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1 **A winter storm in Alderney Race : impacts of**
2 **3D wave-current interactions on the**
3 **hydrodynamic and tidal stream energy**

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11 Due to the climate change, it is necessary to modify the energy modes of production. The mix
12 energetic, based on renewable energies as tidal currents, is one of the solutions to decrease
13 the energy production carbon footprint. This article focuses on hydrodynamic interactions
14 in Alderney Race (France), which is the most energetic tidal site in Western Europe with a
15 maximum potential of 5.1 GW according to Coles et al. (2017). The impact of a winter storm
16 occurring during spring tide is assessed thanks to numerical modeling with a 3D fully-coupled
17 wave-current model and in-situ data. This study starts to analyze the impacts of the storm
18 on the wave field and the current effects on waves. Then, the modifications of the current
19 and tidal stream energy caused by waves are discussed. After a successful validation step
20 with excellent PBIAS and R^2 scores, the main findings are : i) although the current intensity
21 is strong (around $3\text{-}4\text{ m}\cdot\text{s}^{-1}$), the wave action significantly changes the vertical profile of
22 the current, with a reduction of the PBIAS by a factor of 1.78 between simulations with
23 and without wave effects, ii) ocean waves affect the tidal asymmetry, with a flood current
24 whose intensity is 13% higher than for the ebb current, inducing a decrease of 30% in the
25 tidal stream energy, iii) the flow is very sensitive to the angle between the directions of
26 propagation of waves and current, with an acceleration or a reduction of the velocity, as
27 observed in the presence of a 3D turbulent structure, iv) current effects on waves cause a
28 wavenumber shift, changes in significant wave height (modulated by tide), wave direction due
29 to refraction and an increase of the energy transfer from waves to ocean ascribed to the wave
30 breaking. By a feedback mechanism, the modifications of the wave field by current and water
31 level significantly alter the flow with a decrease of its velocity when waves propagate against
32 current. This study shows that the 3D wave-current interactions need to be considered during
33 a storm even during a spring tide event where currents are the strongest.

34 **Keywords**— Marine renewable energy, tidal sea, winter storm, wave-current interactions
35 and coupling, three-dimensional numerical modeling, tidal energy estimate, Alderney race

1. Introduction

In its last report, the Intergovernmental Panel of Climate Change (IPCC¹) highlights again on the necessity for human activities to reduce its greenhouse gas emissions. Nowadays, 70% of the world electric production is based on fossil energy consumption (natural gas, oil and coal). Solar and wind farms are in a high development rate, but cannot provide for all the needs on their own, in the context of a growing demand. Every alternatives to classical electricity product modes have to be investigated, in which tidal farms. Companies exploiting tidal energy are interested in tidal sites where the depth is less than 50 m and the maximum tidal current is larger than 2.5 m.s^{-1} (e.g. Lewis et al. 2015). Once the sites have been selected, they are subjects to a more detailed resource characterisation according the IEC 62600 standard. Then, it is necessary to identify the factors that could affect this resource (e.g. interactions between hydrodynamic processes, marine turbulence, sediment transport).

The Alderney Race (hereinafter referred as AR) (English Channel, France) is the third strongest tidal currents place of the world, the first in western Europe with current speed of up to 5 m.s^{-1} during high spring-tide. This site, with a maximum potential of 5.1 GW which exceeds the estimate for the Pentland firth by 35% (Coles et al. 2017), is very interesting for the exploitation of its current resource and many works have been conducted there (e.g. Mercier et al. 2021; Bennis et al. 2021; Thiébaud et al. 2020). Authors have shown a high variability and level of turbulence along the water column and on the bottom due the interactions between the flow and the seabed morphology, which could have an impact on the resource. However, despite the recent efforts to measure this turbulent activity, difficulties still remain in evaluating turbulent structures, particularly near the bottom, as reported by Mercier et al. (2021). In parallel, innovative numerical modelings (e. g. Bennis et al. 2021; Mercier et al. 2020), based on Large Eddy Simulation (hereinafter referred as LES) methods, were developed in order to help the understanding of the near-bed turbulent motions.

Wave-current interactions (hereinafter referred as WCI) are also an important point for the design of tidal converters, especially concerning the fatigue due to the vertical shear of the current that they cause. This topic was addressed in the framework of the HYD2M program². WCI were studied using *in-situ* and High-Frequency (hereinafter referred as HF) radar measurements as well as by the use of numerical models. Cross-comparisons were carried out. The one-year of *in-situ* data have revealed that wave effects were absent during only 6% of the time from june 2017 to july 2018 (i.e. significant wave height (H_s) less than 0.5 m and wind speed lower than 4 m.s^{-1} during 22 days over 365 days) as reported in Furgerot et al. (2020). This shows that most of the time it is necessary to consider wave effects in studies. Strong vertical shears due to waves (Stokes drift and wave-breaking

1. <https://www.ipcc.ch/srocc/>

2. HYD2M was funded by ANR (ANR-10-IEED-0006-07) for the building of France Energies Marines.

71 turbulence) have been measured in the upper-half of the water column. In the same time,
72 wave effects change both bottom friction and turbulence. As a result, the flow velocity is
73 affected throughout the water column due to waves. Concerning the horizontal shear of the
74 current, which is difficult to determine using Acoustic Doppler Current Profiler (hereinafter
75 referred as ADCP), HF radars have allowed to improve its knowledge. Despite the good
76 accuracy of the surface current measures with HF radar (Lopez et al. 2020), the strong tidal
77 current in AR induces a high level of noise in the doppler spectra making difficult an accurate
78 determination of the sea state characteristics. As reported by Lopez et al. (2018) and for the
79 moment, only the sea state characteristics recorded when the tidal current velocity is around
80 1 m.s^{-1} or less, are coherent to the ADCP data. In parallel, three-dimensional (hereinafter
81 referred as 3D) numerical modeling of the hydrodynamic in AR has shown different effects
82 ascribed to WCI. These effects are described in Bennis et al. (2020) for different sea conditions
83 (ie. slightly to rough conditions according to the Douglas sea scale) : i) the flow velocity is
84 decreased/increased in the upper half of the water column depending on the angle between
85 the directions of propagation of waves and current according to the mechanism pointed out by
86 Groeneweg and Klopman (1998), ii) ocean waves are deviated from their initial direction due
87 to the interactions with surface current which causes wave refraction, iii) the enhancement
88 of the bottom friction caused by waves results in a reduction of the tidal current velocity
89 and tidal stream energy, iv) the turbulent mixing, particularly near the surface, is changed
90 ascribed to the wave breaking induced by WCI. The study carried out in Bennis et al. (2020)
91 was the first one to simulate and analyze the WCI effects in 3D for AR. Pioneer studies have
92 been carried out for other tidal sites and for idealized conditions. For example, Guillou et al.
93 (2016) have used 3D radiation stresses, that were constant over the depth, to simulate WCI
94 in the Iroise sea (Brittany, France) for an application to the Fromveur tidal site. Another
95 example is the work of Hashemi et al. (2015) where they have computed the barotropic (2D)
96 wave-induced flow at the tidal site off the north-western coast of Anglesey Islands (Wales,
97 UK).

98 Therefore, few studies have been conducted on the WCI and to our knowledge, the 3D
99 effects induced by a winter storm on hydrodynamic and tidal stream energy have not yet
100 been studied nor published for AR. This paper continues the researches initiated by Bennis
101 et al. (2020) by assessing the impacts of the Eleanor's storm (2-5 January 2018) with the
102 3D-fully coupled wave-current model (MARS3D-WWIII) and *in-situ* data from wave buoy,
103 ADCP and wind anemometers. It focuses on the role of ocean waves in this high-energy tidal
104 environment targeted for the installation of tidal turbines, through a spatial analysis of the
105 hydrodynamic processes.

106 The manuscript is organized as follows. After a short introduction in section 1, the
107 methodology, including a description of the study site, data, numerical modeling platform,

108 and experiments, is presented in section 2. Then, results are shown and discussed in section
109 3. After a validation step, achieved through cross-comparisons, the spatialized hydrodynamic
110 in AR is commented, particularly in the light of WCI. Conclusions are dressed in section 4.

111 2. Methodology

112 a. *Study Site*

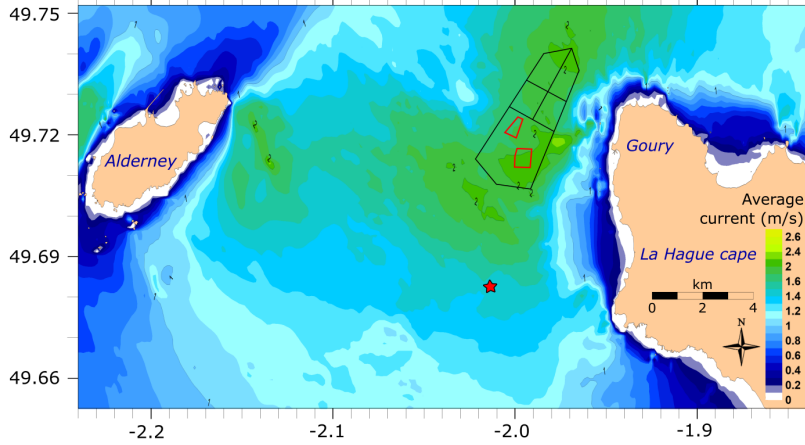
113 The study site is located in the English Channel (EC) separating United Kingdom from
114 France. EC is a shallow epi-continental sea, where the maximum depth of 174 m is reached
115 in the Hurd Deep (150 km in length and 1.5 to 5 km in width). Semidiurnal tides, with a
116 period of 12 h and 24 min, dominates the tidal regime in EC. Along the French coast and
117 mainly in the Mont-Saint-Michel Bay, the tidal range is the greatest of all EC reaching 15 m.
118 The tidal residual, propagating from the western to the eastern EC, combined with average
119 south-westerly winds generates a water replacement time varying from 200 to 500 days, with
120 longer residence times associated with residual currents gyres in coastal areas and gulfs as the
121 Brittany Isles area (Salomon and Breton 1993). Due to the Coriolis force, current velocities
122 are higher along the French coast than the English coast, reaching greater than 1.5 m.s^{-1} in
123 north Brittany and exceeding 4 m.s^{-1} off the Cotentin Peninsula. Turbulent gyres are found
124 around the Channel Islands and also near the capes of Fréhel, Barfleur, Antifer, and Gris
125 Nez. More details related to EC are available in Raoux et al. (2021); Dauvin (2019), for
126 example.

127 Our EC study site is Alderney Race (AR), which is placed off the Cotentin Peninsula
128 between the La Hague cape and the Alderney island (Fig. 1). The depth in AR varies
129 between 25 m and 90 m. The tidal current can exceed 5 m.s^{-1} during spring tides due to a
130 conservation of mass effect that accelerates the tidal flow. Furgerot et al. (2020) have reported
131 an instantaneous flow velocity of 7 m.s^{-1} in exceptional conditions. The mean spring tidal
132 ranges from 6 to 10 m from north to south of the La Hague cape ; A tidal asymmetry occurs
133 between the ebb and flood tides ascribed to the relationship between the tidal constituents
134 (Bailly du Bois et al. 2012, 2020). Wind-waves and swell propagate most of the time from
135 west to east and crossed seas are observed. Rough seas are also seen in AR with ocean
136 waves of a wavelength smaller than 50 m. Highly energetic 3D turbulent structures live in
137 AR (e.g. Mercier et al. 2021; Furgerot et al. 2020) that have a length scale of a few tens of
138 meters. The AR sea bottom is very rough and uneven with different geologic features like
139 submarine cliffs (Furgerot et al. 2019). Strong hydrodynamic interactions (e.g. bottom-flow
140 interactions, wave-current interactions) occur in AR as reported in many studies (e.g. Bennis
141 et al. 2018, 2020; Bourgoïn et al. 2020; Furgerot et al. 2020; Mercier et al. 2020). However,
142 some efforts are still required to understand the hydrodynamic processes during a winter

143 storm. We choose to study the Eleanor’s storm (2-5 January 2018) for which ADCP data are
144 available. As tidal companies would like to install pilot and commercial tidal farms off Goury
145 to have an average flow velocity around 2 m.s^{-1} (Fig. 1, black polygon), the hydrodynamic
146 and WCI in this area will be discussed in details in section 3.

