Modulation of wave-current interactions by horizontal mixing and spatial resolution

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Abstract :

The mechanics of rip currents are complex, involving interactions between waves, currents, water levels and bathymetry that pose particular challenges for numerical modeling. Horizontal turbulent diffusion in a rip system is difficult to measure using dye dilution or surfzone drifters, as shown by the range of published values for the horizontal diffusion coefficient. Here, we studied the effects of horizontal mixing on wave–current interactions by testing several diffusivity estimates in a fully coupled 3D wave–current model run at two different spatial resolutions. Published results using very low diffusion have found that near the shore the wave rays converge towards the rip channel because of refraction by the currents. We showed that this process is modulated by both horizontal mixing and spatial resolution. We found that, without the feedback of currents on waves, the flow is more sensitive to horizontal mixing, with large alterations, especially offshore, and generally lower velocities. These modifications ascribed to mixing are similar to those induced by the feedback mechanism. When a large mixing coefficient is used: (i) the behavior of the rip system is similar for both coupling modes (i.e., with and without the feedback of currents on waves) and for each resolution; and (ii) the evolution of the flow is more stable over time. Lastly, we show that the horizontal mixing strongly decreases the intensity of the 3D rip velocity, but not its vertical shear, which is mainly dependent on the vertical mixing scheme and on the forcing terms.

Highlights

► We continue the 2D work of [Weir et al. \(2011\)](#) with 3D simulations. ► Reference results depend on both horizontal mixing and spatial resolution. ► CEW and horizontal mixing act on the flow in the same way. ► We express wave-current interactions in term of horizontal mixing. ► The vertical shear of the rip velocity is not changed by horizontal mixing and CEW.

Keywords : Coastal ocean modelling, Nearshore processes, Rip currents, Wave-current interactions, Horizontal mixing

28 1 Introduction

29 Rip currents were first investigated by Shepard (1936), and are studied
30 for their important influence on nearshore morphodynamics, cross-shore
31 exchanges, and the hazard they pose to swimmers (MacMahan et al., 2006).
32 From observations made on La Jolla beach in California, Shepard et al.
33 (1941) described the rip structure as being composed of three major features:
34 the feeder, the neck and the head. Scientific studies began as qualitative
35 descriptions based on observations. Since then, theoretical and numerical
36 approaches have been developed for rip currents, using observations for
37 validation.

38 Rip currents are generated by the hydrodynamic instability resulting
39 from wave refraction by currents (Leblond and Tang, 1974; Falques et al.,
40 1999; Yu, 2006) and the convergence of longshore currents in regions of
41 strong alongshore variations in wave conditions (Long and Ozkan-Haller,
42 2005). Transient currents forced by finite crest-length wave breaking also
43 create a type of rip current (e.g., Johnson and Pattiaratchi, 2006; Spydell
44 and Feddersen, 2009; Clark et al., 2012). The feedback mechanism between
45 currents and waves has been reported by several authors (e.g., MacMahan et
46 al., 2006) as playing an essential role in the development of the rip system.
47 The main numerical studies considering the effects of currents on waves
48 (hereafter CEW) reported the following behaviors: a) Leblond and Tang
49 (1974) observed a modification of the flux of wave energy by the currents,
50 with variability along the longshore coordinate; b) Haas et al. (1998) found
51 that CEW reduce the offshore extent of rip currents; c) Yu and Slinn (2003)
52 showed that rips are compacted with CEW because of the large decrease in
53 the wave flux of momentum induced by wave breaking and explained that
54 this decrease is due to changes in wave number (wave ray bending); and d)
55 Weir et al. (2011) who complemented the last of these studies by calculating
56 the change in the wavefield resulting from wave ray bending and from wave
57 energy advected by the current (current flux of wave energy). The latter
58 authors expressed wave-current interactions in terms of bottom friction.

59 Previous studies investigating the effects of current on waves were carried
60 out without explicit turbulence modeling and at high resolution, namely 2
61 and 3 meters in both horizontal directions for Weir et al. (2011) and Yu and
62 Slinn (2003), respectively. Because the systematic use of a spatial resolution
63 lower than the size of the tiniest vortex is not possible, due to computational
64 limitations, the effects of subgrid-scale processes must be parameterized
65 in ocean models (e.g., Sagaut et al., 2013). This is particularly the case
66 for horizontal diffusive mixing, which can be included in the horizontal

momentum equations in several ways: i) modelers often use a diffusion coefficient that is a function of the grid size, but also of the flow and wave field characteristics (e.g., Smagorinsky, 1963; Okubo, 1971; Battjes, 1975); and ii) the discretization of the advection terms in an Eulerian framework with sigma-coordinates and the discretization of the Laplacian operator also generate numerical diffusion (Huang and Spaulding, 2002; Zwillinger, 1989).

Many studies have discussed this numerical diffusion (e.g., Fortunato and Baptista, 1994; Huang and Spaulding, 1996, 2002). Huang and Spaulding (2002) compared the advection scheme of Mellor and Blumberg (1985) with that of Fortunato and Baptista (1994). They found that both schemes produce large artificial diffusion, particularly where the bathymetry is steep. The most popular ocean models still use different versions of the schemes of Mellor and Blumberg (1985) (e.g., POM, ROMS or MARS) and of Fortunato and Baptista (1994) (e.g., POLCOMS).

