Surf zone flushing on embayed beaches

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[1] Using a numerical model, we show that the surf zone of embayed beaches systematically flushes out more floating material (simulated using passive tracers) than on open beaches, with most exits occurring through the headland rips. For obliquely incident waves, a headland rip acts as a persistent conduit for transporting floating material out of the surf zone and into the inner shelf region. Wave angle and embayment size determine which headland rip (upwave or downwave) flushes out more the surf zone material. For narrow embayed beaches, passive drifters exit the surf zone through the upwave headland rip. For wider embayed beaches, the longshore current has enough room to develop and is further deflected against the downwave headland where most drifters exit the surf zone. Our results indicate that wave-exposed rugged coasts strongly enhance exchange of floating matter (e.g., pollutants and nutrients) at the ocean/continent interface. **Citation:** Castelle, B., and G. Coco (2013), Surf zone flushing on embayed beaches, *Geophys. Res. Lett.*, *40*, 2206–2210, doi:10.1002/grl.50485.

1. Introduction

[2] Rip currents are narrow and intense ($O(1\ \mathrm{m\ s^{-1}})$) seaward flows that develop in the surf zone, the area between the shoreline and the onset of wave breaking, and occasionally extend offshore of the breakers [*MacMahan et al.*, 2006]. They are the primary mechanisms for flushing, here defined as the ability of surf zone currents to expel passive tracers toward the inner shelf [*Dalrymple et al.*, 2011]. These currents pose a deadly hazard to swimmers [*Lushine*, 1991] and can also affect marine ecosystems by dictating patterns of transport and dispersion of pollutants, nutrients, and tracers [*Talbot and Bate*, 1987; *Shanks et al.*, 2012]. On a rip-channeled beach, rip currents are driven by alongshore variations in bathymetrically controlled wave breaking [*Bonneton et al.*, 2010; *Bruneau et al.*, 2011] with rip velocity fluctuating on time scales of the order of 1 min (infragravity motions) and 10 min (very low frequency motions, VLFs). Recent field [*MacMahan et al.*, 2010], numerical [*Reniers et al.*, 2009] and laboratory [*Castelle et al.*, 2010] studies show that rip current flow fields consist of semi-enclosed large-scale vortices that retain about 80–90% of floating material (e.g., drifters). Using attractive Lagrangian Coherent Structures (LCSs) [*Shadden et al.*, 2005], transport barriers explaining the pathways of surface floating material that are hidden in the pulsating rip-current surface velocity field. *Reniers et al.* [2010] show that the primary exit mechanism of floating material in rip current circulation is associated with VLF dynamics and the resulting eddies that detach from the main rip current.

[3] Embayed beaches are ubiquitous along hilly or mountainous wave-exposed coasts and are therefore common worldwide [*Short and Masselink*, 1999]. While surf zone retention is well documented on open beaches [e.g., *Spydell et al.*, 2007; *Reniers et al.*, 2009], it has never been addressed in detail on embayed beaches. In contrast to open beaches (and so to the vast majority of existing studies), embayed beaches are usually characterized by rips developing near one or both end points of the beach (hereafter referred to as headland rip, Figure 1). We hypothesize that surf zone ejection of floating material on embayed beaches is more efficient than ejection on open beaches and so could more readily affect cross-shore exchange between the surf zone and the inner shelf. A headland rip is driven by wave shadowing [*Castelle and Coco*, 2012] or the deflection of the longshore current [*Dalrymple et al.*, 2011] against the headland when located at the upwave or downwave side of the embayment, respectively. A headland rip can be further reinforced by the presence of a rip channel against the headland [*Castelle and Coco*, 2012]. While *Short* [2007] suggests that headland rips have stronger and more confined flow than rips on open beaches (and are therefore likely to transport swimmers and floating material further offshore), *Pattiaratchi et al.* [2009] found persistent rip recirculation and therefore high surf zone retention. Overall, surf zone retention of headland rips and surf zone flushing on embayed beaches in general, is a relevant but poorly understood topic.

[4] In this contribution we use a coupled wave-circulation model (section 2) to examine surf zone retention on embayed beaches and the role of wave obliquity and embayment size (section 3). After comparing and discussing differences with open beaches, conclusions are summarized in section 4. We show that surf zone on embayed beaches flushes out much more floating material than on open beaches and that most of surf zone exits occur through the headland rips. We additionally show that wave obliquity and embayment size are crucial to estimate surf zone retention rate on embayed beaches.