147 *b. Data Collection*

148 ADCP data were collected by the HYD2M consortium in 2018 (Furgerot et al. 2020),
149 using a bottom-mounted 500 kHz Teledyne RDI Sentinel V50 (Fig. 1, red star). ADCP was
150 located at $49^{\circ}40'50.00''\text{ N}/2^{\circ}01'46.44''\text{ W}$. The position of the ADCP was chosen to minimize
151 the risks of damage (shock, loss, and bottom trawling) while having strong tidal current
152 to characterize hydrodynamic interactions. The size of the measuring cells (bin) was 1 m
153 with the first cell located at 2 m above the seabed. The wave parameters were estimated
154 from ADCP measurements (20-min burst at 2 Hz every hour) and more specifically from the
155 wave orbital velocity and the surface tracking (or direct echolocation of surface) algorithms
156 (RDI 2017; Strong et al. 2000). For the selected time period and at the ADCP position, the
157 significant wave height is higher than 4 m about 35% of the studied time period (very rough
158 sea, Douglas sea scale), the wave period is ranging 7 – 11 s and waves come from the west
159 sector (between 220 and 300°). The velocity data were 10 minutes averaged to compare with
160 numerical simulations and reach 3.5 m.s^{-1} during flood time period. The flow direction is
161 oriented towards north-east and south-west for flood and ebb, respectively. At this place and
162 time, tidal range varies from 7 to 8 m with a mean depth of 35 m. Data from Met-Office wave
163 buoy (62103), available on EMODnet platform (<http://www.emodnet.eu>), were also used
164 for comparison with the wave model results. Wind measurements at the Goury semaphore
165 have been tested against the numerical wind forcings from Météo-France.



166

FIGURE 1: Study site (AR) located between the Alderney island (land on the left) and the French coast (land on the right). The black polygon represents the appropriate area for future tidal farms. The red areas have been specifically selected for two proposed tidal projects. ADCP location is represented by a red star. The time and depth average flow velocity is superimposed in colored contours according to Bailly du Bois et al. (2020).

167 *c. Numerical modeling*

168 The three-dimensional hydrodynamical model, MARS3D v10 (hereinafter referred as
 169 MARS, Lazure and Dumas 2008), is used in combination with the spectral wave model,
 170 WAVEWATCH-III v4.18 (hereinafter referred as WWIII, Tolman and al. 2014) to simulate
 171 the flow motions under the wave action. MARS computes the flow dynamic under wave, wind
 172 and tide actions. WWIII is a spectral wave model that simulates generation, propagation
 173 and dissipation of ocean waves by solving the wave action equation (more details in Tolman
 174 and al. 2014). For MARS simulations, wave forcing is based on the set of equations of
 175 Ardhuin et al. (2008) and Bennis et al. (2011). All details regarding the equations and their
 176 implementations are available in Bennis et al. (2011, 2014, 2016, 2020). In the light of the
 177 numerous papers describing the sets of equations, they are not detailed here but briefly
 178 overviewed.

179 The generic formulation of momentum equations for a wave-forced, three-dimensional,
 180 incompressible, unsteady, hydrostatic, constant-density flow is :

$$181 \quad \frac{D\hat{\mathbf{U}}}{Dt} = \mathbf{S}_{\text{EPG}} + \mathbf{S}_{\text{VM}} + \mathbf{S}_{\text{HM}} + \mathbf{S}_{\text{WP}} + \mathbf{S}_{\text{BA}} + \mathbf{S}_{\text{BBL}} + \mathbf{S}_{\text{VF}}, \quad (1)$$

182 where $\hat{\mathbf{U}} = (\hat{U}, \hat{V}, \hat{W})$ is the 3D quasi-Eulerian velocity defined as the Lagrangian velocity
 183 minus the Stokes drift. The source terms \mathbf{S}_{EPG} , \mathbf{S}_{VM} , \mathbf{S}_{HM} , \mathbf{S}_{WP} , \mathbf{S}_{BA} , \mathbf{S}_{BBL} , \mathbf{S}_{VF} are
 184 related to the external pressure gradient, the vertical mixing, the horizontal mixing, the

185 wave-induced pressure gradient, the breaking acceleration, the bottom streaming, the vortex
186 force, respectively. This set of equations is compatible with that of McWilliams et al. (2004)
187 used in Uchiyama et al. (2010), Kumar et al. (2012) and Marchesiello et al. (2015), for
188 example.

189 The wave forcing, based on the vortex force formalism applied to the mean flow, consists
190 to add wave forcing terms to the primitive equations of the ocean allowing to take into
191 account the effects of the wave-induced pressure, the Stokes drift, the wave breaking accele-
192 ration, the wave-induced turbulent mixing and the redistributing of the momentum via the
193 vortex force. The well-known turbulent closure, $k - \epsilon$, for vertical mixing is also adapted
194 to include wave-induced source terms of turbulent kinetic energy (k) and dissipation (ϵ)
195 according to Walstra et al. (2000) (more details in Bennis et al. 2014). Boundary conditions
196 for the flow velocity, sea surface height and turbulent quantities are also changed (more de-
197 tails in Bennis et al. 2011, 2020). The coupling between MARS and WWIII is managed by
198 the automatic coupler OASIS developed by CERFACS (Valcke et al. 2015) and is two-way
199 (Bennis et al. 2020). Thus, we are able to simulate the modifications of the flow ascribed to
200 waves and also the changes in the wave field due to the interactions with surface current and
201 sea surface height.

202 *d. Numerical configuration and experiments*

203 The horizontal computational grids of MARS and WWIII are similar with an horizontal
204 resolution of 600 m and it covers the spatial domain going from $47^{\circ}53'60.0''$ N / $6^{\circ}03'32.4''$
205 W to $50^{\circ}27'0.0''$ N / $0^{\circ}43'12.0''$ W (Fig. 2). Even if simulations for Alderney Race at finer
206 resolutions (120 m) compared with in-situ data (Bennis et al. 2020) highlighted very good
207 agreements, we selected a low spatial resolution in order to : 1) be able to compare numerical
208 results with HF radar data at 750-m of radial resolution in the future and, 2) reduce the
209 computing time. Moreover, it is interesting to know if the model is accurate and relevant
210 for a such spatial resolution. MARS simulations are three-dimensional with 25 sigma levels
211 evenly distributed over the vertical. The tidal forcing of MARS is based on the Shom CST
212 France atlas that includes 114 tidal components (Leroy and Simon 2003). MARS is forced
213 by the wave forcing terms computed by WWIII (Eq. (1) and more details in Bennis et al.
214 2011). WWIII uses 32 frequencies from 0.04 Hz to 0.7678 Hz and 24 directions leading to
215 a directional step of 15° . WWIII is constrained at its open boundaries by bi-dimensional
216 (frequency-direction) wave energy spectra from the HOMERE and Ifremer databases (Bou-
217 diere et al. 2013). According to the coupling mode, WWIII is forced by surface current and
218 water level computed by MARS. Wind at 10-m height above the sea from the Meteo-France
219 re-analysis (ALADIN atmospheric model) is used to force MARS and WWIII at the surface.
220 The coupling time step is 20 s, which is greater than or equal to the model time steps (i. e. 4 s

221 for MARS3D and 20s for the global time step in WWIII). Details of numerical experiments
 222 are summarized in Table 1 and presented in Fig. 3.

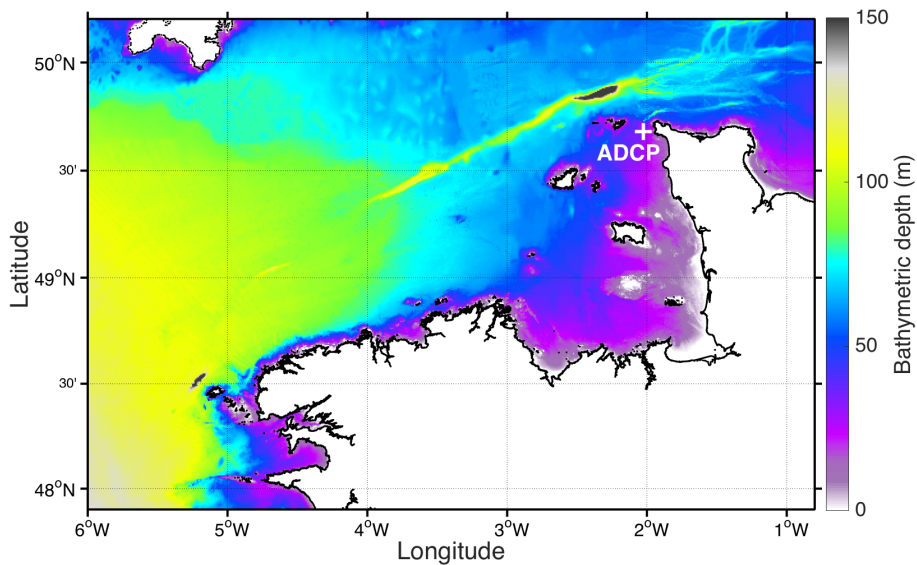
223 Four numerical configurations are tested against data : i) Run A including wind and tide
 224 effects, ii) Run B taking into account only tide effects and iii) Runs C and D integrating tide,
 225 wind and wave effects for two different coupling modes. Run C uses a two-way wave-current
 226 coupling (ie. current and water level effects on waves are considered) while Run D is one-way
 227 (ie. current and water level effects on waves are NOT considered).

	Tide effects	Wind effects	Wave effects	Wave-current coupling
Run A	X	X	-	no
Run B	X	-	-	no
Run C	X	X	X	yes, TW
Run D	X	X	X	yes, OW

228

TABLE 1: Description of the four numerical simulations (Runs A, B, C and D) according to the forcing fields (tide, wind and waves). TW (with current and water level effects on waves) and OW (without current and water level on waves) represent the two-way and one-way coupling modes, respectively.

229



230

FIGURE 2: Bathymetric map (LAT, source : Shom) and spatial dimensions of the horizontal grids of MARS and WWIII. The ADCP location is drawn with a white cross.

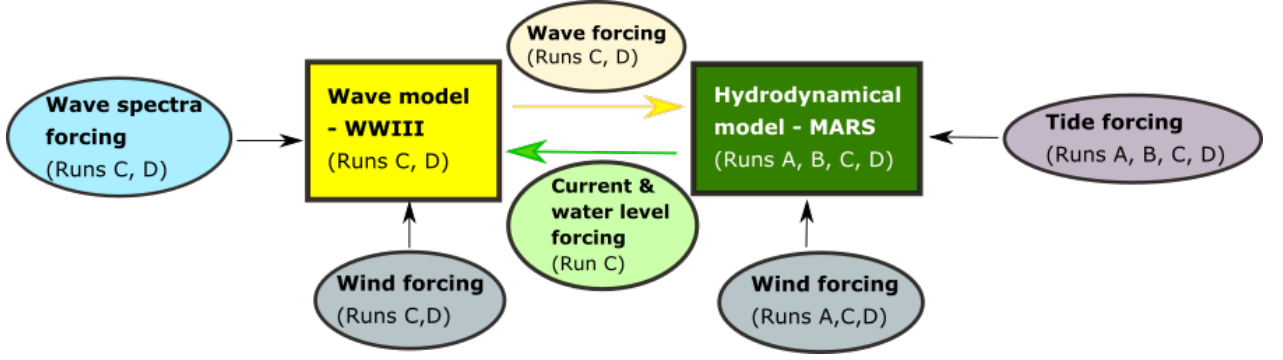


FIGURE 3: Schematic representation of the forcings involved in the numerical modeling according to the test cases (Runs A, B, C, D).

Model accuracy is evaluated through the root mean square error (RMSE), normalized root mean square error (NRMSE), BIAS, PBIAS and R-squared (R^2), such as (e.g. Allen et al. 2007b,a) :

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

$$\text{NRMSE} = \frac{\text{RMSE}}{\max(X_{data}) - \min(X_{data})}, \quad (3)$$

$$\text{BIAS} = \frac{\Sigma(X_{model} - X_{data})}{N}, \quad |\text{PBIAS}| = 100 \times |\text{BIAS}|, \quad (4)$$

$$R^2 = 1 - \frac{\Sigma(X_{data} - X_{model})^2}{\Sigma(X_{data})^2}, \quad (5)$$

where N is the total number of available samples (120). X_{model} and X_{data} represent the samples coming from numerical simulations and in-situ data for 1-5 January 2018, respectively. PBIAS allows us to know if the model is systematically underestimating or overestimating the measurements. $|\cdot|$ denotes the absolute value operator. The closer the value is to zero the better the model. Some categories were defined to estimate the performance levels regarding $|\text{PBIAS}|$: ≤ 10 excellent, $10 - 20$ very good, $20 - 40$ good, ≥ 40 poor (Marechal 2004; Allen et al. 2007a). R^2 is a statistical measure to quantify dispersion around a fitted regression line, with a perfect fit for $R^2 = 1$. R^2 performance levels were defined as : ≥ 0.65 excellent, $0.65 - 0.5$ very good, $0.5 - 0.2$ good, ≤ 0.2 poor (Marechal 2004). The ranges chosen to categorize the performance levels are subjective. They are solely used for evaluating the performances of our numerical model in four categories from excellent to poor.