The diffusion coefficient for nearshore applications is usually measured by dye dilution. The literature usually distinguishes between the absolute diffusivity, which characterizes the ensemble behavior of a cloud of particles, and the relative diffusivity related to the spreading of the cloud around its center of mass. Field studies provide many different values for the diffusion coefficient: i) Imann et al. (1971) found a cross-shore absolute diffusivity (hereafter K_{ax}) between $0.1 \text{ m}^2 \cdot \text{s}^{-1}$ and $5.9 \text{ m}^2 \cdot \text{s}^{-1}$ and an alongshore absolute diffusivity (hereafter K_{ay}) between $0 \text{ m}^2 \cdot \text{s}^{-1}$ and $0.17 \text{ m}^2 \cdot \text{s}^{-1}$; ii) The long-term observations ($\mathcal{O}(10^3) \text{ s}$) of Grant et al. (2005) led to K_{ay} between $40 \text{ m}^2 \cdot \text{s}^{-1}$ and $80 \text{ m}^2 \cdot \text{s}^{-1}$ with larger values for larger waves; and, iii) Clarke et al. (2007) noted that the absolute diffusivity was strongly dependent on wave conditions and on the presence of rip currents. Their assessment was in the range of $10^{-1} \text{ m}^2 \cdot \text{s}^{-1}$ to $10^3 \text{ m}^2 \cdot \text{s}^{-1}$.

Brown et al. (2009) tested another measurement method in order to estimate diffusivity with more accuracy. They used thirty surfzone drifters at Sand City (Monterey Bay, California) over 7 days between April and May 2007. The beach is known for its year-round persistent rip channels with predominantly near-shore normal incident waves (MacMahan et al., 2005). For a given sea state (the significant wave height and the peak wave period were about 1.4 m and 11.4 s, respectively), they found $K_{ax} = 2.2 \text{ m}^2 \cdot \text{s}^{-1} \pm 0.8 \text{ m}^2 \cdot \text{s}^{-1}$ and $K_{ay} = 3.8 \text{ m}^2 \cdot \text{s}^{-1} \pm 1 \text{ m}^2 \cdot \text{s}^{-1}$. The relative diffusivity was estimated as being $1.5 \text{ m}^2 \cdot \text{s}^{-1}$ and $6.5 \text{ m}^2 \cdot \text{s}^{-1}$ and between $1.2 \text{ m}^2 \cdot \text{s}^{-1}$ and $3.6 \text{ m}^2 \cdot \text{s}^{-1}$ in the cross-shore and alongshore directions, respectively.

In the present work we used a 3D fully-coupled wave-current model to study the sensitivity of the rip system to horizontal mixing used to parameterize turbulent diffusion. We tested different diffusivity values in

107 agreement with the scaling of Brown et al. (2009), extended the bidimensional
 108 (2D) work of Weir et al. (2011) to three-dimensional (3D) simulations and
 109 applied the vortex force formalism (McWilliams et al., 2004; Ardhuin et al.,
 110 2008b; Bennis et al., 2011). The main findings of our study are: a) CEW are
 111 modulated by horizontal mixing, with maximum impact at high resolution ;
 112 b) Horizontal mixing acts on the flow in a similar way to CEW; c) CEW are
 113 negligible when using a high mixing coefficient; and, d) the convergence of
 114 the waves towards the rip channel is modulated by both horizontal mixing
 115 and spatial resolution.

116 The rest of this paper is organised as follows: the method used, including
 117 the governing equations and details about the simulations, is described in
 118 section 2; results are presented in section 3, and we summarize our findings
 119 in section 4.

120 2 Methods

121 The 3D fully-coupled MARS-WAVEWATCH III model (more details
 122 in Bennis et al., 2011, 2014) combines the MARS3D hydrodynamic model
 123 (Lazure and Dumas, 2008) and the WAVEWATCH III wave model (Tolman,
 124 2009), hereafter WW3. Exchanges of information between the models are
 125 managed by the PALM coupler (Buis et al., 2008). We can easily investigate
 126 the feedback of currents on waves by turning off the coupling in test simula-
 127 tions. All the results presented here were obtained using a non stationary
 128 coupling procedure. Results obtained for cases with and without feedback
 129 are referred to hereafter as WEC+CEW and WEC-only, respectively (WEC
 130 refers to wave effects on currents and, the behaviors ascribed to CEW were
 131 obtained from the difference between WEC+CEW and WEC-only fields).

132 WW3 is a phase-averaged wave model. The wave action density spectrum
 133 N (N being a function of time, space, wave number and direction) is solved
 134 as:

$$\frac{DN}{Dt} = \frac{Q}{\sigma} \quad (1)$$

135 where Q represents the total source and sink terms, including non-linear
 136 interactions, bottom friction, wave dissipation and bottom scattering (more
 137 details in Tolman (2009)) and σ is the intrinsic wave radian frequency.
 138 High-order conservative numerical schemes are used for spatial discretization.
 139 A CFL (Courant-Friedrichs-Lewy) condition exists, binding the discretizations
 140 in time and in space.

141 MARS3D uses the pressure projection method to solve the 3D, unsteady,
142 Navier-Stokes equations under Boussinesq and hydrostatic assumptions. Finite
143 difference schemes are used for the spatial discretization performed on
144 an Arakawa-C grid (Lazure and Dumas, 2008). The model uses an ADI
145 (Alternating Direction Implicit) time scheme (Bouchtein and Bouchtein,
146 2006), although, the time step of MARS3D is constrained by the CFL
147 condition of WW3 in order to avoid too great a time shift between the
148 two models.

149 Fig. 1 shows the bathymetry for the problem, given the geometry and
150 the computational domain. Since we are interested in rip currents, the rip
151 channels are near the center of the domain and periodic boundary conditions
152 are used at the lateral boundaries. Neumann boundary conditions are
153 employed at the surface and bottom, with the additional parameterization
154 according to Soulsby (1995) for bottom friction (Bennis et al., 2014). Offshore,
155 open boundary conditions are applied based on the method of characteristics
156 (e.g., Zwillinger, 1989). This method consists in complementing the physical
157 boundary conditions using characteristic pathways around which the solution
158 is computed. The scheme of Walstra et al. (2000) is used to parameterize
159 the modification of vertical mixing by waves near the surface and bottom.

