects  
378 have improved the fit to data, with  $R^2 = 0.97$  for Run 6 instead of 0.87 for Run 3.

379 The wave-to-ocean momentum flux is enhanced due to local wind effects, particularly for  
380 the zonal component, which was 60-fold increase, when wind blows hard (on 23 November  
381 around 2 a.m). This increase is ascribed to changes in both wind speed (from 12 m/s on  
382 22 November around 12 p.m. to 17.5 m/s on 23 November around 2 a.m) and direction  
383 (from South-South-West direction on 22 November around 12 p.m. to West direction on 23  
384 November around 2 a.m) during the storm. Wave direction was worse for simulations with  
385 local wind effects between the 22 November at 12 a.m. and the 23 November at 12 p.m.  
386 compared to the simulations without such effects (see Figure 6b, Run 3 vs Run 6). With  
387 local wind effects, waves tend to go towards the North everytime instead of turning East



388 (more explanations hereafter). From the 23 November at 12 p.m to 25 November 11 p.m.,  
389 wave direction fitted well to the observations. Therefore, only this time period will study in  
390 the next section (3c), which deals with waves effects on tidal currents, because changes in  
391 currents due to the waves are partly driven by the direction of propagation of waves, that  
392 should be well represented to perform a right analysis.

393 One of most important physical phenomenon in Alderney Race is the wave refraction  
394 ascribed to the strong tidal current. This phenomenon was well simulated by the coupled  
395 model, particularly when the local wind effects were not included in simulations (see Figure  
396 6b, Runs 3 and 6) : refraction has modified wave direction, which was in the agreement with  
397 observations and former studies (e.g. Wolf and Prandle 1999; Ardhuin et al. 2012). When  
398 wind blowed hard, local wind effects (see Figure 6b, Run 6) tended to smooth refraction  
399 effects because currents were abnormally reduced (more details in section 3c) and therefore  
400 they had less influence on surface waves. Runs 4 and 5, which did not include neither current  
401 effects on waves nor local wind effects, failed to correctly reproduce the measured wave  
402 direction. A modulation of significant wave height was also observed due to refraction (Figure  
403 6a; Runs 3 vs 4 or Run 5 vs 6). Both parameterisations for wave breaking dissipation (ST4  
404 and ST6) adequately simulated modifications in the significant wave height and wave-to-  
405 ocean momentum flux by tide (see Figures 6a,c,d; Runs 3 vs 4 or Run 5 vs 6). The eastward  
406 and northward components of the momentum flux displayed peak values during the ebb,  
407 when the tidal current was southwestward (see Figures 6c,d; Runs 3 vs 6). In that case,  
408 interactions between ocean waves and tide generated wave breaking events that produced  
409 an enhanced wave-to-ocean momentum flux. This is highly visible if we compare the results  
410 of the two coupling modes (see Figure 6c,d; Runs 3 vs 4 or Run 5 vs 6) : peaks were absent  
411 from Runs 4 and 5 because they did not take into account the current effects.

412 Tide also influences the near-bed orbital velocity, and particularly its meridional com-  
413 ponent (Figure 6f, Run 3 and 6) because of the tidal current direction, that was NNE/SSW.  
414 For the Runs 3 and 6, near-bed orbital velocity was modulated by tides with high and  
415 low values during ebb and flood, respectively. In contrast, Runs 4 and 5, being computed  
416 without interactions with the flow, did not have such peaks (see Figure 6f), showing the  
417 impact of wave-current interactions. The zonal component of the near-orbital velocity was  
418 the highest due to the direction of wave propagation, that was mainly from West to East.  
419 Its form resembles significant wave height, with maximum values during the night of 22-23  
420 November (see Figure 6e). The effects of local wind on the near-bed wave orbital velocity  
421 are light in comparison with the tidal ones, except for the 23 November around 2 a.m. where  
422 an increase of 5 cm/s was observed due to the strong wind. On the whole, parameterisations  
423 for wave bottom friction of Hasselmann et al. (1973) and Ardhuin et al. (2003) produced  
424 close near-bed results.

425 The wave-current interactions are also visible on the frequency wave energy spectra (see  
426 Figure 8). To study it in details, we selected eight moments that differ in terms of type  
427 of wave-current interactions (various waves and current directions, low/high tide, flood/ebb  
428 tide, low/high flow velocity). All related informations are summarised in Table 5. All pre-  
429 sented spectra were bi-modal with a swell component, where the maximum of energy was  
430 located in  $f_{p,swell} = 0.07812 \text{ Hz}$  (RTF2, RTE1 and RTE2) and  $f_{p,swell} = 0.09375 \text{ Hz}$  (RTF1),  
431 and a wind-wave component, which reached its maximum in  $f_{p,windsea} = 0.125 \text{ Hz}$  (RTF2,  
432 RTE1 and RTE2) and  $f_{p,windsea} = 0.1406 \text{ Hz}$  (RTF1). The splitting frequency ( $f_c$ ) is around  
433  $0.11 \text{ Hz}$ . For the swell component, all runs produced similar results, that are in agreement  
434 with the ADCP measurements regardless of coupling mode, wave dissipation parameterisa-  
435 tion and local wind effects (see Figure 8). For the wind component, a wave energy decay in  
436  $f^{-4}$  for frequencies between  $f_{p,windsea}$  and  $3f_{p,windsea}$  is observed, as demonstrated by Toba  
437 (1973), Donelan et al. (1985) and others. When frequencies were greater than  $3f_{p,windsea}$ , a  
438 decay in  $f^{-5}$  is found, as defined in Phillips (1958). Numerical results were consistent with  
439 the ADCP data for all runs up to  $2f_{p,windsea}$ . Runs 5 and 6, which have integrated local wind  
440 effects in simulations, overestimated the wave energy beyond  $2f_{p,windsea}$  and had an energy  
441 tail in  $f^{-4}$ . Run 7, which used the same parameterisation for the wave energy dissipation  
442 (ST4) than Runs 5 and 6, did not suffer to this overestimation, showing that the influence  
443 of local wind effects on ST4.

