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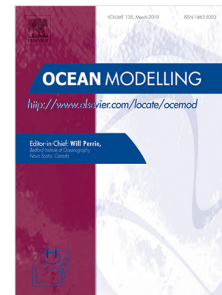
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2 **conditions**

3  
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15

16

## 17 Abstract

18 This study investigates interactions between waves, water levels and currents at the mouth of the  
19 second largest estuary in Europe (the Tagus Estuary, Portugal) under storm waves, combining field  
20 observations and a three-dimensional fully coupled wave-current modelling system. Tidal-induced  
21 water depth variations substantially modulate waves over the ebb shoal. During energetic  
22 conditions, low tide levels promote depth-limited wave breaking and energy transfer towards  
23 higher harmonics (triad interactions), which reduces wave heights and periods. Furthermore, for a  
24 given water level, tidal currents also influence wave propagation and drive strong modulations  
25 over shallow regions characterized by cross-channel current gradients. Flood currents change the  
26 mean wave direction by about 10-15° and tend to focus the wave energy flux towards coastal  
27 regions of the southern margin compared to a run without currents (20 to 30% increase of wave  
28 heights), while ebb currents reduce the wave heights. In addition, model results suggest that the  
29 saturation level associated with wave and current conditions at shallow locations may be close to  
30 the threshold where waves start to dissipate by whitecapping. At the peak of the storm, waves  
31 become a main driver of the circulation at the mouth scale, even in the 45-m deep main channel.  
32 Wave breaking acceleration over the ebb-shoal locally increases flood currents by 50 to 300% and  
33 reduces ebb currents by 20 to 50%.

34 **Keywords:** Wave-current interactions; storm waves; large estuary mouth; the Tagus Estuary.

35

## 36 1. Introduction

37

38 Inlets and estuaries concentrate many socio-economic and environmental issues such as the  
39 maintenance of navigation channels, the stability of adjacent coasts and the flooding of low-lying  
40 areas under extreme events, or the water quality and hydrologic characteristics which are crucial  
41 for the biodiversity. These natural systems are generally subject to the overlap of several forcings  
42 like waves, tide, wind and river discharge, which interact over complex bathymetries characterized  
43 by the presence of channels and shoals. Understanding the impact of wave-current interactions  
44 (WCI) in these environments is crucial to provide accurate predictions of waves, which largely  
45 influence or contribute to storm surges and coastal inundation (e.g. Bertin et al., 2015; Fortunato  
46 et al., 2017), navigation hazards (e.g. Zippel and Thomson, 2017), water quality and nutrient  
47 exchanges (e.g. Delpy et al., 2014; Chen et al., 2019), or sediment transport and morphodynamics  
48 (e.g. Bertin et al., 2009; Dodet et al., 2013; Fortunato et al., 2021).

49

50 WCI have been widely studied for several decades using various approaches including analytical  
51 solutions (Phillips, 1977), field observations (e.g. Wolf and Prandle, 1999; Wargula et al., 2014;  
52 Zippel and Thomson, 2017), laboratory experiments (e.g. Chawla and Kirby, 2002), phase-  
53 resolving models (e.g. Chen and Zou, 2018), or numerical modelling systems coupling a  
54 circulation model with a spectral wave model (e.g. Bertin et al., 2009; Olabarrieta et al., 2011;  
55 Dodet et al., 2013; Akan et al., 2017). Such modelling systems constitute valuable tools to  
56 discriminate and analyze separately the hydrodynamic effect of different physical processes, with  
57 less expensive computational times than phase-resolving models. Therefore, phase-averaged  
58 spectral wave models have been largely used to investigate WCI. While many modeling studies  
59 were performed by investigating separately the respective effects of waves on the mean circulation

60 and the effects of depth-averaged circulations on wave fields (e.g. Smith and Smith, 2001; Kang  
61 and Di Iorio, 2006; Rusu et al., 2011), fully coupled wave-current models have been successfully  
62 applied to realistic coastal environments in the last two decades (e.g. Bertin et al., 2009; Olabarrieta  
63 et al. 2011; Dodet et al., 2013; Akan et al., 2017; Chen et al., 2015, 2019; Lin et al., 2021). In  
64 addition, the coupling between waves and currents in 3D was the subject of several theoretical  
65 works in this period (e.g. Mellor, 2003; Ardhuin et al., 2008). Uchiyama et al. (2010) and Bennis  
66 et al. (2011) proposed a practical framework based on a vortex force formalism, which allows to  
67 simulate realistically the depth-varying mean circulation in coastal areas such as beaches (Kumar  
68 et al., 2012; Guérin et al., 2018) and, more rarely, tidal inlets (e.g. Olabarrieta et al., 2011).

69  
70 Previous studies on WCI highlighted that water level changes caused by tidal oscillations  
71 superimposed on bathymetric effects strongly influence wave propagation and dissipation at the  
72 mouth of inlets or estuaries, in particular due to the presence of ebb delta shoals, which promote  
73 wave breaking and thus reduce wave heights landward (Smith and Smith, 2001; Kang and Di Iorio,  
74 2006; Olabarrieta et al., 2011; Chen et al., 2015). Furthermore, waves can be affected by currents  
75 in different manners. Ebb currents generally promote shoaling and wave steepening, which  
76 increase wave heights by 20% to 80% (e.g. Rusu et al., 2011; Dodet et al., 2013). Depending on  
77 the magnitude and the vertical shear of the flow, wave steepening can exceed a threshold and  
78 opposed currents can dissipate wave energy by whitecapping (e.g. Dodet et al., 2013; Jia et al.,  
79 2015; Akan et al., 2017; Zippel and Thomson, 2017). For shallow depths, ebb currents can even  
80 lead to partial or total wave blocking (Dodet et al., 2013; Bertin et al., 2019). On the contrary,  
81 flood currents generally reduce wave heights due to de-shoaling (e.g. Rusu et al., 2011; Jia et al.,  
82 2015; Mendes et al., 2020). The modulation of wave fields can also occur through current-induced  
83 refraction and Doppler shift effect (e.g. Wolf and Prandle, 1999; Bolaños et al., 2014). Conversely,  
84 waves may influence circulations through different mechanisms such as the Stokes drift, wave  
85 forces and in particular wave breaking-induced acceleration (e.g. Olabarrieta et al., 2011; Chen et  
86 al., 2015), enhanced surface mixing through the injection of turbulent kinetic energy caused by  
87 wave breaking (e.g. Zippel and Thomson, 2015), or enhanced-bottom stress (e.g. Olabarrieta et al.,  
88 2011; Lin et al., 2021).

89  
90 However, the literature on wave-current interactions (WCI) under storm wave conditions remains  
91 scarce, especially for large inlets like the Tagus Estuary Mouth (TEM). Most studies were  
92 conducted under low to moderate energy wave conditions while a few showed that WCI can be  
93 particularly relevant under storm waves (e.g. Bolaños et al., 2014; Bertin et al., 2015; Chen et al.,  
94 2015; Fortunato et al., 2017; Chen et al., 2019). This can be partly explained by the difficulty to  
95 deploy and recover instruments in nearshore regions in presence of energetic waves. Consequently,  
96 the ability of numerical models to reproduce hydrodynamics and WCI during extreme events is  
97 not fully established. In addition, applications generally deal with small to medium-size inlets,  
98 with very few studies focusing on large estuary mouths. In this context, this study aims to  
99 investigate WCI at the TEM, the second largest estuary in Europe, combining field observations  
100 and the application of a 3D fully coupled wave-current modelling system, during a period  
101 characterized by storm waves.

102 The paper is organized as follows. Section 2 presents the main characteristics of the Tagus Estuary,  
103 the field campaign and data processing. The numerical modelling system is described in Section  
104 3. Section 4 describes wave conditions during the campaign period and the model validation at  
105 measuring stations. Interactions between waves, water levels, and currents are described in Section

106 5, while key points provided by this study regarding wave-current interactions are discussed in  
107 Section 6. Finally, the main conclusions are summarized in Section 7.  
108

## 109 2. Study area and field campaign

### 110 2.1. Description of the study site

111

112 The Tagus Estuary, located on the west coast of Portugal, is the second largest estuary in Europe  
113 with a surface area of around 320 km<sup>2</sup>. This estuary is bordered by a metropolitan area of about 2  
114 million inhabitants and combines many socio-economic challenges such as water quality, the  
115 presence of low-lying zones or the stability of the urbanised southern margin. The Atlantic Ocean  
116 is connected to a shallow tide-dominated basin through a 45 m-deep, 10 km-long and 2 km-wide  
117 tidal inlet cut into the bedrock (Figure 1). The continental shelf width is about 40 km in front of  
118 the TEM.

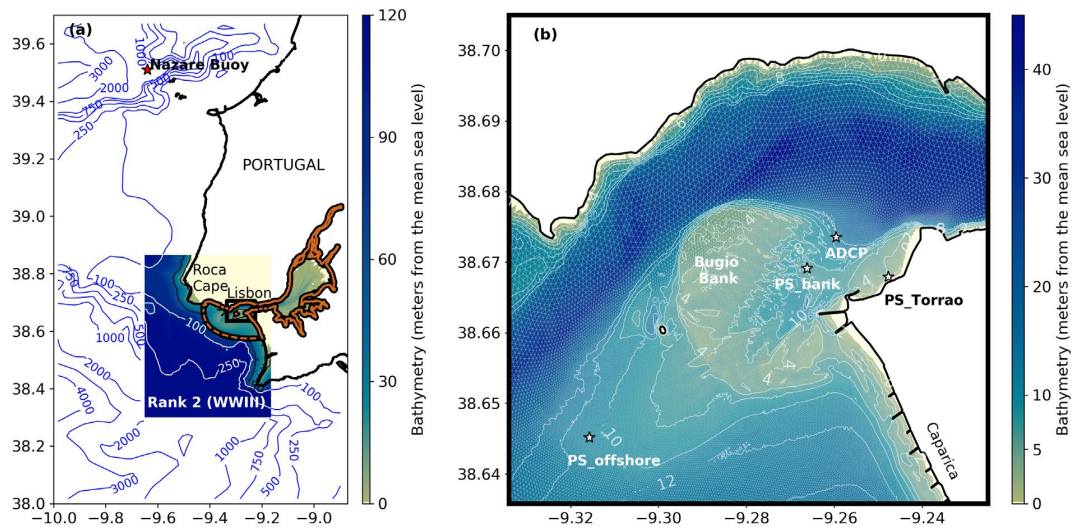
119 The TEM is a semi-diurnal meso-tidal environment characterised by tidal ranges varying from  
120 0.55 m to 3.86 m at the coast (Guerreiro et al., 2015), and by a strong dominance of the ebb with  
121 currents reaching up to 2.5 m/s (Fortunato et al., 1999). The average discharge of the Tagus River  
122 is 336 m<sup>3</sup>/s, but can reach 2000 to 4000 m<sup>3</sup>/s in the winter (Costa et al., 2007; Rodrigues and  
123 Fortunato, 2017), and even occasionally exceeds 10000 m<sup>3</sup>/s (Salgueiro et al., 2013). The estuary  
124 is generally well-mixed given the low average river flow, but it can become partially mixed and  
125 even stratified when the river flow intensifies, in particular during neap tides (Neves, 2010;  
126 Rodrigues and Fortunato, 2017).

127 The wave regime is dominated by long-period swells generated in the North Atlantic Ocean.  
128 During the winter, offshore mean wave conditions correspond to significant wave heights of 2.5  
129 m, peak periods of 12.1 s and a mean wave direction of 305° (Dodet et al., 2010; Mendes and  
130 Oliveira, 2021). Due to the Roca Cape to the northwest, the estuary mouth is partly sheltered from  
131 waves originating from the prevailing northwest direction but is fully exposed to waves coming  
132 from the southwest and the west, which can reach significant heights of 10 m during extreme  
133 storms (Fortunato et al., 2017).

134 At the mouth, complex bed morphologies are found over ebb shoals, like the Bugio Bank (Figure  
135 1b), with bed sediments mainly composed of marine medium sands (Freire et al., 2007). For the  
136 past eight decades, the morphology of the TEM has been experiencing a significant evolution, in  
137 particular a strong erosion of the ebb shoal and the adjoining beaches (Fortunato et al., 2021).