160 The flow is forced by the normal propagation of an incident wave on a
161 barred beach. Each test case uses a regular horizontal grid. The time step
162 varies according to the size of the mesh to ensure the numerical stability
163 of the models and the time synchronization of the coupled system. The
164 coupling time step is also different from the time steps of the two models.

Figure 1: Bathymetry

165 2.1 Governing equations

166 Wave forcing was integrated into the hydrodynamic model with the
 167 vortex force method (McWilliams et al., 2004; Ardhuin et al., 2008b). This
 168 method has been validated for surf zone cases (e.g., Kumar et al. (2012),
 169 Moghimi et al. (2012) and Bennis et al. (2014)) and gives good agreement
 170 with in-situ and laboratory data. The main advantage of the method is
 171 to consider the mean flow instead of the total momentum (Ardhuin et al.,
 172 2008b; Bennis et al., 2011), avoiding the difficult modeling of the vertical
 173 flux of momentum (Ardhuin et al., 2008a).

174 The equations of motion for a wave-forced, 3D, incompressible, unsteady,
 175 hydrostatic, constant-density flow are given in Ardhuin et al. (2008b) and
 176 Bennis et al. (2011). Their generic formulation is:

$$\begin{aligned}
 177 \quad \frac{D\mathcal{U}}{Dt} &= \mathbf{S}_{\text{EPG}} + \mathbf{S}_{\text{VM}} + \mathbf{S}_{\text{HM}} + \mathbf{S}_{\text{WP}} \\
 178 \quad &+ \mathbf{S}_{\text{BA}} + \mathbf{S}_{\text{BBL}} + \mathbf{S}_{\text{VF}} \quad (2)
 \end{aligned}$$

179 where $\mathcal{U} = (U, V, W)$ is the 3D quasi-Eulerian velocity computed as the
 180 Lagrangian velocity minus the Stokes drift. The source terms $\mathbf{S}_{\text{EPG}}$, $\mathbf{S}_{\text{VM}}$,
 181 $\mathbf{S}_{\text{HM}}$, $\mathbf{S}_{\text{BA}}$, $\mathbf{S}_{\text{BBL}}$, $\mathbf{S}_{\text{VF}}$ and $\mathbf{S}_{\text{WP}}$ refer to the external pressure gradient,
 182 vertical mixing, horizontal mixing, breaking acceleration, streaming, vortex
 183 force and wave-induced pressure gradient, respectively. These equations are
 184 similar those of McWilliams et al. (2004) used in Uchiyama et al. (2010) and
 185 Kumar et al. (2012).

186 The k- ϵ turbulent closure scheme, modified according to Walstra et al.
 187 (2000), is used to model vertical mixing (Bennis et al., 2014). Horizontal
 188 mixing is computed as:

$$S_{HM,x} = \frac{1}{\rho} \left(\frac{\partial \left(\rho \nu_H \frac{\partial U}{\partial x} \right)}{\partial x} + \frac{\partial \left(\rho \nu_H \frac{\partial U}{\partial y} \right)}{\partial y} \right) \quad (3)$$

$$S_{HM,y} = \frac{1}{\rho} \left(\frac{\partial \left(\rho \nu_H \frac{\partial V}{\partial x} \right)}{\partial x} + \frac{\partial \left(\rho \nu_H \frac{\partial V}{\partial y} \right)}{\partial y} \right) \quad (4)$$

189 where $S_{HM,x}$ and $S_{HM,y}$ are the cross-shore and alongshore components
 190 of $\mathbf{S}_{\text{HM}}$, respectively. ρ is the water density, and ν_H is the turbulent
 191 kinematic viscosity also known as turbulent diffusivity. Here, ν_H is constant
 192 horizontally, with values between $0.2 \text{ m}^2 \cdot \text{s}^{-1}$ and $3.9 \text{ m}^2 \cdot \text{s}^{-1}$ (see below for

more details). Kumar et al. (2012) also used $0.2 m^2.s^{-1}$ to simulate rip currents while Yu and Slinn (2003) used a numerical diffusivity to suppress the sub-grid scale noise.

As the rip system is very sensitive to the modeling of wave breaking, we choose the same parameterization for wave breaking dissipation as Weir et al. (2011) and Yu and Slinn (2003). The well-referenced parameterizations of Thornton and Guza (1983) (hereafter TG83) and Church and Thornton (1993) (hereafter CT93) were therefore implemented in WW3 according to the following formulations:

• CT93:

$$Q_{CT93} = 1.5\sqrt{\pi}f_p B^3 \frac{H_{rms}}{h} M \left(1 - \frac{1}{\left(1 + \left(\frac{H_{rms}}{H_m} \right)^2 \right)^{5/2}} \right) F(k, \theta), \quad (5)$$

where $M = 1 + \tanh \left(8 \left(\frac{H_{rms}}{H_m} - 1 \right) \right)$. H_{rms} is the root-mean square significant wave height, H_m is the maximum height that can be reached by waves without breaking (here $H_m = \gamma h$, where γ is a tunable model parameter and h is the water depth), f_p is the peak wave frequency, B is a tunable model parameter, k is the mean wave number, θ is the mean wave direction, and $F(k, \theta)$ is the wave spectrum.

• TG83:

$$Q_{TG83} = 48\sqrt{\pi}f_p B^3 \frac{(2m_0)^{5/2}}{H_m^4 h} F(k, \theta), \quad (6)$$

where m_0 is the 0-order moment of the variance density directional spectrum. To fit the data, B and γ are set to 1.52 and 0.35, respectively.

