ON TRIDIMENSIONAL RIP CURRENT MODELING

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1. INTRODUCTION

Rip currents are narrow, seaward currents that extend from the inner surf zone out through the line of breaking waves. Rip currents are usually long (100 m), narrow (10 m) and intense jet flow (reaching 1-2 m/s). They appear to span the entire water column in the shallow breaking zone but they remain confined near the surface as they flow past the breaking zone into deeper water, showing strong vertical shear. Understanding and predicting the complex tridimensional dynamics of rip currents remain a relevant scientific challenge because they play a key role on the beach and surf zone morphodynamics, on the dispersion of material across the surf zone and are a major hazard to swimmers [see MacMahan et al., 2006, for a review].

Despite substantial evidence of tridimensional effects, most modeling studies of rip currents are performed using depth-integrated shallow water equations. Bruneau et al. (2011) used this class of model (MARS coupled with SWAN) to study the Aquitanian coast of France. In June 2007 an intense 5-day field experiment was conducted at the mesotidal-macrotidal wave-dominated Biscarrosse Beach on a well-developed bar and rip morphology. Previous analysis of the field data exposed the main characteristics of a tide-modulated rip current driven by low- to high-energy shore-normal waves (Bruneau et al., 2009a). The model was able to reproduce some of the characteristics of the rip currents but discrepancies with observations at the rip neck were evidenced, particularly in the cross-shore component.

In a parallel study, Bruneau et al. (2009b) showed occurrence of rip current variability, referred to as Very Low Frequency motions (VLF), in the rip neck where VLF pulsations were most intense (reaching 1m/s on time scales of 10 to 30 minutes). The model was specifically tuned (reduced viscosity compared to the otherwise more realistic control simulation) to develop shear instabilities consistent with the analytical solution of Haller and Dalrymple (2001). In this paper, we extend on the work of Bruneau et al. (2009b and 2011) to show that tridimensional wave-current interactions cannot be dismissed in the study of rip current dynamics and that their expression is evident both in their persistent structure and instability behavior.

2. METHODS

2.1 Video monitoring

A main limitation for understanding nearshore processes is lack of appropriate observation, particularly in tropical environments. Traditional in-situ measurement techniques can provide high sampling rates and a direct estimation of many parameters but with coarse spatial resolution that often miss complex dynamical interactions. Additionally, instruments must be deployed in high-energy and sometimes hazardous environments (wave-breaking, strong currents), endangering not only the
instruments, but also the personnel involved. As an alternative, remote sensing techniques can provide synoptic coverage over large areas with a wide range of temporal and spatial resolutions.

The innovative video imaging technique (Holman and Haller, 2013) is particularly suited to coastal observation: low cost and easy to deploy. It is also considered as a non-disruptive observation technique for nearshore research. A video system was deployed at Biscarosse beach in 2007 and new inversion methods (Almar et al., 2009; see Fig. 1) were used to provide a remote estimation of the complete nearshore system, i.e., hydrodynamics (wave height, period, celerity, direction, wavelength, water level, current) and morphodynamics (shoreline, sub- and inter-tidal bathymetry) continuously and over long-term periods and large areas (approximate 2x1 km).

![Video system deployed at Biscarosse beach](image)

**Figure 1.** Coastal video monitoring: description of applications; (a) 5-camera system for Biscarosse (France); (b) Spatial-temporal post-processed image showing wave dynamics. The image is generated from the high frequency acquisition of a cross-shore array of pixels. (c) Bathymetric inversion from wave dispersion. (d) Video-estimated water level. (e) 2D field of wave-breaking dissipation.

### 2.2 The model: ROMS

The objective of the paper is to assess the benefit of tridimensional coastal models. An innovative modeling approach for 3D wave-current interactions (McWilliams et al., 2004) was implemented in the Regional Oceanic Modeling System (ROMS; Shchepetkin and McWilliams, 2005) by Uchiyama et al. (2010) and used for idealized rip current studies (Weir et al., 2011). An upgraded version of this implementation is proposed here based on the AGRIF version of ROMS (Debreu et al., 2012; Penven et al., 2006). It allows additional capabilities such as nesting and wetting/drying, the latter being crucial to the meso-macro-tidal environment of Biscarosse beach.

ROMS is a hydrostatic, incompressible (Boussinesq), free-surface and terrain-following coordinate model with non-conservative forcing, diffusion, and bottom drag. It uses baroclinic-barotropic mode splitting, with explicit fast time-stepping and subsequent conservative averaging of barotropic variables. The discretization is with high-order finite differences that provide both accurate and cost-effective solutions.