2. Model

[5] We use the open source model XBeach [*Roelvink et al.*, 2009] Eastern 2012 version. The model solves coupled 2D horizontal equations for wave propagation, flow, sediment transport, and bottom changes (in this study, we do not consider sediment transport and bottom changes). XBeach includes the wave-group forced VLFs and solves

Additional supporting information may be found in the online version of this article.

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Figure 1. Pictures (courtesy of Prof. A.D. Short) of headland rips extending well beyond the surf zone: (a) Saint James Point (South Australia) and (b) Curl Curl Beach (New South Wales, Australia). The rip current can be identified by the mushroom-shaped plume.

the Generalized Lagrangian Mean (GLM) flow velocity, thus accounting for the Stokes drift, both of which must be accounted for to accurately simulate surf zone retention on natural rip-channel beaches [*Reniers et al.*, 2009]. To verify that VLFs form the dominant exchange mechanism of surf zone floating material and to identify the preferred pathways and trapping zones of floating matter, we additionally compute the Finite-Time Lyapunov Exponent (FTLE) fields whose maximizing ridges represent the LCSs [e.g., *Shadden et al.*, 2005]. We perform FTLE with a time integration interval τ = –10 min to focus on LCS of attracting type on the time scales of VLF flow dynamics (see *Reniers et al.* [2010] for more information on FTLE and LCSs in rip current settings).

[6] We run the model for a number of different embayed beach bathymetries. The headland length is kept constant (450 m) and the alongshore length is varied (L = 250, 500, 1000, and 2000 m). The regular grid spacing is 5 m in both the cross-shore (x axis) and alongshore (y axis) directions. A rip-channel beach was generated starting from a 1:50 planar sloping seabed profile with the offshore boundary at 11.5 m depth. We first superimposed an alongshore-uniform sandbar, located 100 m from the shoreline with its crest in 1.2 m water depth. Then, based on existing field observation [e.g., *Bruneau et al.*, 2011] and morphodynamic modeling of embayed beaches [*Castelle and Coco*, 2012], bar and rip patterns are further superimposed as an alongshore sequence of horns and bays alternating shoreward and seaward of the bar crest with a wavelength λ = 250 m. This results in a realistic bar and rip morphology with rip channel depths of 2 m. Wave forcing is applied at the offshore boundary with a significant wave height H_s = 1 m, a peak wave period T_p = 10 s, and a wave angle to the shore θ = 0, 5°, 10°, 15°, and 20° (clockwise is positive in our frame of reference). Simulations last 1.5 h, but to prevent initial transient effects, we ignore the first 30 min (–30 min < t < 0) and analyze the results for 0 < t < 60 min. For each simulation, passive drifters are initially (t = 0) uniformly seeded at 2 m intervals in the inner surf zone. Drifter trajectories are then calculated at each time step (equal to 1 s) using GLM velocities. In line with previous studies, the outer edge of the surf zone is defined as the location where the alongshore-averaged cross-shore roller energy exceeds 10% of its cross-shore maximum [*Reniers et al.*, 2009], that is, y = 275 m for all the simulations. Retention rate is then computed as the number of drifters within the surf zone compartment expressed as the percentage of the total number of active drifters initially seeded.

3. Results

[7] Figure 2 (see also Animation 1 in the auxiliary material) shows the time evolution of drifter positions and LCSs for an embayed beach with L = 500 m under oblique waves (θ = 20°). The initially uniformly distributed drifters rapidly converge along the LCSs associated with VLFs dynamics (Figures 2a–2c). Drifters subsequently display a mushroom-shape as the seaward-flowing headland rip expands laterally (e.g., Figure 2f) and in the offshore direction up to about three times the surf zone width. A large number of exits from the surf zone is observed with most exits occurring through the downwave ($x \approx$ –250 m) headland rip, which is driven by the deflection of the meandering (alongshore) current flowing against the headland. Our simulations indicate that 100% of the drifters entering in the downwave headland rip exit the surf zone compartment, most of them never making their way back into the surf zone. This contrasts with drifter behavior in correspondence with the upwave headland rip where drifters entering the rip exit the surf zone, but they re-enter it rapidly. Most of the drifters entering the rip at the center of the beach do not exit the surf zone and are subsequently caught by the downwave headland rip. Accordingly, the contributions of the three rip current systems to surf zone flushing are highly contrasting, despite that their seaward mean flow velocities are similar (0.6–0.7 m s^{-1}). The hourly surf zone retention rate for this simulation is about 25%, which is lower than that typically found along open beaches (80–90%).