Q_{CT93} or Q_{TG83} are included in the wave action equation computed by WW3 (see Eq. (1)) as a fraction, Q_{br} , of the Q term. Q_{br} is equal to $\frac{\epsilon_b}{\rho g \sigma}$ of Yu and Slinn (2003) and Weir et al. (2011), where ϵ_b is their dissipation function. To compute $\mathbf{S}_{BA}$ in Eq. (2), Q_{br} is integrated over all directions and wave numbers and then distributed over a characteristic depth:

$$\mathbf{S}_{BA} = \int \frac{(k_x, k_y)}{k C_g} Q_{br}(k, \theta) \delta_z dk d\theta \quad (7)$$

217 where $k_x = k \cos \theta$, $k_y = k \sin \theta$ and where δ_z allows the distribution of $\mathbf{S}_{\mathbf{BA}}$
 218 over the water column. C_g is the wave group velocity. $\mathbf{S}_{\mathbf{BA}}$ is equivalent to
 219 $\mathbf{B}$ in eq. (9) from Weir et al. (2011).

220 2.2 Experiments

221 We aimed to study the dependence of the flow response on horizontal
 222 mixing and compared the two coupling modes. In our model, the bedform
 223 is an approxi-
 224 mation of the beach profile measured at Duck, North Carolina, on October
 225 11, 1990 (Fig. 1). Its analytical expression, $h(x, y)$, was given by Yu and
 226 Slinn (2003) as:

$$\begin{aligned} h_0(x) = & \left(a_1 - \frac{a_1}{\gamma_1} \right) \tanh \left(\frac{b_1 x}{a_1} \right) \\ & + \frac{b_1 x}{\gamma_1} - a_2 \exp \left[-5 \left(\frac{x - x_c}{x_c} \right)^2 \right] \end{aligned} \quad (8)$$

227 where $x_c = 80$ m is the location of the longshore bar. γ_1 , a_1 , b_1 and a_2
 228 are set to 11.74, 2.97 m, 0.075, 1.5 m, respectively. Adding a perturbation
 229 at the longshore bar, the following bottom profile is obtained:

$$h(x, y) = h_0(x) + h_1(x, y) \quad (9)$$

230 with

$$h_1(x, y) = h_0(x) \epsilon \cos \left(\frac{2\pi y}{\lambda} \right) \exp \left[-5 \left(\frac{x - x_c}{x_c} \right)^2 \right] \quad (10)$$

231 where $\epsilon = 0.1$ m and $\lambda = 256$ m are the magnitude and the wavelength
 232 of the perturbation, respectively. Weir et al. (2011) used a perturbation
 233 that was only very slightly different from this one.

234 A narrow Gaussian wave spectrum is used at the offshore boundary to
 235 simulate monochromatic waves as in Weir et al. (2011). The offshore wave
 236 characteristics and some information on bottom topography are given in
 237 Table 1.

238 The loss of information caused by the use of a coarse grid should be noted
 239 and need to develop more suitable parameterizations in the future. After
 240 testing resolutions of 3, 6, 12 and 24 m, we discuss here the results with 3
 241 and 24-m of spatial resolution because they are the most representative ones
 242 for the study of the resolution effects.

Parameter	Value
Significant wave height	$H_s = 1.3 \text{ m}$
Peak wave period	$T = 10 \text{ s}$
Mean wave direction	$\theta = 90^\circ$
Magnitude of perturbation	$\epsilon = 0.1$
Spacing of rip channels	$\lambda = 256 \text{ m}$

Table 1: Common characteristics of all simulations

243 Sixteen different test cases were carried out that differed in their horizontal
244 resolution, horizontal mixing and coupling mode (Table 2).

245 The coupling time step is set to 1 s while the model time step is 0.2 s and
246 0.5 s for WW3 and MARS3D, respectively. The simulated time is one hour
247 for each simulation. We used 15 sigma levels that are evenly distributed
248 over the vertical. Both coupling modes (WEC-only and WEC+CEW) use
249 the same set of parameters to ensure a comparison as clean as possible. For
250 each resolution, sensitivity tests on mixing were carried out with a variable
251 ν_H (Table 2). The maximum values of ν_H are in the range given by Brown
252 et al. (2009). After many tests, we did not keep the values greater than
253 $2.0 \text{ m}^2.\text{s}^{-1}$ (for the resolution of 3 m) and $3.9 \text{ m}^2.\text{s}^{-1}$ (24 m) because they
254 added no new information. Finally, the values of $3.9 \text{ m}^2.\text{s}^{-1}$ and $0.35 \text{ m}^2.\text{s}^{-1}$
255 were given by Okubo (1971) for resolutions of 24 m and 3 m, respectively.

		$\nu_H = 0.2 \text{ m}^2/\text{s}$	$\nu_H = 0.35 \text{ m}^2/\text{s}$	$\nu_H = 0.6 \text{ m}^2/\text{s}$	$\nu_H = 1.0 \text{ m}^2/\text{s}$	$\nu_H = 2.0 \text{ m}^2/\text{s}$	$\nu_H = 3.9 \text{ m}^2/\text{s}$
$\Delta_{xy} = 3 \text{ m}$	WEC-only	x	x	x	x	x	
	WEC+CEW	x	x	x	x	x	
$\Delta_{xy} = 24 \text{ m}$	WEC-only		x		x		x
	WEC+CEW		x		x		x

Table 2: List of test cases for different spatial resolutions and horizontal mixing intensities.

3 Results

As mentioned in Brown et al. (2009), for a similar wave forcing ($H_s = 1.4$ m, $T_p = 11.4$ s and $\theta = 0^\circ$), the absolute and relative diffusivities are within the ranges $[3.1 \text{ m}^2.\text{s}^{-1}; 5.6 \text{ m}^2.\text{s}^{-1}]$ and $[1.9 \text{ m}^2.\text{s}^{-1}; 7.4 \text{ m}^2.\text{s}^{-1}]$, respectively. We chose ν_H within these ranges with a maximum set at $3.9 \text{ m}^2.\text{s}^{-1}$ to improve our understanding of the rip system in these realistic hydrodynamic conditions. For comparison with the former studies of Yu and Slinn (2003), Weir et al. (2011) and Kumar et al. (2012), we also used smaller diffusivities down to the stability limit of the model, with a minimum value of $0.2 \text{ m}^2.\text{s}^{-1}$. As the former studies of Yu and Slinn (2003) and of Weir et al. (2011) did not use a diffusion coefficient, but an artificial diffusivity not mentioned in their papers, we consider that our case with $\nu_H = 0.2 \text{ m}^2.\text{s}^{-1}$ to be almost equivalent to their test case. So, we investigated the impact of the value of ν_H on wave-current interactions for two different spatial resolutions (3 and 24 meters). The high-resolution simulations use mixing coefficients between $0.2 \text{ m}^2.\text{s}^{-1}$ and $2.0 \text{ m}^2.\text{s}^{-1}$. The coefficients ranged from $0.35 \text{ m}^2.\text{s}^{-1}$ to $3.9 \text{ m}^2.\text{s}^{-1}$ at low resolution.