138

139



140 **Figure 1.** (a) Bathymetric contours (blue isobaths) associated with the large-scale rank of the wave model  
 141 WaveWatchIII (WWIII), on which is superimposed the extent and the bathymetry of the second WWIII rank (Rank  
 142 2), forced by the large-scale rank along its open boundary. On (a), the brown contour delimits the SCHISM-WWM  
 143 unstructured grid forced at its open boundary (dotted line) by wave spectra from Rank 2. (b) Zoom over the TEM for  
 144 the SCHISM-WWM configuration, with its bathymetry, the locations of measuring stations (white stars), the  
 145 computational grid, and isobaths (contours every 2 m from 0 to 14 m).  
 146

147

## 148 2.2. Field campaign and data processing

149

150 Three RBR<sup>TM</sup> pressure sensors and one 600 kHz Nortek ADCP (Acoustic Doppler Current  
 151 Profiler) mounted with a pressure sensor were deployed at the TEM during one week (from the  
 152 16<sup>th</sup> to 24<sup>th</sup> November, 2019), during which offshore wave heights ( $H_{m0}$ ) and peak periods ( $T_p$ )  
 153 reached 6 m and 20 s, respectively (Figure 2). From offshore to nearshore locations (Figure 1b),  
 154 sensors PS\_offshore (-9.316; 38.645), PS\_bank (-9.266; 38.67) and PS\_Torrao (-9.247; 38.668)  
 155 were respectively deployed at mean water depths of 10.6 m, 5.9 m and 3 m (Figure 1b).  
 156 PS\_offshore and PS\_bank were fixed to anchors directly deployed on the seabed whereas  
 157 PS\_Torrao was fixed on a pillar, at 1.65 m above the seabed. The station PS\_Torrao is located at  
 158 the beach of the neighbourhood of Segundo Torrão, frequently subject to damages and inundations  
 159 during storms. Continuous pressure measurements were made at a sampling frequency of 2 Hz.  
 160 The ADCP (-9.26; 38.673; mean water depth of 10.24 m), was set in an upward-looking position  
 161 with 0.50 m-thick cells, providing average current profiles every 30 minutes and 20-minute bursts  
 162 of pressure measurements every hour (at 2 Hz). Unfortunately, ADCP measurements are only  
 163 available over the first 1.5 days of the field campaign, due to a malicious act.  
 164

165 To compute wave bulk parameters, pressure time series recorded at PS\_offshore, PS\_bank and  
 166 PS\_Torrao were split into 1 hour-long bursts, corrected from atmospheric pressure and tidal

167 oscillations. The tidal signal was removed by applying a low-pass filter with a 1-hour window and  
 168 pressure was converted to water depth under a hydrostatic assumption. Power density spectra  
 169 associated to frequencies  $f$  were computed by applying a Fast Fourier Transform and by  
 170 considering 10 Hanning-windowed segments (with an overlap of 50%), which results in 17  
 171 equivalent degrees of freedom with a frequency resolution of 0.003 Hz. Note that the number of  
 172 equivalent degrees of freedom was estimated from the power spectral density, and was then  
 173 reduced by 10% (specific to the case with 10 segments) according to the procedure described by  
 174 Elgar (1987). Then, the elevation spectra were reconstructed using the Transfer Function Method  
 175 based on the linear wave theory (TFM; e.g. Bishop and Donelan, 1987) at the three stations,  
 176 PS\_offshore, PS\_bank and PS\_Torrao. The TFM involves wave numbers, computed from the  
 177 linear dispersion relation, which is affected by the presence of ambient currents. The current effect  
 178 was considered in the calculation of the wave number using currents simulated by the numerical  
 179 model at each pressure sensor location, with a similar strategy as de Wit et al. (2019). The  
 180 procedure is described in Appendix A. To avoid noise amplification, the TFM method requires the  
 181 definition of an upper cut-off frequency,  $f_{max}$ , which was set to 0.3 Hz for all pressure sensors (in  
 182 agreement with Inch et al., 2017). From each spectrum, wave parameters can be computed using  
 183 the  $i$ -th moments,  $m_i$ , as follows

$$184 \quad m_i = \int_{f_{min}}^{f_{max}} f^i E(f) df \quad (1)$$

186 The integration of the spectral energy in Eq. (1) requires the definition of a lower cut-off frequency,  
 187  $f_{min}$ , in order to separate the energy band associated with short waves from the one of infragravity  
 188 waves. According to the literature,  $f_{min}$  can be expressed as a function of the peak frequency,  $f_p$ ,  
 189 which corresponds to the frequency where the maximum energy is found in the gravity band (e.g.  
 190 Roelvink and Stive, 1989; Oh et al., 2020). Following Roelvink and Stive (1989), who defined this  
 191 lower cut-off frequency as half the peak frequency,  $f_{min}$  is computed here as

$$192 \quad f_{min} = \max \{ 0.036 \text{ Hz}; \min \{ 0.5 \times f_p; 0.05 \text{ Hz} \} \} \quad (2)$$

193 In Eq. (2),  $f_p$  is firstly computed between 0.04 and 0.3 Hz, and then updated according to the new  
 194  $f_{min}$  estimate. Although a fixed cut-off frequency is employed in most studies, an adaptive approach  
 195 was required here as the incident peak period ranged from 6 and 20 s during the studied period.  
 196 Finally, the significant wave height,  $H_{m0}$ , and the mean wave period,  $T_{m02}$ , are computed as follows

$$200 \quad H_{m0} = 4\sqrt{m_0} \quad (3)$$

$$201 \quad T_{m02} = \sqrt{\frac{m_0}{m_2}} \quad (4)$$

202  
203  
204



205 In order to integrate bulk wave parameters within the same band and ensure consistent  
 206 comparisons between sensors,  $f_{min}$  series computed at PS\_offshore were applied to PS\_bank and  
 207 PS\_Torrao.  
 208

### 209 3. The numerical modelling system

210

211 The modelling system is based on the full coupling, at the source code level, between the third-  
 212 generation spectral wave model Wind Wave Model of Roland et al. (2012, hereafter WWM), and  
 213 the hydrodynamic core based on the Semi-Implicit Cross-scale Hydroscience Integrated System  
 214 Model (hereafter SCHISM) of Zhang et al. (2016). Both models share the same unstructured grid  
 215 and domain decomposition.  
 216

#### 217 3.1. Spectral wave model - WWM

218

219 WWM simulates surface gravity waves generation, propagation and dissipation by solving the  
 220 wave action equation (Komen et al., 1994) that reads:  
 221

$$222 \frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot (\dot{\mathbf{x}}N) + \frac{\partial(\dot{\sigma}N)}{\partial \sigma} + \frac{\partial(\dot{\theta}N)}{\partial \theta} = \frac{1}{\sigma} (S_{in} + S_{nl4} + S_{nl3} + S_{ds} + S_{br} + S_{bf}) \quad (5)$$

223

224 where  $t$  is the time,  $\sigma$  is the relative wave frequency ( $=2\pi f$ , with  $f$  the wave frequency),  $\theta$  is the  
 225 wave direction,  $N$  is the wave action ( $=\frac{E(\sigma, \theta)}{\sigma}$ ,  $E(\sigma, \theta)$  being the discrete variance density of the  
 226 sea level elevation),  $\nabla_{\mathbf{x}}$  is the horizontal gradient operator, and  $\dot{\mathbf{x}}$ ,  $\dot{\sigma}$ , and  $\dot{\theta}$  are the propagation  
 227 velocities in space, frequency and direction, respectively.

228 WWM accounts for water depths and currents fields obtained from SCHISM, with  $\dot{\mathbf{x}} = \mathbf{C}_g + \tilde{\mathbf{u}}$  in  
 229 Eq. (5),  $\mathbf{C}_g$  being the wave group velocity vector ( $=c_g(\cos \theta, \sin \theta)$ , with  $c_g$  the wave group  
 230 velocity computed from the linear wave theory). The advection velocities in the different phase  
 231 spaces include the effect of a “wave-weighted” current field  $\tilde{\mathbf{u}} = (\tilde{u}, \tilde{v})$  that is computed according  
 232 to Kirby and Chen (1989), which enables to consider the circulation over a surface layer where  
 233 waves are assumed to be kinematically active. The right-hand side of Eq. (5) details all the source  
 234 terms, which correspond to the wind input ( $S_{in}$ ), the nonlinear interaction in deep and shallow  
 235 water ( $S_{nl4}$  and  $S_{nl3}$ , respectively), the energy dissipation due to whitecapping ( $S_{ds}$ ), depth-limited  
 236 breaking ( $S_{br}$ ) and bottom friction ( $S_{bf}$ ).

237 The nonlinear energy transfer in deep water (quads),  $S_{nl4}$ , is approximated using the Discrete  
 238 Interaction Approximation following Hasselmann and Hasselmann (1985). The nonlinear energy  
 239 transfer in shallow water (triads),  $S_{nl3}$ , has been prescribed following the Lump Triad  
 240 Approximation introduced by Eldeberky (1996; equation 7.25), using a parameter  $\alpha$  adjusted to  
 241 0.35, which is consistent with the range of values proposed by the author. Both terms linked to

242 wind input ( $S_{in}$ ) and dissipation due to whitecapping ( $S_{ds}$ ) follow Ardhuin et al. (2010). The  $S_{ds}$   
 243 term is defined as

$$245 \quad S_{ds}(\sigma, \theta) = \sigma \frac{C_{ds}^{sat}}{B_r(\sigma)^2} (\max\{B(\sigma, \theta) - B_r(\sigma); 0\})^2 N(\sigma, \theta) + S_{bk,cu} + S_{turb} \quad (6)$$

246  
 247 where  $C_{ds}^{sat}$  is a nondimensional constant of  $2 \times 10^{-4}$ ,  $B_r(\sigma)$  is a threshold, and  $B(\sigma, \theta)$  is the  
 248 nondimensional energy level at each frequency and direction, also called saturation, which is  
 249 defined as

$$251 \quad B(\sigma, \theta) = \int_{\theta-\Delta\theta}^{\theta+\Delta\theta} k^3 \cos^{s_B}(\theta - \theta') E(\sigma, \theta') \frac{C_g}{2\pi} d\theta' \quad (7)$$

252  
 253 with  $k$  the mean wave number, and  $s_B$  a constant set to 2. In Ardhuin et al. (2010), the threshold  
 254 for the saturation  $B_r$  is a constant ( $9 \times 10^{-4}$ ). A directional width,  $\Delta\theta = 80^\circ$ , is introduced in the  
 255 saturation computation in order to account for different dissipation rates in the different directions.  
 256 In Eq. (6), the term  $S_{turb}$  refers to wave-turbulence interactions (Ardhuin and Jenkins, 2006) and  
 257  $S_{bk,cu}$  is a cumulative breaking term that represents the smoothing of small waves by big breakers  
 258 (Ardhuin et al., 2009).

259 However, the sensitivity of model results to the  $S_{ds}$  term will be further discussed by testing an  
 260 alternative formulation. More specifically, the latter was modified in order to mimic observations  
 261 showing pronounced energy dissipation in the high frequency part of spectra when waves faced  
 262 intense and opposed currents. A dependency of the saturation  $B_r$  threshold on the frequency,  $f$ , is  
 263 introduced such as

$$266 \quad B_r(\sigma) = (B_{r,LF} - B_{r,HF}) \times e^{C_{br} \cdot (f_{cr} - f)} + B_{r,HF} \quad (8)$$

267  
 268 In Eq. (8),  $B_{r,LF}$  is the reference saturation threshold of  $9 \times 10^{-4}$  proposed by Ardhuin et al. (2010),  
 269 which is, in this case, associated with low frequencies. It is assumed that for frequencies larger  
 270 than  $f_{cr}$ ,  $B_r$  decreases exponentially, at a rate controlled by the parameter  $C_{br}$ , towards a reduced  
 271 value,  $B_{r,HF}$ , associated with high frequencies (HF). This modification has been introduced as  
 272 model/data comparison revealed a local underestimation of dissipation by whitecapping in the  
 273 model, which will be discussed later. Values of  $f_{cr}$ ,  $C_{br}$ , and  $B_{r,HF}$  tested to assess the model  
 274 sensitivity to the dissipation by whitecapping are detailed in section 3.4.

275 The energy dissipation due to depth-limited wave breaking,  $S_{br}$ , is computed according to the  
 276 model of Baldock et al. (1998), as corrected by Janssen and Battjes (2007), and by using the  
 277 breaking index formulation of Ruessink et al. (2003), which is a function of the dimensionless  
 278 depth  $k_p \cdot h$ ,  $k_p$  being the peak wave number and  $h$  the water depth.

279 Lastly, the wave dissipation by bottom friction,  $S_{bf}$ , is computed in agreement with the empirical  
280 model of Hasselmann et al. (1973) based on the JONSWAP experiments, with a dissipation  
281 coefficient of  $0.038 \text{ m}^2 \cdot \text{s}^{-3}$ , which is adequate for swell waves.  
282

### 283 3.2. Hydrodynamic model - SCHISM

284  
285 SCHISM, which evolved from SELFE (Zhang and Baptista, 2008), solves the 3D Reynolds-  
286 averaged Navier-Stokes equations under hydrostatic and Boussinesq assumptions on unstructured  
287 grids. SCHISM uses an Eulerian-Lagrangian Method combined to semi-implicit schemes to treat  
288 the advection term in momentum equations, which relaxes the numerical stability constraints and  
289 allows using large time steps (CFL numbers larger than one). Wave force terms are included in  
290 the momentum equations in order to account for 3D wave-induced circulations. Wave forces are  
291 computed following the vortex-force (VF) formalism as described by Bennis et al. (2011). The VF  
292 implementation in SCHISM is described in Guérin et al. (2018). Wave-induced breaking  
293 momentum is concentrated in the two upper layers below the surface, as proposed by Bennis et al.  
294 (2011).