The interaction of surface gravity waves and currents is implemented in ROMS through vortex-force (VF) formalism. Eulerian wave-averaged current equations for mass, momentum, and tracers are included based on an asymptotic theory by McWilliams et al. (2004) plus non-conservative wave effects due to wave breaking, associated surface roller waves, bottom streaming, and wave-enhanced vertical mixing and bottom drag. The nonlinear parameterization of Soulzby (1995) for wave-enhanced bottom drag is particularly relevant to the present case with strong tidal flow. All parameterizations are described in details in Uchiyama et al., 2010 (see also Blaas et al., 2007 for bottom drag formulation).

The currents are coupled with a ray-theory spectrum-peak propagation and refraction model (WKB model) that includes the effect of currents on waves and dissipation due to shoaling-induced wave breaking. The system is thus fully coupled within a unique executable code that is easy to handle.

The advantage of the vortex-force over radiation-stress formalism is to cleanly decouple conservative and non-conservative effects on currents and, within the conservative effects, the vortex force and Bernoulli head components. The non-conservative components (acceleration/dissipation) are those that require parametrization and are thus responsible for the largest uncertainties in our model formulation. Clear identification of these terms is thus of primary interest. Another advantage of the VF formalism is numerical since it requires taking one less derivative in space and thus produces fewer numerical approximations (Weir et al., 2011).

The coupled system is applied to the nearshore surf zone during the 2007 Biscarrosse field measurement campaign (see Bathymetry in Figure 2). Offshore measurements of tidal elevation, wave height and winds are used to force the model for 5 days from the 13th to the 17th of June 2007. The horizontal resolution is 10m; there is 20 vertical sigma levels equally spaced. The horizontal viscosity coefficient is given by the flow- and resolution-dependent Smagorinsky formulation (between 0 and 2 m²/s). The baroclinic time step is 2 seconds and 30 barotropic sub-steps are performed every baroclinic step. The cost of 3D computations is thus moderate and the full 3D model is only marginally more expensive than the 2D part.

![Model domain and interpolated bathymetry](image)

**Figure 2.** Model domain and interpolated bathymetry. The orange dot shows the measurement station 54 at the rip neck where model-data comparisons are presented.

In the following, the model results are compared to observations and tridimensional effects are investigated with emphasis on the vertical profile of cross-shore currents.

### 3. Calibration and Validation

#### 3.1 Calibration with video data
There is still no consensus on many parameterizations: wave-driven flow acceleration and turbulent mixing, contribution of the breaking wave roller, bottom friction and boundary layer streaming (e.g., Uchiyama et al., 2010). In particular, the parameterization of breaking wave dissipation is crucial to nearshore dynamics but is generally guided by scarce data.

One of the novelties of our method lies in the tuning of breaking wave dissipation (including roller dissipation) in the wave model by direct comparison with 2D video imagery (Figure 3). The wave model uses the parameterization of Church and Thornton (1993), which has the particularly of producing more shoaling of the incoming wave before breaking and thus more intense breaking than other choices (Weir et al., 2011). It relies on two empirical constants: the breaking wave parameter $\gamma_b$ (wave height-to-depth ratio) and $B_b$ the percentage of the wave face that is broken. Values of 0.3 and 1.3, respectively, provide the best fit to data. As opposed to Bruneau et al. (2011), there is no need here to add a time dependence on $\gamma_b$ as the fit to data appears valid for both low- and high-energy conditions. The fraction $\alpha_b$ of breaking waves converted into rollers is taken as 0.5 and reveals only little sensitivity.

Figure 3. Normalized wave-breaking dissipation from the video data and from ROMS after calibration.

3.2 Validation with in-situ data

Figure 4 shows a model-data comparison for wave height and cross-shore currents at station S4 located at the rip neck (see Figure 2). The observation shows a strong increase of wave height on the 15th of June due to offshore forcing but strongly modulated by large tides (with range of close to 4 m) that shift back and forth the cross-shore position of the breaking line. High-energy conditions from June 15th lead to strong offshore-directed rip currents in excess of 75 cm/s. The model is able to reproduce the evolution of both wave height and currents. The wave model fit is quite remarkable during high-energy conditions and is accompanied by an equally remarkable fit of simulated currents with data. This appears in contrast with the 2D simulations shown by Bruneau et al. (2011) and we will now try to understand the reasons for improvement.

![Normalized breaking wave dissipation](image)

Figure 4. Model-data comparison at station S4 for wave height (top) and cross-shore currents (bottom).