[8] Figure 3 shows drifter positions at t = 60 min for a number of embayed beaches exposed to waves with θ = 0 and 20°. Results show that for narrow embayed beaches (L = 250 m) with either one rip channel against each headland (Figures 3a and 3b) or one rip channel at the center (Figures 3c and 3d), a large number of drifters have exited the surf zone by the end of the simulation for both shore-normal waves (Figures 3a and 3c) and obliquely incident waves (θ = 20° in Figures 3b and 3d). In contrast with the case of an embayed beach with L = 500 m (Figure 2), for

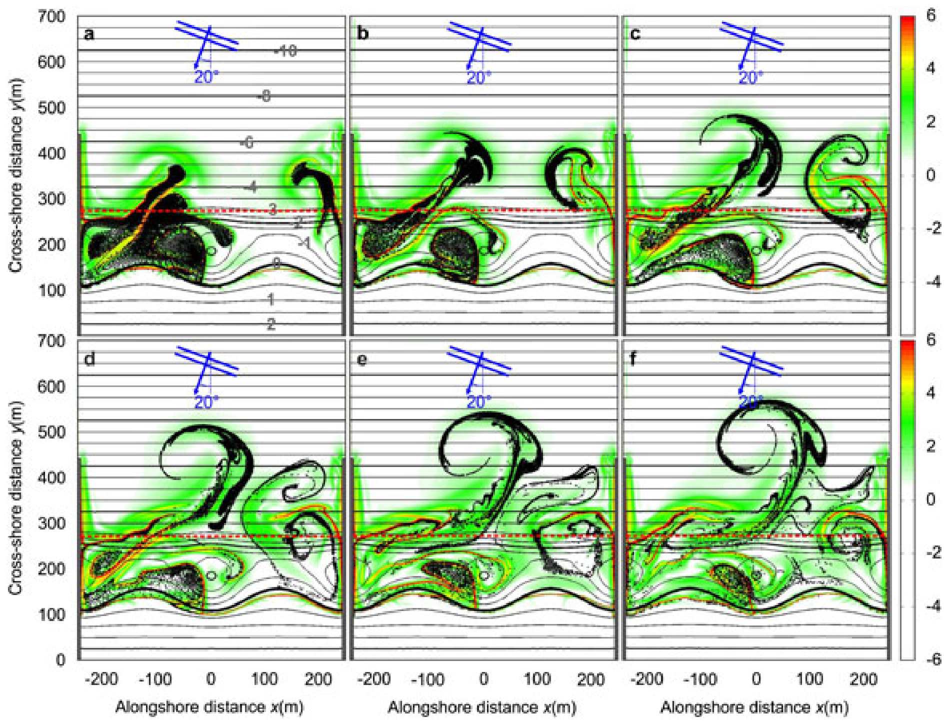

Figure 2. Snapshots of backward-time (τ = –10 min) FTLE field and computed drifter positions (black dots) for an embayed beach with L = 500 m exposed to waves with H_s = 1 m, T_p = 10 s, and θ = 20° at (a) 10, (b) 20, (c) 30, (d) 40, (e) 50, and (f) 60 min (black dots) after virtual drifter seeding in the surf zone. Color bar indicates FTLE in s^{-1}, iso-contours (0.5 m intervals) are contoured in the background; the dashed red line and thick black line indicate the edge of the surf zone compartment and the shoreline, respectively. See Animation 1 in the auxiliary material. Time evolution shows that initially, uniformly distributed drifters rapidly converge along the LCSs (FTLE ridges corresponding to most intense green and red tones) associated with VLFs dynamics forming narrow streaks with a large number of exits from the surf zone compartment through the two headland rips.

L = 500 m, it is the upwave headland rip that acts as a persistent conduit for transporting drifters out of the surf zone (yellow arrows in Figures 3b and 3d, see also Animation 2 in the auxiliary material). In this case, the embayment size is too small to allow development of a longshore current within the embayment. Therefore, we do not observe the formation of a downwave headland rip driven by the deflection of the longshore current. Instead, drifters are either trapped within the downwave headland rip eddy (Figure 3b) or transported and further expulsed through the upwave headland rip (Figure 3d). Surf zone retention is about 50% and 20% for θ = 0 and θ = 20°, respectively.