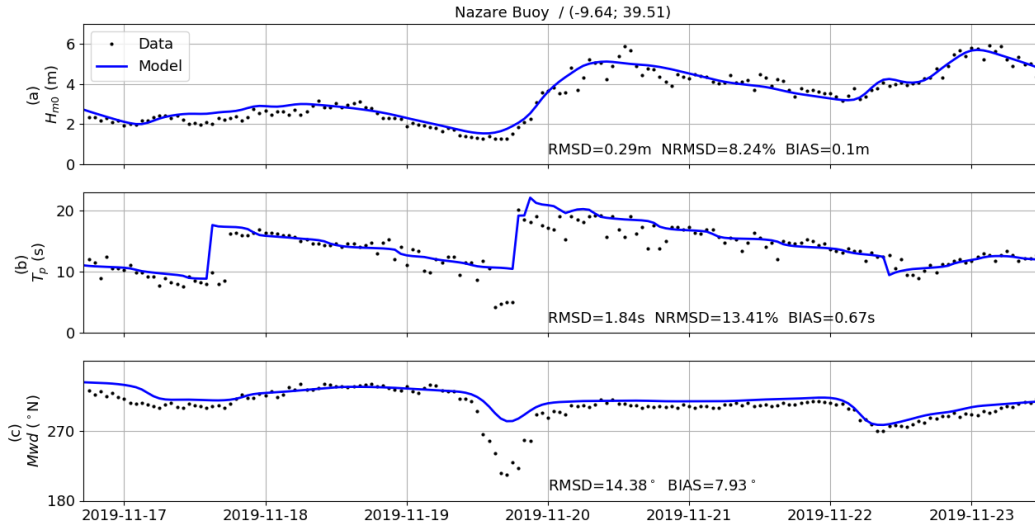
295 Regarding turbulence, the model uses a closure based on the Generic Length Scale (GLS)  
296 turbulence model of Umlauf and Burchard (2003), in a  $k - \varepsilon$  configuration (Rodi, 1993). At the  
297 boundaries, the turbulent kinetic energy ( $TKE$ ) and the mixing length ( $l$ ) are specified as Dirichlet  
298 boundary conditions, and account for wave-enhanced turbulence. At the surface, the  $TKE$  is  
299 defined by accounting for both wind stress (Pond and Pickard, 1998) and vertical mixing due to  
300 wave breaking (Moghimani et al., 2013). According to Feddersen (2012), 15% of the energy  
301 dissipated by wave breaking is effectively transformed into  $TKE$ . The length scale associated with  
302 the surface wave-enhanced turbulence is defined as a function of a surface roughness set to  
303  $0.6 \times H_{m0}$  (Terray et al., 1996).

304 The wind stress is also used as a boundary condition for the internal Reynolds stress at the surface.  
305 At the bottom, the Reynolds stress is prescribed through a bottom stress that combines the effects  
306 of waves and currents (Soulsby, 1997), assuming a roughness length  $z_0$  of  $5 \times 10^{-4} \text{ m}$ , which was  
307 the best compromise to reproduce vertical profiles of currents at the ADCP location (Section 4.2).  
308

### 309 3.3. The Tagus Estuary configuration

310  
311 The unstructured grid used for the Tagus Estuary is characterized by a spatial resolution varying  
312 from 500 m at its offshore open boundary to 25 m over shallow parts of the Bugio Bank and along  
313 adjacent beaches within surf zones (Figure 1). For the vertical discretization, 21 S-levels are  
314 considered with a refinement in upper and lower parts of the water column ( $\theta_b = 1$  and  $\theta_f = 3$  in  
315 the formulation of Song and Haidvogel (1994)). Both hydrodynamic and wave models use the  
316 same time step, here set to 10 s.

317 The tidal forcing is computed considering 21 constituents from the global tide model FES2014  
318 (Lyard et al., 2021), linearly interpolated along the open boundary. The atmospheric forcing  
319 originates from the Climate Forecast System Reanalysis (CFSR; Saha et al., 2014) with temporal  
320 and spatial resolutions of 3 hours and  $0.2^\circ$ , respectively. CFSR winds and atmospheric pressure  
321 series were compared against observations at the Nazaré Buoy (longitude=-9.54; latitude=39.51;  
322 depth=2000 m; location on Figure 1a). The accuracy of atmospheric reanalyses is characterized  
323 with the root mean square discrepancy (RMSD), the normalized RMSD (NRMSD), and the bias  
324 (BIAS). The wind speed is on average well predicted with a normalized root mean square  
325 discrepancy (hereinafter NRMSD) of 21.6%. Given weak river runoffs during our field campaign  
326 (average of  $80 \text{ m}^3/\text{s}$ ; maximum of  $146 \text{ m}^3/\text{s}$ ; source: <https://snirh.apambiente.pt/>), river discharge  
327 and baroclinic effects associated with temperature and salinity were neglected in numerical  
328 simulations. The spectral wave forcing originates from a 2-rank structured and nested  
329 configuration of the WaveWatchIII (WWIII) spectral wave model, forced by CFSR winds  
330 described above. The WWIII configuration is based on the *TEST471* (Arduin et al., 2010;  
331 WW3DG, 2019). The first rank covers the North Atlantic with a 20-km resolution. The second  
332 rank, forced at its open boundaries by the first one, encompasses the entire estuary bay with a 500  
333 m resolution, in order to reproduce wave refraction around the Roca Cape (Figure 1). Both WWIII  
334 ranks use a spectral discretization of 36 frequencies (0.036 to 1 Hz) and 48 directions. At the  
335 Nazaré Buoy, significant wave heights and peak periods computed from WWIII show a very good  
336 agreement with the observations, with NRMSD of 8% and 13%, respectively (Figure 2). Finally,  
337 spectra from the second WWIII rank are interpolated along the open boundary of the SCHISM-  
338 WWM grid, and WWM is run by considering 24 frequencies ranging from 0.036 and 0.4 Hz, and  
339 24 directions.  
340  
341



342 **Figure 2.** Comparisons between observed (black dots) and modelled wave parameters (thick solid line) at the Nazare  
 343 Buoy (see location on Figure 1a): **(a)** significant wave height  $H_{m0}$ , **(b)** mean wave period  $T_{m02}$ , and **(c)** mean wave  
 344 direction  $Mwd$ . Model predictions are computed with the WaveWatchIII model (Rank 1).  
 345

### 346 3.4. Numerical experiment

347

348

349

350 Wave transformations and wave-current interactions have been investigated through a set of 6  
 351 simulations. The reference simulation, *Ref*, considers a full coupling between hydrodynamic and  
 352 wave models and includes all the physics of waves (i.e. all source terms), as described in section  
 353 3.1. To investigate the tidal modulation of waves obtained from *Ref*, two simulations are  
 354 considered in the following analysis: *Run 2* only includes variations of tide levels without current  
 355 effects on waves, and *Run 3* does not account for the effect of both water level oscillations and  
 356 currents on waves. In order to evaluate the importance of wave-induced circulations in *Ref*, wave  
 357 forces were ignored in the hydrodynamic model SCHISM in the simulation *Run 4*. Further  
 358 simulations are dedicated to sensitivity analyses. First, while a constant saturation threshold  $B_r$  is  
 359 assumed in the whitecapping dissipation term in *Ref* ( $9 \times 10^{-4}$ , as suggested by Ardhuin et al.  
 360 (2010)), an adaptive saturation threshold is considered in another simulation, *Run 5*, assuming an  
 361 exponential decrease towards high frequencies ( $C_{br}=30$ ) from  $B_{r,LF}=9 \times 10^{-4}$  to  $B_{r,HF}=9 \times 10^{-5}$  beyond  
 362 the frequency  $f_c=0.2$  Hz (Eq. 8). Moreover, the implication of triad wave interactions on wave  
 363 transformations was quantified by turning off the  $S_{nl3}$  term (Eq. 5) in simulation *Run 6*. Model  
 364 configurations for the 6 numerical simulations are summarized in Table 1.  
 365

Simulation	Current effect on waves?	Water level effect on waves?	Wave forces?	Adaptive whitecapping threshold?	Wave triads ( $S_{nl3}$ )?
Ref	Yes	Yes	Yes	No	Yes
Run 2	No	Yes	Yes	No	Yes
Run 3	No	No	Yes	No	Yes
Run 4	Yes	Yes	No	No	Yes
Run 5	Yes	Yes	Yes	Yes	Yes
Run 6	Yes	Yes	Yes	No	No

366 **Table 1.** Model configurations for the 6 numerical simulations.

367

#### 368 4. Wave conditions and model validation at sensor locations

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370 The model validation is described here for the reference simulation, *Ref* (see Section 3.4), in terms  
 371 of water levels, wave bulk parameters and depth-dependent currents. A more thorough analysis of  
 372 model results is then provided in section 5.

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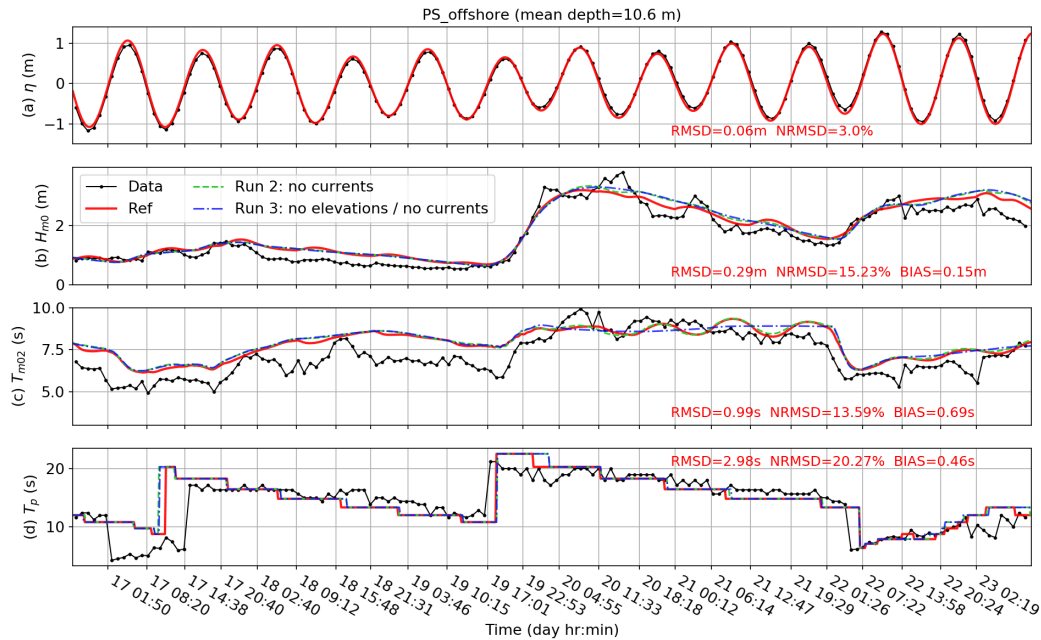
##### 378 4.1. Water levels and wave bulk parameters

379

380 Water levels are well reproduced by the model at PS\_offshore, PS\_bank and PS\_Torrao, with  
 381 NRMSD (RMSD normalized by the mean tidal range) of 3%, 4%, and 2.5%, respectively.

382 At PS\_offshore (Figure 3), measured significant wave heights,  $H_{m0}$ , vary between 0.5 and 1.5 m  
 383 during the first half of the period (“calm” period) and then increase substantially during stormy  
 384 conditions and reach 3.65 m. Wave heights are generally well reproduced by the model with a  
 385 NRMSD of 15%. Nevertheless, the model tends to slightly overestimate  $H_{m0}$  during “calm periods”  
 386 ( $< 1.5$  m), and peaks occurring at low tide under energetic wave conditions ( $> 2$  m) are not  
 387 reproduced. Mean wave periods,  $T_{m02}$ , obtained from pressure measurements range between 5 and  
 388 8 s during calm periods and between 8 and 10 s during the storm.  $T_{m02}$  periods are well reproduced  
 389 overall by the model with a NRMSD of 14%, despite a persistent bias of 0.7 s over the period. The  
 390 discrete peak period,  $T_p$ , reaches up to 20 s during the storm and is well reproduced by the model  
 391 with a NRMSD of 20% and a weak positive bias of 0.5 s. In more details, this larger error compared  
 392 to other bulk parameters is mostly due to the presence of a bimodal sea state on the 17<sup>th</sup> November  
 393 where the local wind sea is underestimated by the model. If this period is discarded, the NRSMD  
 394 drops to 12%.

