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Mean Lagrangian flow behavior on an open coast rip-channeled beach: A new perspective

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A B S T R A C T

The accepted view of rip currents is that they are an efficient mechanism for transporting material out of the surf zone. Previous rip current campaigns on natural beaches have focused on Eulerian measurements with sparse *in situ* pressure and current meter arrays. Here, for the first time, spatially synoptic estimates of rip current flow patterns, vorticity, and Lagrangian transport behavior are measured in the field using a fleet of 30 position-tracking surfzone drifters during multiple rip current occurrences on an open coast beach in Monterey, CA. Contrary to the classic view (Shepard et al., 1941), the rip current flow field consisted of semi-enclosed, large-scale vortices that retained the drifters and resulted in a high number of Lagrangian observations that are temporally and spatially repeated. Approximately 19% of the drifters deployed in the rip currents exited the surf zone per hour, on average during the experiments. The observed surf zone retention of drifters is consistent with measurements from different open coast beach rip current systems (14% at meso-macrotidal Truc Vert, France and 16% at macrotidal Perranporth, United Kingdom). The three-hour-average cross-shore rip current velocity at Monterey was 30 cm/s with peak time-averaged velocities of 40–60 cm/s depending on wave and tidal conditions. Drifters that episodically exited the surf zone were transported approximately 2 surf zone widths offshore at ~20 cm/s.

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1. Introduction

Rip currents are seaward-directed flows of water that commonly occur on most beaches. They originate close to the shoreline and extend seaward across the surf zone, and beyond (Shepard et al., 1941; Inman and Brush, 1973; Short, 2007). Rip currents play an important role in dispersing material , such as suspended sediments, bubbles, planktonic organisms, nutrients, humans, and other floating material, across the surf zone (Shepard et al., 1941; Inman et al., 1971; Inman and Brush, 1973; Talbot and Bate, 1987; Short and Hogan, 1994; Johnson and Pattiaratchi, 2004a; Grant et al., 2005; Clarke et al. 2007; Vagle et al., 2001, 2005; Short, 2007; Brown et al., 2009). Inman and Brush (1973) referred to rip currents as "freeways" that transport material outside the surf zone to the inner-shelf. Rip currents are responsible for 80% of all surf zone rescues and more than 100 fatalities each year in the U.S. [www.usla.org].

Short (1985, 1999, 2007) identifies four types of rip currents: 1) accretionary beach rip currents, 2) erosional beach rip currents, 3) topographic rip currents, and 4) mega-rips. Accretionary beach rip currents are generally fixed in location for days to weeks, where erosional beach rip currents tend to migrate alongshore. Accretional and erosional rip currents are classified together herein, as open coast beach rip currents. Topographic rip currents are systems where the flow is controlled by solid structures such as groins, jetties, headlands and reefs (Wright et al., 1980; Wind and Vreugdenhil, 1986; Short, 2007). The seaward-directed flows occur adjacent to these features. Mega-rips are large-scale topographic rip currents generally associated with small (3–4 km) embayed beaches that form 1–2 rip currents during large waves that quickly flush the embayed surf zone (Short, 1985, 1999). We include in the mega-rip classification, rip currents controlled by offshore controls, such as submarine canyons, during large waves (Shepard and Inman, 1950; Long and Ozkan-Haller, 2005).

The Lagrangian surface current behavior for rip-channeled open coast beaches away from permanent topographic features are described herein. Scott et al. (2007) found that open coast beach rip currents occur during normal wave conditions and are the most

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Table 1
A summary of drifter observations, which include: 1) drifter deployment duration; 2) observed circulation pattern; 3) drifter exits per hour; 4) number of drifters entering a rip current, R_{in}, relative to the surf zone exits, S_{exit}; 5) significant wave height, H_{mo}; 6) mean wave period, T_{mo}; 7) morphodynamic parameter, Ω, as a function of sediment fall velocity, w_s; 8) location of the surfzone edge; and 9) surfzone width.

Year day	Drifter duration (h)	Circulation pattern	Exits/h (%)	Exits R_{in}/S_{exit} (%)	H_{mo} (m)	T_{mo} (s)	Ω	Surf zone edge (m)	Surf zone width (m)
RCEX—Monterey, California 2007									
117	3.0	Rip current	22	7	1.4	11.4	3	203	155
124	3.4	Rip current	15	6	1.0	13.9	2	172	126
125	3.1	Rip current	4	2	1.6	8.5	4	188	140
127	3.0	Meandering	28	23	0.9	8.8	2	162	122
130	3.0	Meandering	24	16	1.0	9.6	2	162	120
135	2.1	Meandering	21	2	0.8	7.8	2	136	90
139	2.5	Alongshore	0	6	0.5	6.0	2	137	105
ECORS—Truc Vert, France 2008									
75	3.0	Alongshore	0	0	1.3	11.8	3		
77	2.7	Rip current	34	18	1.5	10.1	3		
79	2.0	Meandering	31	12	1.3	12.3	2		
83	1.0	Alongshore	0	0	2.1	12.1	4		
92	2.5	Rip current	0	0	1.8	11.0	4		
93	3.0	Meandering	0	0	2.3	15.0	3		
94	2.8	Rip current	0	0	1.5	11.6	3		
95	2.7	Rip current	22	13	0.9	11.4	2		
MaTRiX—Perranporth, U.K. 2008									
215	1.0	No distinct pattern	0	0	0.8	8.3	3	700	152
216	2.3	Rip current	19	5	0.8	9.1	2	697	180
217	2.7	Rip current	13	3	1.3	7.1	5	698	187
218	2.3	Alongshore	0	0	1.3	9.1	4	694	163
220	3.5	Alongshore	2	2	0.9	9.1	3	675	157