The waves come from offshore with a significant wave height of 1.3 meters and a peak wave period of 10 seconds. Figure 2 shows for both parameterizations (TG83 and CT93) the alongshore-averaged root mean square significant wave height ($\langle H_{rms} \rangle$) and the alongshore-averaged wave breaking dissipation flux ($\langle \Phi_{oc} \rangle$) as a function of the cross-shore distance. The wave shoaling is small due to the beach slope and the offshore conditions. Wave heights are higher when using the CT93 breaking parameterization, which makes the rip unstable as explained in Weir et al (2011). $\langle \Phi_{oc} \rangle$ shows two peaks, each of which related to a different breaking event. All the parameterizations predict that the highest peak is located approximately 150 meters from the shore. The shapes of $\langle H_{rms} \rangle$ and $\langle \Phi_{oc} \rangle$ are similar to the ones described in Yu and Slinn (2003) and Weir et al. (2011). In the following, TG83 is used for all the simulations.

The total change in H_{rms} (ΔH_{rms}) ascribed to CEW is shown as a function of the cross-shore distance in Figure 3. ΔH_{rms} is caused by wave ray bending, which is dependent on the alongshore gradient of the rip current, and also by the current velocity flux (see Weir et al., 2011, for more details). At the highest resolution, the two processes interact. From now, the 'shallow depths' term refers to depths less than 2 m located at a distance up to 100 m from the shore. Over shallow depths, ΔH_{rms} is negative showing that the effects of the current flux of wave energy are dominant. Elsewhere, we observe positive values inside the rip channel and negative values outside it

Figure 2: Alongshore-averaged root-mean square significant wave height (left panel) and alongshore-averaged wave breaking dissipation flux (right panel) computed by the TG83 and CT93 parameterizations.

295 (Figure 3, top row). As a result, the modulation of the wave height by CEW
 296 is generated by wave ray bending for $\nu_H = 0.35 \text{ m}^2 \cdot \text{s}^{-1}$ and $\nu_H = 2.0 \text{ m}^2 \cdot \text{s}^{-1}$.
 297 For the same mixing coefficient ($\nu_H = 0.35 \text{ m}^2 \cdot \text{s}^{-1}$), the maximum of ΔH_{rms}
 298 is about 0.04 m at high resolution while it reaches about 0.016 m at a spatial
 299 resolution of 24 m. Near the shore ($X \leq 100 \text{ m}$), wave ray bending slightly
 300 dominates and two regions with positive values of ΔH_{rms} appear (Figure 3,
 301 bottom-left panel). For $\nu_H = 3.9 \text{ m}^2 \cdot \text{s}^{-1}$, the increase in wave height inside
 302 the rip channel becomes negligible (about 0.005 m). Indeed, the horizontal
 303 diffusivity is too high, leading to a large reduction in the rip velocity and its
 304 alongshore gradient. Therefore, the interactions with waves are significantly
 305 affected by mixing.

306 Figure 4 shows the alongshore perturbation of the wave group velocity
 307 computed as the difference between the local wave group velocity and the
 308 alongshore-averaged value. These snapshots show the simulations run at
 309 high resolution. These wave fields show that CEW cause wave divergence
 310 by refraction. For the WEC-only case, we have only refraction by bottom
 311 topography, which drives the waves towards the peak of the bar (Figure
 312 4, top plot). When CEW are activated, refraction by currents moves the
 313 waves towards the rip channel (Figure 4, middle and bottom plots). When
 314 the smallest mixing coefficient is used ($\nu_H = 0.2 \text{ m}^2 \cdot \text{s}^{-1}$), refraction by

Figure 3: ΔH_{rms} after 60 minutes. Top row: simulations with $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$ (left panel) and with $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$ (right panel) at a spatial resolution of 3m. Bottom row: simulations with $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$ (left panel) and with $\nu_H = 3.9 \text{ m}^2.\text{s}^{-1}$ (right panel) at a resolution of 24m. Contours are equally spaced between -0.038 m and 0.038 m .

315 currents dominates refraction by bottom topography near the shore. Thus,
 316 waves converge towards the rip channel (Figure 4, middle plot). Horizontal
 317 mixing modifies the interactions between the two refraction processes: the
 318 higher the mixing coefficient, the weaker the rip velocity and its alongshore
 319 gradient. As a result, near the shore and with $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$, refraction
 320 by bottom topography dominates refraction by the rip current because the
 321 alongshore gradient of the rip current is decreased by the mixing. Thus, the
 322 effects of the rip current are not strong enough to balance the effects of the
 323 bottom topography. Finally, over shallow depths, the waves diverge from
 324 the rip channel towards the peak of the bar (Figure 4, bottom plot).

325 Figure 5 shows the alongshore component of the wave group velocity
 326 for $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$ and $\nu_H = 3.9 \text{ m}^2.\text{s}^{-1}$. The results are shown for
 327 both computational grids. As explained above, refraction by bathymetry
 328 generates divergence towards the bar due to positive values of C_{gy} to the
 329 right of the channel and negative values to the left (Figure 5, first column).