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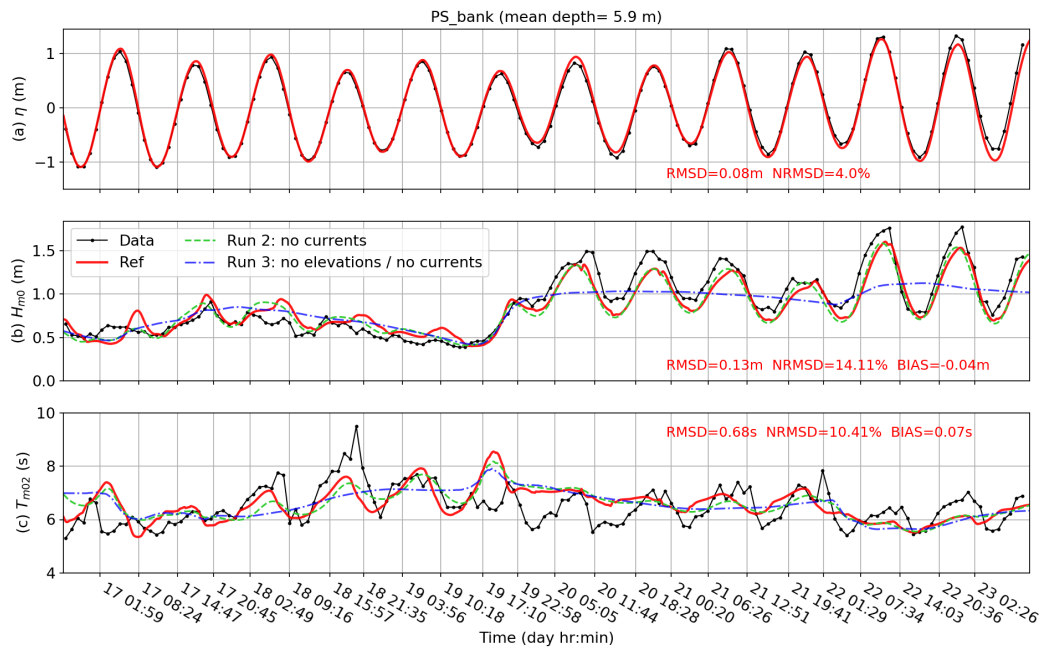
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**Figure 3.** Comparisons of sea surface elevation (a), significant wave height  $H_{m0}$  (b), mean wave period  $T_{m02}$  (c) and wave peak period  $T_p$  (d) at PS\_offshore station (see location on Figure 1b) between data and model results from simulations *Ref*, *Run 2* (no currents) and *Run 3* (no elevations and no currents). RMSD, NRMSD and BIAS values indicated on each subplot refer to simulation *Ref*.

At PS\_bank (Figure 4), measured wave heights range between 0.5 and 0.8 m during the calm period, and between 0.8 and 1.8 m during energetic conditions. Wave heights are strongly tidally-modulated, with a minimum at low tide and fluctuations ranging from 0.25 m to 1 m. Modelled  $H_{m0}$  are reproduced with a NRMSD of 14%, with a good ability to capture tidal modulations, despite a slight but persistent underestimation on flood during energetic conditions. Tidal-induced modulations of measured  $T_{m02}$  are also substantial (around +/- 1.5 s) with values ranging between 5 and 10 s. Modelled  $T_{m02}$  are well reproduced with a NRMSD of 10%, in spite of weaker tidal-induced fluctuations leading to both under- and over-estimations throughout the period.



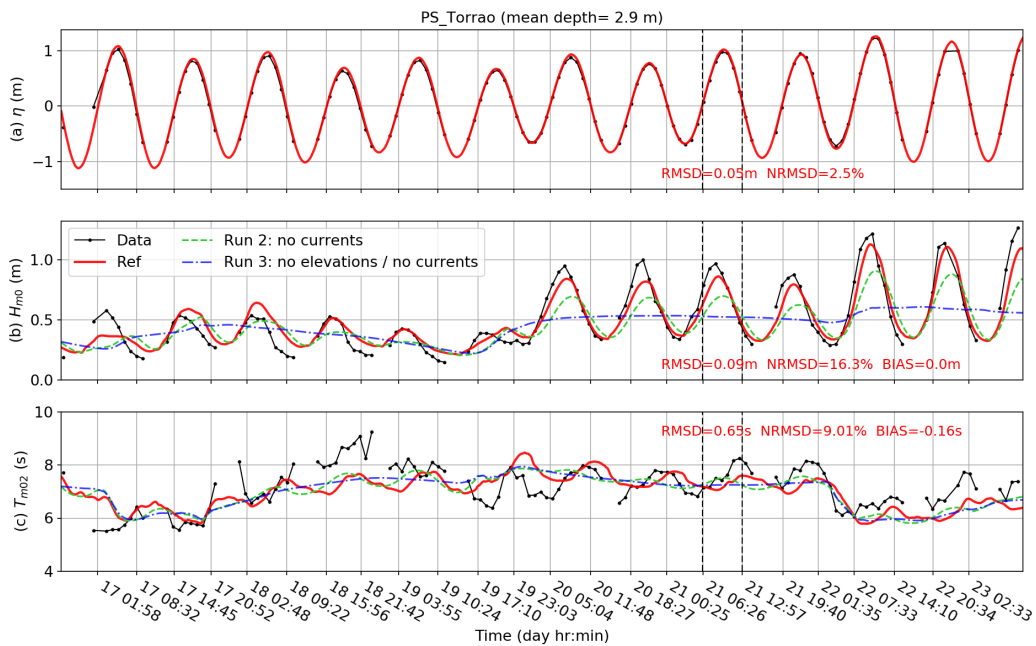
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**Figure 4.** Comparisons of sea surface elevation (a), significant wave height  $H_{m0}$  (b), and mean wave period  $T_{m02}$  (c) at PS\_bank station (see location on Figure 1b) between data and model results from simulations *Ref*, *Run 2* (no currents) and *Run 3* (no elevations and no currents). RMSD, NRMSD and BIAS values indicated on each subplot refer to simulation *Ref*.

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Finally, at PS\_Torrao station (Figure 5), similar fluctuations as at PS\_bank are observed for wave heights and periods. Due to its more sheltered location, wave heights are comprised between 0.25 and 0.5 m during the calm period and reach up to 1.25 m throughout the campaign period.  $H_{m0}$  values are well reproduced by the model with a NRMSD of 16%. Regarding wave periods, measured  $T_{m02}$  range between 6 and 9 s and are reproduced by the model with a NRMSD of 9%, although the model tends to underestimate the drop in wave period at low tide as in PS\_bank. The discrete peak period  $T_p$  does not exhibit significant spatio-temporal variations in comparisons with the mean period  $T_{m02}$ .  $T_p$  values obtained at PS\_bank and PS\_Torrao appear very close to those at PS\_offshore, and are thus omitted here. At these two shallow stations,  $T_p$  is reproduced by the model with a NRMSD of about 15%.





430

431 **Figure 5.** Comparisons of sea surface elevation (a), significant wave height  $H_{m0}$  (b), and mean wave period  $T_{m02}$  (c)  
 432 at PS\_Torrao station (see location on Figure 1b) between data and model results from simulations *Ref*, *Run 2* (no  
 433 currents) and *Run 3* (no elevations and no currents). RMSD, NRMSD and BIAS values indicated on each subplot refer  
 434 to simulation *Ref*. Thicker vertical ticks refer to specific dates used in the following analyses.

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#### 436 4.2. Currents

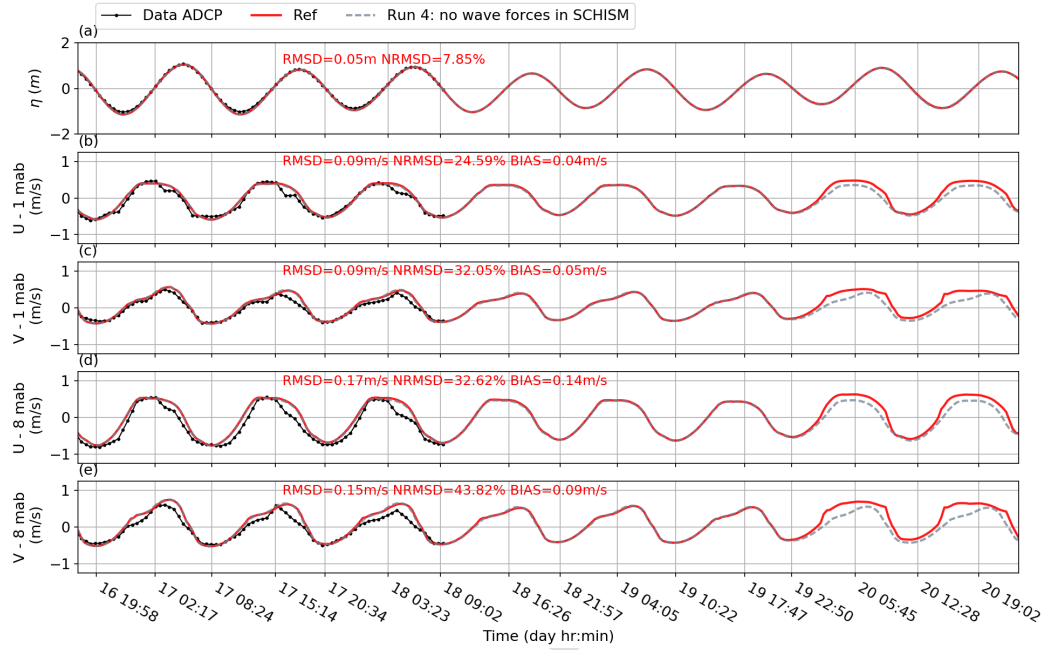
437

438 At 1 meter above the bed, both zonal ( $U$ ) and meridional ( $V$ ) components of currents data from the  
 439 ADCP are well reproduced by the model with NRMSD values of 25% and 32%, respectively  
 440 (Figure 6b,c). Maximum currents occur during the flood and the ebb, with average magnitudes of  
 441 0.54 m/s and 0.67 m/s, respectively. The current flows towards the east-northeast during the flood  
 442 and reverses during the ebb towards the west-southwest. At 8 m above the bed, the current direction  
 443 is similar but its magnitude is around 30% higher (Figure 6d,e). Like near the seabed, the current  
 444 is about 25% higher on ebb than on flood, with average values of 0.9 m/s and 0.7 m/s, respectively.  
 445 At the surface, the model tends to overestimate the duration of maximum current phase associated  
 446 with the flood for both components, resulting in a generally weaker agreement with observations  
 447 (NRMSD of about 35%).

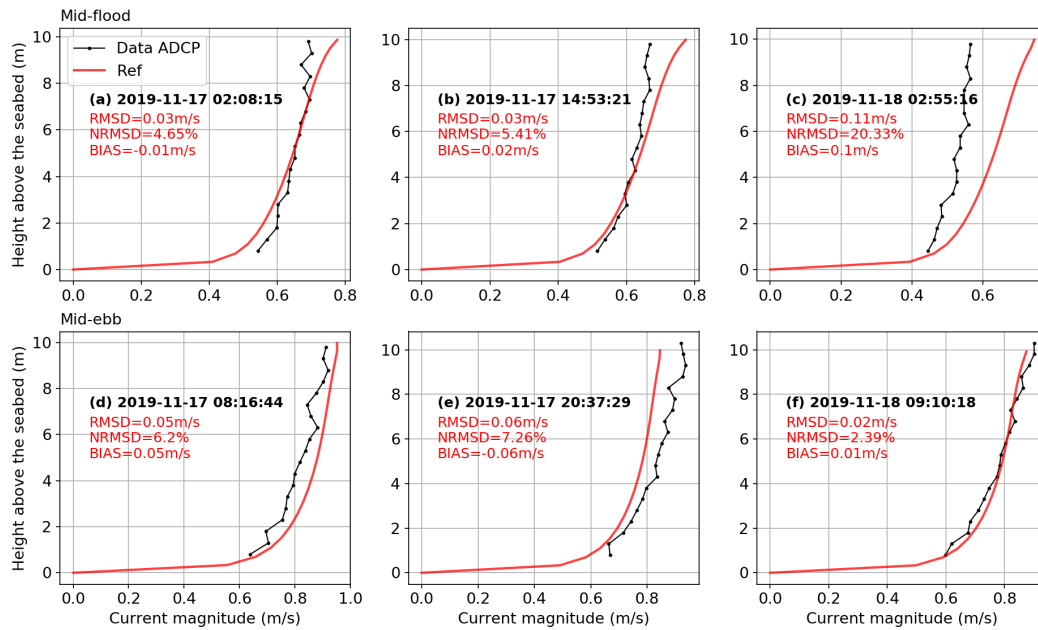
448 Focusing on vertical profiles of currents at mid-flood and mid-ebb times (Figure 7), the agreement  
 449 between observations and model results is generally good. NRMSD values range between 4.6%  
 450 and 20.3% at mid-flood, and between 2.4% and 7.3% at mid-ebb.

451 Although no measurements were available during this period, the comparison between our  
 452 reference run and a simulation without wave forces suggests important differences during

453 energetic wave conditions (from the 19<sup>th</sup> of November at 22:50), with flood currents increased by  
 454 30% close to the surface.  
 455  
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457  
 458 **Figure 6.** Comparisons of ADCP data and model results from simulations *Ref* and *Run 4* (no wave forces in SCHISM)  
 459 in terms of sea surface elevation (a; around mean sea level), and zonal ( $U$ ) and meridional ( $V$ ) components of currents  
 460 at 1 m above the bed (on b and c, respectively) and 8 m above the bed (on d and e, respectively). Statistical parameters  
 461 RMSD, NRMSD and BIAS refer to the *Ref* accuracy with respect to observations.