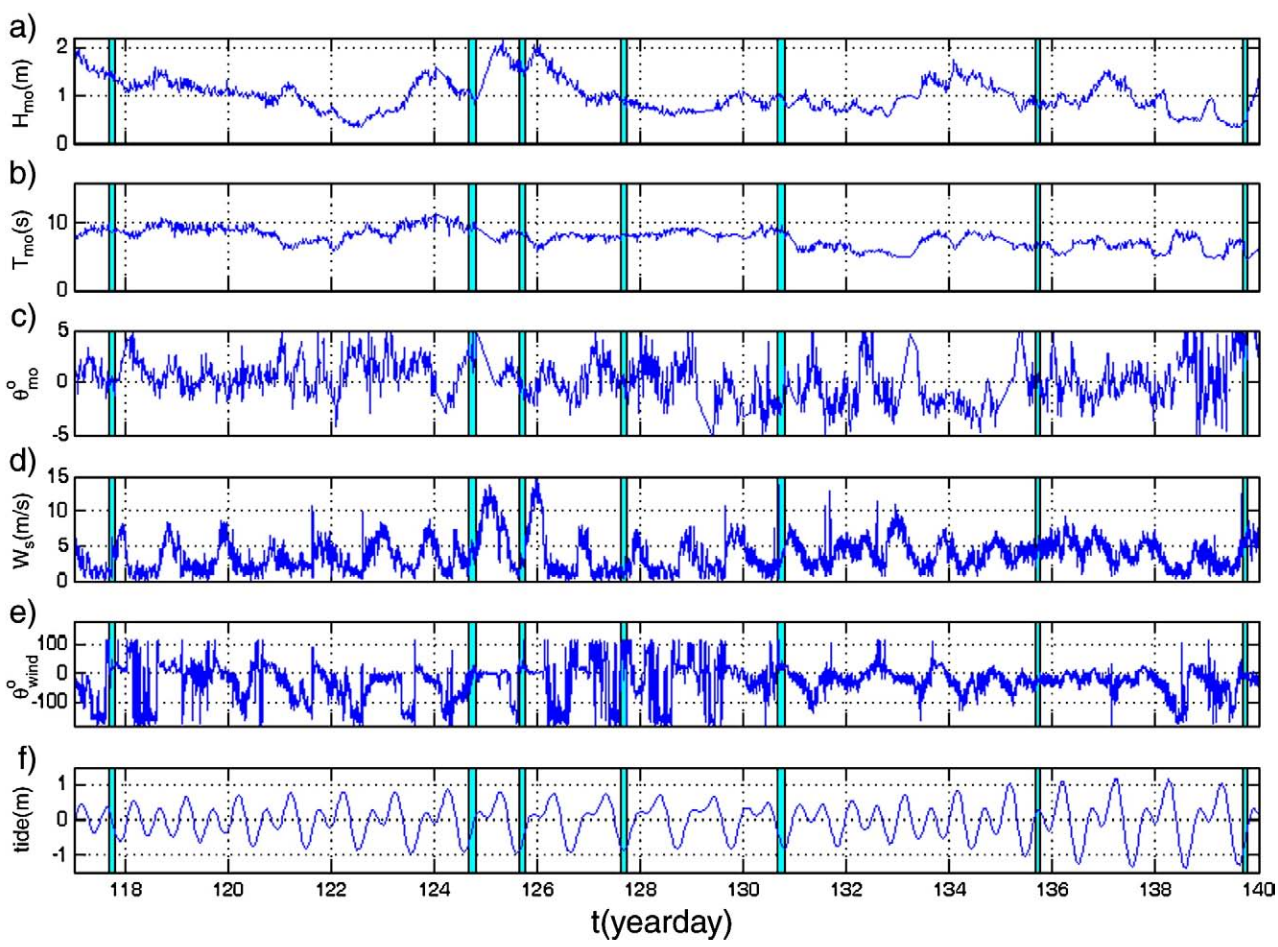

Fig. 1. a) Significant wave height, H_{mo} b) mean wave period, T_{mo} and c) mean wave direction, θ_{mo}, at 13 m water depth. d) Wind speed, w_s and e) direction, θ_{wind}, at Del Monte (3 km south of the experimental site). f) Tidal elevation from NOAA tidal station in Monterey harbor (6 km south of the experimental site). Shaded regions represent times of drifter deployments.

commonly observed rip current types. These open coast beach rip currents are generally coupled to an underlying morphology characterized by deeper, cross-shore oriented rip channels incised in shallower shore-connected shoals or bars (Brander, 1999; Brander and Short, 2000; Sonu, 1972; MacMahan et al., 2006; Short, 2007; amongst others). On beaches with these morphologically-coupled rip currents, the alongshore bathymetric variation creates alongshore variations in depth-limited wave breaking that induce alongshore gradients in pressure and momentum driving water from the shore-connected shoals toward the rip channels (Bowen, 1969; Dalrymple, 1978). Wave-driven onshore flows over the shore-connected shoals or bars transition to alongshore flows (feeder currents) near the shoreline that converge in the rip channel and become cross-shore, rip current flows. The strong narrow rip current flow has traditionally been assumed to shoot beyond the break point and terminate well offshore of the surf zone (Shepard et al., 1941; Inman and Brush, 1973). However, the spatially synoptic rip current flow pattern has not been tested in the field to date.

The dimensions of the surf zone width and rip channel spacing for a morphologically-controlled rip current system, have made it costly and difficult to obtain spatially synoptic velocity measurements using only fixed instrumentation, thus reducing the likelihood of capturing the synoptic circulation pattern without the aid of a numerical model (Chen et al., 1999; Haas et al., 2003; Schmidt et al., 2005; Castelle et al., 2007; Reniers et al., 2007). In addition, influences of adjacent rip current cells (Reniers et al., 2007) or alongshore flow patterns have traditionally been overlooked. To overcome the constraints of deploying stationary instrument arrays, both shore-observed dye (Inman et al., 1971; Sonu, 1972; Huntley et al., 1988; Talbot and Bate, 1987; Brander, 1999; Brander and Short, 2001) and a few shore-observed drifters (Shepard et al., 1941; Shepard and Inman, 1950; Sonu, 1972; Huntley et al., 1988; Brander and Short, 2001) were visually tracked to elucidate Lagrangian rip current flow behavior. To date, only Talbot and Bate (1987) have qualitatively evaluated potential surf zone retention of rip currents by tracking dye. Thus, while commonly accepted, the traditional paradigm of cross-shore exchange of water by open coast rip current systems has yet to be thoroughly examined and quantified.