3. Results and Discussion

In this section and after a validation step, the spatialized hydrodynamic of AR during the Eleanor’s storm is analyzed with a special interest in the area selected for implementation of tidal turbines (Fig. 1, black polygon). Sea states and wind are first described and discussed. Then, we focus on the flow velocity and tidal stream energy.

a. Sea States and wind

During the studied period, the Eleanor’s storm generated strong wind in EC. The anemometers at the 62103 wave buoy and Goury Semaphore recorded a wind velocity about $20 \text{ m}\cdot\text{s}^{-1}$ around 4 a.m. on 3 January 2018 (Fig. 4d). The wind velocity continued to increase at the buoy location until it reached a maximum value of $25 \text{ m}\cdot\text{s}^{-1}$ around 7 a.m. on 3 January 2018 (Fig. 4d, black circles). In contrast, a different behavior was observed in Goury where the wind velocity decreased slightly after 4 a.m. on 3 January 2018 (Fig. 4d, blue circles).

The storm was coming from the Atlantic Ocean with a wind blowing from the west, with a direction around 270° (Fig. 4e). The storm energy decreased during its propagation in EC from west to east, explaining the weaker wind velocity in Goury. A very good agreement is found between the wind data, from the buoy and Goury Semaphore, and the numerical wind forcings from ALADIN, respectively with an NRMSE of 0.13 and 0.16, a |PBIAS| of 9.22% and 14.59% and a R^2 of 0.96 and 0.95 (Table 2). Main differences are likely due to the coarse horizontal resolution (around 7.5 km) of the ALADIN model and the output time step of 6 hours which does not allow to simulate the impacts of the hourly variations of the wind. Moreover, NRSME and |PBIAS| are stronger at Goury than at the buoy position. That is probably caused by the land location of the Goury Semaphore, that generates different turbulent motions in the atmospheric boundary layer. As the wind generates sea states by moving the sea surface, ocean waves and wind at 10-m height are correlated. As a result the time evolution of the significant wave height (H_s , Fig. 4a) follows the time evolution of the wind most of the time (Fig. 4c). Maximum values of H_s and of the wind velocity occurred at the same time, on the mornings of the 3 and 4 January. The H_s of 7.5 m on 3 January at 7 :15 a.m. estimated from ADCP is difficult to explain because it is inconsistent with wind data recorded by the Goury Semaphore (Fig. 4d, blue circles). This H_s was calculated with an algorithm based on the wave orbital velocity. Using another algorithm based on the surface tracking method (Fig. 4a, light blue crosses), the post-processed H_s is similar to that calculated by the wave orbital velocity method except for the highest H_s values on 3 and 4 January. In particular, a H_s around 4 m is observed on 3 January at 7 :15 a.m, which is closer to the numerical results. The differences between the H_s post-processed by the two

287 algorithms occur when the tidal current is strongest. It is possible that the algorithm using
 288 the wave orbital velocity method has some difficulty separating the wave orbital velocity
 289 from the tidal current when this latter is strong. Further investigations are needed to clarify
 290 this situation. However, as the flow response to wave effects is consistent with the ADCP
 291 data (Section 3b), the simulated Hs should not be too far from the real Hs and the values
 292 calculated by the surface tracking method appear more realistic.

293 Despite this problem, statistics for Hs computed over 5 days have revealed excellent
 294 scores with with a |PBIAS| of 7.42% and 1.78 % at the wave buoy and ADCP locations,
 295 respectively, and an NRMSE lower than 0.24 (Table 2). The dispersion of the model data is
 296 excellent with values of R^2 around 0.93. Very good scores are also obtained for wave period
 297 and direction (Table 2). When the surface tracking method is used, the lowest wave periods
 298 (around 4 s) disappear from the post-processed data (Fig. 4b, light blue crosses), improving
 299 the fit to the numerical results. These low values correspond to the highest values of Hs
 300 discussed before, showing that the wave orbital velocity algorithm also generates spurious
 301 values for wave period for a strong tidal current. Changes in wave direction inducing wave
 302 motions towards the northeast during the ebb and towards the southeast during the flood
 303 ascribed to wave refraction by currents were also well reproduced for this period (Fig. 4e),
 304 following the conclusions of Bennis et al. (2020); Ardhuin et al. (2012).

305 The impacts of the surface current and water level on the wave field are presented on
 306 maps Fig. 6 through the relative difference (Δ) defined as :

$$307 \quad \Delta R = 100 \cdot \left(\frac{R_{tw} - R_{ow}}{R_{ow}} \right), \quad (6)$$

308 where ΔR stands for the relative difference related to the R parameter. R_{tw} and R_{ow}
 309 represent the value of R produced by Run C and D, respectively.

310 To ease the analysis, 3 zones were defined on the map Fig. 5a (#W1 La Hague point,
 311 #W2 northern part of the peninsula and #W3 south part) for which we will comment the
 312 dynamic. Results of Run C (with current and water level effects on waves) and D (without
 313 current and water level effects on waves) are compared by this mean for the significant wave
 314 height (ΔH_s), the wave direction (ΔDir) and the mean wavelength (ΔLm). The dynamic
 315 was particularly studied for three time points (T0, T1 and T2), for which the flow velocity
 316 is maximum (Fig. 7). T0, T1 and T2 are on 3 January at 1 :15 a.m. (low tide), 7 :15 a.m.
 317 (high tide) and 2 :15 p.m. (low tide), respectively. At high tide (T1) an increase in Hs (i.e.
 318 $\Delta H_s > 0$ and red color on map Fig. 6) of about 20% due to tidal effects was observed in
 319 #W1 (Fig. 6d) and anywhere else a decrease (i.e. $\Delta H_s < 0$ and blue color on map Fig. 6). In
 320 #W1, as shown in Fig. 5b, e, the angle between wave and current directions of propagation
 321 (θ_{wc}) is large ($\geq 110^\circ$) and the current velocity is very high ($\simeq 3\text{-}4 \text{ m}\cdot\text{s}^{-1}$), explaining high
 322 positive values of ΔH_s . The enhancement of waves, leading to higher waves, when waves

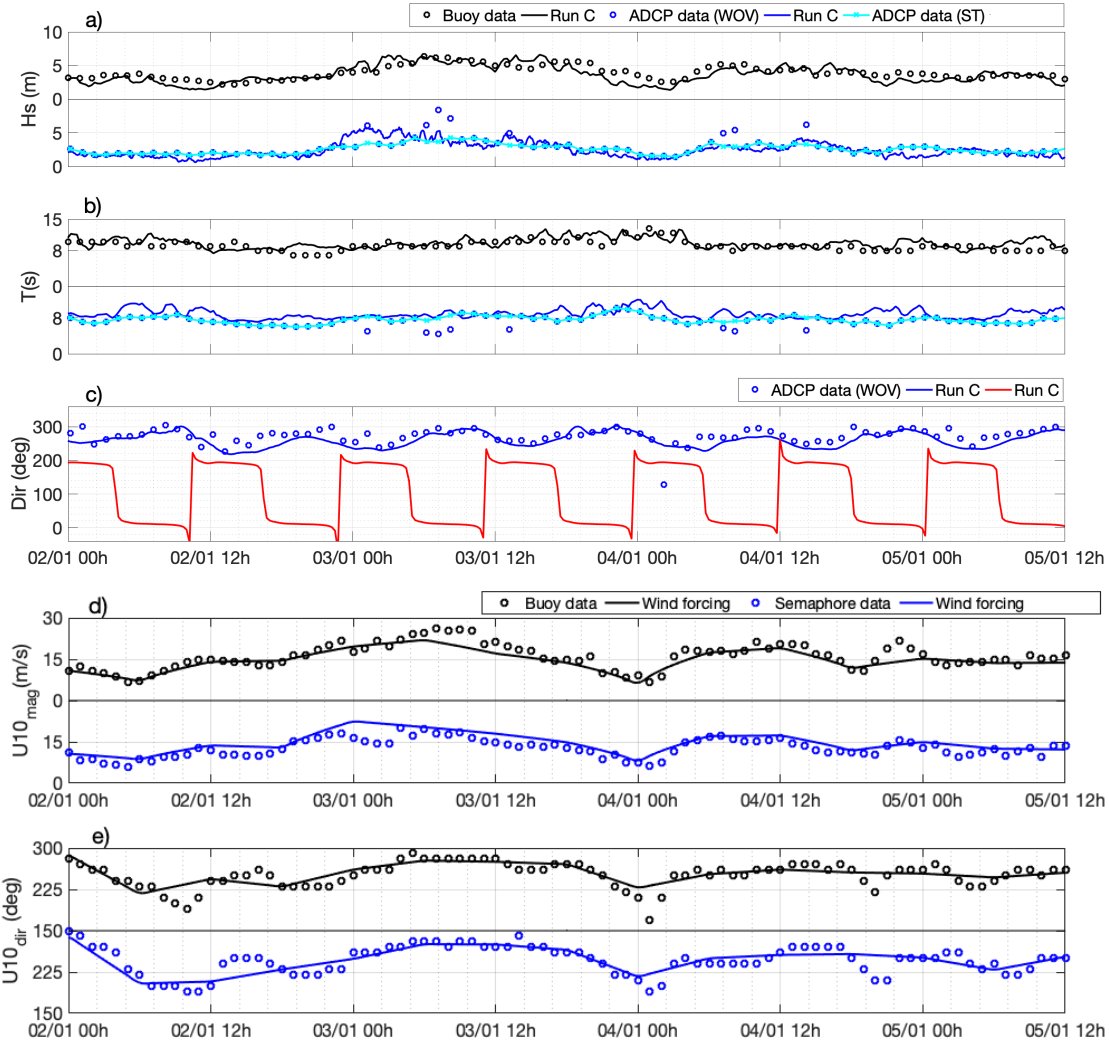
323 propagate against current is already well documented (e.g. Wang and Sheng 2018; Guillou
 324 2017) and it is observed here. Due to the same mechanism, at low tide (T0, T2) an increase
 325 in Hs in #W2 (Fig. 6a,g) was caused by large θ values reaching almost 180° (Fig. 5a,c,d,f).
 326 In contrast, a decrease in the south part of the domain (#W3) for the three time points
 327 has been generated by orthogonal waves and current. It is noticeable that near the coast
 328 at T2 where the tidal current is weak ($\leq 1 \text{ m.s}^{-1}$) the Hs is significantly affected by tide
 329 with a reduction around 15%. Otherwise, the variations of the wave to ocean energy flux
 330 (Foc) ascribed to tidal effects on waves were coherent with the Hs variations. When Hs is
 331 increased, wave breaking occurred and then wave energy is transmitted to the water column,
 332 that produces positive values of ΔFoc (not shown here).

333 Another well-known tidal effect on sea states is the change in the wave direction due to the
 334 refraction phenomenon caused by tidal current. At high tide (T1) and low tide (T0, T2) two
 335 different behaviors were observed (Fig. 6 b,e,h) : i) the flood current, propagating towards
 336 the northeast during high tide, deviates waves towards the southeast, that corresponds to
 337 positive values of ΔDir (in red), ii) the ebb current at T0 and T2, which is oriented southwest
 338 at low tide, brings waves towards the northeast, that is represented by negative values of
 339 ΔDir (in blue).

340 Moreover, tidal currents generate a wavenumber shift producing variations into wave-
 341 length and intrinsic wave frequency, leading to modifications of the wave velocity and changes
 342 in Hs (e.g. Wang and Sheng 2018; Draycott et al. 2018). Thus, when Hs is enhanced due
 343 the action of an opposing current, wavelength is reduced, and vice versa. That was mainly
 344 observed in #W3 at T0 and T2, in #W2 off the coast at T2, in #W1 at T1 and T0 (Fig.
 345 6 c,f,i). At the ADCP position, the tidal modulation of the wavelength is weak (Fig. 8b,
 346 gray dashed and solid lines). However, at other locations (e.g. $49^\circ 42' 29.88'' \text{N} - 2^\circ 6' 5.40'' \text{W}$)
 347 as presented in Fig. 8a, b, the tidal modulation is clearly visible for all tidal cycles with a
 348 decrease and an increase in wavelength during the ebb and flood, respectively.

349 Frequency wave-energy spectra show a modulation of the energy during the tidal cycle
 350 because of the wave-current interactions (Fig. 9). Indeed, at $T0 - 30'$, $T0$, $T0 + 1\text{h}30'$, tidal
 351 current flows towards the southwest and causes an enhancement of the wave energy (Fig.
 352 9a,b,c). The peak of energy is around 0.12 Hz that corresponds to a wave period (T_{0m-1})
 353 around 8.3 s which is characteristic of wind-sea. For frequencies higher than 0.2 Hz, all the
 354 wave energy is dissipated. In contrast, at $T0 + 3\text{h}30'$, $T1$, $T1 + 2\text{h}$, tidal flow reverts back and
 355 is oriented to the northeast. That induces a reduction of wave energy due to wave-current
 356 interactions (Fig. 9d, e, f). The level of energy is maximum around 0.09 Hz. At $T0 - 30'$
 357 and $T0 + 1\text{h}30'$, wave energy is two times higher for the wind sea than at the other time
 358 points. Wind forcing being applied to the wave model every 6 hours, waves at $T0 - 30'$,
 359 $T0$, $T0 + 1\text{h}30'$ and $T0 + 3\text{h}30'$ are not re-energized by wind and hence had lost energy over

360 time. The wind intensity easing a little bit after 6 a.m. and therefore the wave energy for
 361 Run D slightly decreases with a maximum value around $20 \text{ m}^2/\text{Hz}$. The results of Run C,
 362 including the effects of currents and water level on waves, show a reduction in wave energy
 363 mainly for the swell, leading to have similar levels of energy for both swell and wind-sea
 364 parts at T1+2h (Fig. 9f).