[9] For an embayed beach with L = 1000 m exposed to shore-normal waves (Figure 3e) surf zone retention increases up to 61%. Both headland rips retain most of the drifters that recirculate within the headland rip eddy. Most of drifter exits occur through the nearby rip at $x \approx$ -250 and 250 m. This contrasts with the situation with θ = 20° (Figure 3f) for which a meandering alongshore current develops within the embayment and further deflects against the downwave headland. The downwave headland rip behaves similarly to the situation in Figure 2 with 100% of the drifters being caught by the rip exiting the surf zone and moving offshore up to a distance about three times the surf zone width. Further along the beach, surf zone exits are occasional and almost non-existent in correspondence of the upwave headland rip. The hourly surf zone retention rate is about 46%.

[10] Figure 4 synthesizes surf zone retention rate computations for all the simulations. Hourly surf zone retention (Figure 4a) vary from 18 to 68% which is systematically smaller than rates computed for the open beach situations (black line). Overall, surf zone retention rate decreases with increasing L and increasing θ, while no clear trend is observed for open beaches. The saturation of surf zone retention at about 35% ($\theta \geq$ 5°) for L = 250 m with one rip channel at the center of the beach (the yellow dotted line in Figure 4a) is due to clusters of drifters re-entering the surf zone compartment at $t \approx$ 50 min. This is further illustrated in Figure 4b that shows the temporal evolution of the retention rates for all the simulations with θ = 20° and so the difference between narrow and large or even open beaches. On open beaches, the retention rate decreases slowly over the course of the hour simulated towards a value of 80%. At the opposite extreme, narrow embayed beaches, retention rates drop much more rapidly and stabilize around 20–30%. The same trends are observed with an increased influence of wave angle for narrow embayed beaches. This highlights the rapid surf zone flushing on embayed beaches.

4. Conclusions

[11] Consistent with previous work on open beaches [*Reniers et al.*, 2010], VLFs form the dominant exchange mechanism of surf zone floating material on embayed beaches where headland rips are the driving mechanism for