Recent improvements in position accuracy and reductions in size of Global Positioning Systems (GPSs) have enabled the development of self-tracking surfzone drifters (Schmidt et al., 2003; Schmidt et al., 2005; Johnson et al., 2003; Johnson and Pattiaratchi, 2004b). Johnson and Pattiaratchi (2004a) described the Lagrangian statistics associated with a transient rip current head using 4 drifters. Schmidt et al., 2003, 2005, using 3–4 drifters, found coherent horizontal motions related to bathymetric irregularities, where a few drifters would travel in circular paths before exiting the surf zone. However, the number of GPS drifters was limited by the high cost of each unit. Overhead video tracking of O(100) drifters in laboratory provided more detailed quantitative maps of rip current flow patterns (Kennedy and Thomas, 2004), but this technique is not practical in the field with oblique looking cameras whose pixel resolution requires large-size drifters to

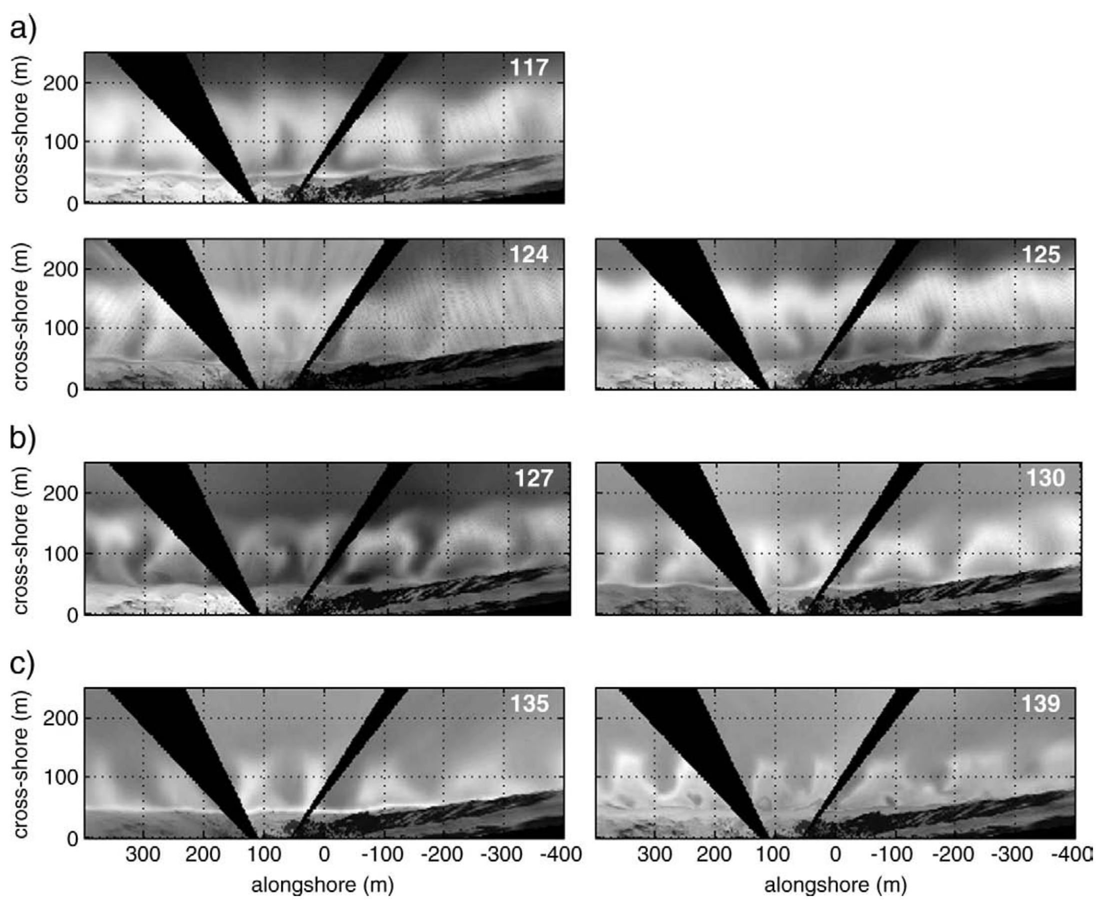

Fig. 2. Three video cameras overlooking the experiment site were mounted on a tower 18.2 m above the mean sea level. Rectified time-averaged images depict variations in depth-limited wave breaking from which morphologic beach patterns can be inferred (Lippmann and Holman 1989). The rectified time-averaged intensity images compare well with the bathymetric surveys (MacMahan et al., 2005). Depth-limited wave breaking occurs on the bar outlining shallow regions, while the deeper sections of the rip channel have minimal wave breaking. Time-averaged rectified video images obtained during drifter deployments for when waves were greater than 1 m (a), approximately 1 m (b), and less than 1 m (c). Yeardays located in upper right-hand corner of images. All images were obtained at 1700 GMT.

be observed. MacMahan et al. (2009) re-engineered inexpensive GPS units that resulted in a drastic cost reduction for accurate position estimates allowing for the first time the cost-effective opportunity to deploy a fleet of drifters to obtain synoptic Lagrangian surf zone measurements.