365

FIGURE 4: Data of buoy 62103 (black circles) against absolute wave bulk parameters of Run C (black line) for significant wave height (a), wave period (b), magnitude (d) and direction (e) of the wind velocity at 10-m height (from ALADIN). ADCP data, processed using wave orbital velocity (blue circles) and surface tracking (light blue crosses) methods, against absolute wave bulk parameters (blue line) of Run C for significant wave height (a), wave period (b) and wave direction (c). Goury Semaphore data (blue circles) against the ALADIN numerical wind forcing (blue line) for magnitude (d) and direction (e) of wind at 10-m height. (c) Current direction is drawn in red line. All data and model results are plotted over time.

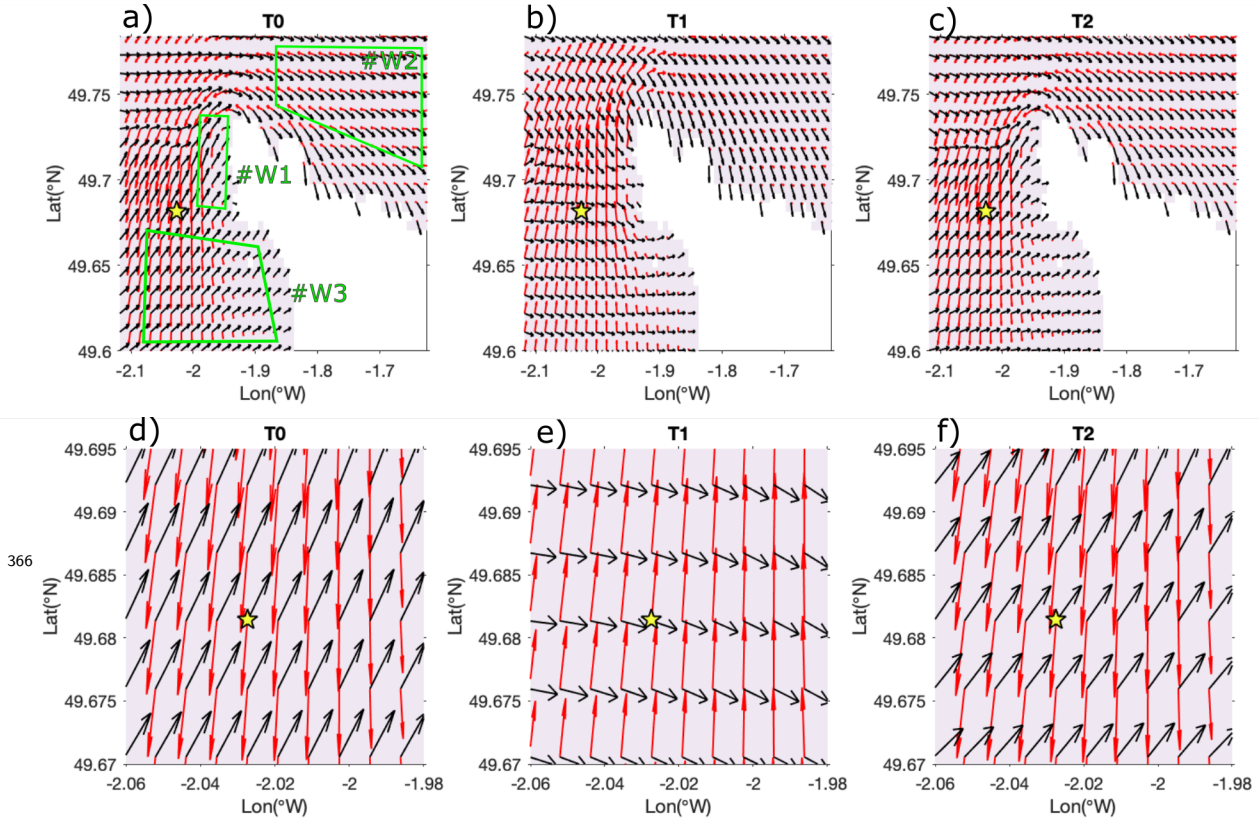


FIGURE 5: First row (a,b,c) : wave (black arrows) and current (red arrows) directions drawn each 2 grid points at T0 (a, low tide), T1 (b, high tide) and T2 (c, low tide). ADCP position is marked by a yellow star while the #W1, #W2 and #W3 areas are represented by green polygons. Second row (d,e,f) : Same legend as for the first row but for a zoom around the ADCP position where vectors are plotted every grid points.

367

	Hs (b/m)	Hs (a/m)	T (b/m)	T (a/m)	Uw (b/m)	Uw (s/m)	Uwd (b/m)	Uwd (s/m)
R^2	0.93	0.92	0.97	0.97	0.96	0.95	–	–
NRMSE	0.24	0.18	0.26	0.33	0.13	0.16	0.12	0.14
PBIAS	7.42	-1.78	5.06	-3.82	-9.22	14.59	1.10	1.10
RMSE	1.04	0.80	1.61	1.18	2.84	2.82	21.10	21.10

368

TABLE 2: Statistics (R^2 , NRMSE, PBIAS, RMSE) calculated using Eq. (2), (3), (4), (5) related to the comparison between buoy data and model (label : b/m), ADCP data and model (label : a/m), Goury semaphore data and model (s/m). Statistics for significant wave height (Hs), wave period (T), magnitude (Uw) and direction (Uwd) of the wind velocity at 10-m height are presented.

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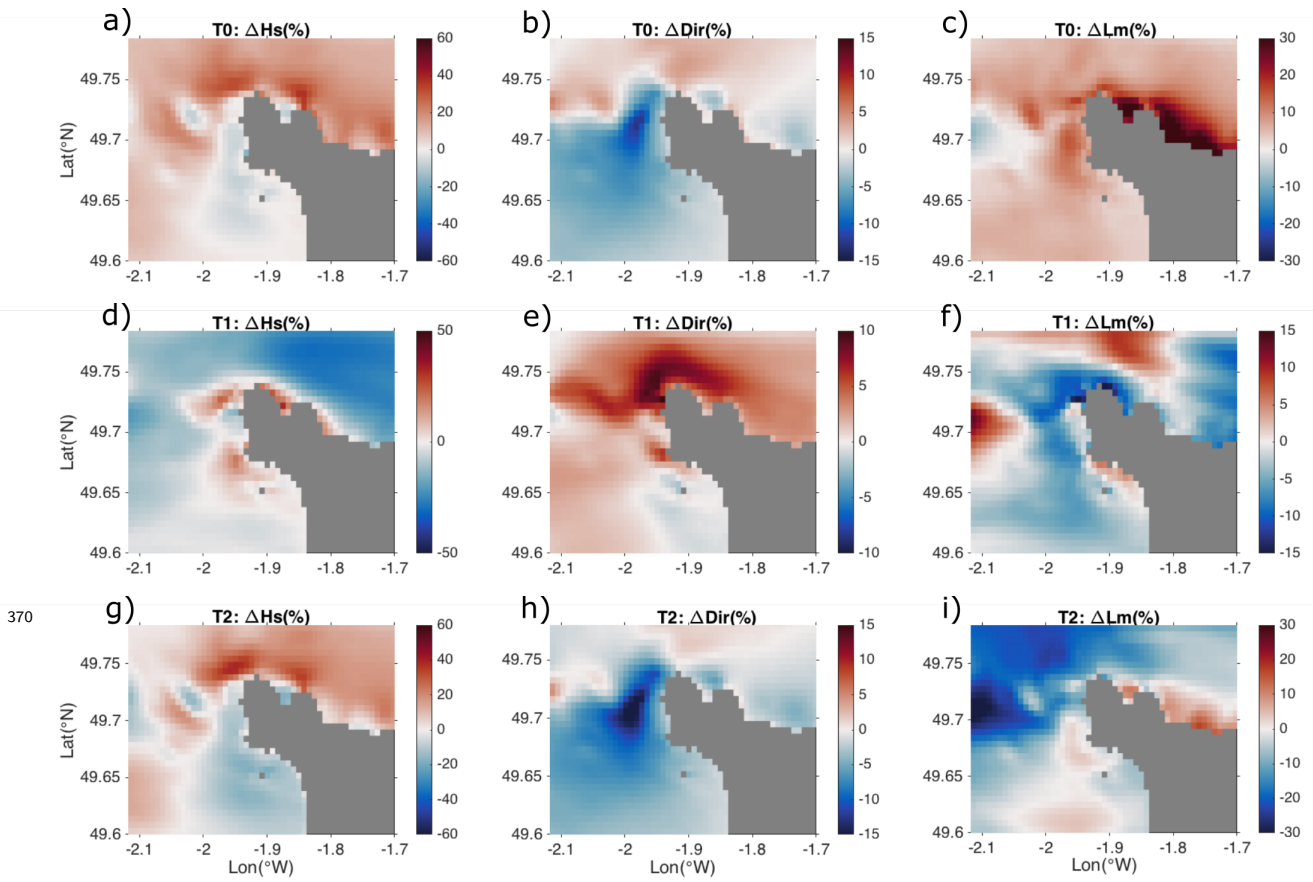


FIGURE 6: Relative differences for the relative bulk parameters from WWIII computed between Run C (with current and water level effects on waves) and Run D (without current and water level effects on waves). Positive values represent an overestimation of Run C relative to Run D. Three time points : T0 (low tide, first row : a, b, c), T1 (high tide, second row : d, e, f) and T2 (low tide, third row : g, h, i) are presented. Differences concern three bulk parameters : significant wave height (first column : a, d, g), mean wave direction (second column : b, e, h) and mean wavelength (third column : c, f, i).