4. ANALYSIS AND SENSITIVITY

4.1 Comparing 2D and 3D solutions

To analyze the extent of errors related to the 2D shallow water hypothesis, we now compare our standard solution with a 2D version. In this case the barotropic mode is advanced alone. Note that the barotropic (depth-averaged) flow of the 2D model is different from that of the 3D model because in the latter it receives contribution from the baroclinic flow, in particular the baroclinic contribution to nonlinear terms (Reynolds stresses of type $\text{uu}$, $\text{vv}$, where the overbar denotes the depth average). For the bottom drag due to currents, we use an equivalent formulation to the 3D case. Assuming that in shallow water the logarithmic layer extends all the way to the surface, we can integrate the velocity profile to obtain a 2D drag coefficient of the form:

$$C_{D_d} = \frac{\kappa^2}{\ln(H/z_0)}$$  \[1\]

where $H$ is total depth, $z_0$ is bottom roughness and $\kappa$ is Von Karman constant. This formulation ensures that the 2D bottom stress equals that of the 3D model for the same

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1 The total bottom drag law is a nonlinear combination of current and wave contributions according to Soulsby (1995). The bottom stress due to waves has no dependence on the vertical grid.
barotropic flow (again assuming logarithmic velocity profiles).

Figure 5 shows a comparison of the barotropic components of ROMS in its shallow water and 3D versions (ROMS2D and ROMS3D, respectively). It appears that ROMS2D strongly underestimates the cross-shore flow during high-energy conditions, especially the rip currents (negative values at time 150-170). This result is also very comparable to that of the 2D model used in Bruneau et al. (2011). Interestingly, the barotropic mode of the 3D model shows larger velocities implying a significant role played by the baroclinic contribution to barotropic nonlinear terms. This result is quite important as it shows that the total flow cannot simply be addressed by linear combination of a depth-averaged model and a vertical profile technique, a common approach in morphological models (e.g., De Vriend and Stive, 1987).

![Figure 5. Barotropic component of cross-shore velocity in ROMS2D and ROMS3D.](image)

The vertical structure of the 3D flow has several dependences. First, it is strongly affected by the profile distribution function of breaking and roller acceleration. The best fit to data is obtained with a surface-intensified breaking force, consistent with Uchiyama et al. (2010). On the other end, the wave-induced mixing scale is larger than breaking acceleration scale and requires a smoother vertical distribution function (again as in Uchiyama et al., 2010). We also find that the choice of bottom friction formulation is less sensitive than breaking acceleration for representing the proper flow structure. Finally, the currents’ vertical structure is significantly shaped by the vertical component of vortex force and wave-enhanced pressure force.

4.2 Rip current instabilities

Turbulence generated by the coastal circulation is probably responsible for large mixing and transport in coastal waters (Brocchini et al., 2004). Weir et al. (2011) show that the feedback effect of currents on waves reduces the cross-shore extension of turbulence but in the same time enhances nearshore eddy energy. In particular, rip currents contain energetic low-frequency oscillations in the presence of steady wave forcing. Haller and Darlymple (2001) used an analytic model to study the linear stability of a rip current and show that their oscillations can be explained by a jet instability mechanism. In their study, turbulent mixing, bottom friction and bottom slope play a large role in controlling the shear layer (i.e., the spread at the rip neck) and thus the shear layer instability process (growth rate and phase speed).

VLF motions are shown in Biscarrosse data as a signal of period 10 to 30 mn (Bruneau et al, 2009b). A consistent signal of this type appears in our 3D simulations. Figure 6 shows a snapshot of rip current flow advecting a passive tracer. It clearly suggests the presence of turbulence in the jet behavior. The frequency of variability associated with this jet instability is about 20 mn.

![Figure 6. Snapshot of surface flow (vectors) advecting a passive tracer initially released in 1-m depth.](image)

Interestingly, VLF motions are absent from the 2D simulations (but not from the barotropic mode of the 3D model; Figure 5). Similarly, Bruneau et al. (2009b) did not capture any VLF frequency in their standard 2D simulations and needed considerable reduction of turbulent mixing to generate instabilities. We interpret this result as evidence that the barotropic mode of 2D equations is too weak to produce the critical threshold of current shear that triggers instabilities. This is at least the case for the Biscarrosse event. Consistently, a sensitivity test with increased viscosity in our 3D simulation also prevented instability generation.

The role of bottom slope, explained through bottom stretching effect in the potential vorticity balance, is to reduce the spread of the rip current at least on the anticyclonic side, resulting in shear increase. However, the 3D nature of the jet reduces bottom stretching because the jet tends to be more surface-intensified in this case with less bottom interaction. Therefore, we may expect that the bottom slope plays a lesser role in the full 3D model.

5. CONCLUSIONS

We have presented some validation of tridimensional rip current modeling in the Aquitanian coastal zone using in-situ and remote video sensing. We showed the benefits of 3D versus 2D modeling for the simulation of mean rip currents and their low-frequency variability. We conclude that tridimensional nearshore models may provide a valuable and cost-effective alternative to more usual 2D approaches, which miss the vertical flow structure and its nonlinear interaction with the 2D flow.
ACKNOWLEDGMENTS

We appreciate financial support from the IRD ad CNRS. We also thank the EPOC group for providing in-situ data from the June 2007 campaign.

REFERENCES