Figure 4: Alongshore perturbation of the high-resolution wave group velocity (blue arrows) at $t=60$ minutes: WEC-only with $\nu_H = 0.2 \text{ m}^2.\text{s}^{-1}$ (top panel), WEC+CEW with $\nu_H = 0.2 \text{ m}^2.\text{s}^{-1}$ (middle panel) and WEC+CEW with $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$ (bottom panel). Bathymetry is shown by black dashed contours.

330 Refraction by currents modifies the direction, and thus produces an inverse
 331 wave motion leading to negative values of C_{gy} to the right of the channel and
 332 positive values to the left (Figure 5, last column). At low resolution with
 333 $\nu_H = 3.9 \text{ m}^2.\text{s}^{-1}$, wave diversion by the rip current is very weak and CEW are
 334 not strong enough to overcome the effects of refraction by bathymetry where
 335 the depth is shallow; therefore, the WEC+CEW alongshore group velocity
 336 looks like that of the WEC-only case (Figure 5, bottom -left and -middle
 337 plots). At the same spatial resolution with $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$, the patterns
 338 caused by current refraction are present for the WEC+CEW case. Indeed,
 339 as the mixing is strongly decreased from $3.9 \text{ m}^2.\text{s}^{-1}$ to $0.35 \text{ m}^2.\text{s}^{-1}$, the rip
 340 velocity and its alongshore gradient are larger and therefore interact with the
 341 waves. Near the shore ($X \leq 100\text{m}$), we observe a special situation for which
 342 the effects of the two refraction processes cancel each other out (Figure 5,
 343 central plot): waves go straight to the shore. At the highest resolution and
 344 with the same mixing coefficient ($\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$), different patterns are
 345 observed for C_{gy} , showing the impact of spatial resolution on the wave field.
 346 Because the bathymetry and rip system are better represented on a finer
 347 grid, wave-current interactions are simulated more accurately.

348 Figure 6 shows the high-resolution depth-averaged vorticity fields for the
 349 WEC-only and WEC+CEW cases and for different values of ν_H ($0.2 \text{ m}^2.\text{s}^{-1}$,
 350 $0.6 \text{ m}^2.\text{s}^{-1}$, $1.0 \text{ m}^2.\text{s}^{-1}$ and $2.0 \text{ m}^2.\text{s}^{-1}$). CEW reduce the offshore extension
 351 of the flow in each case because they produce forcing effects opposed to
 352 that of the topography (Yu and Slinn, 2003). Horizontal mixing, by its
 353 smoothing effect on the flow, also contributes to an attenuation of the
 354 offshore rip system. Therefore, horizontal mixing and CEW act similarly
 355 on the WEC-only vorticity field, and it is possible to express CEW in
 356 terms of horizontal mixing: the WEC-only vorticity computed with $\nu_H =$
 357 $2.0 \text{ m}^2.\text{s}^{-1}$ is similar to the WEC+CEW vorticity obtained with $\nu_H =$
 358 $1.0 \text{ m}^2.\text{s}^{-1}$ (Figure 6). When $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$, the WEC+CEW and WEC-
 359 only fields look similar because horizontal mixing and CEW move WEC-only
 360 closer to WEC+CEW. Furthermore, we note that the WEC+CEW flow is
 361 less altered by horizontal mixing (notably with weaker offshore reduction)
 362 than the WEC-only flow. Compared with Weir et al. (2011), the evolution
 363 of the rip system at high resolution is not modified by horizontal mixing for
 364 $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$ (Figure 7). When CEW are activated, the rip system is
 365 stable after 20 minutes (Figure 7, bottom row), but, the system continues
 366 to grow offshore for the WEC-only case. Horizontal mixing stabilizes the
 367 WEC-only flow, and thus modifies its evolution, which becomes similar to
 368 the WEC+CEW case, when the mixing coefficient is high (Figure 6, bottom
 369 row).

Figure 5: C_{gy} for cases WEC-only, WEC+CEW and CEW shown from left to right. Top row: $\Delta_{xy} = 3$ m and $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$. Middle row: $\Delta_{xy} = 24$ m and $\nu_H = 0.35 \text{ m}^2.\text{s}^{-1}$. Bottom row: $\Delta_{xy} = 24$ m and $\nu_H = 3.9 \text{ m}^2.\text{s}^{-1}$. All figures are plotted after 60 minutes. Contours are equally spaced from -0.21 m.s^{-1} to 0.21 m.s^{-1} .

Figure 8 shows the depth-averaged cross-shore and alongshore velocities normalized by the maximum velocity of the WEC-only case. Several mixing cases and both coupling modes are shown for the simulations run at 3-m spatial resolution. We observed that the cross-shore velocity was more altered by mixing and CEW than by the alongshore velocity. As waves propagate normally to the shore, an alongshore motion is generated by refraction. For $\nu_H = 0.2 \text{ m}^2.\text{s}^{-1}$, CEW decrease the cross-shore velocity by a factor equivalent to 50% of the maximum WEC-only velocity. The higher the mixing coefficient, the more this factor is reduced. For $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$, we observe a reduction by a factor equivalent to 18%. As the cross-shore velocity is modified, interactions with waves are also changed. So, the increase of H_{rms} by CEW is also halved between the $0.2 \text{ m}^2.\text{s}^{-1}$ and $2.0 \text{ m}^2.\text{s}^{-1}$ cases (Figure 9). A ratio of two is maintained between the rip velocity and the wave height. The simulations run at low resolution show that even a small ΔH_{rms} (0.015 m at its maximum) modifies the wave fields by CEW (Figure

Figure 6: High resolution depth-averaged vorticity fields for the WEC-only (left column) and WEC+CEW (right column) cases after 60 minutes. Four cases of mixing are represented (from top to bottom) : $\nu_H = 0.2 \text{ m}^2.\text{s}^{-1}$, $\nu_H = 0.6 \text{ m}^2.\text{s}^{-1}$, $\nu_H = 1.0 \text{ m}^2.\text{s}^{-1}$, $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$. Bathymetry is shown by black dotted contours.

