BATHYMETRIC CONTROLS ON RIP CURRENTS AND ALONGSHORE FLOWS

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Abstract: Prediction of rip currents and alongshore currents is important for forecasting swimming hazards and estimating transport of sediments, pollutants, and larvae across the surf zone and along the shoreline. Nearshore circulation patterns driven by breaking waves are controlled strongly by the geometry of nearshore bathymetric features including crescentic or channel-incised sandbars. Here, field observations (channels dredged in Duck, NC) and a numerical model (COAWST) are used to investigate the sensitivity of the nearshore hydrodynamic response to the size, shape, and position of bathymetric perturbations under a range of wave forcings and tidal elevations. To interpret the observations and model results, depth-averaged momentum balances are used to relate the flow response to the seafloor geometry and incident wave forcing.

Introduction

Nearshore rip currents and alongshore flows are hazardous to swimmers and are important mechanisms for transporting sediments, pollutants, and larvae across the surf zone and along the shoreline. Wave breaking on alongshore non-uniform beaches can drive strong rip currents or meandering alongshore flows (Sonu 1972; MacMahan et al. 2010; Garnier et al. 2013; Houser et al. 2013; Winter et al. 2014), and the strength and pattern of the circulation is sensitive to waves, tides, and bathymetry. Beach hazard warning systems often rely on statistical forecasts (Dusek and Seim 2013) owing to insufficient bathymetric data for site-specific hydrodynamic modeling. Predictions of nearshore circulation may be improved by incorporating information about local bathymetry (Voulgaris et al. 2011), but it is unknown which features of the bathymetry most strongly control the flows. Here, field observations (Duck, NC) and a numerical model (COAWST) are used to investigate the sensitivity of the nearshore hydrodynamic response to the size and shape of bathymetric perturbations under a range of wave forcing.

Field Observations

The nearshore circulation response to a range of bathymetric perturbations and wave conditions is investigated with a series of five dredging experiments performed in summer 2012 at the US Army Corps of Engineers Field Research Facility in Duck, NC. In each experiment, a single channel was dredged in 1- to 3-m water depth using the propellers of a landing craft (Figure 1). The channels had a range of initial geometries (on average 2-m deep, 30-m wide), were excavated barred and terraced bathymetries, and evolved at variable rates. Flows, waves (significant height from 0.5 to 1.5 m, angle relative to shore normal from -35° to +35°), mean sea levels (tidal range ~ 1 m), and bed elevations were measured in and near the channels for approximately one week as each channel evolved. Flows observed near the channels included alongshore currents and rip currents (up to ~1 m/s).

Figure 1. The propellers of a landing craft were used to dredge shore-perpendicular channels.

Numerical Model

Nearshore circulation is simulated using COAWST (Warner et al. 2010), a three-dimensional coupled wave-current-sediment transport modeling system that has skill simulating nearshore observations (Kumar et al. 2012). The model is forced with a wave spectrum at the offshore edge of the domain (8 m water depth), and is used to simulate the hydrodynamic response over either the observed bathymetry (watercraft surveys, daily or weekly depending on conditions) or idealized bathymetry (a planar beach with a superposed Gaussian sandbar intersected by a channel). Simulations for several cases with realistic bathymetry and observed wave forcing are consistent with the observed circulation patterns and flow strengths (not shown).

Results

For a range of wave conditions, the observations and model are used to investigate the sensitivity of the nearshore circulation to variations in the seafloor geometry, including sandbar height and width, and channel depth and width. To interpret the observations and model results, depth-averaged momentum balances are used to relate the flow response to the seafloor geometry and incident wave forcing. The relative sizes of terms in the full cross- and alongshore momentum balances are considered: temporal acceleration, advective acceleration, vortex force (wave refraction on mean flows, e.g., Smith, 2006), pressure gradients (mean sea surface tilts), wave breaking acceleration [gradients in wave momentum flux (radiation stress) associated with wave breaking], bottom stress, and horizontal mixing.

Alongshore variations in bathymetry produce alongshore gradients in wave breaking-driven setup. The pattern of wave setup that occurs near seafloor depressions (or channels in a sandbar) and the associated pressure gradients drive convergent flows that feed rip currents. As the depth of the perturbation increases, so do alongshore gradients in wave breaking and mean sea level, and thus the modeled strength of the rip jet also increases. The strength and structure of the modeled alongshore flows (driven by breaking obliquely incident waves) are also sensitive to the sandbar and channel geometry. For waves obliquely incident on the channels, the resulting circulation pattern is a meandering alongshore flow, including an offshore-directed flow or rip current between the center and downstream edge of the channel. The offshore-directed flow is the result of both the response of the alongshore flow to the topography and the pattern of wave setup resulting from alongshore gradients in wave breaking on the irregular topography. Seafloor geometry and wave forcing control the strength and position of the offshore-directed flow maximum. The size of the displacement of the rip current from the channel center (axis of maximum channel depth) toward the downstream edge of the channel is larger for a larger alongshore flow or a deeper channel. For waves that are steeply obliquely incident, the inertia of the alongshore current may be large enough that the alongshore current bypasses the channel, and the offshore-directed flow or rip current and associated converging alongshore flows are suppressed.