Lagrangian information is ideal for many applications as it describes the particle pathways of material transport for varying spatial and temporal scales over a broad horizontal region. Here, observations of 30 surfzone drifters deployed in a natural rip current system are used to answer the question "How is material transported by surface currents within the surf zone of an open coast rip-channeled beach"? This study describes the methods and results associated with Lagrangian observations obtained during rip current experiments in a range of surfzone environments at Monterey, California, Truc Vert, France, and Perranporth, United Kingdom. These observations were made to specifically test traditionally accepted views of rip current circulation.

2. Field sites

In the following, the Monterey, CA, experiment is described in detail. Truc Vert, France, and Perranporth, United Kingdom, experiments have been described elsewhere and their relevant observations, and are included to generalize the results and conclusions discussed herein.

2.1. Monterey, CA

A rip current field experiment (RCEX) was performed in late April and early May, 2007, at Sand City, Monterey, California. The site was selected owing to its year round persistent rip currents formed by near shore-normal incident waves (MacMahan et al., 2005; Thornton et al., 2007) and existing knowledge from previous experiments (RIPEX 2001) (MacMahan et al., 2004a,b, 2005, 2006; Reniers et al., 2006, 2007; Thornton et al., 2007). The foreshore of the beach is relatively steep (1:10) flattening out to a low-tide terrace (1:100) with quasi-periodic, O(125 m), incised rip channels, continuing with a 1:30 offshore slope, representative of a transverse barred beach as described by the Wright and Short (1984) morphodynamic model. The morphodynamic parameter, $\Omega = H_{mo}/(T_p w_s)$, has been used to describe beach states that are associated with rip currents (Wright and Short, 1984; Short, 1985), and ranges from 2 to 4 for RCEX (Table 1) where H_{mo} is the significant wave height, T_p is the peak period, and w_s is the fall velocity based on the mean grain size of 0.35 mm. Beaches

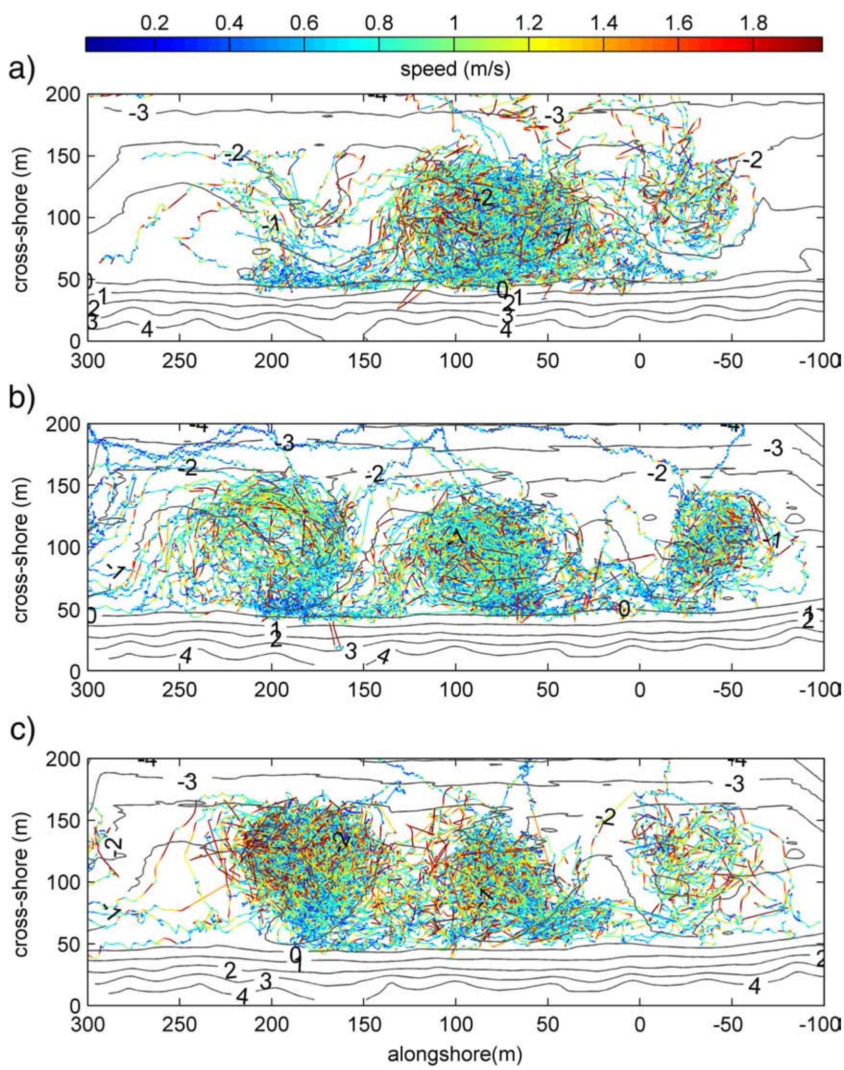

Fig. 3. Drifter position and speed (the color of the line represents speed) tracks for drifter deployments on yeardays 117 (a), 124 (b), 125 (c), 127 (d), 130 (e), 135 (f), and 139 (g). Bathymetric contours are plotted in the background in gray. The color bar at the top represents drifter speed. Note that there are different alongshore scales.