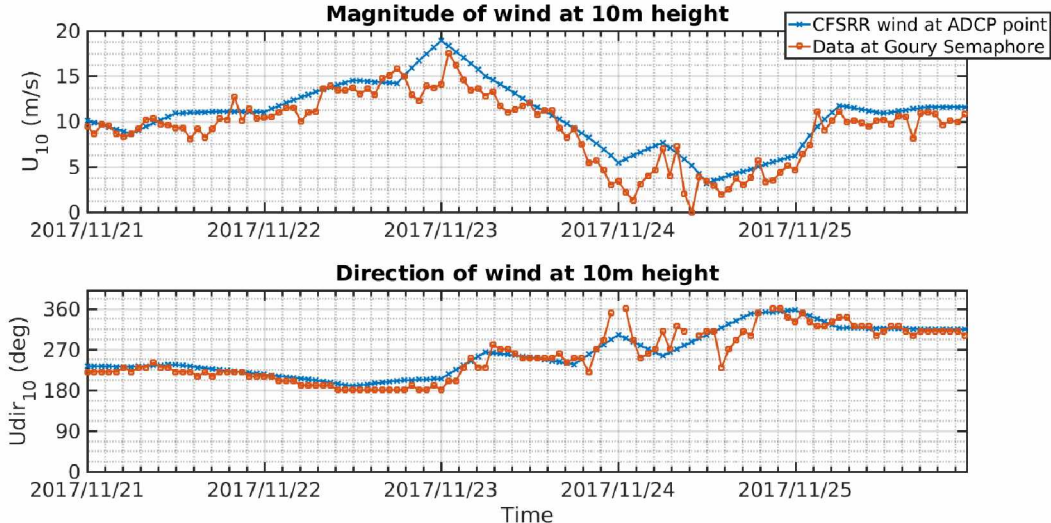


FIGURE 4: Time series for  $U_{10}$  (top panel) and  $Udir_{10}$  (bottom panel) : CFSRR inputs are in blue and data from the Goury semaphore are in red.

	<b>NRMSE</b>	<b>R<sup>2</sup></b>	<b>PBIAS (%)</b>
<b>U<sub>10</sub></b>	0.10	0.96	13.97
<b>Udir<sub>10</sub></b>	0.11	0.98	3.82

TABLE 3: NRMSE, R<sup>2</sup> correlation and PBIAS for  $U_{10}$  and  $Udir_{10}$ .

	<b>Runs</b>	<b>NRMSE</b>	<b>R<sup>2</sup></b>	<b>PBIAS (%)</b>
447 <b>H<sub>s</sub></b>	Run 3	0.16	0.87	-27.95
	Run 4	0.16	0.87	-25.57
	Run 5	0.10	0.95	12.07
	Run 6	0.08	0.97	5.89

448 TABLE 4: NRMSE, R<sup>2</sup> correlation and PBIAS for significant wave height (H<sub>s</sub>). Runs 3, 4,  
5 and 6 are presented.

	<b>Date</b>	<b>W ⊥ C</b>	<b>W+C</b>	<b>U<sub>c</sub><sup>s</sup>(m/s)</b>	<b>SSH(m)</b>
449	<b>RTF1</b> (flood)	23/11/2017 10 :45 p.m.	X		2.01 1.87
	<b>RTF2</b> (flood)	24/11/2017 00 :45 a.m.	X		1.13 0.67
	<b>RTE1</b> (ebb)	24/11/2017 02 :45 a.m.		X	0.93 -1.18
	<b>RTE2</b> (ebb)	24/11/2017 03 :45 a.m.		X	1.99 -1.82
	<b>RTF3</b> (flood)	25/11/2017 11 :00 a.m.	X		1.87 1.76
	<b>RTF4</b> (flood)	25/11/2017 01 :45 p.m.		X	0.63 0.11
	<b>RTE3</b> (ebb)	25/11/2017 04 :15 p.m.		X	1.56 -1.47
	<b>RTE4</b> (ebb)	25/11/2017 05 :00 p.m.		X	2.07 -1.73

450 TABLE 5: Waves-current direction (W ⊥ C when waves and current direction are orthogonal and W + C for an angle between waves and current direction less than 80°), surface current velocity (U<sub>c</sub><sup>s</sup>) and sea surface height (SSH) at RTF1, RTF2, RTE1, RTE2, RTF3, RTF4, RTE3 and RTE4. Directions follow the oceanographical convention for the flow and the meteorological convention for waves. Values are from numerical simulations.

