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WAVE BREAKING, EDDIES, AND TRANSIENT RIP CURRENT DYNAMICS IN LARGE-SCALE WAVE BASIN EXPERIMENTS

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1 INTRODUCTION

Rip currents transport contaminants, nutrients, larvae, and, unfortunately, occasionally even swimmers between the surf zone and inner shelf. Transient rip currents are ephemeral ejections associated with surfzone eddies that are ubiquitous even on alongshore-uniform beaches. During directionally spread wave conditions, depth-limited breaking along finite-length regions, known as short-crested breaking, leads to spatial variation in the breaking force and corresponding vertical vorticity input to the water column. An inverse energy cascade from the injected vorticity may result in larger scale horizontal surfzone eddies, consistent with two-dimensional turbulence. These large-scale eddies enhance dispersion within the surf zone and may mutually advect offshore as a transient rip current. While this hypothesis is widely discussed in the literature, we do not have strong observational evidence for the processes connecting the wave field to the formation of large-scale horizontal eddies. To overcome the challenges of isolating and measuring the processes leading to transient rip currents in the field, we examined these processes in large-scale laboratory experiments.

2 LABORATORY EXPERIMENTS

Laboratory experiments with an alongshore-uniform barred bathymetry were conducted in the O.H. Hinsdale Wave Research Laboratory's Directional Wave Basin (49 m x 26.5 m x 2 m) at Oregon State University, U.S.A. We used the 29-paddle piston-type wavemaker to generate irregular waves with varying significant wave heights ($0.21 - 0.28$ m), peak periods ($1.5 - 3$ s), and directional spreads ($2 - 30$ deg.). The sea-surface elevation was measured with in situ pressure gauges, a three-dimensional scanning lidar, and stereo processing of optical imagery (Figure 1a,c, Baker *et al.*, 2023a). The surfzone velocity field was measured with in situ acoustic Doppler velocimeters and particle image velocimetry from visible-band imagery (Figure 1a,e, Baker *et al.*, 2023b). Wave and velocity statistics estimated from highly-resolved remotely sensed surface elevation and velocity maps are similar to in situ observations (Baker *et al.*, 2023a; 2023b).

3 VORTICITY INJECTION BY SHORT-CRESTED BREAKING WAVES

Breaking wave spatiotemporal patterns and their relation to vorticity injection were characterized with remotely sensing. We identified breaking wave crests based on threshold exceeding image brightness and stereo derived surface elevation. The average along-crest-length of breaking waves decreases while the total number of crest ends within the surf zone increases with increasing directional spread (Figure 1b, Baker *et al.*, 2023a). We applied a bore model to estimate the along-crest wave dissipation profile for each crest from stereo reconstructions. Then, we computed the breaking force (F_{br}) and its curl (Figure 1c,d), which drives the time-rate of change in surfzone vorticity at the scale of individual waves ($\nabla \times F_{br} \approx \partial\omega/\partial t$). Unlike previous observations that assumed breaking is uniform along-crest (Clark *et al.*, 2012), $\nabla \times F_{br}$ is highly irregular along individual wave crests and varies from crest to crest. Averaging over many crests, $\nabla \times F_{br}$ is positively and negatively signed near opposite crest ends. The shape of the crest-averaged $\nabla \times F_{br}$ varies by surfzone region, and the shape near crest ends strongly depends on assumptions about the decay of dissipation outside of an identified breaking region (Baker *et al.*, In Prep).