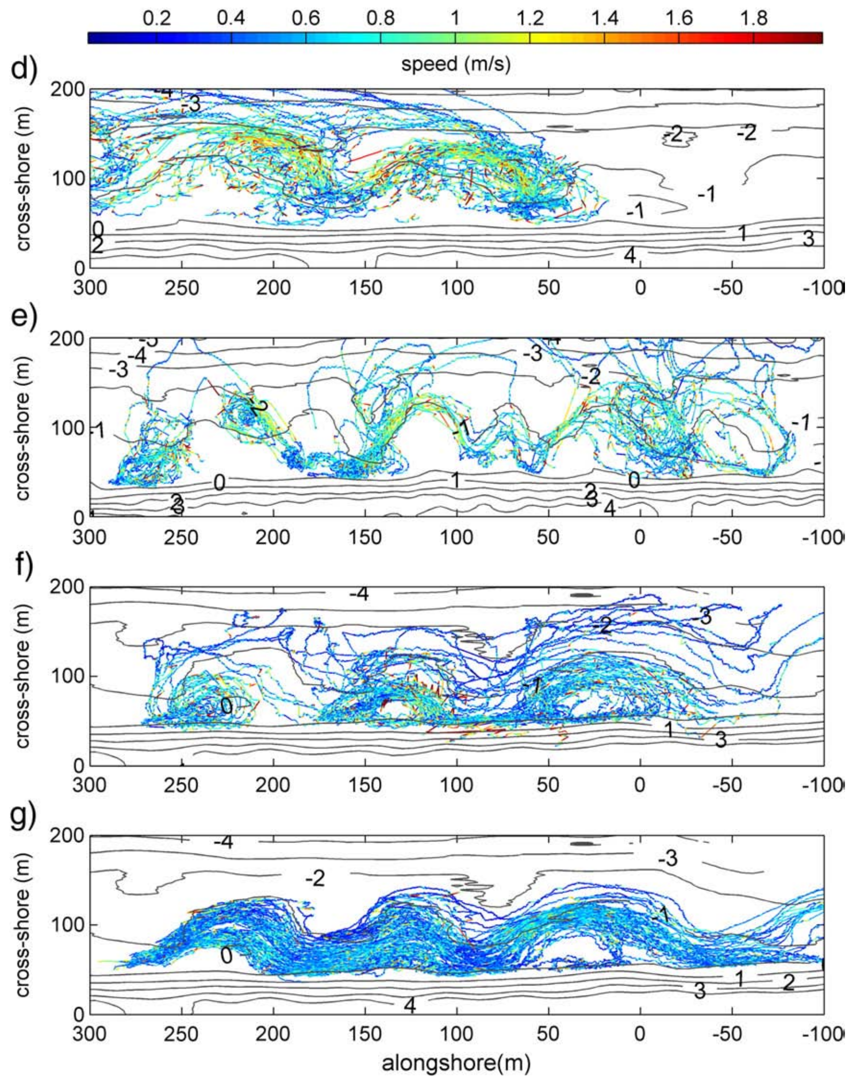

Fig. 3 (*continued*).

with values $2<\Omega<6$ are classified as open coast beach rip current systems. Monterey is located in a mesotidal setting (~2 m tidal range at spring tides). A more detailed description of the field site is given by MacMahan et al. (2005).

2.2. Truc Vert, France and Perranporth, United Kingdom

In 2008, surfzone drifters were deployed on two additional beaches that have commonly-occurring rip currents: 1) Truc Vert, France, and 2) Perranporth, United Kingdom. Truc Vert is characterized by a transverse bar and rip system within the intertidal zone, which has alongshore rip channel spacing of 300–400 m (Castelle et al., 2007). The mean grain size was 0.35 mm. The morphodynamic parameter, Ω, ranges from 2 to 4, corresponding to an open coast beach rip current system (Short, 2007). An outer subtidal cresentic bar with O(1000 m) wavelength is present farther offshore (see Castelle et al., 2007 for additional details). Truc Vert is located in a meso-macrotidal setting (~4 m tidal range at spring tide).

Perranporth is characterized as an open coast rhythmic bar and rip morphology, which had wavelengths of 300–400 m and amplitudes of 1.5–2 m. The mean grain size was 0.30 mm (see Scott et al., 2007 for further site details). The Ω ranged from 2 to 5, again corresponding to an open coast beach rip current system. Perranporth is located in a macrotidal setting (~5 m tidal range at spring tides).

3. Experiment at Monterey, California

3.1. Wave and bathymetric observations

Significant wave height ($H_{\mathrm{mo,13m}}$), mean wave period, and mean wave direction were measured by an acoustic Doppler current profiler (ADCP) deployed in 13 m water depth 380 m from the shoreline (Fig. 1). The ADCP was cabled to a shore-based data acquisition system and continuously sampled at 1 Hz.

Bathymetric surveys were performed using a survey-grade GPS mounted on a sonar-equipped personal watercraft, PWC (MacMahan, 2001). At high tides and low wave energy conditions, the PWC traversed from offshore to the outer edge of the transverse bars and within the rip channels. At low tides, the transverse bars and feeder channels were surveyed by a walking person carrying the GPS housed in a water-tight back-pack. The beachface and foredune were surveyed with the GPS mounted on an all-terrain vehicle. Bathymetry is referenced to mean sea level (MSL). Bathymetric surveys were performed on yeardays 112, 121, 131, and 138.

3.2. Surfzone drifter and deployments

The drifters are described in detail by MacMahan et al. (2009) and consist of a 0.7 m long by 0.03 m diameter PVC mast upon which a small GPS antenna is mounted. The mast is attached to a 0.25 m long by 0.1 m diameter submerged PVC tube with external fins for sail area and contained ballast material. The surfzone drifters were designed to minimize surfing in the breaking waves and were shown to closely follow simultaneous release of dye. The GPS unit is housed in a waterproof box attached to the mast just above the water line. The GPS units internally record carrier phase information at the maximum sampling frequency of 0.5 Hz and are therefore post-processed to give an accuracy of <40 cm in position and <1 cm/s in velocity (MacMahan et al., 2009).

Surfzone drifters were deployed during a variety of wave and tide conditions. Depending on the field conditions, the number of drifters deployed ranged from 16 to 27 and was deployed in clusters ranging from 4 to 16 drifters. When drifters exited the pre-defined study region, they were removed from the ocean and re-deployed in another cluster. The number of clusters deployed on a given day was dependent upon flow behavior. The drifter clusters were generally released in the primary rip channel, but occasionally deployed in neighboring channels depending on the flow patterns. Drifter deployments occurred every few days during a field experiment providing observations over a range of tidal elevations and wave conditions. The position data were quality controlled to remove erroneous points, and gaps in the time series were interpolated, consistent with surfzone drifter observations by Spydell et al. (2007).