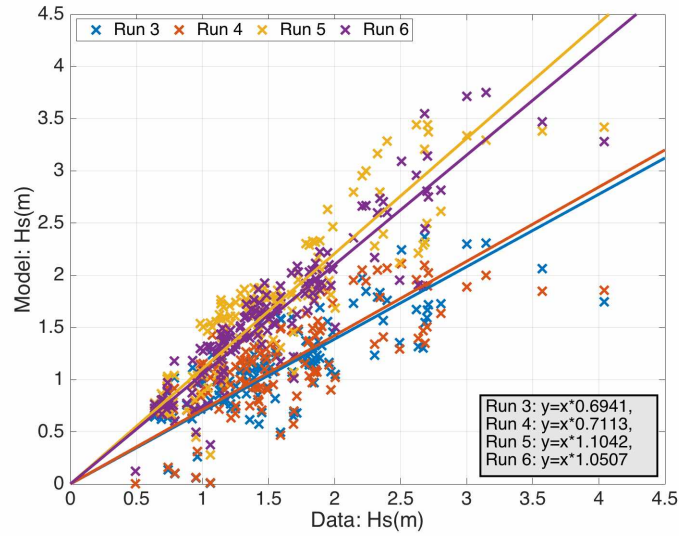
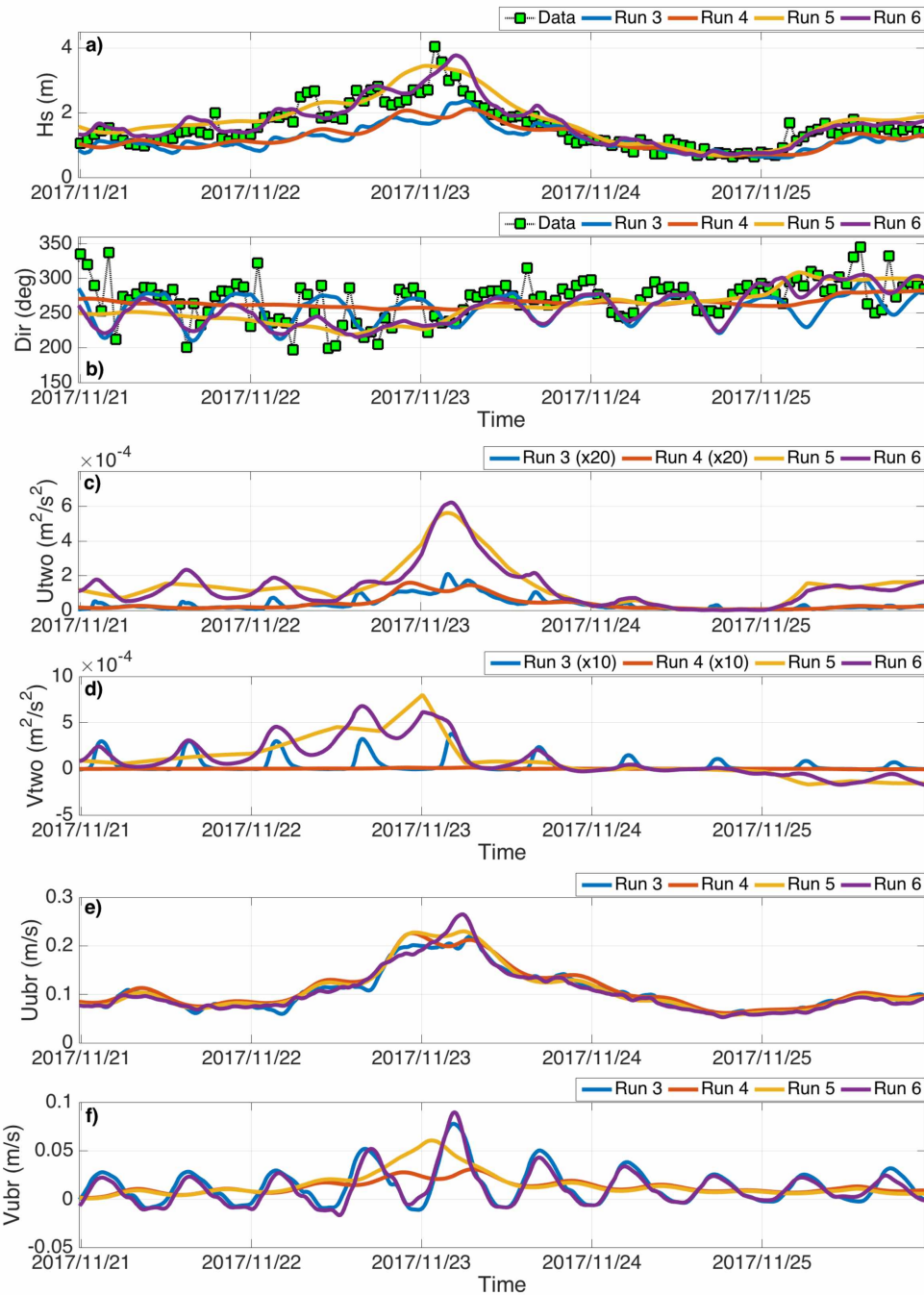


FIGURE 5: Scatter plots for the significant wave height ( $H_s$ ) for Run 3 (blue crosses), Run 4 (red crosses), Run 5 (yellow crosses) and Run 6 (purple crosses). In-situ data and model results are drawn along x-axis and y-axis, respectively. Regression lines are plotted in blue, red, yellow and purple solid lines for runs 3, 4, 5 and 6, respectively.



452

FIGURE 6: Time series of sea states characteristics, from 21 to 25 November 2017, integrated over frequencies (32) and directions (24) : a) significant wave height, b) wave direction (meteorological convention), c) zonal component of wave-to-ocean momentum flux, d) meridional component of wave-to-ocean momentum flux, e) zonal component of near-bed wave orbital velocity, f) meridional component of near-bed wave orbital velocity. ADCP data are in black-green squares while numerical results for Runs 3, 4, 5 and 6 are in blue, red, yellow and purple solid lines, respectively.

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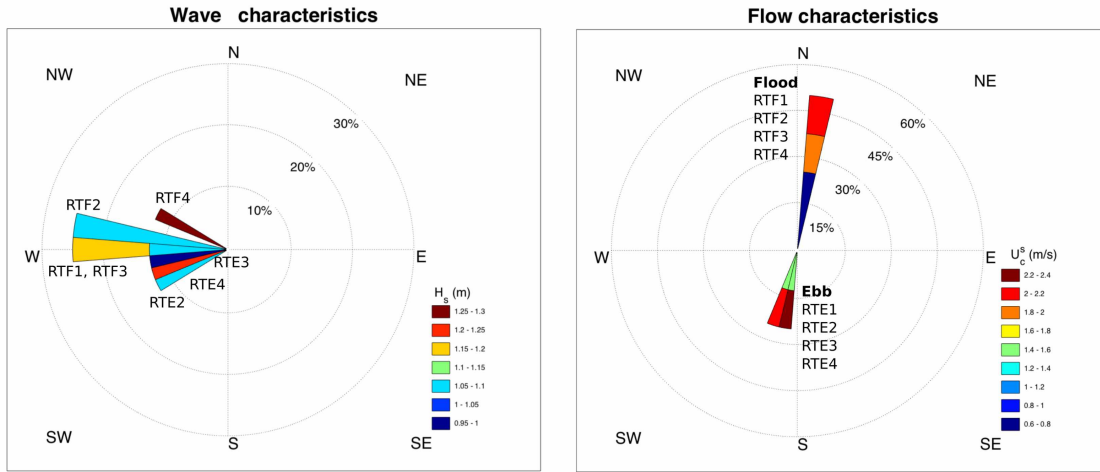


FIGURE 7: Left panel : Wave direction (polygon) and significant wave height (color). Right panel : Direction (polygon) and velocity magnitude (color) of the current. Only RTF1, RTF2, RTE1, RTE2, RTF3, RTF4, RTE3 and RTE4 are shown. Directions follow the oceanographical convention for the flow and the meteorological one for waves. Results are from numerical simulations.