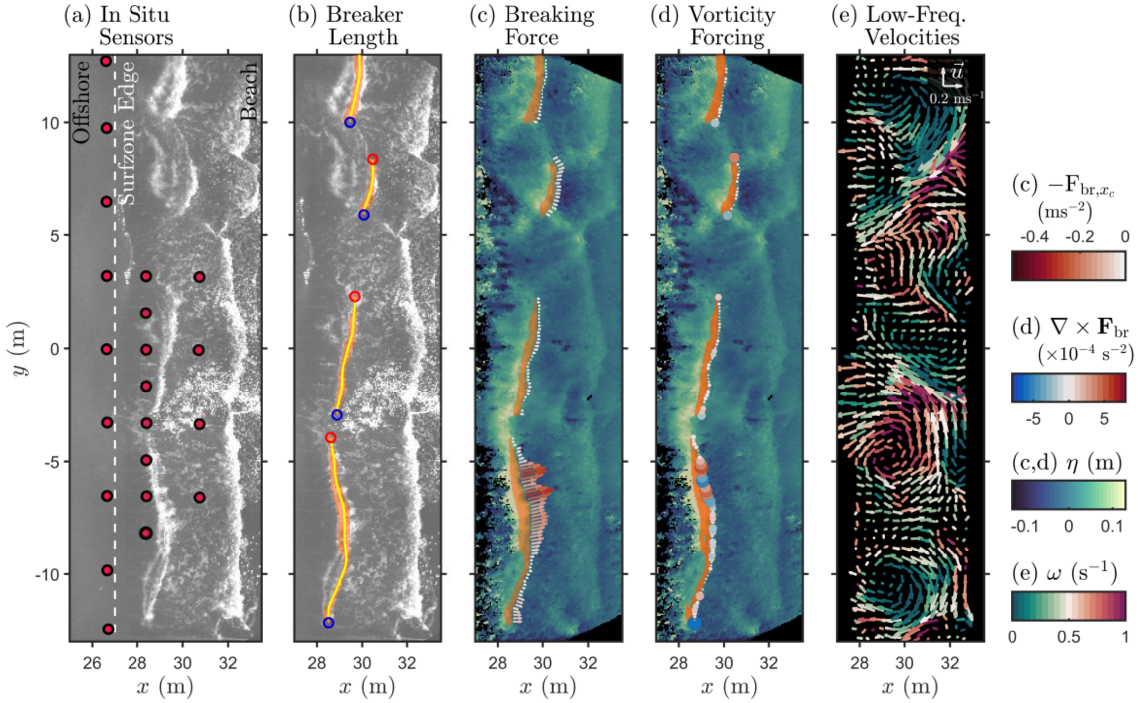

Figure 1. Plan view (alongshore, y, vs. cross-shore, x) snapshots from directionally spread wave conditions ($H_s = 0.24$ m, $\sigma_\theta = 28$ deg.) (a) Colocated pressure sensors and ADVs within and offshore of the surf zone (red circles) overlain on an optical image (dashed white surfzone edge). (b) The along-crest length (yellow) and ends (blue/red circles) of identified breaking crests (orange regions). (c) The breaking force (F_{br}, red arrows) and (d) the curl of the breaking force ($\nabla \times F_{br}$, blue/red circles) overlain on the surface elevation from stereo reconstructions. (e) Low-frequency remotely sensed surface velocities (u) colored by vorticity (ω).

4 TWO-DIMENSIONAL INVERSE ENERGY CASCADE

We examined the relationship between wave forcing conditions and the dynamics and energetics of low-frequency surfzone eddies. To accomplish this, structure functions were computed from alongshore surface velocities derived with particle image velocimetry (Figure 1d). For wave fields with large directional spreads, third-order structure functions are consistent with a bidirectional energy cascade, where energy is transferred to smaller scales through a direct cascade and larger scales through an inverse cascade. In contrast, there is not conclusive evidence of an inverse energy cascade for wave fields with moderate directional spreads (Baker *et al.*, 2023b). Energy flux between scales increase with wave height and directional spread and varies by surfzone region. However, energy associated with very low-frequency eddies estimated from in situ sensors may not increase monotonically with directional spread. Relationships between directional spread and breaking crest length in laboratory-scale, wave-resolving numerical model simulations are consistent with observations. Moreover, these simulations suggest that low-frequency motion and cross-shore exchange peak at intermediate directional spread (Nuss *et al.*, In Review). These findings contribute to our knowledge of processes that enhance surfzone mixing and lead to transient rip current ejections, a coastal hazard for recreational swimmers and conduit for cross-shore material exchange.

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