There were seven ~3-hour surf zone drifter deployments over the course of the experiment (Table 1). All deployments took place in the morning to avoid adverse windage effects from diurnal afternoon sea breezes (Fig. 1). Typical wind speeds during drifter deployments were approximately 1 m/s with a maximum of 6 m/s. Assuming wind slippage similar to that of Murray, (1975), who used a similar drifter with a longer mast of the same diameter, the maximum bias error for the experiment is estimated at 0.01 m/s per m/s of wind (MacMahan et al., 2009).

$H_{mo,13m}$ was greater than 1 m for the first three deployments on yeardays 117, 124, and 125, approximately 1 m on yeardays 127, 130, 135, and less than 1 m on yearday 139. When $H_{mo,13m}>1$ m, wave breaking occurs within the rip channel. When $H_{mo,13m}<1$ m, there was minimal to no wave breaking in the rip channel. The surf zone edge is defined as the seaward extent of wave breaking as determined from rectified time-averaged video images (Fig. 2). The average surf zone edge for all rip current days occurred around $y=180$ m, which coincides with where the steeper offshore slope transitions to the flatter low-tide terrace bar. For $H_{mo,13m}>1$ m and $H_{mo,13m}\sim 1$ m, the surf zone width (X_s) is computed from shoreline to the outer edge of the breaking region in the rip channel (Table 1). For $H_{mo,13m}<=1$, X_s is computed from the shoreline to the outer edge of wave breaking on the shore-connected shoal. The average surf zone width was $X_s\sim 135$.

4. Synoptic rip current drifter observations

4.1. Rip current Lagrangian paths

The drifter positions were transformed to local cross-shore (x) and alongshore (y) coordinates. The drifter paths for all drifters deployed during RCEX for each day are plotted in Fig. 3. Drifters were typically released at $y=\sim 60$, $x=\sim 75$m within a rip channel. Two basic circulation patterns were observed for an open coast rip-channeled beach: 1) rip current and 2) sinuous alongshore current (Table 1). Conceptual circulation patterns are shown in Fig. 4 to highlight the differences in the observed drifter-derived flow patterns. Two types of rip current circulation patterns were observed: 1) symmetric and 2) asymmetric. The symmetric rip current has two opposing circulation cells that equally occupy half of the shore-connected shoal and rip channel, whereas the asymmetric rip current occupies one rip channel and one shore-connected shoal (Fig. 4). Rip current circulation patterns

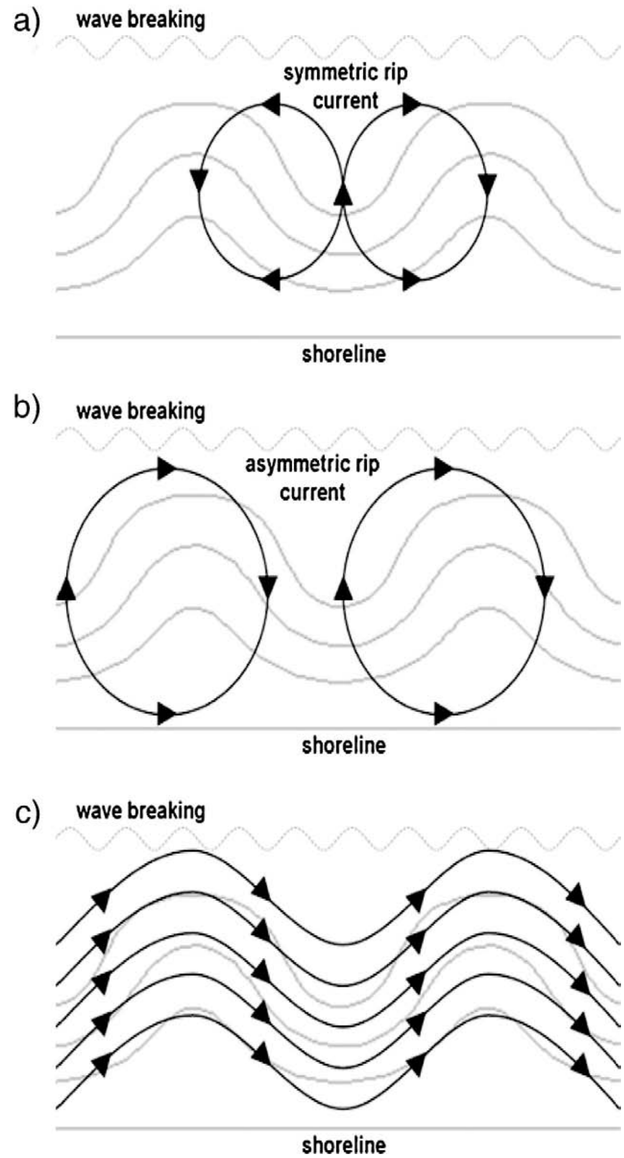

Fig. 4. Conceptual circulation patterns for an open coast rip-channeled beach for a) a symmetric rip current, b) an asymmetric rip current, and c) sinuous alongshore current. Black lines represent the velocity flow field, gray lines are the bathymetric contours, and gray sine wave is location of the surf zone where wave breaking begins.

were observed when $H_{mo,13m}>1$ m (yeardays 117, 124 and 125). The drifters moved in circular patterns coupled with the underlying. A rip current circulation has two rip current vortices located between adjacent rip channels. Some drifters moved to neighboring rip current systems and a few drifters moved offshore.