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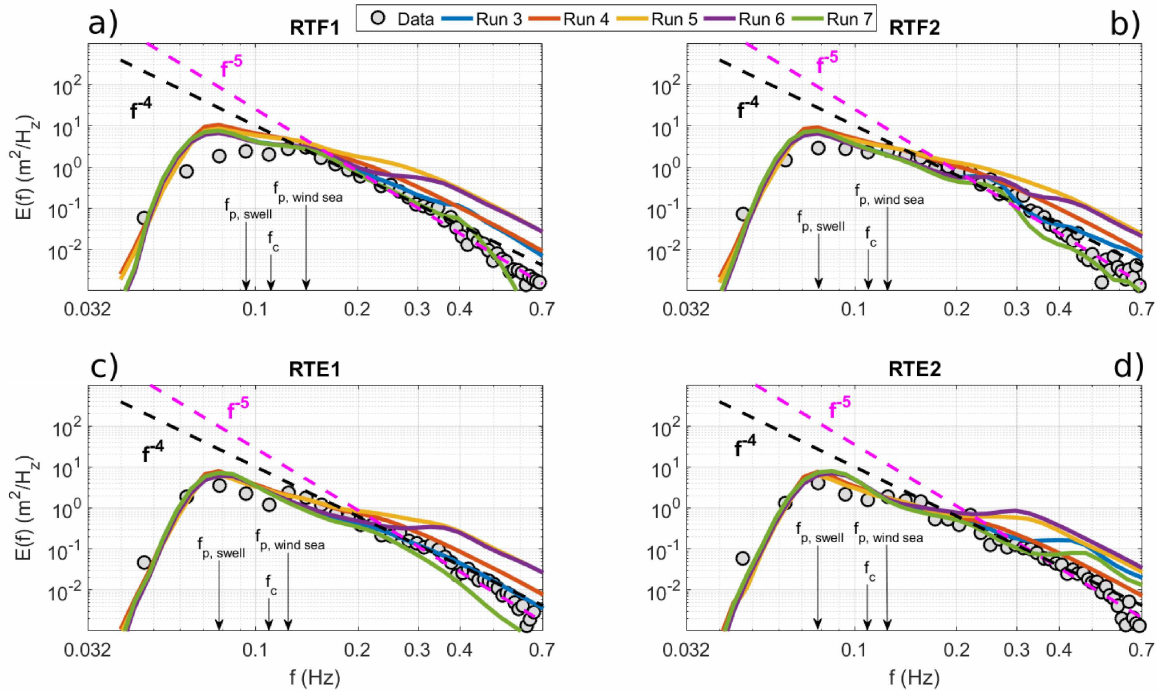


FIGURE 8: Frequency wave energy spectra at : a) RTF1, b) RTF2, c) RTE1 and d) RTE2. The first (a,b) and second (c,d) rows are for flood and ebb tides, respectively. Magenta and black dashed lines are for  $o(f^{-5})$  and  $o(f^{-4})$ , respectively. Note that the x-axis and y-axis are a log10 scale.  $f_{p,swell}$ ,  $f_{p,windsea}$ ,  $f_c$  (around  $0.11 \text{ Hz}$ ) represent the peak frequency for swell and wind sea, and the splitting frequency, respectively.

455 *c. Time Series of the Tidal Stream Velocity*

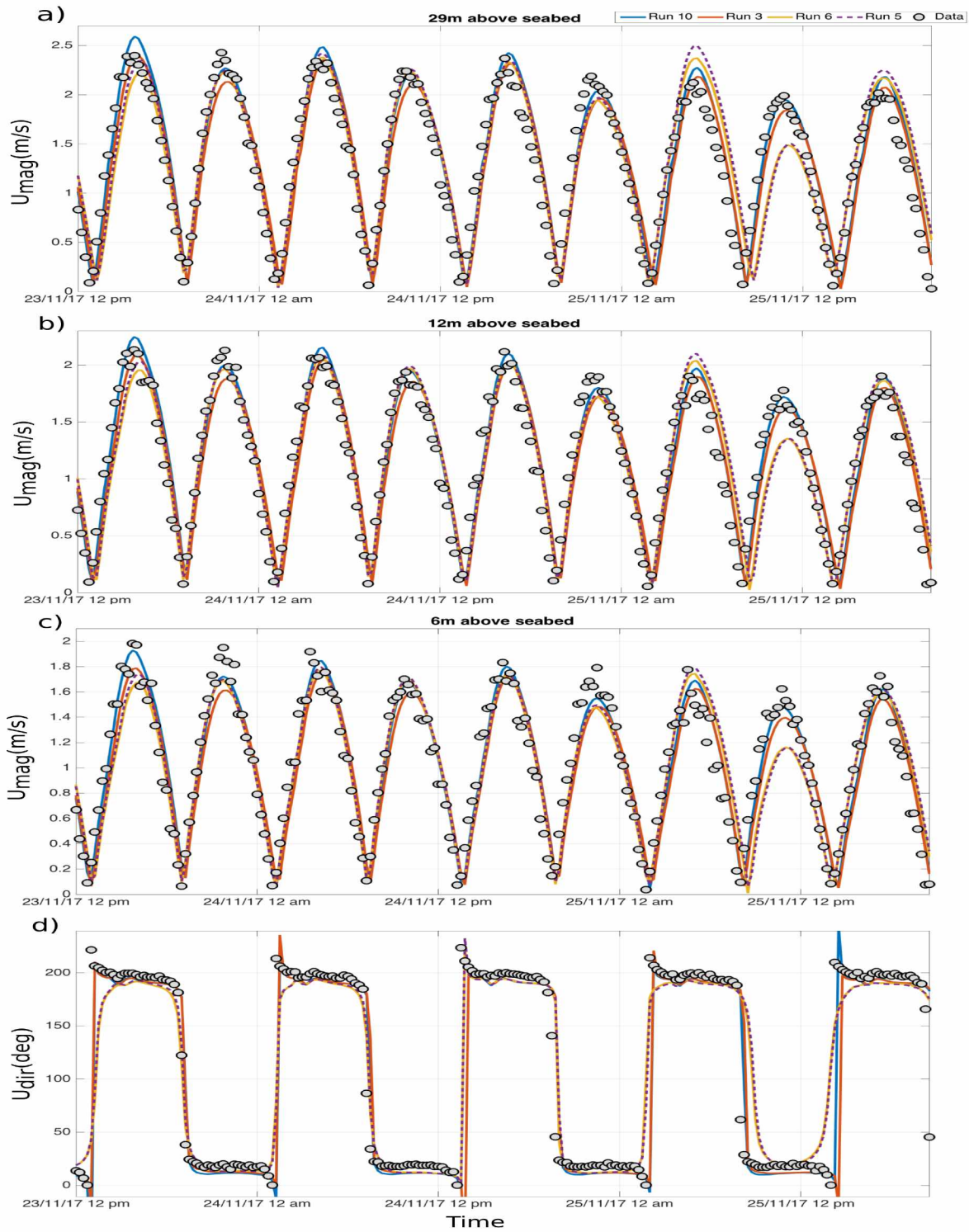
456 We now investigate how the Alderney Race circulation was impacted by ocean waves.  
457 Figure 9 shows time series of magnitude and direction of the measured current velocity at 25,  
458 12 and 6 meters depth above seabed at the ADCP location between 23 November 2017 at 12  
459 p.m and 25 November 2017 at 8 p.m, where the tidal flow velocity varied between 0 and 2.5  
460 m/s. First, we start by discussing the results without local wind effects (Runs 3 and 10). On  
461 the whole, the numerical results for cases with (Run 3) and without waves (Run 10) were  
462 consistent with the data and were close each other (see Figures 9 and 10 and Table 6). Good  
463 and similar NRSME (0.09 and 0.11) and  $R^2$  (0.97 and 0.98) for both runs were observed.  
464 PBIAS were excellent, because they range from 0.6% to 3.8%, but they showed that velocity  
465 was underestimated by the model when wave effects were activated while an overestimate  
466 occurred where wave effects were disabled. Wave effects tend to reduce systematically the  
467 velocity magnitude (e.g. Grant and Madsen 1979; Xie et al. 2001; Zhang et al. 2004) due to  
468 wave enhancement of bottom friction. At low tide, as the model without waves overestimated  
469 tidal velocity, simulations with waves had a better fit with in-situ data. Flow direction (see  
470 Figure 9d), and its changes belonging to the tidal cycle were well reproduced by the model.  
471 Close results were obtained for Run 3 (TW mode) and Run 4 (OW mode, not displayed  
472 here). Even if current and sea level produced significant changes in the wave field (see Figure  
473 6), the impact of feedback on the tidal current and water level remained weak.