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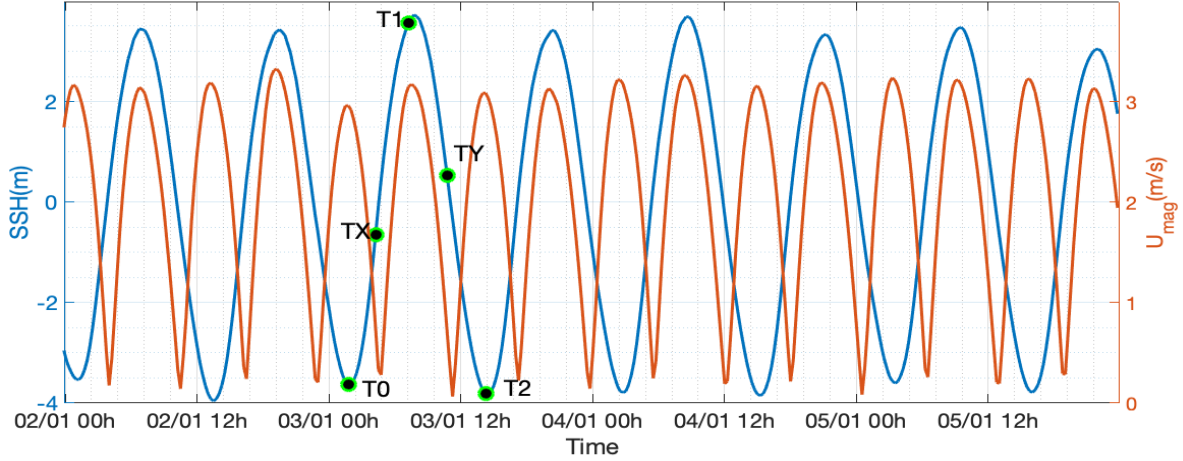
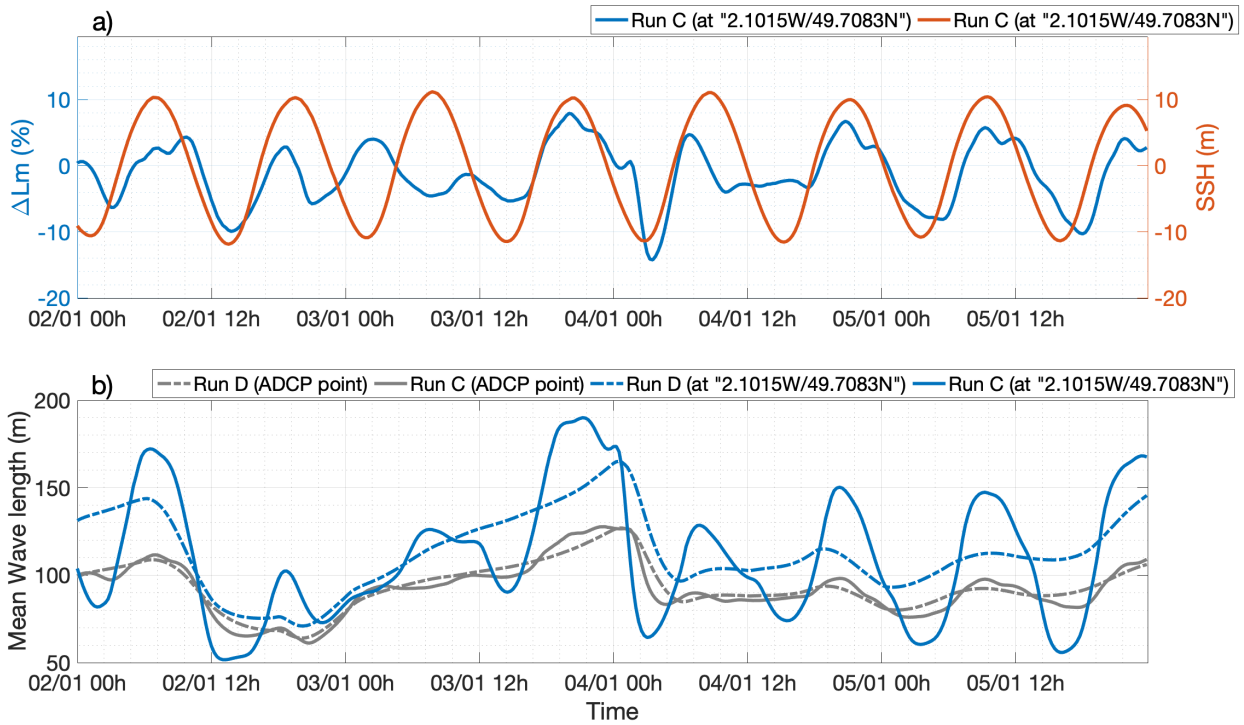
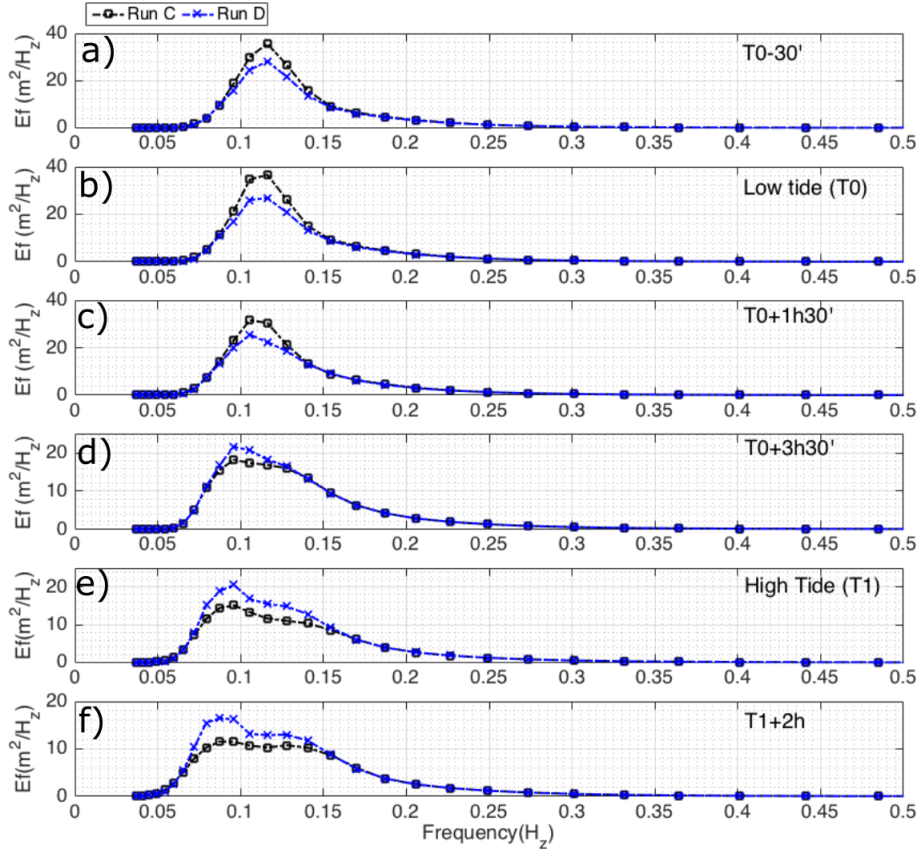


FIGURE 7: Time series at ADCP location computed by Run C for sea surface elevation (blue line) and velocity magnitude of the flow (red line) with marks at T0 (3/01, 1 :15 a.m., low tide), T2 (3/01, 7 :15 a.m., low tide), T1 (3/01, 2 :15 p.m., high tide), TX (3/01, 4 :15 a.m.) and TY (03/01, 10 :45 a.m.).



372

FIGURE 8: (a) Time evolution of the sea surface height (SSH, red solid line) and of the relative difference for the mean wavelength (ΔL_m , blue solid line) for the Run C at 2.1015W/49.7083N. (b) Time series of the mean wavelength for Run C (with current and water level effects on waves) at the ADCP position (gray solid line) and at 2.1015W, 49.7083N (blue solid line). Times series for Run D (without current and water level effects on waves) at the ADCP position (gray dashed line) and at 2.1015W, 49.7083N (blue dashed line).



373

FIGURE 9: Relative frequency-wave energy spectra over the tidal cycle computed by WWIII. Model results for Run C (with current and water level effects on waves, black line with dots) and Run D (without current and water level effects on waves, blue line with crosses) are presented for different time points : (a) T0-30', (b) T0, (c) T0+1h30', (d) T0+3h30', (e) T1 and (f) T1+2h. The vertical scale of graphs a), b), c) differ from graphs d), e) and f).

374 *b. Flow characteristics and tidal stream energy*

375 In this section, a validation step is first performed using ADCP data for flow velocity.
 376 Then, wave effects on the current are assessed and discussed as well as the changes in the
 377 flow caused by the modification of the wave field by both current and water level. This study
 378 concerns a given geographical area (1.6°W to 2.1°W ; 49.68°N to 49.78°N) that includes the
 379 locations of the future tidal farms and ADCP point (Fig. 1).

380 1) VALIDATION STEP : NUMERICAL RESULTS VS MEASUREMENTS

381 The coupled model has been already tested against ADCP data for Alderney Race in
 382 Bennis et al. (2020) for moderate hydrodynamic conditions in terms of sea states and tide.
 383 Despite the successful validation with excellent scores for R^2 and PBIAS in Bennis et al.
 384 (2020), an additional step of comparison is necessary to evaluate the model performances
 385 during these special conditions (storm event and spring tide).

386 The statistics of performance were better for the moderate conditions studied in Bennis
 387 et al. (2020) than in the present case. To support this assertion, we can compare cases with
 388 tide only (Run B, Table 4, vs Run 10 in Bennis et al. (2020)) and cases with tide, winds
 389 and waves (Run C, Table 5, vs Run 6 in Bennis et al. (2020)). Dispersion of the data is
 390 slightly worse in the pure tide case than in the previous study with a R^2 decreasing from
 391 0.98 to 0.95, but still remains an excellent score. NRMSE is modified a quit a bit from 0.09
 392 in Bennis et al. (2020) to 0.15 here. PBIAS is now around 10% whereas it was around 3%
 393 previously. For the case with all forcing, R^2 and NRMSE are almost unchanged between
 394 both time periods. In contrast, PBIAS has varied from about 2% to 6% now, which is
 395 an excellent score as defined in Section 2c. Discrepancies between the two sets of results
 396 have several origins. First, the simulations presented here use an horizontal resolution about
 397 5-fold coarser than in simulations of Bennis et al. (2020) (600-m vs 120-m of horizontal
 398 resolution). This lower resolution acts as a spatial filter and smooths the computed current
 399 and sea surface height, with a reduction of their intensities as well as a mitigation of the
 400 gradients. Moreover, the location of the numerical ADCP point is slightly different from the
 401 real, leading to loss of precision due to sub-grid scale effects. Second, the particular event
 402 (Eleanor’s storm and spring tide) makes more difficult the measurements and can affect their
 403 accuracy. In particular, the strong aeration of the flow ascribed to breaking waves disturbs
 404 the recording and the processing of the data. Here, the statistics computed at different
 405 depths (25m to 2m) and their means (Tables 3, 4, 5) show a great improvement when the
 406 wave effects are activated : Run A and B, computed without wave effects, have a PBIAS
 407 around 10%, while for Run C, where wave effects were taken into account, PBIAS is around
 408 5.6%. So, accounting for wave effects has decreased PBIAS by a factor of 1.78.

409

	25 m	20 m	15 m	10 m	8.5 m	6 m	2 m	MEAN
R^2	0.95	0.95	0.95	0.95	0.94	0.95	0.96	0.95
NRMSE	0.15	0.15	0.15	0.15	0.16	0.15	0.13	0.15
PBIAS	10.17	11.06	10.94	10.90	9.60	10.02	8.00	10.09
RMSE	0.44	0.43	0.42	0.39	0.40	0.35	0.27	0.38

410

TABLE 3: Statistical parameters for **Run A** (with tide and wind effects) computed for the velocity magnitude on the basis of model and data results. Columns refer to different water depths.

	25 m	20 m	15 m	10 m	8.5 m	6 m	2 m	MEAN
R ²	0.95	0.95	0.95	0.95	0.94	0.95	0.95	0.95
NRMSE	0.15	0.16	0.16	0.16	0.16	0.16	0.14	0.16
PBIAS	10.02	10.82	10.60	10.45	9.13	9.53	7.58	9.73
RMSE	0.46	0.45	0.43	0.39	0.41	0.36	0.28	0.40

TABLE 4: Same legend as Table 3 but for **Run B** (with tide effects).

	25 m	20 m	15 m	10 m	8.5 m	6 m	2 m	MEAN
R ²	0.96	0.96	0.96	0.96	0.95	0.96	0.97	0.96
NRMSE	0.13	0.13	0.13	0.13	0.14	0.13	0.12	0.13
PBIAS	6.65	7.15	6.93	6.70	5.42	5.39	1.04	5.61
RMSE	0.39	0.38	0.36	0.34	0.36	0.31	0.24	0.34

TABLE 5: Same legend as Table 3 but for **Run C** (with tide, wind and wave effects).

Time series of the velocity magnitude over the depth are presented in Fig. 10. Numerical results for Run A, B and C, are compared to data. Three time periods (TP1, TP2 and TP3) are particularly studied (Fig. 12). They have been chosen for their different wind conditions (wind speed is greater than 15 m.s⁻¹ for TP1 and TP3 and smaller than 15 m.s⁻¹ for TP2).

Flow velocity ranges from 0.15 m.s⁻¹ to 3.1 m.s⁻¹ in the dataset. A tidal asymmetry is observed, as reported in the bibliography, with a more intense flood flow (about 3%) compared to the ebb flow. However, the study of the velocity profiles of the pure tidal case (Fig. 10b) and of the case with waves (Fig. 10c) highlights that wave effects affect this asymmetry by reducing the ebb flow velocity. This reduction is clearly visible in the dataset during the TP1 and TP3 time periods, where the wind velocity at 10-m height is greater than 15 m.s⁻¹ (Fig. 4d). The peak velocity of the TP1 ebb flow is around 2.7 m.s⁻¹ whereas the one related to the TP1 flood tide is around 3.1 m.s⁻¹. So, the peak velocity is 13% weaker for ebb than for flood. Note that the ebb flow velocity is also reduced by 11% during TP3, where wind velocity is around 15 m.s⁻¹. A decrease of 13% in the current intensity led to a tidal stream energy (Eq. (7)) fall of about 30% (Fig. 11). In contrast, the peak velocity for periods of low wind ($U_{10} \leq 15$ m.s⁻¹), like for TP2, is smaller by 3% for the ebb in comparison to the flood, which is in agreement with the bibliography.

435 Wave effects are partly transmitted to the water column by the vertical mixing (Fig.
 436 12c), which is increased or decreased depending on the hydrodynamic conditions (Fig. 13).
 437 A strong increase (up to $0.25 \text{ m}^2 \cdot \text{s}^{-1}$) is observed during TP1 due to the strong wind and
 438 particularly affects the ebb flow because of the angle between the current and wave directions
 439 of propagation. In Fig. 15a, we observe at T0 (03/01 at 1 :45 a.m., TP1 ebb tide) that current
 440 propagates against waves at the ADCP point. This causes intense wave breaking leading to
 441 an injection of TKE in the water column. This additional turbulent source increases the
 442 vertical mixing and produces a reduction in the velocity magnitude. For the TP1 flood tide,
 443 vertical mixing is lesser enhanced due to a perpendicular direction of propagation between
 444 waves and current.