When $H_{mo,13m}$ decreased, drifters meandered alongshore in a sinuous pattern coupled to the underlying morphology (Fig. 3). The sinuous alongshore current followed the rip channel bathymetry and bore little resemblance to the traditional view of alongshore currents (yearday 139). A combination of rip current and sinuous alongshore current was also observed, which is referred to as a meandering current (yeardays 127, 130 and 135). Drifters in meandering currents roamed up and down the beach, sometimes remaining within a particular rip current cell or migrating to the next rip current cell, but the drifters tended to follow constant isobaths when moving alongshore.

4.2. Surf zone exits

In general, the drifters associated with rip current flow patterns were contained within the surf zone. Episodic rip current bursts caused an occasional drifter to exit the surf zone, but they were surprisingly infrequent (Table 1). The highest percentage of drifters exited on yearday 127 and was 28% per hour (weighted by number of drifters and length of deployments), which is believed to be related to the low tide and lower wave energy reducing the morphodynamic coupling/forcing. The second highest day for escapes was yearday 130 (24% per hour) with similar conditions. Both of these days exhibited meandering current patterns. Combining the rip current pattern days and meandering current pattern days, the average number of drifter exits was 19% per hour.

Owing to the small number of surfzone drifter exits, drifter exit tracks for all deployments are combined together in Fig. 5. For RCEX, the exiting drifters generally traveled approximately two surf zone widths offshore from the shoreline, consistent with observations by Schmidt et al. (2003, 2005). As the focus of the experiment was directed toward the surf zone, these drifters were often removed from the ocean after they exited the surf zone. However, on a few occurrences the drifters exited the surf zone and later re-entered the surf zone. There appears to be a crude relationship between the offshore extent and the possibility of surf zone re-entrance, which decreases with increasing distance offshore. The drifter exits have a range of directions, relative to shore-normal, and it appears that if the drifter exits the surf zone normal to the shoreline, it travels farther offshore. Though these drifter observations outside of the surfzone are limited, they provide useful insight about the behavior of rip current exits, particularly as a mechanism for exchanging material from the surf zone.

The deployment scheme at Truc Vert, France and Perranporth, United Kingdom was similar to the deployments at Monterey. A range of wave height and periods were present at all three sites (Table 1), but note that deployments were limited to $H_s<2.5$ m, and that drifters were not deployed during the largest days at Truc Vert where $H_s>5$ m during the experiment. Rip currents, meandering and alongshore currents occurred at all three sites for different days (Table 1). Combining days when rip or meandering currents occurred (excluding alongshore current days for which virtually no exits occurred) the average percent drifter exits per hour were 14% for Truc Vert and 16% for Perranporth (Table 1). The relatively low surfzone drifter exits are consistent amongst all beaches.

4.3. Synoptic velocity observations

Velocities are calculated using a forward-difference scheme on the drifter locations. Davis (1991) and Swenson and Niiler (1996) noted that the velocity statistics calculated from Lagrangian observations are subject to biases in sample density and temporal intervals. For regions with high flows, there are limited statistical observations as the drifters quickly move through the regions, whereas low flow regions have more observations per unit time. In general, oceanographic drifters are released in specific regions (O (100 km)) and once they exit those regions they never return. For the surfzone drifter observations described herein, the biases are decreased as the rotational nature of the rip currents resulted in many Lagrangian observations that are repeated spatially. For alongshore current flow patterns, drifters were quasi-continuously (re-) released upstream and removed downstream, which only biases the end points. Therefore, the density of data is extremely high compared with typical oceanographic drifter data. Some statistical uncertainty does remain. Davis (1991) suggested that the spatial averaging area should be much larger than spatial and temporal de-correlation scale of the dominant motions. For the purposes of resolving the synoptic surfzone circulation patterns and corresponding flow characteristics, 10 m by 10 m areas (bins) are used. These bins are smaller than the scales of the predominant flow field (i.e. the circular pattern around the entire surf zone).

Each drifter was considered an independent observation when in a particular defined bin. If the drifter re-entered the same bin, it was considered a new independent observation if $t>l_g/U$ had elapsed, where l_g is the length of the bin (10 m) and U is the average speed in the bin for all drifter observations, i.e. the drifter had traveled a distance greater than the length of the bin. For rip current circulation patterns, drifters generally looped back into the same bin after ~5 min. Only bins with at least 5 independent velocity observations