474 As regards the cases taking into account local wind effects (Runs 5 and 6) and between the  
475 23 November 12 p.m. and 25 November 2 a.m., tidal current were little impacted by local wind  
476 effects and numerical results were close to the data (see Figure 9). Indeed, NRMSE (around  
477 0.11),  $R^2$  (around 0.97) and PBIAS (0.62% – 3.79%) were in the same order of magnitude  
478 for Run 3 (without local wind) and Run 6 (with local wind). That could be explained by  
479 the wind speed at the ADCP point which was weak for this time period, ranging from 4 to  
480 10 m/s (see Figure 4). Beyond the 25 November at 2 a.m., when the wind started blowing,  
481 a strange behaviour was observed, particularly during the flood with a change in current  
482 direction, that induced a loss in the current intensity of around 0.5 m/s, with a smoother  
483 transition between ebb and flood directions and a shift in direction to the East. As the tidal  
484 current direction was modified, wave-current interactions were impacted. The decrease in  
485 velocity magnitude being similar for Runs 5 and 6, that is not induced by a change in wave  
486 field due to wave-current interactions. During this time period, waves went towards the East  
487 (see Figure 6b), and therefore the change in tidal current direction has reduced the angle  
488 between waves and current, leading to a decrease in the current intensity, as reported by  
489 Groeneweg and Klopman (1998). As a result, this problem comes from the ocean model  
490 MARS and suggests a mis-evaluation of the wind effects on the flow and particularly of the  
491 wind stress. Further investigations are required.

492 We noted an occasional phase delay that varied over time from 0 to 30 min. The delays  
493 differed depending to the tidal cycles. For example, in tidal cycles containing RTF1, RTF2,  
494 RTE1 and RTE2, the phase delay was constant at 15 min and in the same direction for all  
495 runs, regardless the coupling mode and the local wind effects. In contrast, we noted different  
496 time delays at RTF3 (no time delay for runs with and without local wind effects), RTF4  
497 (30 min and no time delay for runs without and with local wind effects, respectively), RTE3  
498 (30 min and no time delay for runs without and with local wind effects, respectively) and  
499 RTE4 (15 min for runs with and without local wind effects) times, which were part of the  
500 same tidal cycle. It is interesting to see that the delay was removed in simulations with local  
501 wind effects at RTF3, RTF4 and RTE3. That suggests that time delay could be due to waves  
502 and wind through the bottom stress, which was based on the near-bed wave orbital velocity.  
503 In addition, the maximum value of 30 min often corresponded to the reverse tide occurring  
504 sooner in the in-situ dataset. At this time, waves effects on the current were strongest. To  
505 investigate the role of waves and wind, measurements of the near-bed wave orbital velocity  
506 are required.

507 Furthermore, time delay could be partially corrected by expressing  $z_m$  (Eq. (5)) as a  
508 fraction of the mean depth ( $D$ ). In this study and after many simulations, the fraction was  
509 set to 5%. Some sensitivity tests were performed with  $z_m$  at 50% (Uchiyama et al. 2009),  
510 26.7%, 11.4%, 5.71%, 2.67% and 1.33% of  $D$  and the related velocities are presented in  
511 Figure 11. A one-hour delay was observed, as shown on Figure 11, between both extreme  
512 cases (50% and 1.33% of  $D$ ), highlighting the link between the bottom stress formulation  
513 and time delay. Tidal asymmetry also appeared also to be sensitive to the  $z_m$  value, with  
514 differences between tidal phases that were accentuated by large  $z_m$  values. Because the  
515 depth where the logarithmic profile is imposed was strongly dependent on the turbulence  
516 level, these tests showed that one of the sources of the time delay was ascribed to the  
517 modification of the turbulence level by the interactions between seabed morphology, ocean  
518 waves and tidal current. Parameterisation using an apparent roughness as recommended by  
519 Grant and Madsen (1979); Signell et al. (1990); Mathisen and Madsen (1999) may be a way  
520 of improvement, in addition to use of high spatial resolution bathymetry based on Furgerot  
521 et al. (2019).