462  
463 **Figure 7.** Comparisons of vertical profiles of currents (magnitude) obtained from the ADCP data and model results  
464 from simulation *Ref*, at 3 mid-flood (from **a** to **c**) and 3 mid-ebb situations (from **d** to **f**). Statistical parameters RMSD,  
465 NRMSD and BIAS refer to the *Ref* accuracy with respect to observations.

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469 **5. Analysis of wave-tide-current interactions**

470  
471 The wave modulations caused by the tide are assessed through a comparison between *Ref*  
472 (reference physical setting and full coupling between SCHISM and WWM), *Run 2* (no currents in  
473 WWM), and *Run 3* (no elevations and no currents in WWM). Regarding model predictions from  
474 the reference run *Ref*, two simulations are included hereafter in order to discuss the importance of  
475 wave energy dissipation caused by whitecapping (*Run 5* with an adaptive saturation threshold  $B_r$   
476 in Eq. 8), and of wave triad interactions (*Run 6* without triads).

477  
478 **5.1. Impact of water level variations on short waves**

479  
480 **5.1.1. Wave heights**

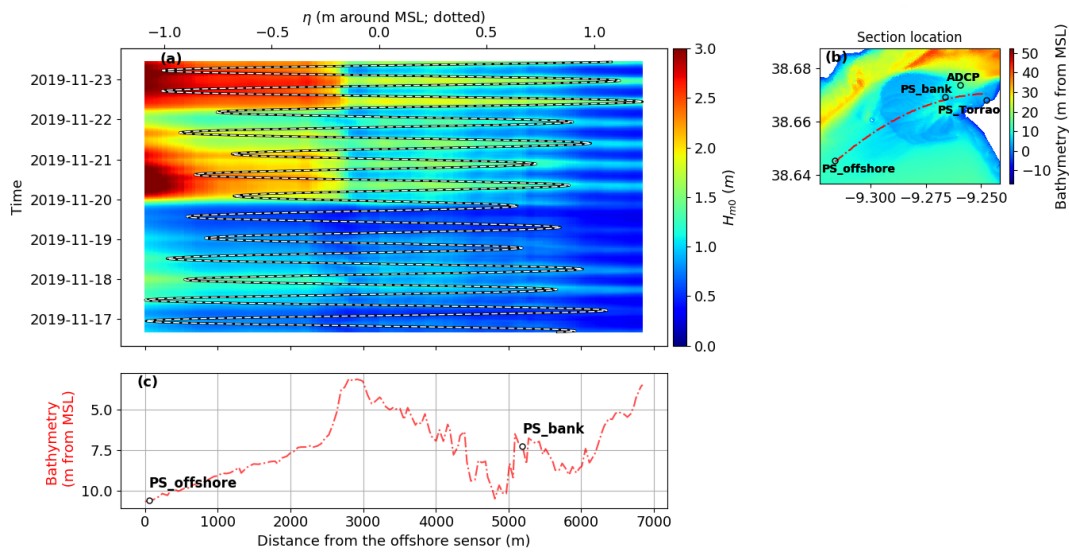
481  
482 At PS\_offshore, both observed and modelled wave heights only exhibit a very limited tidal  
483 modulation by water levels during calm periods because of its large water depth (10 m), as  
484 highlighted by the similarity between results obtained from *Run 2* and *Run 3* (Figure 3b).

485 At the shallower station PS\_bank, the tidal signature on  $H_{m0}$  is different, with, to first order, a  
486 positive correlation between  $H_{m0}$  and the water depth. Focusing on high tide (HT) and low tide  
487 (LT) situations, when currents are the weakest, data provide evidence for larger  $H_{m0}$  (+54%)  
488 during HT (Figure 4). Including water level variations without currents in the wave model (*Run 2*)  
489 enables to reproduce this modulation of  $H_{m0}$  between LT and HT, which is completely missed  
490 otherwise (*Run 3*). In addition, similarities between model results from *Ref* and *Run 2* on Figure 4  
491 suggest that wave modulations are mostly controlled by changes in water levels, with only minor  
492 effects of currents. In *Ref*,  $H_{m0}$  at HT are 58% higher than at LT.

493 At PS\_Torrao, similar patterns can be observed for  $H_{m0}$  with even more pronounced trends:  
494 observed and modelled (simulation *Run 2* without current effects)  $H_{m0}$  at HT are 157% and 92%  
495 higher than at LT, respectively. However, as highlighted by the differences between *Run 2* and *Ref*  
496 results, a substantial part of the modulation is due to currents at this location. In *Ref*,  $H_{m0}$  at HT are  
497 130% higher than at LT, which is closer to the observed ratio. This behaviour will be further  
498 examined in section 5.2.

499 The distributions of wave heights provided by the model (*Ref*) throughout the period of interest  
500 are illustrated along a section crossing the Bugio Bank roughly in the alignment of measurement  
501 stations (Figure 8). The major role played by water level changes on depth-limited wave breaking  
502 and subsequent  $H_{m0}$  modulations is clearly highlighted. During the energetic period,  $H_{m0}$  at HT  
503 suffers a substantial decrease of 30% at the southwest edge of the ebb delta when the water depth  
504 is about 4 m (around X=3000 m on subplots (a) and (c) of Figure 8). At LT, the breaking point is  
505 shifted a few hundred metres offshore (i.e. towards PS\_offshore) and the  $H_{m0}$  decrease is very  
506 pronounced over the same region and reaches up to 75%. Therefore, the height of waves  
507 propagating over the Bugio Bank at HT is on average 50% higher than at LT. In addition,  $H_{m0}$  at  
508 LT never exceeds 0.75 m at the coast.

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**Figure 8.** (a) Spatio-temporal variations of significant wave heights,  $H_{m0}$  (m), computed from simulation *Ref* along a section crossing the Bugio Bank and fitting the sensor positions (black circles) and the mean direction of waves, as shown on (b). On (a) temporal variations of sea surface elevation are superimposed (white dashed line; top abscissa axis). The bathymetry along the section is illustrated on (c).

### 5.1.2. Wave periods

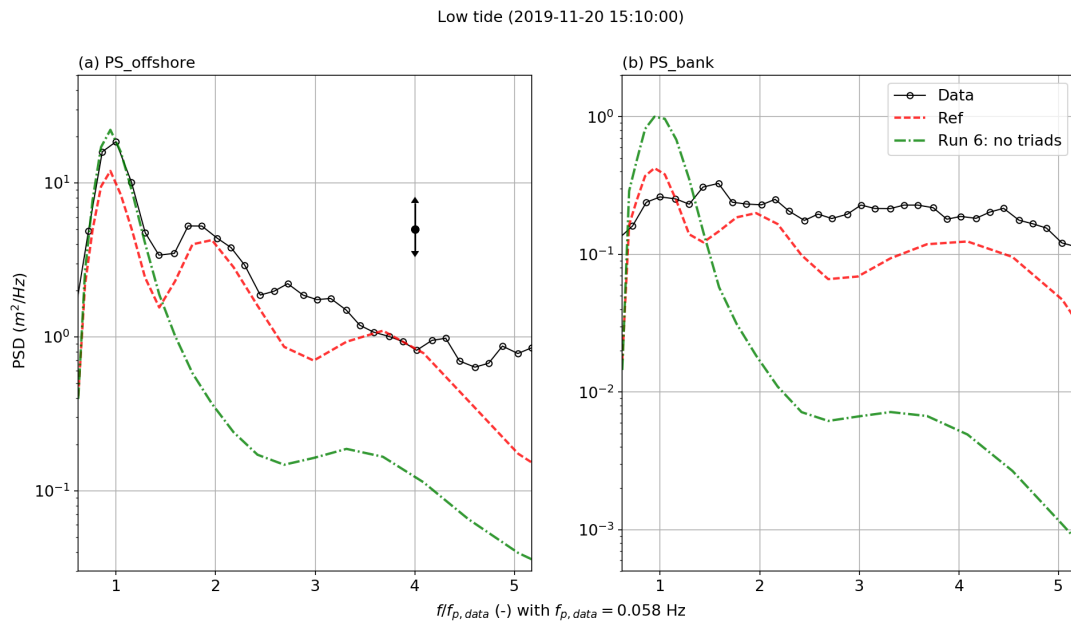
Coherently with  $H_{m0}$  variations, observed wave periods do not exhibit significant tidal modulations at PS\_offshore during calm periods (Figure 3c,d). Only small  $T_{m02}$  differences correlated with tidal levels are highlighted by the model during the energetic period. Modelled  $T_{m02}$  at HT are between 5 and 10% higher than at LT in *Run 2* accounting for tide elevations, which is not the case in *Run 3*.

At PS\_bank, a pronounced tidal modulation of wave periods is observed. Focusing on HT/LT differences, measured  $T_{m02}$  are on average 18% larger at HT (Figure 4c). By accounting for water level changes in WWM (*Run 2*), the model is able to reproduce a part of the tidal modulation with  $T_{m02}$  at HT around 7% higher than at LT.

At PS\_Torrao, the sensor was generally not submerged at LT, making it difficult to highlight clear trends compared to the HT situation based on observations. However, coherently with PS\_bank, measured  $T_{m02}$  are on average 8% higher at HT (Figure 5c). Modelled  $T_{m02}$  at HT are only 3% higher than at LT in *Run 2*.

During the energetic period (between the 20<sup>th</sup> and the 22<sup>nd</sup> November), measured wave periods  $T_{m02}$  decrease from PS\_offshore to PS\_bank (or PS\_Torrao). Model results highlight that this trend can only be reproduced by considering triad wave interactions, which result in nonlinear energy transfers from low to high frequencies. Indeed, triad wave interactions are usually identified as a

539 key mechanism for energy transfers between wave frequencies in the nearshore region, that may  
 540 cause substantial changes in wave characteristics (e.g. Elgar and Guza, 1985; Beji and Battjes,  
 541 1993; Herbers et al., 2000; Rusu and Soares, 2011; Cavaleri et al., 2018).  
 542  $T_{m02}$  computed from run *Run 6*, that ignores triads, are almost similar at the three sensor locations  
 543 and display a strong positive bias compared to the observations (not illustrated here). Focusing on  
 544 a LT situation during the energetic period (the 20<sup>th</sup> November at 3 pm), the wave spectrum derived  
 545 from bottom pressure observation at PS\_offshore provides evidence for this type of energy transfer  
 546 with successive peaks obtained at  $f_p$  (peak frequency) and  $2 \times f_p$  (Figure 9a). While *Ref* mimics the  
 547 spectrum shape with the different energy peaks, *Run 6* misses this trend and strongly overestimates  
 548  $T_{m02}$  (by 70%). At PS\_bank, the energy remains concentrated in the frequency band lower than 0.1  
 549 Hz in *Run 6* with a  $T_{m02}$  of 14.4 s, whereas the energy becomes more distributed over frequencies  
 550 in data and *Ref* with  $T_{m02}$  values of 5.7 s and 6.7 s, respectively (Figure 9b). Note that energy is  
 551 also transferred to the third harmonic in observations ( $3 \times f_p$ ), which is not reproduced by the model  
 552 in simulation *Ref*. This is further discussed in section 6.1.  
 553



554  
 555 **Figure 9.** Power spectral density (PSD) as a function of normalized frequency (by  $f_{p,data}=0.058$  Hz) obtained from  
 556 pressure measurements, and simulations *Ref* and *Run 6* at PS\_offshore **(a)** and PS\_bank **(b)** during a low tide situation  
 557 occurring at the storm peak (the 20<sup>th</sup> of November at 3:10pm). On (a), the error bar refers to the 95% interval of  
 558 confidence of the PSD (Bendat and Piersol, 1971).

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565 5.2. Impact of currents on the wave field

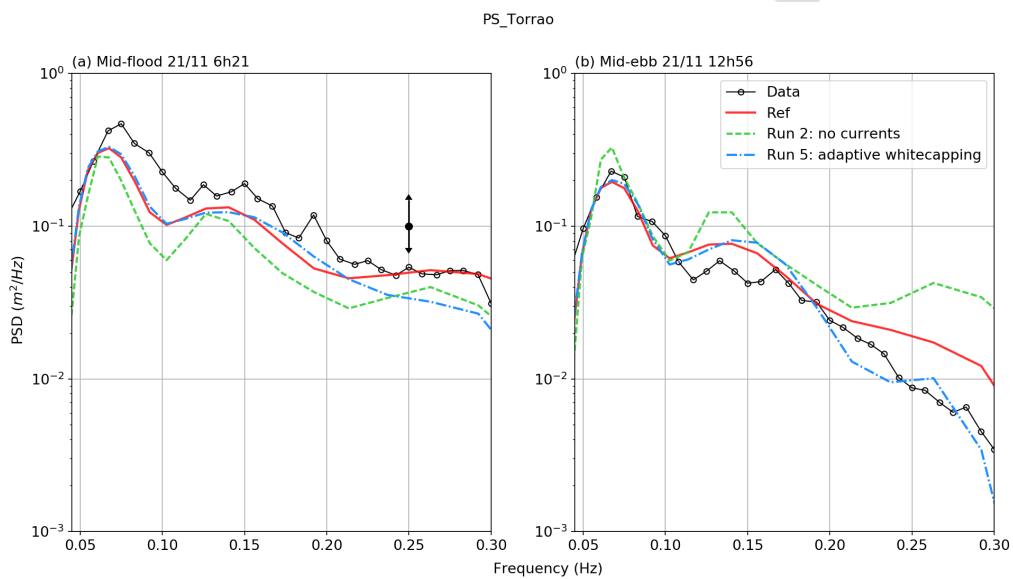
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568 The offshore location of PS\_offshore only shows a slight influence of currents on wave parameters  
 569 during the energetic period, with differences of only a few percent for wave heights and periods  
 570 (weak differences between *Ref* and *Run 2* on Figure 3b, 3c).