5). In contrast, when the mixing is increased ($\nu_H = 3.9 \text{ m}^2.\text{s}^{-1}$), ΔH_{rms} is about 0.005 m at its maximum, and the alongshore group velocity shows the same patterns for both coupling modes (Figure 5) ; the two coupling modes

388 give similar results.

Figure 7: Evolution over time of the high-resolution depth-averaged vorticity for $\nu_H = 0.35 \text{ m}^2 \cdot \text{s}^{-1}$: WEC-only (top row) and WEC+CEW (bottom row). Colored contours are equally spaced between -0.015 s^{-1} and 0.015 s^{-1} . Bathymetry is shown by black dotted contours.

389 Figure 10 shows the vertical profiles of the high-resolution 3D cross-shore
 390 velocity inside the rip channel. As in Kumar et al. (2012), the maximum rip
 391 velocity is located within the water column, and the rip current decreases
 392 towards the bottom and the surface. The vertical profiles are changed
 393 by CEW. The WEC-only velocity is more intense than the WEC+CEW
 394 velocity, particularly when the mixing coefficient is weak. For a diffusion
 395 coefficient of $0.2 \text{ m}^2 \cdot \text{s}^{-1}$, CEW reduce the maximum cross-shore velocity
 396 by 25%, whereas we obtain a 8% reduction with a diffusion coefficient of
 397 $2.0 \text{ m}^2 \cdot \text{s}^{-1}$. As for the barotropic fields, the offshore extension of the rip
 398 system is reduced by CEW and horizontal mixing. Mixing causes maximum
 399 alterations for the WEC-only case for which the maximum 3D velocity is
 400 reduced by 20% between the $0.2 \text{ m}^2 \cdot \text{s}^{-1}$ and $2.0 \text{ m}^2 \cdot \text{s}^{-1}$ cases whereas this
 401 reduction is limited to 3% when CEW are activated.

402 Horizontal mixing does not modify the vertical shear of the rip velocity
 403 because it modifies each 2D slice of the horizontal velocity equally in the
 404 vertical. This shows that the vertical structure is mainly forced by the
 405 set of equations used to compute the wave-current interactions, and also
 406 by the vertical mixing scheme. Wave breaking and dissipation by bottom

Figure 8: Total change in high-resolution depth-averaged velocities ascribed to CEW normalized by the maximum velocities for the WEC-only case at $t = 60$ min. All mixing cases are represented. Cross-shore profiles of the cross-shore velocity inside the rip channel in $Y = 267$ m (left panel) and alongshore profiles of the alongshore velocity at the velocity maximum in $X = 117$ m (right panel).

Figure 9: Total change in H_{rms} ascribed to CEW inside the rip channel after 60 minutes. The simulations were run at high resolution. Four cases of mixing are shown: $\nu_H = 0.2 \text{ m}^2 \cdot \text{s}^{-1}$, $\nu_H = 0.6 \text{ m}^2 \cdot \text{s}^{-1}$, $\nu_H = 1.0 \text{ m}^2 \cdot \text{s}^{-1}$, $\nu_H = 2.0 \text{ m}^2 \cdot \text{s}^{-1}$.

407 friction in the wave bottom boundary layer significantly affect the vertical
 408 velocity profiles (e.g., Walstra et al., 2000 and Uchiyama et al., 2010). These
 409 processes are parameterized thanks to the vertical turbulent closure, that

410 was modified to this end. The mathematical modelling of the wave-current
 411 interactions also influences the vertical profiles, as discussed in Ardhuin
 412 et al. (2008b) and Bennis et al. (2011). CEW appear too weak to change
 413 the vertical shear and act similarly to the horizontal mixing by reducing the
 414 intensity of the rip current and its offshore extension. Lastly, as reported by
 415 some previous authors (e.g., Kumar et al., 2012; Teles, 2013), the structure of
 416 the rip velocity varies with depth. Thus, 3D simulations are useful because
 417 the vertical profiles cannot be deduced from 2D runs. These profiles are
 418 very important when studying hydro-sedimentary motions inside the water
 419 column but also near the bottom.

Figure 10: High resolution cross-shore profiles of the 3D cross-shore velocity
 taken inside the rip channel for the WEC-only (top row) and WEC+CEW
 (bottom row) cases after 60 minutes. Four cases of mixing are represented
 with from left to right: $\nu_H = 0.2 \text{ m}^2.\text{s}^{-1}$, $\nu_H = 0.6 \text{ m}^2.\text{s}^{-1}$, $\nu_H = 1.0 \text{ m}^2.\text{s}^{-1}$,
 $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$. Colored contours are equally-spaced between -0.5 m.s^{-1}
 and 0.5 m.s^{-1} .

420 4 Summary and conclusions

421 Field measurement of diffusivity in rip current systems is difficult and
 422 many different values exist in the literature. In this paper, we numerically
 423 tested different ranges of diffusivity values in order to improve our understand-
 424 ing of the sensitivity of the rip system to this kind of mixing. Our test case
 425 was the same as that used by Weir et al. (2011) and Yu and Slinn (2003), and
 426 we started by revisiting their experiments. As explained above, we consider
 427 that we can reproduce their results by using the smallest diffusion coefficient
 428 ($0.2 \text{ m}^2.\text{s}^{-1}$); a section of this paper concerns the validation of our approach.