522

FIGURE 9: Time series of magnitude (a,b,c) and direction (d) of the current velocity at 29 m (a), 12 m (b,d), 6 m (c) depth above seabed. All panels show numerical results for Runs 3 (TW, red solid line), 5 (OW+local wind effects, purple dash line), 6 (TW+local wind effects, yellow solid line) and 10 (without waves, blue solid line). In-situ data are shown with black circles. Directions are based on oceanographic conventions.

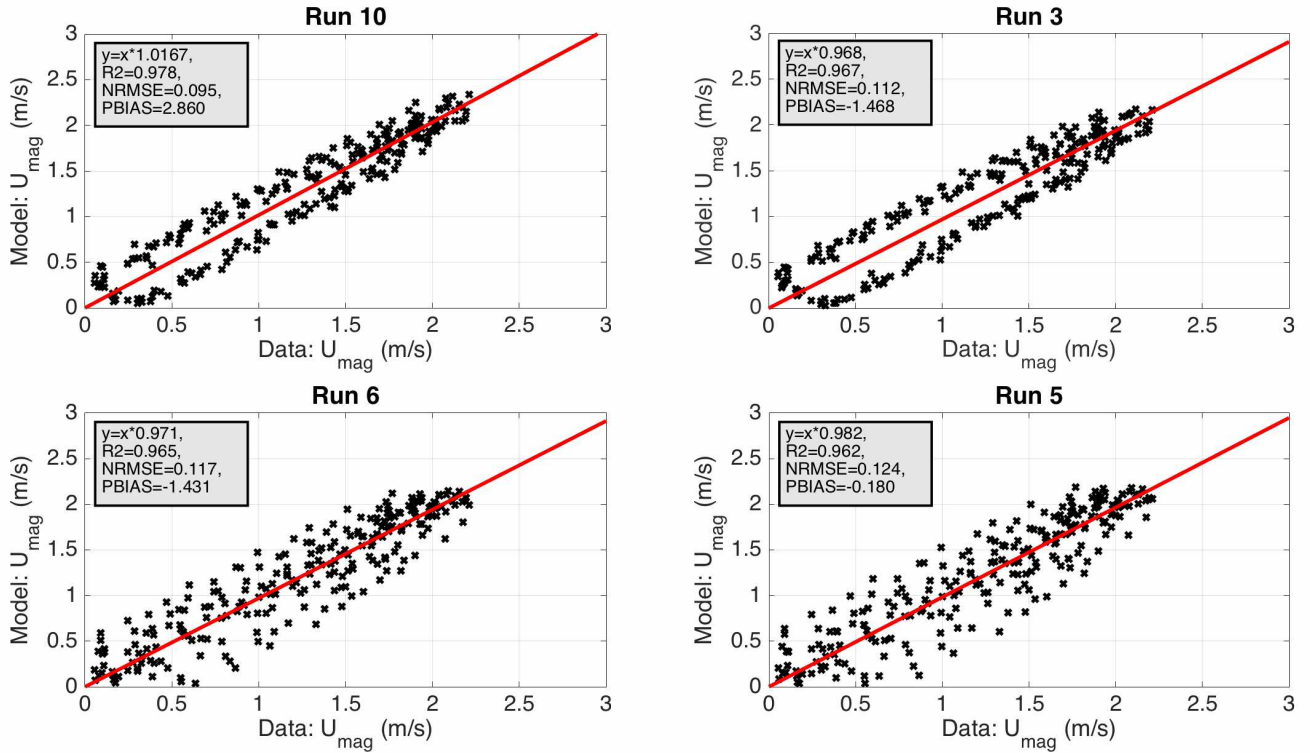
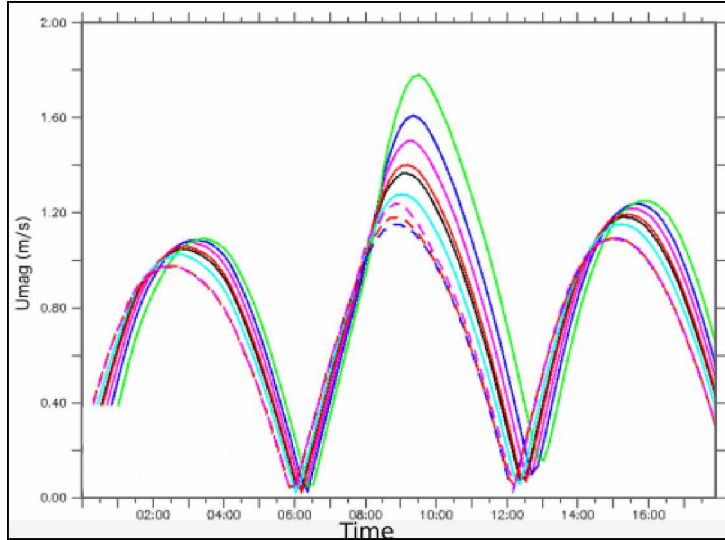


FIGURE 10: Scatter plots for the velocity magnitude (black crosses) at 15 metres above seabed for Run 10, Run 3, Run 6 and Run 5. In-situ data and model results are drawn along x-axis and y-axis, respectively.

	Runs	NRMSE	R <sup>2</sup>	PBIAS (%)
<b>z = 29 m</b>	Run 3	0.11	0.97	-0.62
	Run 5	0.14	0.95	1.92
	Run 6	0.12	0.96	-0.41
	Run 10	0.10	0.98	3.76
<b>z = 12 m</b>	Run 3	0.11	0.97	-1.78
	Run 5	0.12	0.96	-0.44
	Run 6	0.11	0.97	-1.66
	Run 10	0.09	0.98	2.58
<b>z = 6 m</b>	Run 3	0.10	0.97	-3.79
	Run 5	0.11	0.96	-2.33
	Run 6	0.11	0.96	-3.53
	Run 10	0.09	0.98	0.74

TABLE 6: NRMSE, R<sup>2</sup> correlation and PBIAS for velocity magnitude at different depths (29 m, 12 m and 6 m). Runs 3, 5, 6 and 10 are presented.