571

572



573

574 **Figure 10.** Power spectral density (PSD) obtained from pressure measurements, and simulations *Ref*, *Run 2* (*no*  
 575 *currents*) and *Run 5* (*adaptive whitewater*) at PS\_Torrao during successive mid-flood (a) and mid-ebb (b)  
 576 situations, the 21<sup>st</sup> of November at 6:21 and 12:56, respectively (see the corresponding thick vertical ticks on Figure 5).

577

578 Focusing on successive mid-flood (MF) and mid-ebb (ME) situations for equivalent water depths  
 579 enables to assess the influence of currents on wave heights and periods at the shallower locations.  
 580 At PS\_bank, observations do not provide evidence for a clear effect of currents on  $H_{m0}$  and  $T_{m02}$   
 581 when comparing successive MF and ME situations (Figure 4).

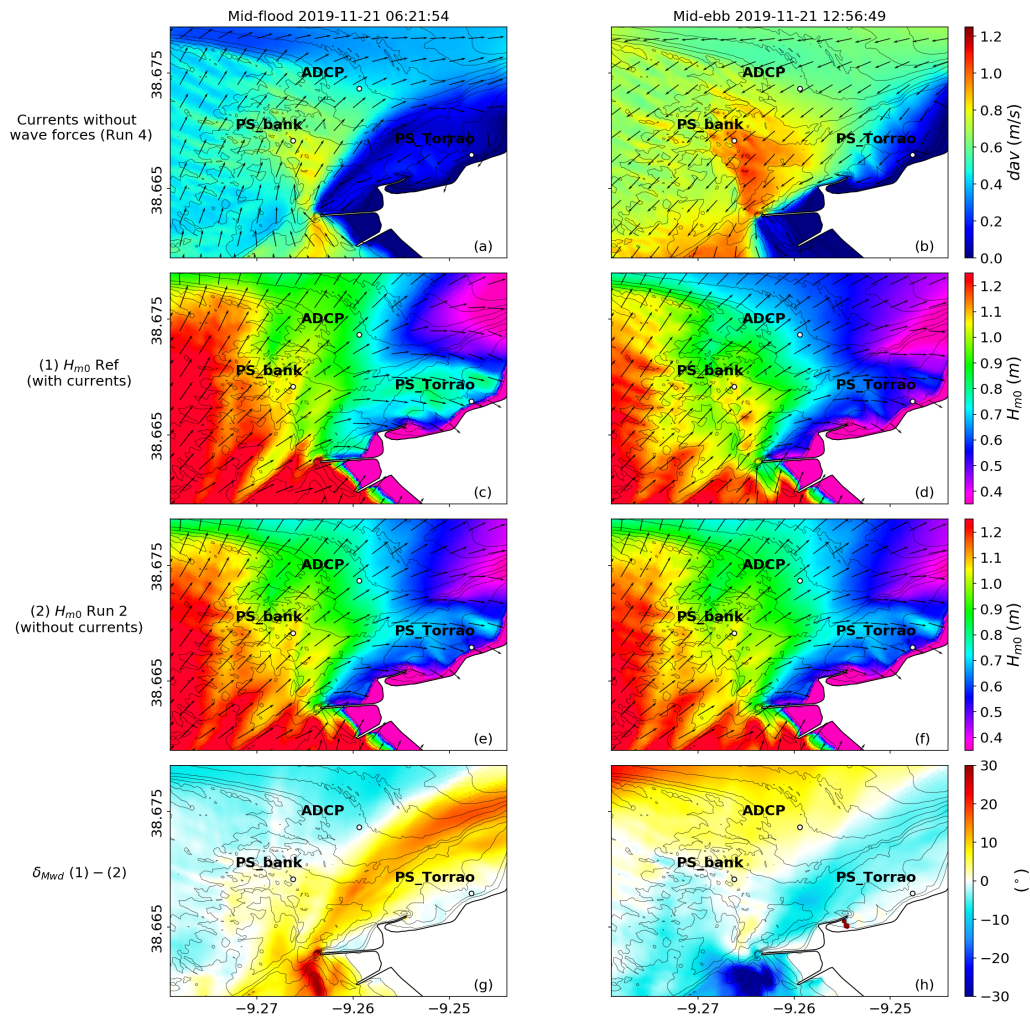
582 At PS\_Torrao, observations reveal that at MF, on average,  $H_{m0}$  are 78% higher, and  $T_{m02}$  are 11%  
 583 lower than at ME (Figure 5). In simulation *Ref*,  $H_{m0}$  and  $T_{m02}$  at MF are 31% higher and 7% lower  
 584 than at ME, respectively, thus in agreement with observations. Neglecting currents in *Run 2* leads  
 585 to similar  $H_{m0}$  and  $T_{m02}$  between MF and ME, and to substantial underestimations by 15-25% of  
 586 maximum  $H_{m0}$  occurring over tidal cycles during the energetic period. Wave spectra obtained from  
 587 observations and simulations *Ref* and *Run 2* at PS\_Torrao clearly highlight the substantial  
 588 underestimation of the wave energy in the model when currents are neglected, in particular during

589 the flood (Figure 10a). Therefore, substantial current-induced modulations of wave parameters are  
590 superimposed on those controlled by water level changes.

591 To understand the processes responsible for these current-induced modulations, spatial fields of  
592 wave heights and directions were compared between simulations *Run 2* (without currents) and *Ref*  
593 (with currents) during two successive MF and ME situations characterized by similar offshore  
594 wave conditions (Figure 11). In *Ref*, flood currents enhance refraction and induce a clockwise  
595 rotation of waves of 10-15° in comparison with the simulation *Run 2*, over the region between  
596 PS\_bank and PS\_Torrao (Figure 11g). Consequently, more wave energy is focused towards  
597 PS\_Torrao, with wave heights in *Ref* 19% higher than in *Run 2* at mid-flood (Figure 11c,e). Note  
598 that this energy focusing reaches its maximum at the end of the flood, with waves heights 25 to  
599 30% higher in the simulation accounting for currents (*Ref*). In contrast, ebb currents induce a  
600 counterclockwise rotation of waves of 10° (differences between *Ref* and *Run 2* on Figure 11h), and  
601 reduce the wave energy reaching the region around PS\_Torrao. Thus,  $H_{m0}$  computed from *Ref* at  
602 PS\_Torrao is 16% lower than in *Run 2* at ME (Figure 11d,f).

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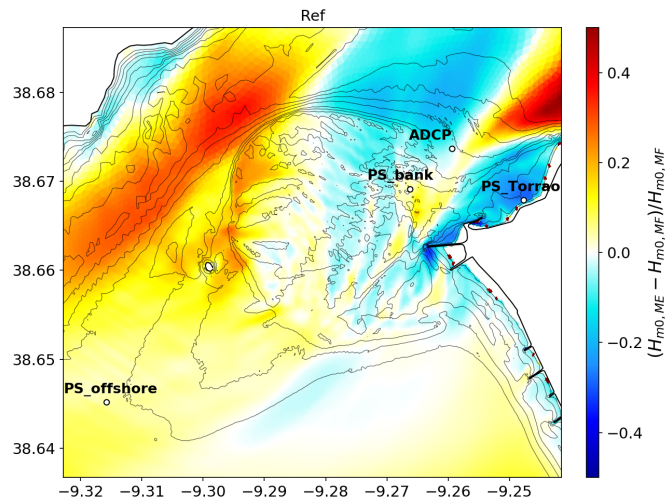
604

605 **Figure 11.** Spatial distributions of depth-averaged currents,  $dav$ , at successive mid-flood (a) and mid-ebb (b)  
 606 during the storm peak and the corresponding fields of significant wave height,  $H_{m0}$ , from simulations (1) *Ref* (with  
 607 currents) and (2) *Run 2* (without currents) at mid-flood, (on (c) and (e), respectively), and at mid-ebb, (on (d) and (f),  
 608 respectively) (see the corresponding thick vertical ticks associated with these specific dates on Figure 5). Changes in  
 609 the mean wave direction between *Run 2* and *Ref* (1-2) are illustrated at mid-flood and mid-ebb on (g) and (h),  
 610 respectively.

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 615 **Figure 12.** Increasing/decreasing trends of the significant wave height,  $H_{m0}$ , between two successive mid-flood (MF,  
 616 20<sup>th</sup> November at 5:02am) and mid-ebb (ME, 20<sup>th</sup> November at 11:46am) situations during the storm peak, obtained  
 617 from simulation *Ref*. Trends are expressed as  $(H_{m0,ME}-H_{m0,MF})/H_{m0,MF}$ , a positive value meaning that  $H_{m0}$  increases at  
 618 ME, and vice versa.

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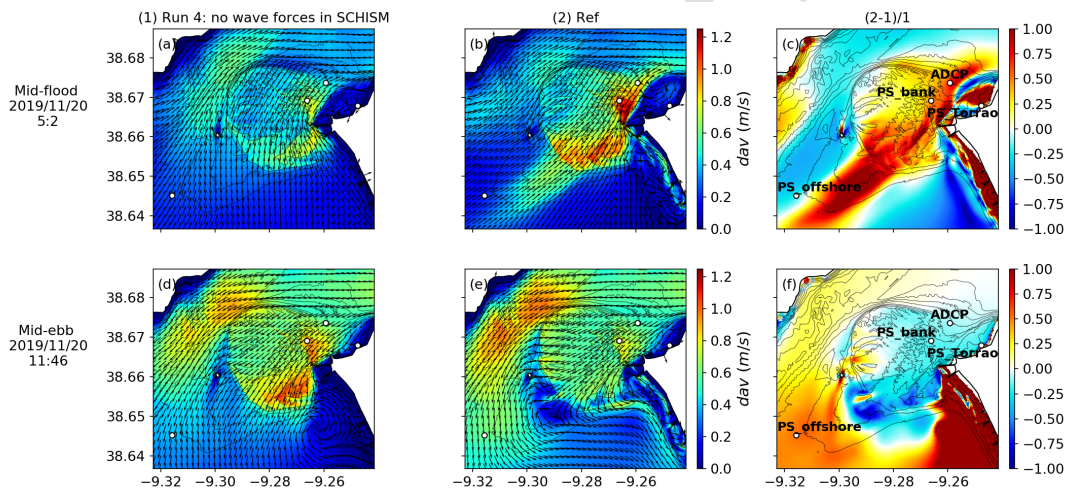
621 At a broader extent, circulations affect wave characteristics at the mouth scale, in particular  $H_{m0}$ ,  
 622 with different effects depending on the location (current exposure, water depth, sheltered areas and  
 623 wave dissipation level). Figure 12 illustrates that the  $H_{m0}$  decrease occurring between MF and ME  
 624 is not specific to the station PS\_Torrao but concerns large areas of the TEM. Indeed, over the  
 625 eastern part of the bank,  $H_{m0}$  is generally 10 to 40% lower during the ebb. To our knowledge, such  
 626 a modulation of waves due to current effects on their propagation has never been described at the  
 627 mouth of a large estuary. This aspect is further discussed in section 6.2. Besides,  $H_{m0}$  at ME are  
 628 not smaller than at MF over the entire mouth. In deeper areas like in the main channel, opposed  
 629 currents during the ebb promote shoaling without increasing wave steepness enough to induce  
 630 dissipation by whitecapping. As a result,  $H_{m0}$  during ME are about 20-25% higher than during MF  
 631 over these regions, which corroborates previous findings at the TEM (Rusu et al., 2011) or for  
 632 other inlet systems (e.g. Elias et al., 2012; Dodet et al., 2013; Jia et al., 2015; Akan et al., 2017).  
 633 In addition, as already reported in other studies (e.g. Olabarrieta et al., 2011; Dodet et al., 2013;  
 634 Akan et al., 2017), our results suggest that the strong wave focusing effect of the ebb jet in the  
 635 main channel induces a redirection of wave energy from adjacent regions, where wave heights  
 636 thus appear reduced during the ebb. Note that previous studies dedicated to interactions between  
 637 waves and large-scale currents highlighted that pronounced wave height modulations could be  
 638 induced by currents in jet area through reflection, refraction or trapping phenomena depending on  
 639 their orientation with respect to wave directions (e.g. cases of the Agulhas current or the Gulf  
 640 Steam; see Irvine (1987), Holthuijsen and Tolman (1991), Kudryavtsev et al. (1995), Lavrenov  
 641 (1998)). In particular, when currents are opposed to waves direction, trapping effect can lead to a

642 substantial focusing of wave energy in the jet region (mostly resulting from refraction of waves by  
 643 currents). By using a third-generation spectral wave model, Holthuijsen and Tolman (1991)  
 644 highlighted this phenomenon in the Gulf Stream region. Over the deep channel area, model results  
 645 during the energetic peak of the period show that ebb currents tend to induce an anticlockwise  
 646 rotation of wave directions (by a few degrees) to the west of the Bugio Bank (comparison between  
 647  $H_{m0}$  fields of simulations *Ref* and *Run 2* without current effects on waves; not illustrated here).  
 648 This slight refraction of waves at the main channel entrance focuses wave energy in the jet area  
 649 during the ebb.