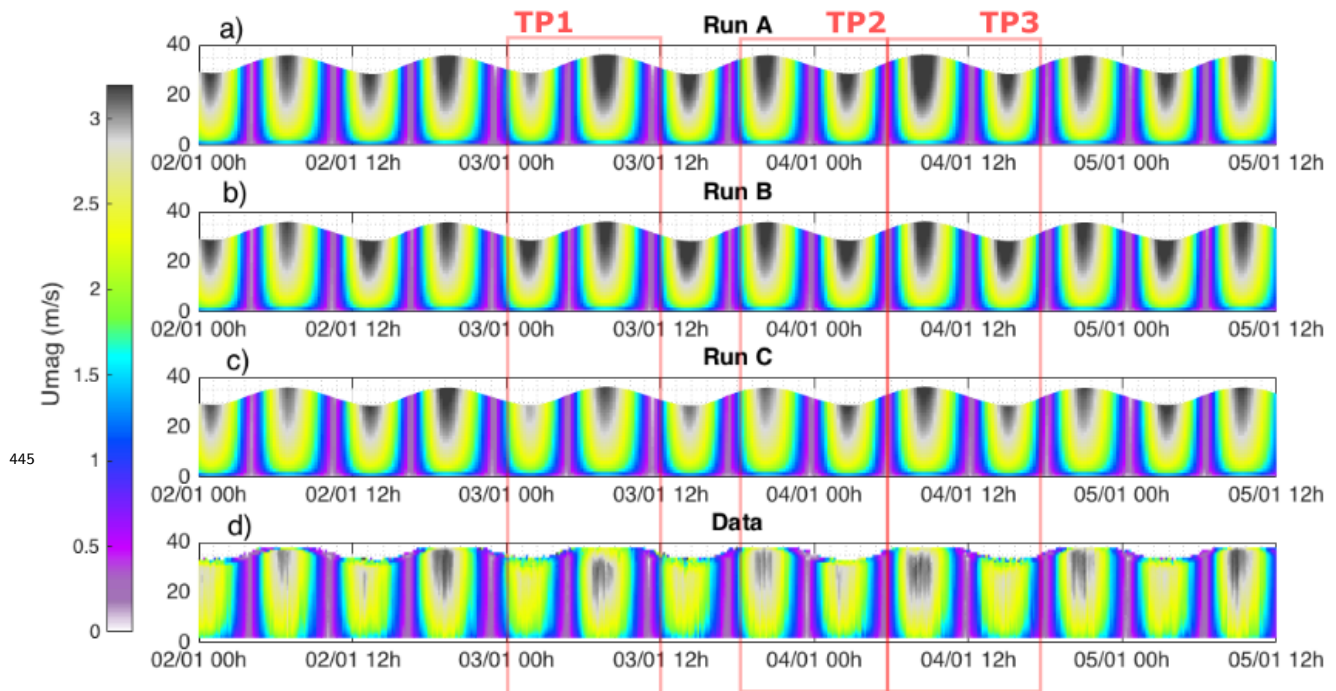


FIGURE 10: Time series of the flow velocity magnitude over the depth at the ADCP location for the model (a,b,c) and for in-situ measurements (d). (a) Run A : simulation with tide and wind effects, (b) Run B : simulation with tide effects, (c) Run C : simulation with tide, wind and wave effects.

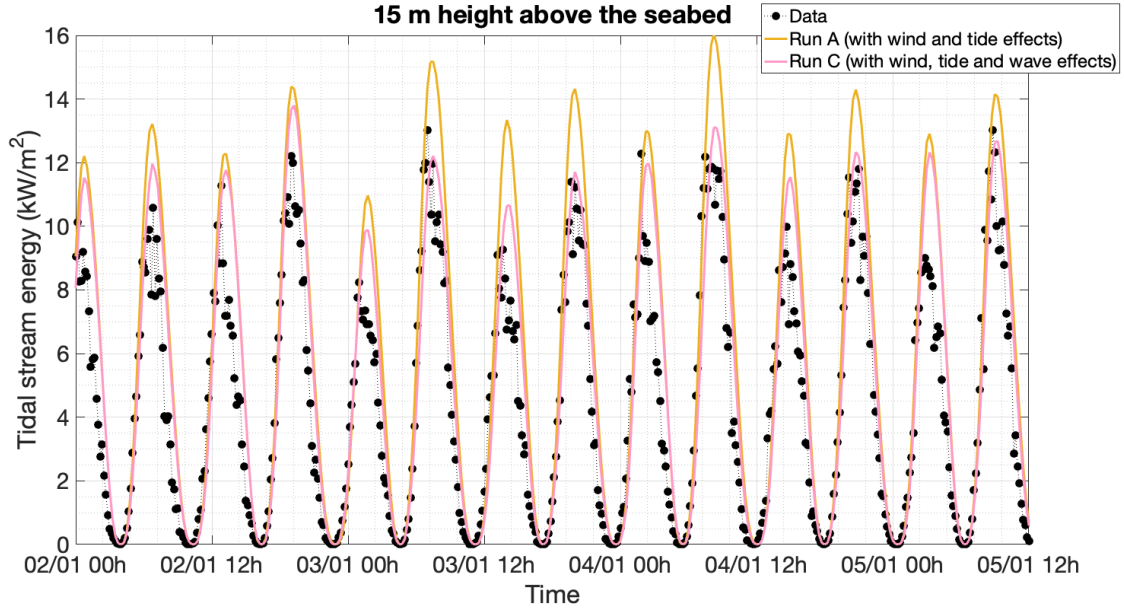


FIGURE 11: Time series of the tidal stream energy at 15 m depth at the ADCP location for the model (Run A in yellow and Run C in magenta) and for in-situ measurements (black circles).

447 Vertical mixing is not the only one effect modifying the vertical structure of the flow
 448 velocity. Our coupled model, using the vortex force formalism of Ardhuin et al. (2008) and
 449 Bennis et al. (2011), treats wave effects as being an assemblage of the vortex force and
 450 the Bernoulli head gradient. These terms are presented in Fig. 12a, d. We observe that the
 451 vortex force reaches its maximum values during the ebb phase (up to $2 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-2}$) and is
 452 enhanced for strong winds (e.g. TP1). Moreover, its action is located in the half upper of
 453 the water column. As the vortex force depends on the Stokes drift velocity, it is interesting
 454 to see that this velocity (Fig. 12b) follows similar behaviors than the vortex force (Fig. 12a).
 455 The magnitude of Stokes drift is the highest for TP1 and reaches $0.2 \text{ m} \cdot \text{s}^{-1}$ near the surface.
 456 The gradient of the Bernoulli head at the surface also acts on the flow and is presented in
 457 Fig.12d. Values are maximum during TP1 and TP3, where waves are the highest and so the
 458 pressure exerted on the water column is the strongest. In addition, as explained and shown
 459 in Bennis et al. (2020), the bottom friction is enhanced by waves and leads to reduce the
 460 flow velocity along the water column, without change in the vertical shear. This effect partly
 461 explains why the flow velocity for Run C (with waves) is weaker than for Run A and Run B
 462 (Fig. 10). Finally, vertical profile of the flow velocity at four time points (T0 : 3/01 at 1 :45
 463 a.m., TX : 03/01 at 4 :15 a.m., T1 : 03/01 at 7 :15 a.m., TY : 03/01 at 10 :45 a.m.) for which
 464 the current dynamic is discussed in sections 3a and 3b.2 are presented in Fig. 14. Numerical
 465 results are improved by the inclusion of wave effects in simulations (Run C) in comparison
 466 with the results of Run A : both intensity and shape of the flow velocity are coherent with

467 the data. However, some discrepancies are still noticeable, particularly at the T0 time point.
 468 This could be explained by the spatial resolution of 600m, which acts as a spatial filter.

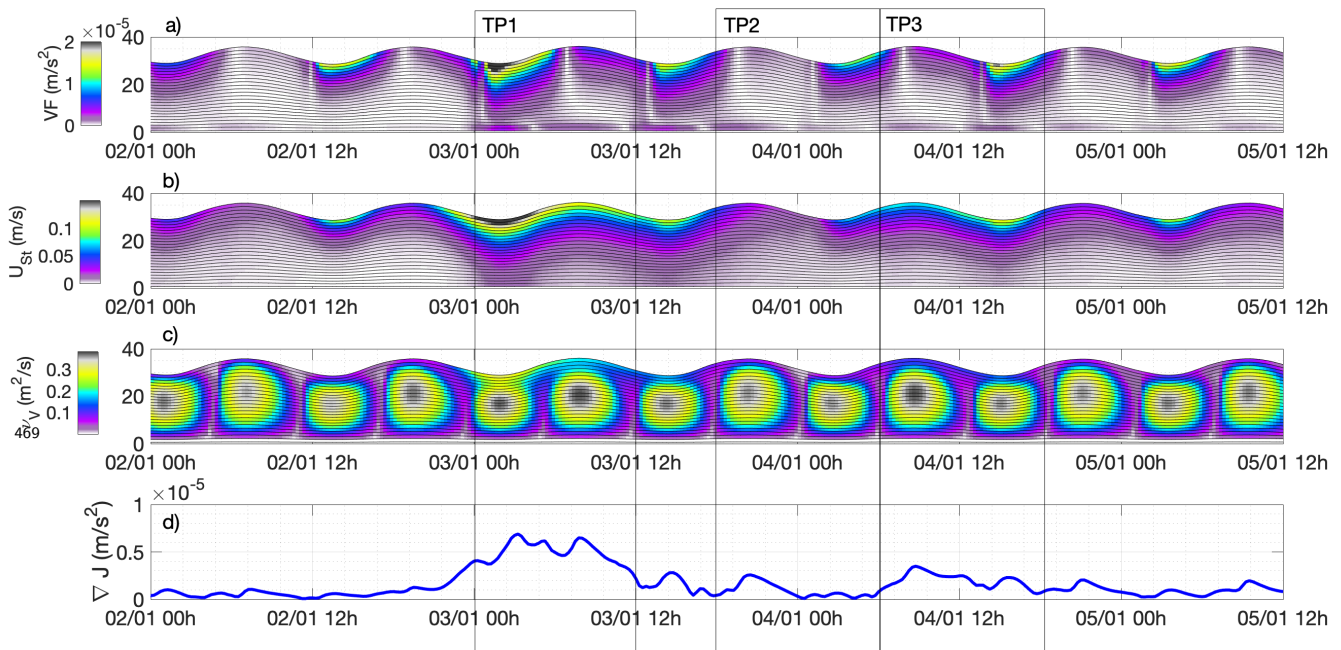


FIGURE 12: Time series over the depth at the ADCP location related to the vortex force (a), the magnitude of the horizontal Stokes drift (b), the vertical turbulent viscosity (c). Time evolution of the Bernoulli head gradient at the surface (d). Black lines represent the vertical discretization (25 sigma levels).

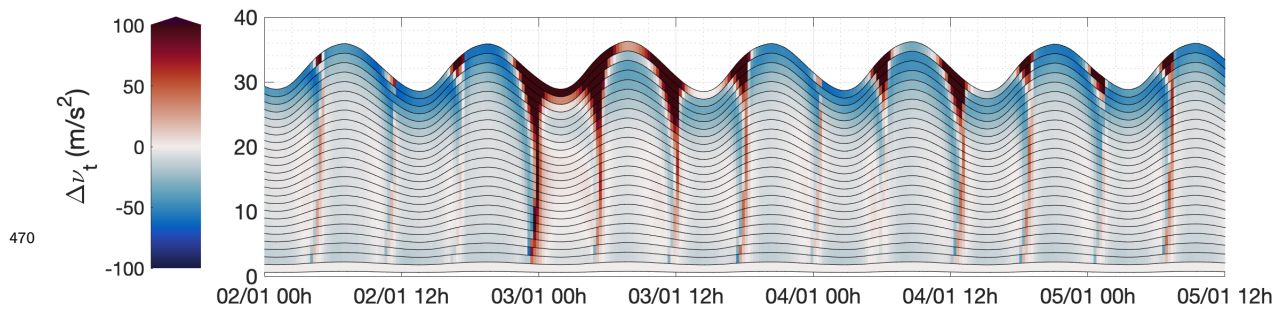


FIGURE 13: Relative difference (Eq. (6)) for the vertical viscosity over depth and time between Run C (with wave effects) and Run A (without wave effects) at the ADCP location. Positive values represent an overestimation of Run C relative to Run A.