526

FIGURE 11: Time series of the velocity magnitude for different values and formulations of  $z_m$  parameter. Simulations do not include wave effects and used a  $z_0$  equal to  $0.008m$ . Reference test was based on the quadratic formulation (black solid line). Green line is for Uchiyama et al. (2009) using  $z_m = 50\%D$ . Other lines represent current velocity simulated with  $z_m$  set to  $26.7\%D$ ,  $11.4\%D$ ,  $5.71\%D$  and  $2.67\%D$  for the solid blue, magenta, red, cyan lines. Dashed blue, red and magenta lines are for  $z_m = 1.33\%D$  and using Okubo (1971) with  $f_{visc} = 17$ ,  $f_{visc} = 10$  and Smagorinsky (1963), respectively.

527

528 *d. Vertical Structure of the Tidal Stream Velocity*

529 The vertical shape of the tidal stream velocity in Alderney Race is known to depend  
 530 primarily on the tidal phase, surface wave effects, bottom friction and turbulent mixing.  
 531 Thibault and Sentchev (2017) and others (e.g. Lewis et al., 2017) found that, in some parti-  
 532 cular cases, the vertical shear of the tidal sea current follows a power law (see Eq. (1) of Lewis  
 533 et al., 2017) scaled with a roughness coefficient. This form fits well with their data for a calm  
 534 sea. Otherwise, they showed that ocean waves, when their effects are significant, change the  
 535 shear flow and increase the error between model and measurements. They recommend the  
 536 use of a 3D fully wave-current model, which is what we used here. It is not easy to compare  
 537 vertical profiles of the flow to observations in a location such as Alderney Race. Indeed, there  
 538 are some difficult issues : i) the very rough bottom ejects intermittent 3D highly energetic  
 539 turbulent eddies that modify the vertical shape of the flow, ii) the phase delay complicates  
 540 the comparison : all presented plots are corrected by phase delay by adjusting the tide rever-  
 541 sal time, iii) measurements near the surface lack precision because they have been filtered  
 542 to eliminate spurious values induced by the acoustic signal reflection on the sea surface, but

543 also by the air bubbles from wave breaking turbulence, and iv) ocean waves and current are  
544 orthogonal most of the time, which brings us further away from simple case where ocean  
545 waves and current directions are aligned or opposite. We need to define a scale to perform  
546 the analysis : waves and current are considered as opposite for  $|\Delta\theta_{w/c}| = 180^\circ$ , aligned for  
547  $|\Delta\theta_{w/c}| = 0^\circ$  and orthogonal for  $|\Delta\theta_{w/c}| = 90^\circ$ , with  $|\Delta\theta_{w/c}|$  the angle between waves and  
548 tidal current directions of propagation. Despite these issues, we compared vertical profiles  
549 to in-situ measurements.

550 Comparisons between model and data results were carried out at RTF1, RTF2, RTE1,  
551 RTE2, RTF3, RTF4, RTE3 and RTE4, where tidal current and wave directions differed as  
552 well as tide conditions (see Table 5). Some statistical calculations were performed for the  
553 velocity magnitude. NRSME varied from 0.02 to 0.15, except at RTF3 where a value of  
554 0.36 was reached in case of Run 6. R-squared ranged from 0.96 to 0.99 except at RTF3  
555 for Run 6 where it was around 0.92. PBIAS showed that sometimes model overestimated  
556 the measured velocity and sometimes underestimations occurred. PBIAS were less than  
557 4%, which is excellent, except for Run 6 at RTF2 and RTF3 where they were around 21%.  
558 Therefore, statistical parameters showed a very good agreement ( $R^2 \geq 0.96$ ,  $\text{NRMSE} \leq 0.15$ ,  
559  $\text{PBIAS} \leq 4\%$ ) between in-situ measurements and model results for all runs, except for Run  
560 6 at RTF3 and RTF2. Discrepancies for Run 6 are due to the mis-evaluation of local wind  
561 effects in the ocean model when wind blowed hard, as explained before. However, these  
562 parameters do not allow us to analyse if the vertical shapes were along the right direction.

563 For flood cases, at RTF1, RTF2, RTF3, wave and current directions were orthogonal  
564 while at RTF4  $|\Delta\theta_{w/c}|$  was around  $80^\circ$ . At RTF4, simulations with wave effects (Runs 3  
565 and 6) produced higher velocity than the one without wave effects (Run 10). The wave  
566 forcing had improved the results, that were consistent with the ADCP data. Runs 6 and 3  
567 velocities were different by their vertical structure : from 20 to 30m depth above seabed, Run  
568 6 velocity was reduced while, for Run 3, the velocity was increased. Both vertical structures  
569 being in agreement with the measurements, it is difficult to conclude. However, these forms  
570 in the upper part of the water column represent different type of wave-current interactions :  
571 aligned waves and current cause a decrease in surface flow while opposite waves and current  
572 accelerate the surface flow due to Stokes drift effects (e.g. Groeneweg and Klopman 1998).  
573 As explained previously, at RTF4, when local wind effects were included in the simulations  
574 (Run 6), the angle between waves and current tended to become small, and as a result the  
575 surface flow velocity was decreased. That what we are seen in Figure 12.

576 At RTF2, inappropriate boosting of the flow was visible when the wave forcing is acti-  
577 vated, while Run 10 (without waves) fitted well to the data. The inclusion of the local wind  
578 effects in simulations had worsened the results. However, the form of the vertical profiles  
579 with wave effects (Runs 3 and 6) was good in comparison to measurements except for near

580 the seabed, showing that the discrepancies came from the bottom friction, which appeared  
 581 as being mis-evaluated.

582 For RTF1 and RTF3, the results with and without waves (Runs 3, 6 10; see Figure 12)  
 583 were quite similar and fitted the ADCP data. Wave effects had little improved the results by  
 584 reducing the velocity, except for Run 6 at RFT3. At these time points, as the tidal current  
 585 was higher at about 1.9 m/s at the surface (see Table 5) and the waves were small (see Figure  
 586 6a), the wave effects were overwhelmed by the tidal effects and particularly those ascribed  
 587 to Stokes drift, which were in the order a few cm/s. At RTF3, as explained previously, the  
 588 tidal current was abnormally reduced.