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### 652 5.3. Impact of waves on currents

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656 **Figure 13.** Spatial distributions of depth-averaged currents,  $dav$  in m/s, at successive mid-flood (MF) and mid-ebb  
 657 (ME) situations during the storm peak, obtained from simulations (1) *Run 4* [no wave forces in SCHISM] (on (a) and  
 658 (d), respectively) and (2) *Ref* (on (b) and (e), respectively). The increasing/decreasing trends of  $dav$  between *Run 4*  
 659 and *Ref* at MF and ME  $[(2-1)/1]$  are illustrated on (c) and (f), respectively.

660

661 Depth-averaged velocity fields of two successive MF and ME situations occurring during the peak  
 662 of the energetic period are compared by accounting (*Ref*) or not (*Run 4*) for wave-induced forces  
 663 in the circulation model SCHISM (Figure 13).

664 During flood, currents computed from simulation *Run 4*, that does not include wave-induced  
 665 forcing, are weak and oriented northward for water depths higher than 7 m at the south of the  
 666 mouth (Figure 13a). Over the Bugio Bank, they progressively rotate towards the northeast  
 667 according to the coastline orientation and reach their maximum, around 0.8 m/s, in the secondary  
 668 flood channel in which the ADCP and PS\_bank are located. Flood currents enter the main channel

669 flowing towards the north-east with maximum velocities of 0.6 m/s. In *Ref*, when wave-induced  
670 circulations are considered, a noticeable change in the current direction is obtained over most of  
671 the estuary mouth, with a mean flow oriented according to the average wave direction, i.e. towards  
672 the north-east (Figure 13b). Specific circulations caused by waves can be noticed. Pronounced  
673 currents (around 0.6 m/s) develop in the shallow region located between PS\_offshore and the  
674 southwestern border of the Bugio Bank, which corresponds to the offshore extension of the ebb  
675 delta. The model analysis of wave force terms involved in the momentum balance enabled to  
676 identify the wave breaking-induced acceleration (WBA) as the main contributor of these wave-  
677 induced currents. Indeed, during energetic conditions, the surf zone extends offshore and WBA  
678 induces this specific wave-induced circulation. Furthermore, a littoral drift is clearly visible along  
679 the Caparica Coast (adjacent beach of the southern margin, Figure 1b), which flows towards the  
680 northwest due to the obliquity of waves coming from the southwest (refraction over the Bugio  
681 Bank). In the secondary channel and over the southern part of the Bugio Bank, flood currents are  
682 significantly increased (+60% on average; Figure 13c) by WBA whereas, simultaneously, the  
683 entering flow in the main channel is reduced by 20%.

684 During the ebb, waves coming from the southwest tend to deviate the tidal stream from the main  
685 channel southward. Thus, a counterclockwise circulation is generated around the ebb delta in  
686 simulation *Ref* (Figure 13e), that is not found in *Run 4* (Figure 13d) where currents remain mainly  
687 oriented towards the south-southwest. The circulation influenced by waves in *Ref* exhibits an  
688 onshore orientation to the south of the Bugio Bank, and then turns towards the south-east along  
689 the 7-m isobath. Over the Bugio Bank, WBA substantially reduces the magnitude of ebb currents,  
690 in particular in the secondary channel (-20% on average, up to -50%; Figure 13f). In order to  
691 compensate for the influence of this opposed wave-induced circulation, the ebb tidal jet intensifies  
692 in the main channel (+20%).

693 It should be reminded that MF and ME situations presented on figure 13 are characterized by  
694 intense tidal flows and energetic wave conditions. When  $H_{m0}$  at PS\_offshore becomes lower than  
695 1 m, the contribution of waves to circulations vanishes because waves are too small to break on  
696 the ebb shoal (not illustrated).

697 During HT and LT tidal levels, when tidal currents are weak, the entire mouth circulation can be  
698 driven by waves. During the storm peak, wave-induced circulation described a band extending  
699 from PS\_offshore to the ADCP station, with currents ranging from 0.5 and 0.9 m/s (not illustrated  
700 here). At the ADCP station, the relevance of wave-induced circulations during energetic conditions  
701 is clearly highlighted, with substantial or even dominant contributions to currents between LT and  
702 MF levels (Figure 6). Indeed, the wave-induced circulation is more intense at LT over the southern  
703 border of the Bugio Bank, due to reduced water depths which promote wave breaking.

704 Lastly, as recently highlighted at the mouth of other inlets (e.g. Akan et al., 2017), wave-induced  
705 circulations in turn influence wave fields at the TEM (not illustrated here). In particular, waves  
706 tend to reinforce the ebb stream in the main channel, which promotes wave steepening and results  
707 in larger  $H_{m0}$  (+10%).

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## 713 6. Discussion

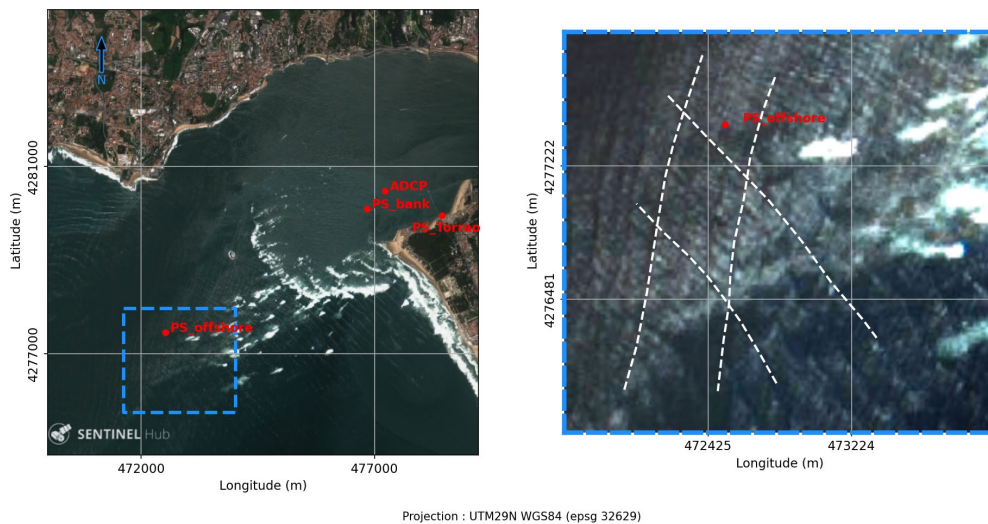
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### 715 6.1. Model predictive skills and limitations

716

717 After the arrival of the large swell on the 20/11 ( $H_{m0}$  larger than 2 m with  $T_p$  over 20 s), wave  
718 heights measured at PS\_offshore increase by +35% at low tide in comparison with the high tide  
719 situation (see low tides of the 20/11 at 3pm and the 21/11 at 3h30am on Figure 3b). The model  
720 fails to reproduce this  $H_{m0}$  increase during low tide levels associated with energetic conditions,  
721 even when currents are considered. At PS\_offshore, located at a mean water depth of 10.6 m,  
722 changes in water levels between high tide and low tide can only explain small variations of  $H_{m0}$   
723 due to shoaling (around 3%). During this type of energetic conditions, satellite images show  
724 complex interference wave patterns over the offshore extension of the Bugio Bank (Figure 14),  
725 where PS\_offshore is located. These observations suggest that wave propagation becomes  
726 complex over this region and may result from combined refraction and diffraction processes,  
727 which would tend to concentrate the wave energy at some locations, thereby increasing wave  
728 heights. The fact that the model fails to reproduce increased  $H_{m0}$  at low tide could be explained by  
729 the fact that diffraction is not considered here.

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**Figure 14.** Satellite image (Sentinel mission) at the Tagus Estuary Mouth, the 18<sup>th</sup> April of 2018, with a zoom provided over the region where the sensor *PS\_offshore* is located (dashed white lines depict some wave crests). On this date, offshore conditions at the Nazaré Buoy (location on Figure 1a) were energetic and close to those associated with the

735 storm peak of the present field campaign, with  $H_{m0}$  of 6 m,  $T_p$  of 17.5 s and a  $Mwd$  of 295°N. Note that no satellite  
736 image was available during the storm peak due to the presence of clouds.

737 The comparison between observed and modelled PSD at low tide (Figure 9) showed triad  
738 interactions promote substantial energy transfers from the spectral peak to higher harmonics.  
739 However, in more details, energy is accurately transferred to the second ( $2\times f_p$ ) but not to the third  
740 ( $3\times f_p$ ) harmonic. This problem is inherent to the Lumped Triad Approximation of Eldeberky  
741 (1996) (Booij et al., 2009) and could partly explain why the model slightly underestimates the tidal  
742 modulation of  $T_{m02}$ . Moreover, the performance of the LTA is not optimal on complex  
743 bathymetries, such as in barred beaches (Mendes et al., 2018), and more research is needed to  
744 adequately account for triads in phase-averaged wave models.

745 The model also underestimates the energy reduction associated with high frequencies during ebb.  
746 In addition, the tidal modulation of  $T_{m02}$  at PS\_bank or PS\_Torrao, which generally shows that  
747  $T_{m02}$  increases during the ebb, is weaker than in the observations. As ebb currents over the ebb  
748 delta can reach 1 m/s, we hypothesize that the drop of wave energy in the high frequency part of  
749 wave spectra observed along the coast during the ebb (e.g. Figure 10) is due to dissipation by  
750 whitecapping, as proposed in previous studies (e.g. Westhuysen et al., 2007; Ardhuin et al., 2010;  
751 Westhuysen, 2012; Dodet et al., 2013). In an additional simulation (*Run 5*), an adaptive saturation  
752 threshold  $B_r$  was considered in the original formulation of Ardhuin et al. (2010), assuming an  
753 exponential decrease of the latter for  $f > 0.2$  Hz (HF). As illustrated on Figure 10b, the reduced  $B_r$   
754 values for HF result in sharper reductions of the wave energy during the ebb at PS\_Torrao, in  
755 agreement with observations. Therefore, it may mean that, based on the original formulation that  
756 considers a constant  $B_r$ , the saturation level is close but just below this threshold above which the  
757 whitecapping is activated (i.e. critical steepening). Since other studies provided evidence for  
758 overestimations of wave energy associated with high frequencies under moderate to intense current  
759 conditions (e.g. Bennis et al., 2020), specific attention should be paid to the whitecapping  
760 dissipation in future studies.

761 In future research, more attention should be paid to non-linear interactions occurring when waves  
762 face intense countercurrents. Countercurrents promote wave steepening and subsequent  
763 dissipation by breaking, but also induce resonant interactions that strongly affect the non-linear  
764 evolution of waves, which results in substantial energy transfers and frequency downshift (e.g.  
765 Shugan et al., 2015). Therefore, in addition to the possible inadequate formulation of the saturation  
766 threshold for whitecapping discussed above, the fact that these resonant interactions are not  
767 represented in spectral wave models could locally explain the discrepancies between wave spectra  
768 modelled and derived from field observations. In addition, the wave action equation solved by  
769 spectral wave models is not fully valid in areas such as the TEM, since it was derived for waves  
770 propagating in “slowly varying media” (Bretherton and Garrett, 1968). Hence, other approaches  
771 should probably be used to investigate these processes in detail.