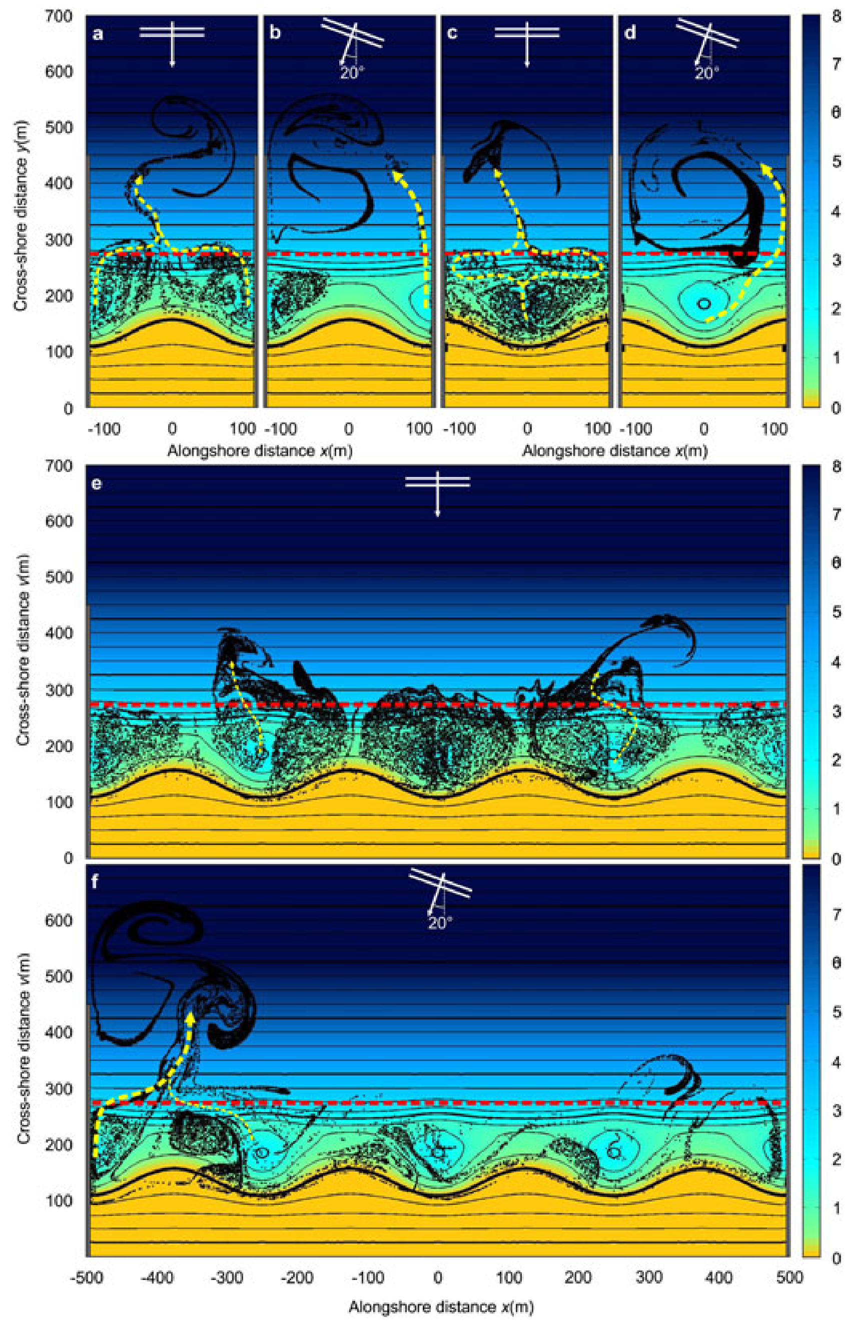

Figure 3. Snapshot of drifter positions (black dots) for embayed beaches exposed to waves with H_s = 1 m, T_p = 10 s and θ = 0 or 20° 60 min after virtual drifter seeding. (a,b) L = 250 m with one rip channel against each headland, (c,d) L = 250 m with a rip channel at the center of the beach, (e,f) L = 1000 m. In Figures 3a–3f, the surf zone compartment is indicated by the dashed red line, iso-contours (0.5 m intervals) are contoured in the background and the preferred path of surf zone exits are indicated by the yellow arrows (thickness increases with increasing flushing). See animation 2 in the auxiliary material for the simulation in Figure 3b).

surf zone flushing. Compared to the open beach case, headland rips cause more drifters to be rapidly expelled out of the surf zone. Drifters also travel farther offshore in the case of embayed beaches. For narrow embayed beaches, i.e., when surf zone circulation is dominated by the embayment size, drifters exit the surf zone through the upwave headland rip. For wider embayed beaches, the longshore current meandering over the bar and rip patterns has enough room to develop and is further deflected against the downwave headland. In the latter situation, drifters exit the surf zone preferably through the downwave headland rip while they tend to recirculate within the eddy associated to the upwave headland rip. For obliquely incident waves, in both situations considered, the headland rip acts as a persistent conduit for transporting floating material out of the surf zone and into the inner shelf region. Our results indicate that wave-exposed rugged coasts (displaying calanques, rocky points, and headlands) strongly enhance exchange of floating matter between the surf zone

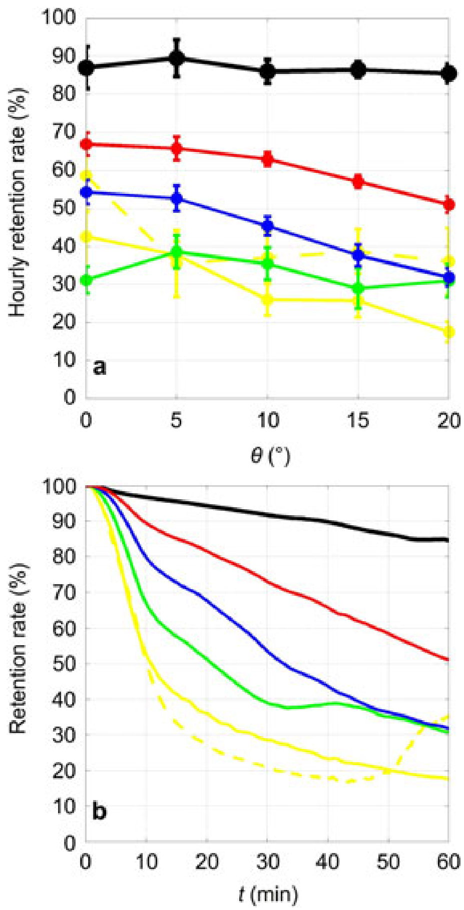

Figure 4. (a) Hourly surf zone retention rate ±1 standard deviation (denoted by the vertical lines) versus offshore wave angle θ and (b) time series of surf zone retention for waves with $\theta = 20°$. Mean retention rate computed for open beach (thick black line), embayed beach with L = 2000 m (red line), L = 1000 m (blue line), L = 500 m (green line) and L = 500 m with one rip channel against each headland (solid yellow line) and L = 500 m with one rip channel at the center of the beach (dashed yellow line). For each configuration the mean is calculated averaging results from 10 simulations.

and the shelf, which is important for the transport and dispersion of pollutants, nutrients, and tracers impacting marine ecosystems. Future detailed field observations of drifter trapping and ejection on embayed beaches and in headland-rip settings will be crucial to improve our skill to predict the transport and dispersion of floating material at the interface between oceans and continents.