589 During the ebb, at RTE1, RTE2, RTE3 and RTE4,  $|\Delta\theta_{w/c}|$  were less than  $90^\circ$  and around  
 590  $60^\circ$ . For all time points, waves effects had improved the results by reducing the velocity in  
 591 the upper water column due Stokes drift effects, as expected in the former studies. Nice  
 592 fits with observations were obtained, particularly at RTE3 and RTE4 where waves are more  
 593 energetic than at RTE1 and RTE2 (see Figure 6). Local wind effects, which had induced  
 594 error during the flood on 25 November, had not worsened the vertical structure at RTE3  
 595 and RTE4.

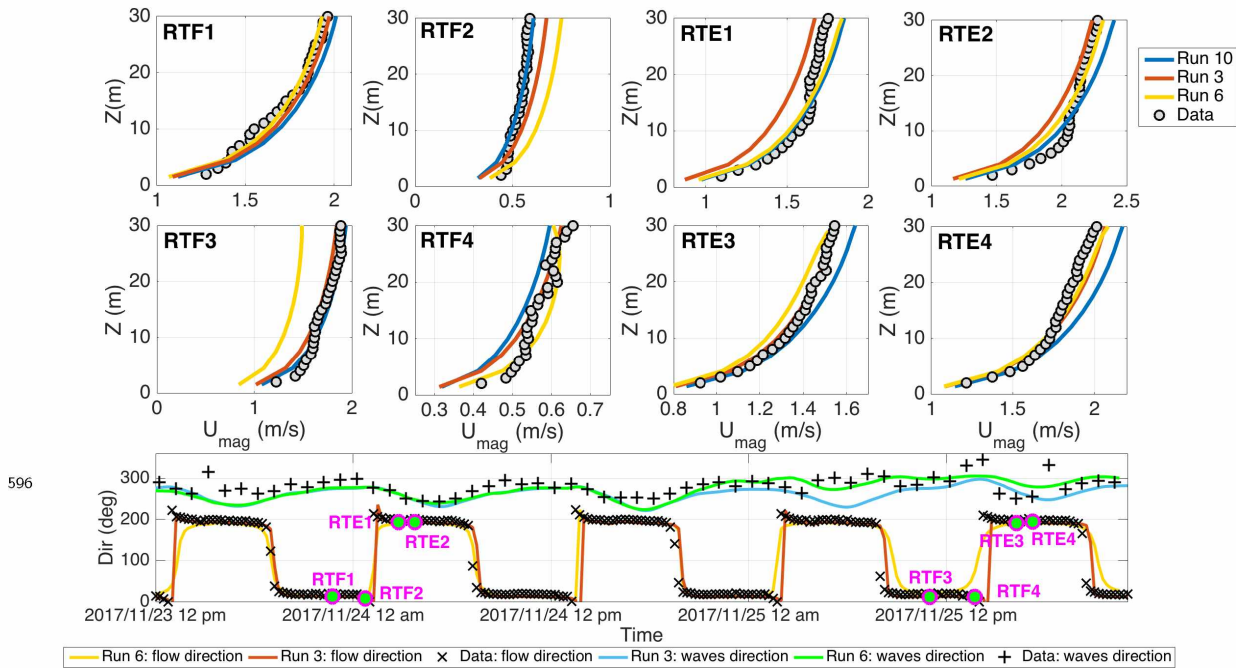


FIGURE 12: **Top and middle panels** : Flow velocity magnitude over depth at RTF1, RTF2, RTE1, RTE2, RTF3, RTF4, RTE3 and RTE4; in-situ measurements are in black circles while numerical results for Runs 3, 6 and 10 are in red, yellow and blue lines, respectively. **Bottom panel** : Time series of the flow direction for Run 3 (red line) and 6 (yellow line) and the related wave direction in light blue and green line, respectively. Measured wave and current directions are in black crosses and plusses.

## 4. Conclusions and perspectives

The purpose of this study is twofold with a first step dealing with the validating of our modelling platform for the study site and a second step aiming to show the impacts of wave-current interactions on the hydrodynamic of the Alderney Race. To reach these goals, realistic 3D fully-coupled wave-current-turbulence simulations have been carried out and tested against in-situ measurements.

On the whole, our numerical model is successfully validated through statistical parameters (PBIAS, NRMSE, MAE,  $R^2$ ) in comparison with observations for mean sea water level, significant wave height, mean wave direction, frequency wave energy spectra, flow velocity magnitude and direction. However, a non-stationary time lag was observed sometimes between model and measurements. This problem was found to be sensitive to the waves and wind effects and had been partially fixed when these effects were included, probably due to the near-bed wave orbital velocity which changes the bottom stress. In addition, time lag was also shown as being modified by the depth where a logarithmic velocity profile is applied, highlighting the effects of the near-bed turbulence. Therefore, further studies are required to investigate what are the role in the time lag of the bottom turbulence, near-bed wave orbital velocity as well as the bathymetry effects, that drive the hydrodynamic. Furthermore, when the wind blowed hard (wind speed greater than 15 m/s), the flow velocity was abnormally decreased (of about 0.5 m/s) due to a mis-evaluating of the local wind effects in the ocean model. This point needs to be improved in the future by working on the wind stress formulation and the relating wave contribution.

Wave-current interactions were observed in Alderney Race. Ocean waves impacted the flow due to : - the Stokes drift effects, that induced an increase/decrease in the current depending on the angle between waves and current, with a maximum influence near the surface, - the wave enhancement of the bottom friction that reduced the tidal current. Furthermore, tidal current has modified ocean waves through : - the refraction of waves by the current, that have generated changes in waves directions and - the wave breaking ascribed to tidal current, that increased the turbulent mixing within the water column. The main results of this paper is the significant influence of ocean waves on the vertical profile of the flow whereas waves are small (significant wave height less than 1.5 m). Moreover, changes in vertical profiles were occurred even for a strong surface current (around 2.3 m/s) due to the angle between waves and flow direction.

Consideration of ocean waves effects has improved the simulation of the tidal current and particularly the reproduction of its vertical shape, showing that these effects have to be taken into account for the tidal converter dimensionning.

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## Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

On behalf of the authors

Anne-Claire Bennis

## **Author Contribution Statement**

**A.-C. Bennis:** Conceptualization, Writing – original draft, Writing – review and editing, Methodology, Software, Validation, Investigation, Supervision, Funding Acquisition.

**L. Furgerot:** Writing – review and editing, Data curation, Formal analysis, Validation, Resources.

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