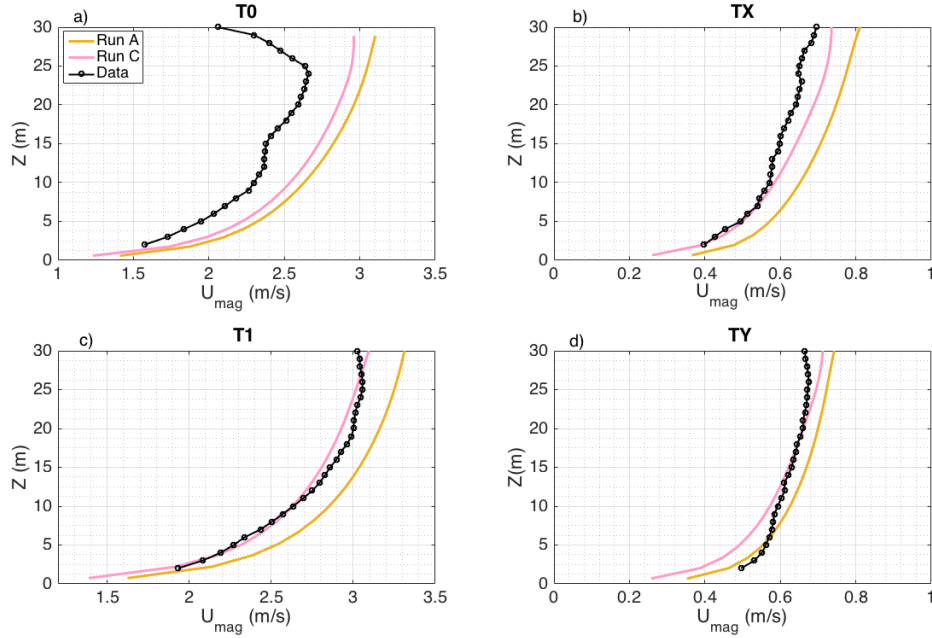


FIGURE 14: Magnitude of the flow velocity at ADCP location over the depth at T0 (a, low tide), TX (b, low tide slack), T1 (c, high tide) and TY (d, high tide slack) for Run A (yellow solid line ; with tide and wind effects), Run C (magenta solid line ; with tide, wind and wave effects) and ADCP data (black line with dots).

2) WAVE EFFECTS ON CURRENT

To analyze and comment the wave effects on the hydrodynamic as well as to understand how current and water level effects on waves affect current by a feedback mechanism, we define two different zones (Fig. 15b) : i) Area #1 located off the French northern coast and, ii) Area #2 located off the Cotentin cape including a part of Alderney Race.

The surface flow velocity characteristics (magnitude and direction) are presented in Fig. 15 at T0 (a), TX (b), T1 (c) and TY (d) time points. Between T0 and TX, the flow flows towards the South-West due to the ebb tide. In contrast, the flow motion is oriented towards the North-East at T1 and TY ascribed to the flood tide. T0 and T1 occur at high tide and the magnitude of the flow velocity reaches 4 m.s^{-1} in the Area #2 (Alderney Race). Velocities are weaker at TX and TY due to slack tide events with a maximum value of 1.5 m.s^{-1} . The mean wave direction is also shown in Fig. 15 (black arrows). In Area #2 ocean waves propagates from West to East with a deviation towards the North at T0 and TX, while they are deflected towards the South at T1 and TY. This change in wave direction is caused by a modification of the wind direction, and by the refraction by currents in smaller proportions, as shown in Fig. 4c. In Area #1, waves travel towards the South-East for all time points. We

488 note different angles (θ_{wc}) between the flow and wave direction of propagation, that range
 489 from 0° to 180° . In Area #1, waves and current are opposite ($\theta_{wc} \geq 160^\circ$) at T0 and TX,
 490 while they are oriented in the same direction ($\theta_{wc} \leq 20^\circ$) at T1. The wave-current dynamic
 491 at T1 is more complicated due to a turbulent structure located near the coast and for which
 492 the flow velocity reaches 1.5 m.s^{-1} . The flow direction is driven by this turbulent structure
 493 and turns over 360° . It becomes opposite to the wave direction at the centre of the turbulent
 494 structure. As tidal converters will be implemented inside the Area #2, it is also relevant
 495 to analyze the related hydrodynamic. In this area, where tidal currents are the strongest
 496 in the Western Europe, waves and current directions are perpendicular most of the time or
 497 opposite as shown in Fig. 15 and 5. This fact makes difficult the understanding of the wave-
 498 current interactions. Indeed, the response of the flow is known and clear for waves following
 499 the current and for waves encountering an opposite current (e.g. Groeneweg and Klopman
 500 1998), but it is more complex for waves perpendicular to the current.

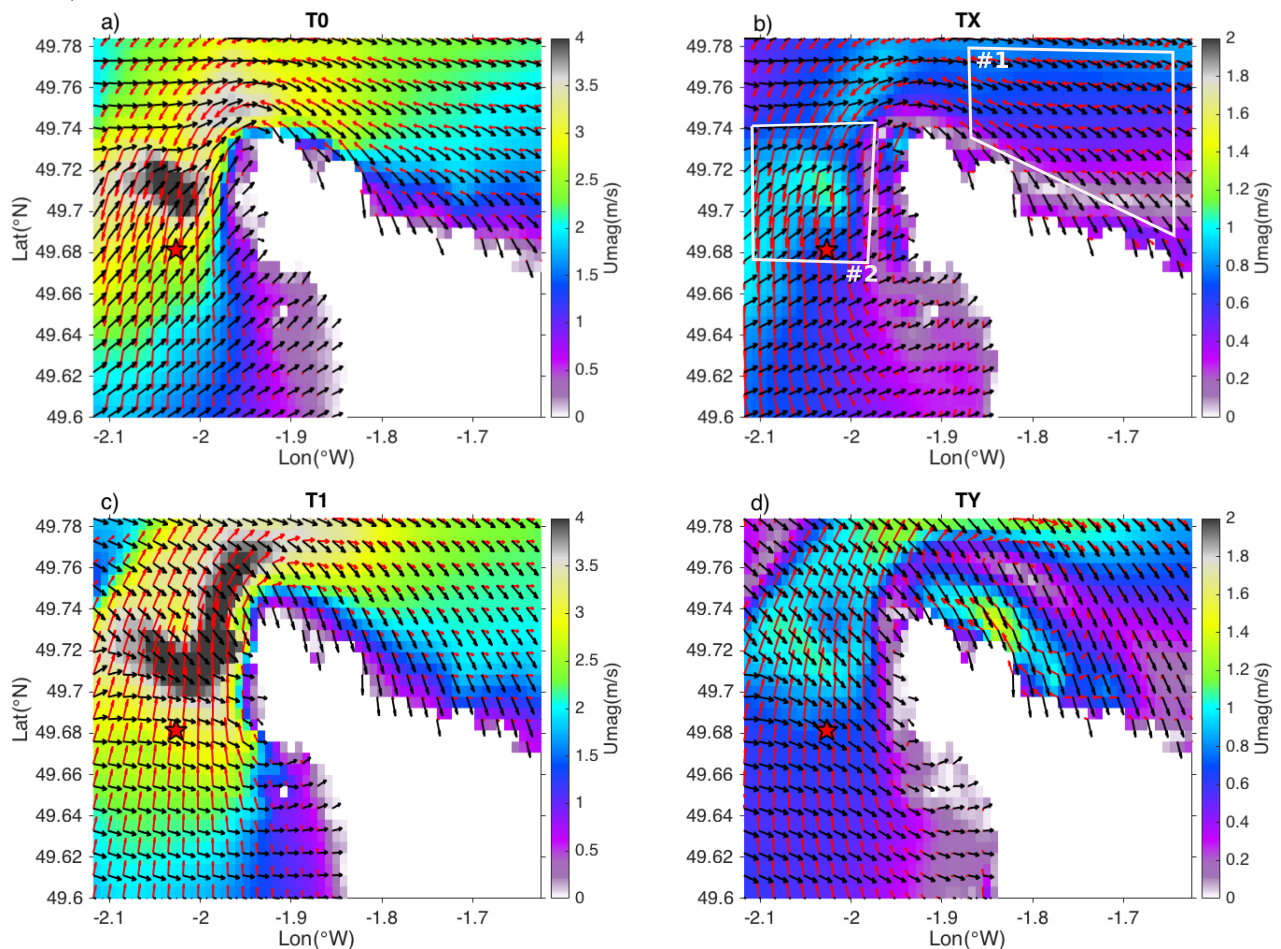


FIGURE 15: Magnitude (in color) and direction of the surface flow (red arrows) velocity and mean wave direction (black arrows) at T0 (a, low tide), TX (b, low tide slack), T1 (c, high tide), TY (d, high tide slack). ADCP location is marked with a red-black pentagram.

502 Wave effects on the near surface and bottom hydrodynamic are presented in Fig. 16
 503 thanks to the absolute difference (ΔU_{wc}) for the flow velocity magnitude between Run C
 504 (with tide, wind and wave effects) and Run A (with tide and wind effects) results. As
 505 changes are similar at T0 and TX, only the T0 case is shown (Fig. 16a,d). Please note
 506 that positive values (in red) of ΔU_{wc} represent an increase of the flow velocity. For the
 507 Area #1, the flow velocity is strongly increased ($\Delta U_{wc} \leq 1 \text{ m.s}^{-1}$) at T0 because waves
 508 propagate against current (Fig. 15). Current and water level effects on waves also contribute
 509 to this increase (Fig. 17; more details hereafter). In contrast, the flow velocity is reduced
 510 ($\Delta U_{wc} \geq -0.8 \text{ m.s}^{-1}$) at T1 because waves and current travel in the same direction. Near
 511 the coast, a smaller area is concerned by a higher current ($\Delta U_{wc} \leq 0.15 \text{ m.s}^{-1}$) ascribed
 512 to sub-grid scale effects that change the directions of propagation. At TY, two different
 513 behaviors are observed due to the turbulent structure : i) ΔU_{wc} is positive, representing an
 514 increase of the flow velocity, where waves and current are opposite and, ii) ΔU_{wc} is negative,
 515 representing a decrease of the flow velocity, off the turbulent structure where waves follow
 516 the current direction of propagation (Fig. 16c, top-right corner). Differences between Fig. 16c
 517 and 16f show that the turbulent structure is a three-dimensional with an higher intensity
 518 near the surface than near the bottom. Therefore, the flow direction is less deflected by
 519 the turbulent structure near the bottom and θ_{wc} remains small, so that the flow velocity
 520 is reduced ($\Delta U_{wc} \leq 0$). The hydrodynamic in Area #2 is also impacted by wave effects
 521 although the strong intensity of current. At T0, TY and T1, occurring at high tide, ($|\Delta U_{wc}|$)
 522 reaches 1 m.s^{-1} . At T0, the flow is accelerated by the wave effects because $\theta_{wc} \geq 110^\circ$. At
 523 T1, the flow decelerates under the wave action ascribed to a θ_{wc} smaller than 90° . At TY,
 524 wave direction is perpendicular to the current direction and a reduction of the flow velocity
 525 is observed. At the limit between Area #1 and Area #2, a modification of the response of
 526 the flow to the wave effects appeared, with an acceleration of the flow velocity in Area #1
 527 while the velocity is reduced in #2. That is due to the turbulent structure which deviated
 528 the flow direction and change the wave-current interactions.

529 Overall, the wave impacts on the flow affect in the same way (reduction/acceleration) the
 530 surface flow (Fig. 16a,b,c) and the near-bottom flow (Fig. 16d,e,f), with more intense effects
 531 near the surface since waves propagate at the surface. Even if the flow response is found
 532 to be mainly ascribed to the angle between the wave and current directions of propagation
 533 according to Groeneweg and Klopman (1998), the effects of the enhancement of the bottom
 534 friction by waves should not be ignored. As shown in Bennis et al. (2020), the modification
 535 of bottom friction by waves generates a decrease of the flow velocity on the entire water
 536 column. So, when the flow velocity is decelerated or accelerated by waves, it is necessary to
 537 consider a possible reduction due to bottom friction in the changes.