The circulation was modeled for three different synthetic perturbation sizes ranging from 1.0 to 0.1 m deep relative to the elevation of the sand bar crest (Figure 2). The three cases have the same incident (8-m water depth) significant wave height (0.75 m) and angle of wave propagation relative to shore normal (20°). The deepest rip channel (Figure 2A, color contours and Figure 2D, red curve) is 1-m deep relative to the elevation of the bar crest, and the other curves simulate half infill (Figure 2B, color contours and Figure 2D, green curve) and nearly complete infill (Figure 2C, color contours and Figure 2D, gray curve). For the 1-m deep depression in the 1-m high sandbar, the mostly alongshore-directed mean current turns offshore near the downstream edge of the channel (Figure 2A, arrows), producing relatively strong offshore-directed flows (Figure 2E, red curve for 10 < x < 20 m) and weaker onshore-directed flows near the upstream edge of the channel (Figure 2E, red curve for -10 < x < -20 m). For a channel that has filled halfway (0.5-m deep relative to the bar crest), there is a nearly alongshore-uniform alongshore current onshore of the bar crest, with small "meanders" in the flow near the channel (Figure 2B, arrows), and a smaller downstream shift of the cross-shore flow maxima (Figure 2E, green curve). For a channel that is nearly filled (0.1-m deep relative to the bar crest), the alongshore flow is nearly alongshore uniform (Figure 2C, arrows), with cross-shore flows less than 0.1 m/s (Figure 2E, gray curve).

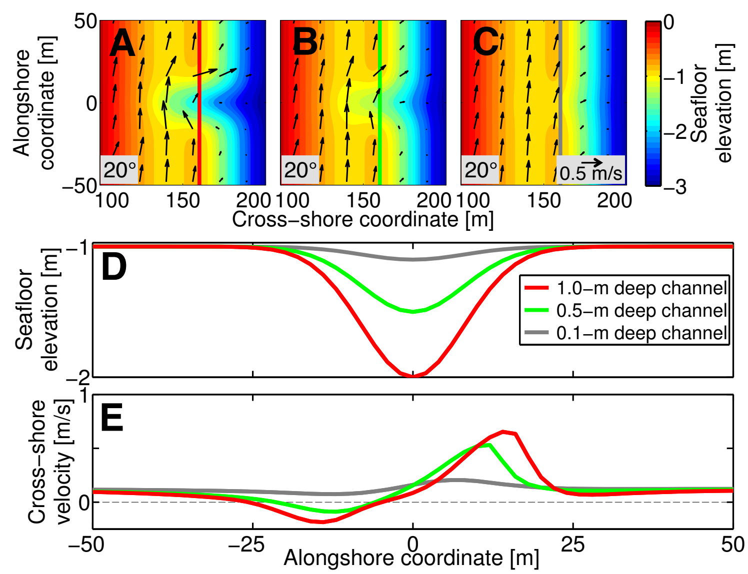

Figure 2. Simulated depth-averaged Eulerian velocity vectors versus cross- and alongshore coordinate with waves from 20° from the south (positive alongshore coordinate is north) for rip-channeled bathymetry (color contours) for three channel depths: (A) 1.0-m, (B) 0.5 m, and (C) 0.1 m. (D) Seafloor elevation and (E) depth-averaged Eulerian cross-shore flows versus alongshore coordinate for the three cases, at the cross-shore position of the colored lines in A, B, C.

Conclusions

Model simulations (COAWST) of the nearshore hydrodynamic response to obliquely incident waves (20° relative to shore normal) show that the flow transitions from a rip current to an alongshore flow with decreasing channel depth from 1.0 to 0.1 m. For a larger channel depth, the rip current is shifted toward the downstream edge of the channel. For a smaller channel depth, the rip current position is closer to the center of the channel. Ongoing work investigates transitions from rip currents to alongshore currents with other variations in the seafloor geometry and with variations in the wave properties. In particular, simulations using observed bathymetry (Duck, NC, 2012) are consistent with observations of nearshore circulation patterns from the rip channel dredging study (not shown), and the simulations are used to test hypotheses about dynamical balance shifts associated with the observed flow pattern transitions. In addition, the model simulations for a range of bathymetries and wave conditions are used to investigate the changes in the dominant terms in the momentum balance as the channel geometry or wave properties change. The model simulations allow investigation of a wider parameter space than provided by the observations.

Acknowledgements

We thank the PVLAB field crew for rapidly deploying a remarkable number of sensors in a surfzone rip channel, then doing it all over again four more times, the USACE Field Research Facility for excellent field support, and members of the COAWST user community for assistance with the model development. Funded by the Assistant Secretary of Defense (Research and Engineering) and the Office of Naval Research.

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