772

773

## 774 6.2. New insights on wave-current interactions

775

776 Despite the potential limitation of the model regarding energy dissipation by whitecapping (section  
777 6.1), a substantial part of wave modulations was identified to be driven by current-induced  
778 refraction over some regions of the TEM characterized by weak local circulations (including  
779 PS\_Torrao). According to model results, this effect of currents on the propagation of waves locally  
780 contributes to 20-30% of the tidal modulation of wave heights, while tidal ranges were medium,  
781 suggesting larger values under spring tides. Flood currents enhance refraction and induce a  
782 clockwise rotation of waves by 10-15°, thereby focusing more wave energy towards the southern  
783 margin of the mouth, while ebb currents produce an opposite effect by reducing the energy  
784 reaching the coast. To our knowledge, such an effect of currents on the tidal modulation of waves  
785 has never been described before. In addition to well-known current effects on waves propagation  
786 and dissipation (e.g. review of Wolf and Prandle, 1999), recent knowledge on wave-current  
787 interactions at the mouth of inlet systems mainly concerned wave focusing (e.g. Olabarrieta et al.,  
788 2011 ; Dodet et al., 2013 ; Akan et al., 2017) and steepening due to opposing currents during the  
789 ebb (e.g. Rusu et al., 2011 ; Elias et al., 2012; Dodet et al., 2013; Jia et al., 2015; Akan et al., 2017),  
790 and subsequent dissipation by whitecapping (e.g. Westhuysen, 2012). This study highlights that  
791 wave modulations due to current-induced refraction, a process previously identified between  
792 islands or on the inner shelf (e.g. Hopkins et al., 2006; Arduin et al., 2012), can also be relevant  
793 at the mouth of large estuaries.

794

795 Besides, the literature on wave-induced circulations is mostly restricted to small and medium-size  
796 inlet systems (e.g. Bertin et al., 2009; Olabarrieta et al., 2011; Wargula et al., 2014; Chen et al.,  
797 2015; Akan et al., 2017), while their contribution in case of large estuaries remains mostly  
798 unexplored. Yet, Fortunato et al. (2017) showed that onshore directed waves forces resulting from  
799 wave breaking over the Tagus Ebb Delta could generate wave-induced setup reaching tens of  
800 centimeters inside the estuary during extreme events (1941 storm with offshore significant wave  
801 heights of 14 m). The present study further revealed that storm waves can also substantially impact  
802 the mean circulation, even at the scale of a wide and deep estuary mouth. Qualitatively, some  
803 similarities can be underlined with smaller inlet systems regarding circulation patterns (e.g.  
804 Olabarrieta et al., 2011; Orescanin et al., 2014; Chen et al., 2015; Akan et al., 2017), although the  
805 impact of short wave breaking is more pronounced in this study, especially in secondary channels  
806 (locally increased by a factor 3). In addition, according to Fortunato et al. (2017), the return period  
807 of the storm waves considered in this study is less than one year, with several occurrences during  
808 each winter. By considering extreme events with return periods of 10 years (offshore significant  
809 wave height  $H_s \approx 10$  m) or 100 years ( $H_s \approx 15$  m), we could expect that wave-induced circulations  
810 would substantially intensify and become fully dominant.

811

## 812 7. Conclusions and perspectives

813

814 Interactions between waves, currents and water levels have been assessed at the mouth of the Tagus  
815 Estuary (the second largest estuary in Europe) during storm wave conditions, by combining field  
816 observations and the application of a 3D fully-coupled wave-current modelling system. Three  
817 pressure sensors and one ADCP were deployed across the ebb delta at water depths ranging from  
818 3 to 11 m. Wave-current interactions were firstly investigated at measurement stations, which  
819 enabled to ensure the model validity in terms of both waves and currents. Series of numerical  
820 simulations were performed over the entire estuary mouth in order to discriminate the effects of  
821 water levels and currents on wave fields on the one hand, and the influence of waves on circulations  
822 at different tidal phases on the other hand. The main conclusions and perspectives from this work  
823 are:

- 824 • As already reported at the mouth of other inlet systems, the combination between  
825 bathymetric features associated with the shallow ebb delta region and the mesotidal forcing  
826 plays a key role in the modulation of waves. During energetic conditions, low tide levels  
827 promote depth-limited wave breaking over the ebb shoal, which results in reduced wave  
828 heights shoreward (by 50% to more than 100% depending on the location).
- 829 • Triad wave interactions associated with wave non-linearity developing by shallow water  
830 depth promote energy transfers from the spectral peaks to higher harmonics and thereby  
831 explain the observed decrease of the mean wave period  $T_{m02}$  as the water depth is reduced.  
832 In more details, the LTA approach used in this study fails to transfer energy to the third  
833 harmonic, which partly explains why the model underestimates the drop of  $T_{m02}$  at low tide.  
834 More advanced approaches for triad modelling (e.g. Salmon et al., 2016) will have to be  
835 considered to see if they better predict energy transfers with complex sea states as in the  
836 TEM.
- 837 • At the mouth, current-induced refraction appears as a major process explaining a  
838 substantial part of the modulation of wave heights (20-30%), never described in case of a  
839 large estuary. Flood currents change the mean wave direction by 10-15° and tend to  
840 concentrate the wave energy towards coastal regions of the southern margin, while an  
841 opposite effect is induced by ebb currents. On the contrary, in the deep main channel, ebb  
842 currents opposed to wave direction focus the wave energy through refraction and promote  
843 wave shoaling ( $H_{m0}$  increased by 20%).
- 844 • Regarding the current effect on wave dissipation over some regions of the ebb shoal,  
845 model-data comparison suggests that the saturation level is close but just below the  
846 threshold above which whitecapping starts to occur and that further developments are  
847 needed to better model wave dissipation in such conditions.
- 848 • During energetic conditions, wave breaking-induced acceleration occurring over the ebb  
849 shoal substantially influences both the orientation and the magnitude of circulations at the  
850 estuary mouth and along adjacent coasts. Wave forces enhance (resp. reduce) tidal currents  
851 by 50 to 300% over the ebb shoal during the flood (resp. the ebb), leading to a relative



852 decrease (resp. increase) of 25% of the tidal flow in the deep main channel. However, due  
853 to a malicious act, no current measurements were available under energetic wave  
854 conditions and these findings presently rely on modeling results. Although very  
855 challenging, future field campaigns will have to be carried out at the mouth of large estuary  
856 mouths under storm waves.

- 857 • The influence of waves on circulations in turn affects wave fields, e.g. enhanced  $H_{m0}$   
858 increase at the main channel entrance during the ebb, demonstrating the complexity of  
859 interactions between waves and currents, and the interest of considering a fully coupled  
860 wave-current model.

861

862 This study highlighted that complex interactions between waves and tidal currents can occur at the  
863 mouth of a large estuary, including substantial modulations of waves heights caused by current-  
864 induced refraction and intense wave-induced circulations. Further research should be dedicated to  
865 extreme wave events, which appear challenging for both data acquisitions and numerical  
866 modelling.

867

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869

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883

884

## 885 Appendix A. Solving the wave dispersion relation with current effect

886

887 Energy density spectra (PSD) obtained from pressure measurements by applying Fast Fourier  
888 Transforms need to be converted in elevation spectra  $E(f)$ . A Transfer Function Method based on  
889 the linear wave theory (e.g. Bishop and Donelan, 1987) is used at each frequency  $f$  such as

890

$$891 \quad E(f) = \frac{PSD(f)}{K_p(f)^2} \quad (A.1)$$

892

893 and

894

$$895 \quad K_p(f) = \frac{\cosh(k(f)h_{sensor})}{\cosh(k(f)h)} \quad (A.2)$$

896

897 where  $h_{sensor}$  is the sensor height above the bottom,  $h$  is the water depth, and  $k$  is the wave number  
898 computed from the linear wave theory. The dispersion relation from the linear wave theory reads

899

$$900 \quad \sigma^2 = gk \tanh(kh) \quad (A.3)$$

901

902 where  $\sigma$  is the relative angular frequency. In the presence of intense currents,  $k$  can be substantially  
903 modulated and thus requires a correction to ensure the relevance of elevation spectra. First, the  
904 wave number  $k$  has to be computed without current-wave interaction. The logarithmic matching  
905 method of Guo (2002) has been applied to Eq. (A.3) as follows

906

$$907 \quad k = \frac{\omega_a^2}{h(1-e^{-\omega_a\beta})^{-1/\beta}} \quad (A.4)$$

908

909 with

910

$$911 \quad \omega_a = \frac{\omega}{\sqrt{g/h}} \quad (A.5)$$

912

913 where  $\omega$  is the absolute angular frequency ( $=2\pi f$ ; in rad/s),  $g$  is the gravitational acceleration, and  
914  $\beta$  is a shape parameter set at 2.4908.

915 According to Sanchez (2012), a wave number accounting for the current,  $k_{cur,0}$ , can be computed  
916 as

917

$$918 \quad k_{cur,0} = 0.3k + \frac{0.7(\omega - kU)^2}{g \tanh(kh)} \quad (A.6)$$

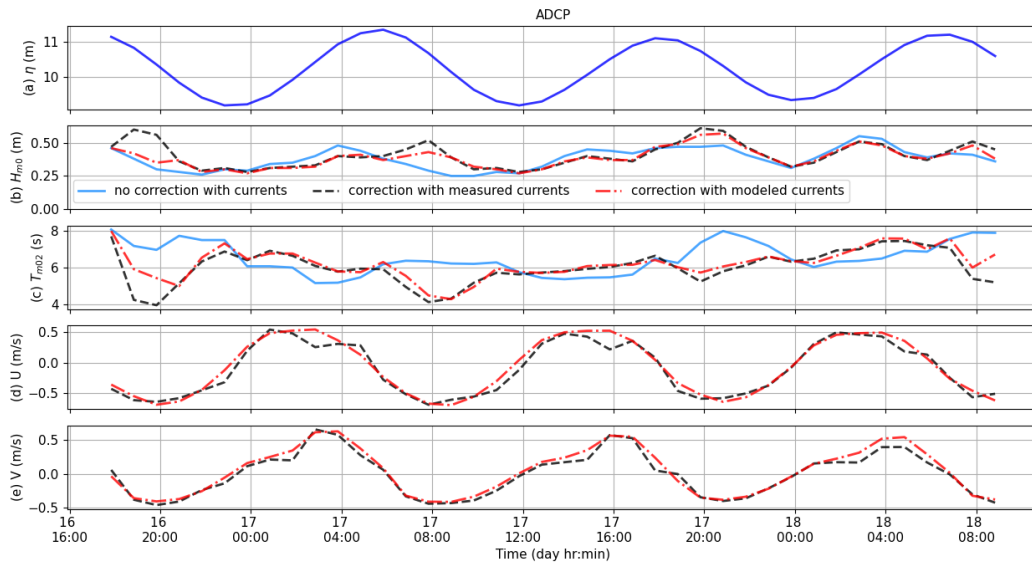
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920 where  $U$  is the current velocity in the wave direction. Finally, a Newton-Raphson iterative method  
921 (10 iterations considered here; Eq. A.7) is applied to improve the accuracy of the final solution by  
922 defining the initial  $k$  value,  $k_{i=0}$ , as  $k_{cur,0}$ .

923

$$924 \quad k_{i+1} = k_i - \frac{gk_i \tanh(k_i h) - (\omega - k_i U)^2}{g(\tanh(k_i h) - k_i h(\tanh(k_i h)^2 - 1)) + 2U(\omega - k_i U)} \quad (A.7)$$

925



926

927

**Figure A1.** (a) Water elevations measured at the ADCP station (see location on Figure 1b). Temporal series of  $H_{m0}$  (b) and  $T_{m02}$  (c) obtained without current effect (solid line), or by including measured (dashed line) or modelled (dashed-dotted line) currents in the wave dispersion relation, with the corresponding zonal ( $U$ ) and meridional ( $V$ ) components of currents illustrated on (d) and (e), respectively.

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Pressure measurements from the ADCP have been processed by considering 20-minute-long bursts, corrected from atmospheric pressure and detrended. The effect of tidal currents on the reconstitution of elevation spectra is investigated through comparisons on wave bulk parameters  $H_{m0}$  and  $T_{m02}$  (see more details on their computation in section 2.2), as illustrated on Figure A1. The current effect becomes substantial during the flood and the ebb, when currents reach their maximum. As expected, flood currents tend to reduce  $H_{m0}$  and increase  $T_{m02}$ , while ebb currents have opposite effects. Consistent corrections are obtained by considering currents from the ADCP or from the model, which underlines the relevance of the latter regarding hydrodynamics.

Given their substantial impact on the modulation of mean wave parameters, tidal currents are included in the processing of pressure measurements at all stations, with a similar procedure than the one used by de Wit et al. (2019). Indeed, tidal currents provided by the model are used at the other measuring stations where current measurements are unfortunately not available, given its ability in describing tidal-induced circulations at the Tagus Estuary Mouth.

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**Highlights:**

- Wave-current interactions at a large estuary mouth are analyzed under storm waves
- Refraction of waves by currents explains up to 30% of the modulation of wave heights
- Wave-breaking acceleration is a major driver of the circulation at the mouth scale

Journal Pre-proof

**Baptiste Mengual** : Conceptualization, Methodology, Software, Writing – Original Draft ; **Xavier Bertin** : Conceptualization, Methodology, Writing – Review & Editing, Supervision ; **Florian Place** : Conceptualization, Methodology – Review & Editing ; **Marc Pezerat** : Methodology, Software, Writing – Review & Editing ; **Thibault Coulombier** : Methodology, Writing – Review & Editing ; **Diogo Mendes** : Conceptualization, Methodology, Writing – Review & Editing ; **André Busto** : Conceptualization, Methodology, Writing – Review & Editing ; **Fortunato** : Conceptualization, Methodology, Writing – Review & Editing.

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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:

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