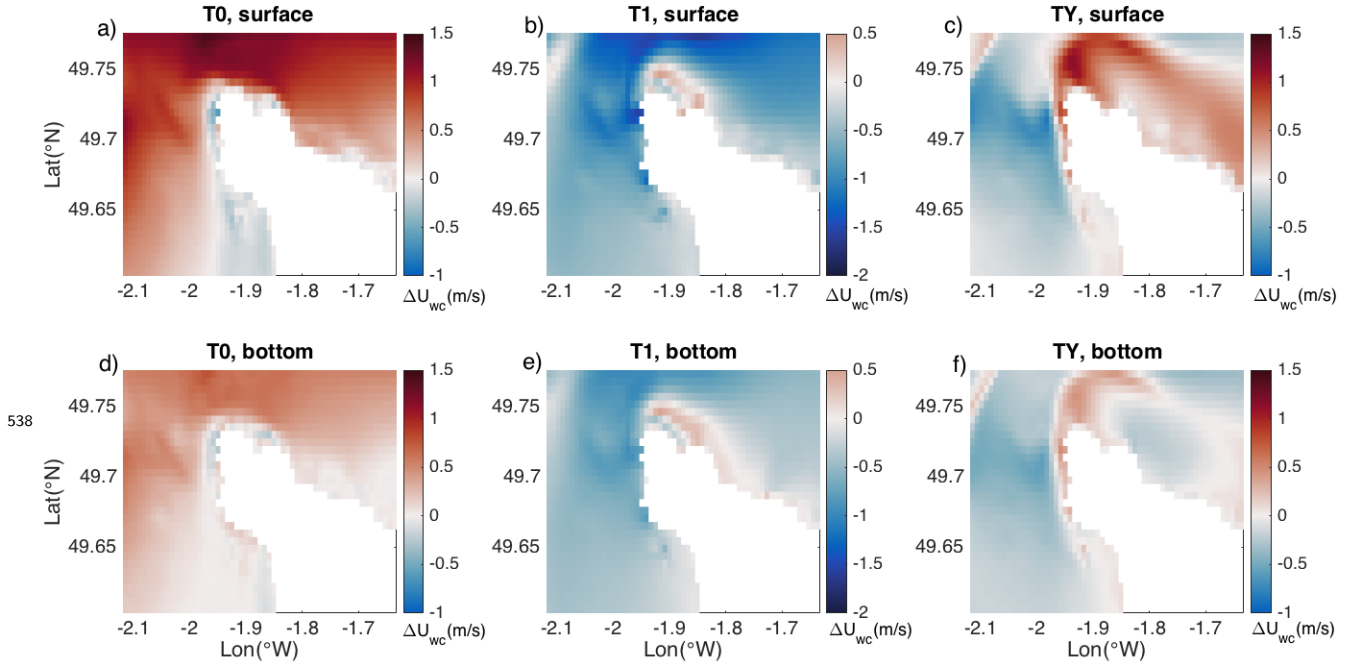


FIGURE 16: Absolute difference (ΔU_{wc}) between simulations with (Run C) and without (Run A) wave effects for the velocity magnitude near the surface (first row) and the bottom (second row) at T0 (a, d, low tide), T1 (b, e, high tide) and TY (c, f, high tide slack).

539 The impacts on the flow of the changes in the wave field due to current and water level
 540 effects are presented in Fig. 17. The absolute difference (ΔU_c) between Run C (two-way,
 541 with current and water level effects on waves) and Run D (one-way, without current and
 542 water level effects on waves) results is used for the analysis. Please note that positive values
 543 (in red) of ΔU_c refer to an increase of the velocity magnitude ascribed to the modifications
 544 of the wave field. In Area #1, waves and current are opposite at T0 and TX. A decrease
 545 ($\Delta U_c \leq 0.14 \text{ m.s}^{-1}$ at TX and $\Delta U_c \leq 0.1 \text{ m.s}^{-1}$ at T0) of the magnitude of the flow velocity is
 546 induced by the modification of the wave forcing terms due to the wave refraction by current,
 547 as observed for rip currents flowing in the opposite direction from the wave direction (e.g.
 548 Bennis et al. 2016; Weir et al. 2011). At T1, a slight increase (few centimeters per second),
 549 which is almost negligible, is caused by the current and water level effects on waves. In Area
 550 #2, at T0 and T1 occurring at high tide, the strong current significantly affects the wave
 551 field and so produces high variation in the flow velocity reaching 0.2 m.s^{-1} . At TX, where
 552 currents are weak (low tide), changes in flow velocity are negligible ($\Delta U_c \leq 0.05 \text{ m.s}^{-1}$). For
 553 the three time points in Area #2, current effects on waves cause an acceleration of the flow
 554 which is maximum near the surface and slows down over the depth. Near the bottom, the
 555 flow is almost unchanged (Fig. 17d,e,f).

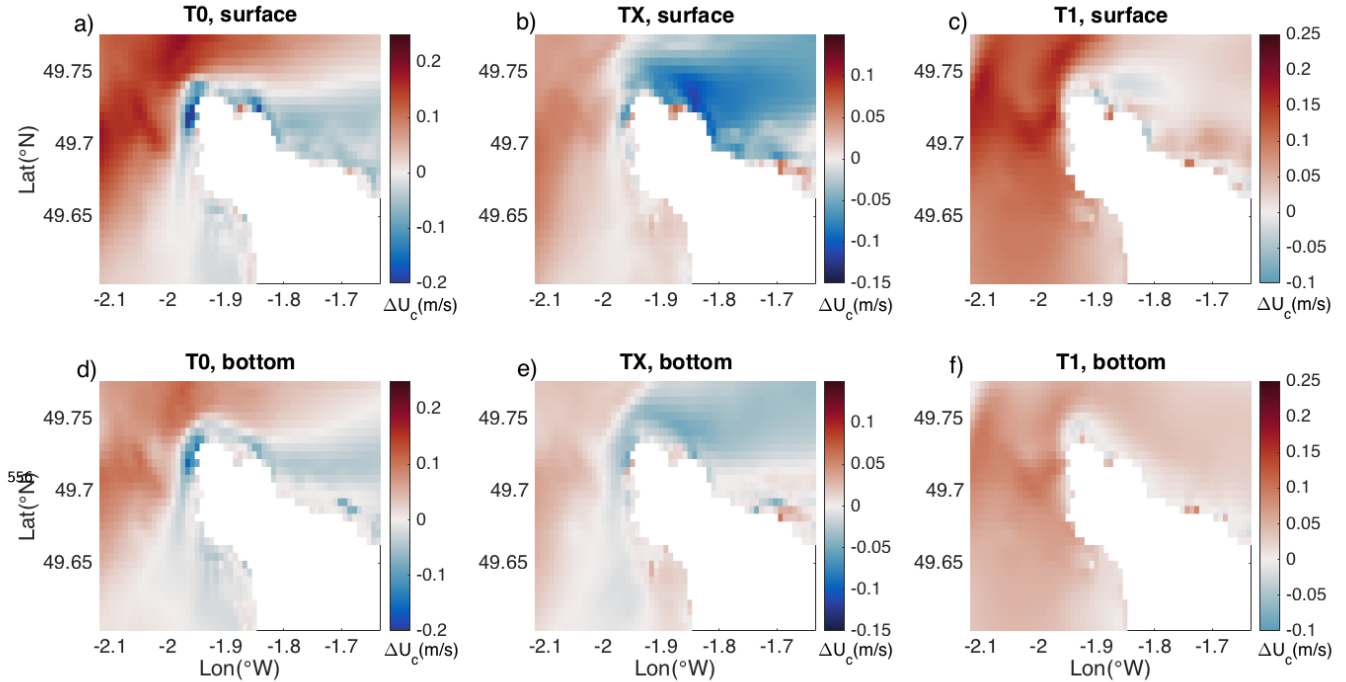


FIGURE 17: Absolute difference (ΔU_c) computed between simulations with wave effects in two-way (Run C, with current and water level effects on waves) and in one-way (Run D, without current and water level effects on waves) for the velocity magnitude. Near-surface (first row) and -bottom (second row) flow at T0 (a, d, low tide), TX (b, e, low tide slack) and T1 (d, f, high tide).

557 The tidal stream energy is an useful indicator for tidal companies to predict the energy
 558 potential and its formulation is :

$$559 \quad P = \frac{1}{2} \rho \hat{U}_{mag}^3, \quad (7)$$

560 where \hat{U}_{mag} is the magnitude of the quasi-Eulerian flow velocity and ρ is the water density.

561 The tidal energy converters for Alderney Race are rather high : the turbines of Hydro-
 562 Quest and Simec-Atlantis, anchored to the seabed, have a height around 22 m. Due to this
 563 design, the tidal stream energy at 15-m depth is representative of the extracted power by
 564 the converters. The absolute difference (ΔP) between Run C (with wave effects) and Run A
 565 (without wave effects) is used for the analysis below. Please note that positive values (in red)
 566 of (ΔP) refer to an increase of P due to wave effects. As the tidal stream energy (P) is based
 567 on the flow velocity, its behavior at 15-m depth in Alderney Race (Area #2) is similar to the
 568 current behavior, as shown in Fig. 18. At T0, P is increased up to $25 \text{ kW} \cdot \text{m}^{-2}$ due to high
 569 tide and the related wave-current interactions. In the bibliography (e.g. Guillou et al. 2016;
 570 Lewis et al. 2017), authors have reported that wave effects produce a reduction in the tidal

571 stream energy because the studies were carried out in cases where wave-current interactions
 572 mainly influence the bottom friction. Here, the wave enhancement of the bottom friction is
 573 not the major effect because of the special hydrodynamic conditions (i.e. the Eleanor’s storm
 574 and spring tide). It is interesting to show cases, such as at T0 and T1 (not presented here),
 575 where the tidal stream energy is increased by waves. In contrast, about $35 \text{ kW}\cdot\text{m}^{-2}$ are lost
 576 at T1. Maximum changes in P are located in the main vein of the current, with a reduction
 577 by a factor of 2 at T0 and a 1.7-fold increase at T1.

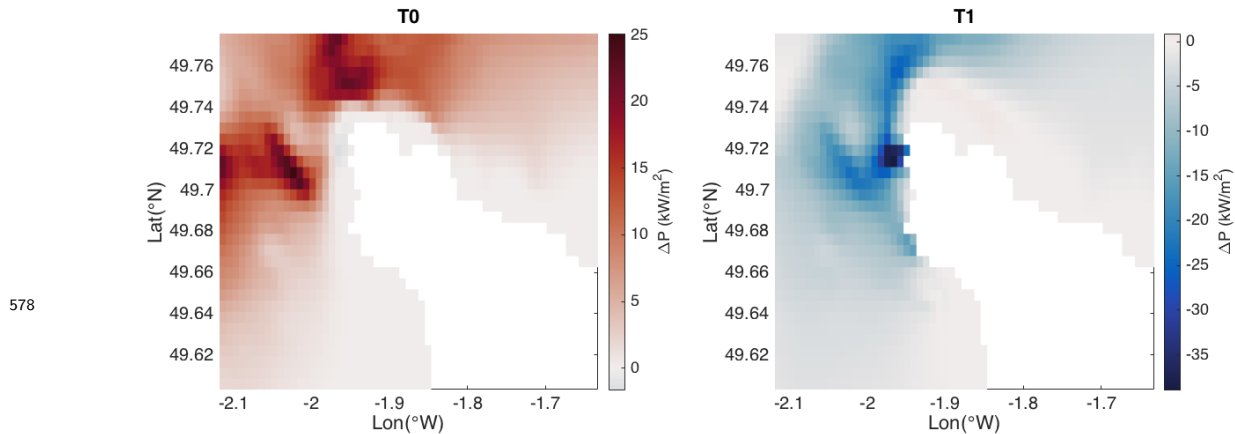


FIGURE 18: Absolute difference for the tidal stream energy (ΔP) between simulations with (Run C) and without (Run A) wave effects for the tidal stream energy at 15-m depth and at T0 (left panel, low tide) and T1 (right panel, high tide).

579 4. Conclusions

580 The impact of a winter storm during spring tide on the hydrodynamic and tidal stream
 581 energy in AR was studied for the first time here. The excellent scores obtained for the
 582 validation of the numerical model with *in-situ* data have revealed the good capacity of the
 583 coupled numerical model, MARS-WWIII, for simulating the hydrodynamic for this time
 584 period. However, data are limited in geographic and temporal scope and it is possible that
 585 lower scores are obtained at other locations. In the future, comparisons with spatialized
 586 data (e. g. HF radar data) will be carried out for completing the validation of the model.
 587 Our results have shown that ocean waves during the Eleanor’s storm have significantly
 588 affected the flow although they occurred during spring tide. With such tidal conditions,
 589 one may have thought that the wave effects on the flow would have been negligible. This
 590 study has proven the contrary. In that case, ocean waves has changed the vertical structure
 591 of the tidal current and also its intensity. The main effect was a strong variation in the
 592 tidal asymmetry due to waves. Ebb flow was found 13% lower than the flood flow for the

593 present storm conditions instead of 3% for calm conditions. That is an important result for
594 industry because it means that the energy extracted from the ebb flow is reduced by 30%.
595 Although the tidal companies plan to stop the converters during extreme events such as
596 storms, they are interested in knowing such information to define when to shut down the
597 turbines. Otherwise, the wave field is found to be strongly influenced by the tidal current
598 as already reported in Bennis et al. (2020), showing that coupled wave-current numerical
599 simulations are required for AR. This study was performed during spring tide because ADCP
600 data were available. In the future, further works are necessary to generalize these results by
601 investigating different hydrodynamic conditions such as a storm during neap tide or a storm
602 with different characteristics.

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