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References

Bonneton, P., N. Bruneau, B. Castelle, and F. Marche (2010), Large-scale vorticity generation due to dissipating waves in the surf zone, *Discrete Cont. Dyn.-B*, *13*(4), 729–738, doi:10.3934/dcdsb.2010.13.729.

Bruneau, N., P. Bonneton, B. Castelle, and R. Pedreros (2011), Modeling rip current circulations and vorticity in a high-energy meso-macrotidal environment, *J. Geophys. Res.*, *116*(C07026), doi:10.1029/2010JC006693.

Castelle, B., and G. Coco (2012), The morphodynamics of rip channels on embayed beaches, *Cont. Shelf Res.*, *43*, 10–23, doi:10.1016/j.csr.2012.04.010.

Castelle, B., et al. (2010), Laboratory experiment on rip current circulations over a moveable bed: Drifter measurements, *J. Geophys. Res.*, *115*(C12008), doi:10.1029/2010JC006343.

Dalrymple, R. A., J. H. MacMahan, A. J. H. M. Reniers, and V. Nelko (2011), Rip currents, *Annu. Rev. Fluid Mech.*, *43*, 551–581.

Lushine, J. B. (1991), A study of rip current drownings and related weather factors, *Nat. Weather Digest*, *16*, 13–19.

MacMahan, J. H., E. B. Thornton, and A. J. H. M. Reniers (2006), Rip current review, *Coast. Eng.*, *53*, 191–208, doi:10.1016/j.coastaleng.2005.10.009.

MacMahan, J. H., et al. (2010), Mean Lagrangian flow behavior on an open coast rip channeled beach: A new perspective, *Mar. Geol.*, *268*, 1–15, doi:10.1016/j.margeo.2009.09.011.

Pattiaratchi, C., D. Olson, Y. Hetzel, and R. Lowe (2009), Wave-driven circulation patterns in the lee of groynes, *Cont. Shelf Res.*, *29*, 1961–1974, doi:10.1016/j.csr.2009.04.011.

Reniers, A. J. H. M., J. H. MacMahan, E. B. Thornton, T. P. Stanton, M. Henriquez, J. W. Brown, J. A. Brown, and E. Gallagher (2009), Surf zone retention on a rip-channeled beach, *J. Geophys. Res.*, *114*, doi:10.1029/2008JC005153.

Reniers, A. J. H. M., J. H. MacMahan, F. J. Beron-Vera, and M. J. Olascoaga (2010), Rip-current pulses tied to Lagrangian coherent structures, *Geophys. Res. Lett.*, *37*, doi:10.1029/2009GL041443.

Roelvink, J. A., A. J. H. M. Reniers, A. van Dongeren, J. V. de Vries, R. McCall, and J. Lescinski (2009), Modelling storm impacts on beaches, dunes and barrier islands, *Coast. Eng.*, *56*, 1133–1152, doi:10.1016/j.coastaleng.2009.08.006.

Shadden, S. C., F. Lekien, and J. E. Mardsen (2005), Definition and properties of Lagrangian coherent structures from finite-time Lyapunov exponents in two-dimensional aperiodic flows, *Physica D*, *212*, 271–304, doi:10.1016/j.physd.2005.10.007.

Shanks, A. L., S. G. Morgan, J. H. MacMahan, and A. J. H. M. Reniers (2012), Surf zone physical and morphological regime as determinants of temporal and spatial variation in larval recruitment, *J. Exp. Mar. Biol. Ecol.*, *392*, 140–150.

Short, A. D. (2007), Australian rip systems—Friend or foe, *J. Coastal Res.*, *SI 50*, 7–11.

Short, A. D., and G. Masselink (1999), Embayed and structurally controlled embayed beaches, in *Handbook of Beach and Shoreface Morphodynamics*, edited by A. D. Short, pp. 230–250, Wiley, Chichester.

Spydell, M., F. Feddersen, and R. T. Guza (2007), Observing surf-zone dispersion with drifters, *J. Phys. Oceanogr.*, *37*, 2920–2939, doi:10.1175/2007JPO3580.1.

Talbot, M. M. B., and G. C. Bate (1987), Rip current characteristics and their role in the exchange of water and surf diatoms between the surf zone and nearshore, *Estuar. Coast. Shelf S.*, *25*, 707–720.