429 We then tested different diffusivity values in the range of the observations
 430 of Brown et al. (2009) for a similar wave forcing, with a maximum value of
 431 $3.9 \text{ m}^2.\text{s}^{-1}$ given by Okubo (1971). For all cases, the simulations are 3D,
 432 in contrast with the previous 2D studies that were performed with spatial
 433 resolutions of 3-m and 2-m. This allows us to highlight the importance
 434 of 3D effects. Two different spatial resolutions (3 m and 24 m) were also
 435 tested for different diffusivity values in order to understand the link between
 436 mixing, spatial resolution and wave-current interactions. For each case, we
 437 investigated how the hydrodynamic conditions and spatial resolution change
 438 the wave-current interactions in a 3D framework.

439 Our 2D results, obtained by integrating the horizontal momentum over
 440 depth, for a diffusion coefficient set at $0.2 \text{ m}^2.\text{s}^{-1}$ and with a 3-m spatial
 441 resolution, were tested against the results of Weir et al. (2011) and Yu
 442 and Slinn (2003). Our simulations showed a rip system quite similar to
 443 these previous studies: i) refraction by currents dominates refraction by
 444 bathymetry for shallow depths, which induces a wave motion towards the
 445 rip channel; ii) changes in wave height and wave number are produced by
 446 CEW; iii) CEW significantly reduce the offshore flow because they produce
 447 an opposite forcing to the rip motion, and thus block the system's growth,
 448 iv) CEW decrease the intensity of the flow; and, v) the flow is stabilized
 449 by CEW. This validation shows that our 3D model is able to correctly
 450 reproduce the 2D flow simulated by pure 2D models. We conclude that the
 451 3D effects have little impact on the depth-averaged flow although the flow
 452 shows vertical shear. This could be because the vertical shear is not strong
 453 enough to significantly impact the barotropic fields, noting that the set of
 454 equations of Bennis et al. (2011) is valid only for a weak shear. When the
 455 shear is stronger, and in these cases with the inclusion of the shear-induced
 456 pressure term of Ardhuin et al. (2008b) given in their eq. (40), the 3D effects
 457 could significantly modify the depth-averaged flow.

458 The horizontal resolution modifies wave-current interactions because of
 459 the coarse description of the bathymetry. For the same value of mixing
 460 coefficient ($0.35 \text{ m}^2.\text{s}^{-1}$), the change in wave height is reduced by a factor of
 461 two when the calculations are run at low resolution. This change is generated
 462 by nearshore wave ray bending and by the current velocity flux, as shown
 463 in Weir et al. (2011). At low resolution, waves go straight to the beach
 464 because wave diversion by bathymetry exactly compensates wave divergence
 465 by currents. This result suggests that the refraction by bathymetry needs
 466 to be parameterized in coarse resolution models.

467 When we use a mixing coefficient above $0.2 \text{ m}^2.\text{s}^{-1}$, the waves go to the
 468 peak of the bar instead of converging on the rip channel. This shows that

469 refraction by bathymetry is dominant, and thus mixing changes the balance
 470 between the two refraction processes. For a diffusivity of $2.0 \text{ m}^2.\text{s}^{-1}$, the
 471 high-resolution depth-averaged vorticity without CEW is similar to the one
 472 obtained with CEW, because they have a weaker impact on the flow. We
 473 observed the same behavior at low resolution for $\nu_H = 3.9 \text{ m}^2.\text{s}^{-1}$. We noted
 474 that the high-resolution vorticity field computed without feedback and with
 475 $\nu_H = 2.0 \text{ m}^2.\text{s}^{-1}$ looks like the one obtained for the WEC+CEW case with
 476 $\nu_H = 1.0 \text{ m}^2.\text{s}^{-1}$. We noted that mixing and CEW act in the same way:
 477 horizontal mixing reduces the offshore extension of the system, smooths
 478 the rip velocities and their alongshore gradients and stabilizes the flow.
 479 Thus, it modifies the interactions with the waves. The maximum alterations
 480 ascribed to mixing are found for the WEC-only case, showing that this
 481 flow is more sensitive than the WEC+CEW flow. At high resolution, the
 482 maximum value of the 3D cross-shore velocity is reduced by 20% between
 483 the $0.2 \text{ m}^2.\text{s}^{-1}$ and $2.0 \text{ m}^2.\text{s}^{-1}$ cases, whereas this reduction is limited to 3%
 484 when CEW are activated. For the largest values of the diffusivity ($2 \text{ m}^2.\text{s}^{-1}$
 485 and $3.9 \text{ m}^2.\text{s}^{-1}$), the WEC-only and WEC+CEW flow patterns are similar.
 486 We hypothesize that mixing processes suppress the part of the flow that
 487 would be in disagreement with the WEC+CEW flow, indicating that the
 488 WEC-only solution for a diffusivity less than $2 \text{ m}^2.\text{s}^{-1}$ might not be realistic.

489 For all cases, the vertical shear of the 3D cross-shore velocity is not
 490 modified by CEW or horizontal mixing, which shows that it is strongly
 491 dependent on the vertical mixing scheme and on the forcing terms. In
 492 contrast, the intensity of the 3D velocity is strongly affected both by CEW
 493 and horizontal mixing, with similar effects. For a diffusion coefficient of
 494 $0.2 \text{ m}^2.\text{s}^{-1}$, CEW reduce the maximum 3D cross-shore velocity by 25%,
 495 whereas we obtain an 8% reduction with a diffusion coefficient of $2.0 \text{ m}^2.\text{s}^{-1}$.
 496 The two mechanisms decrease the velocity and its alongshore gradient, and
 497 reduce its offshore extension.

498 To conclude, horizontal mixing was found to have direct impacts on
 499 wave-current interactions. We showed that the conclusions of Weir et al.
 500 (2011) and Yu and Slinn (2003) depend on both horizontal mixing and
 501 spatial resolution. When a larger mixing is used (here above $2.5 \text{ m}^2.\text{s}^{-1}$),
 502 CEW vanish. This result is important because the wave-current models
 503 are also used to simulate coastal seas where mixing is taken into account
 504 to represent subgrid scale processes. In the future, these results could be
 505 applied to 3D morphodynamic studies.

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