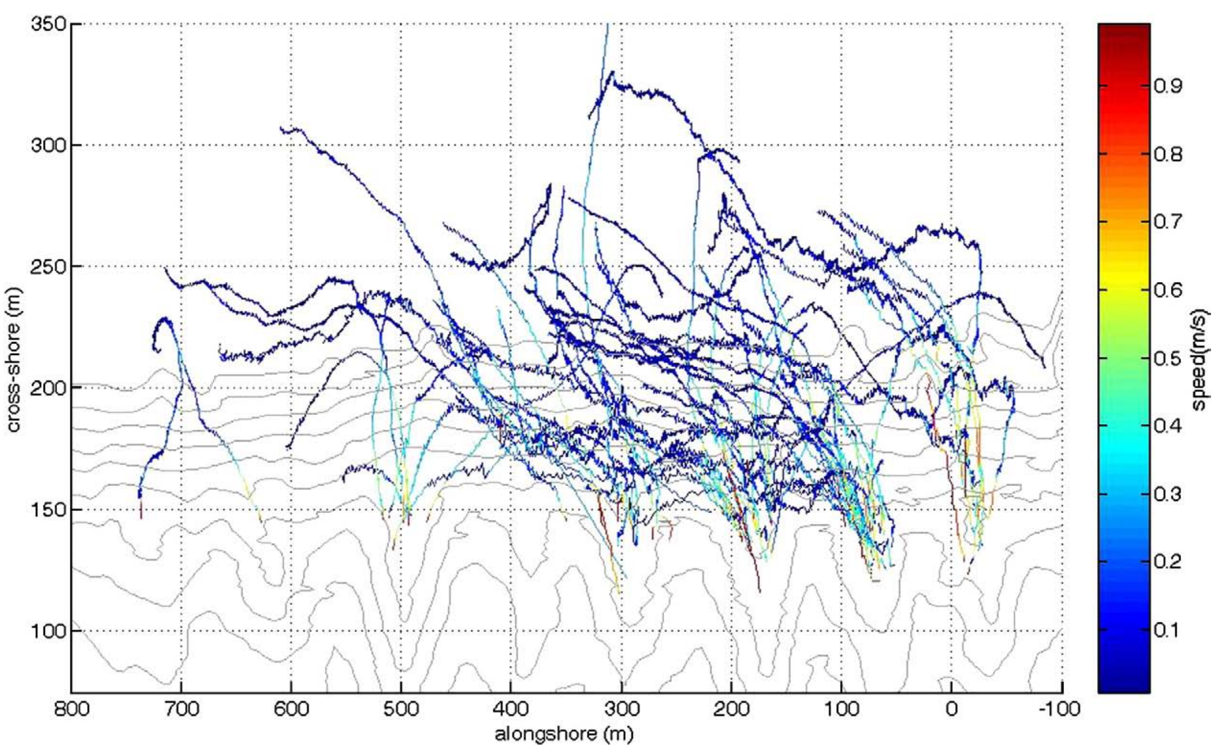

Fig. 5. Drifter position and speed (the color of the line represents speed) tracks for drifters that exited the surf zone for all seven deployments during RCEX. Bathymetric contours are plotted in the background in gray. Color bar plotted to the right representing drifter speed.

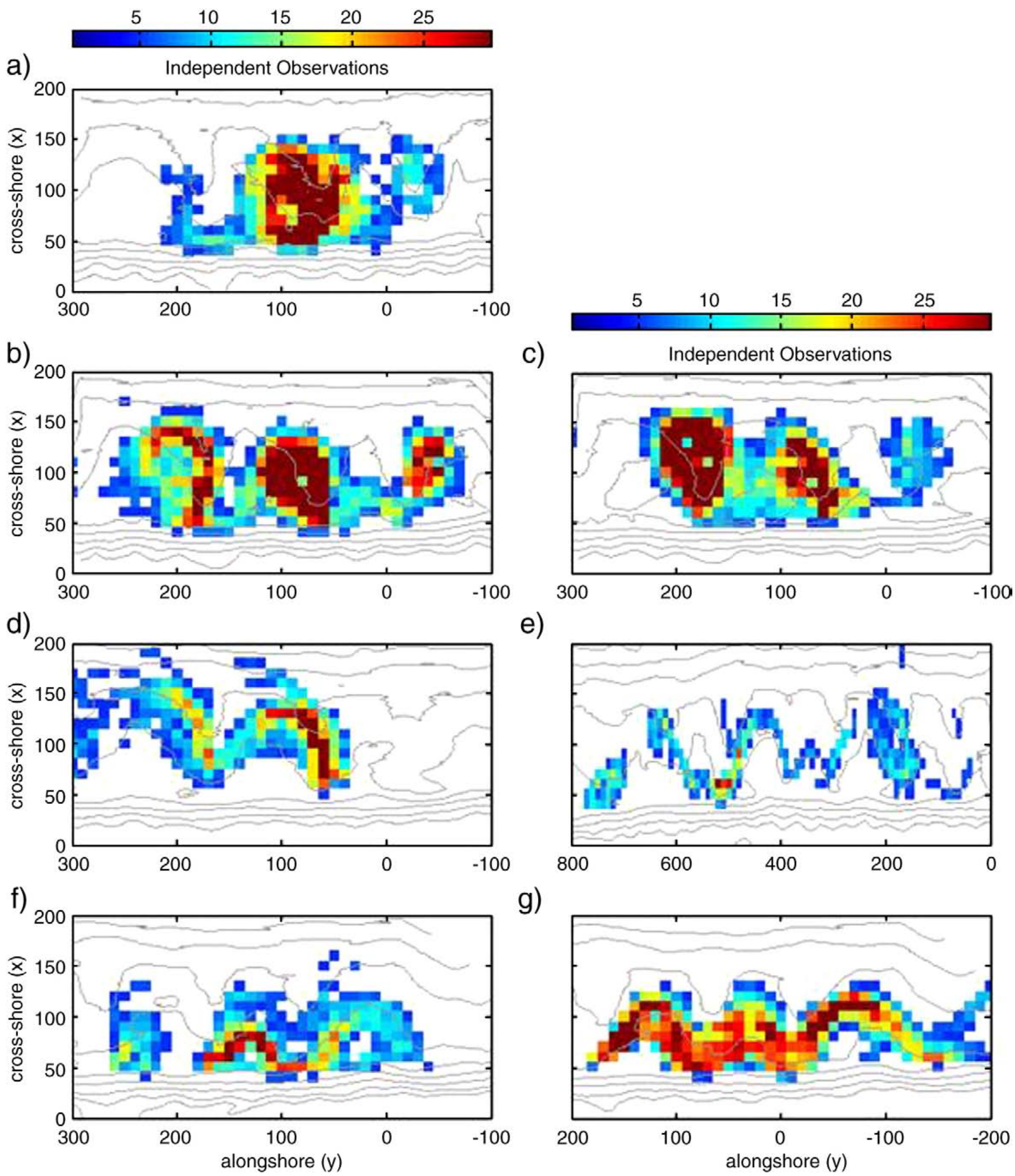

Fig. 6. Color represents total number of independent observations for 10 m by 10 m bins with greater than five independent observations for yeardays 117 (a), 124 (b), 125 (c), 127 (d), 130 (e), 135 (f), and 139 (g). Bathymetric contours are plotted in the background in gray. The color bar at the top represents the total number of independent drifter observations. Note that there are different alongshore scales.

(degrees of freedom) are included as being statistically reliable, which is consistent with Spydell et al. (2007) The total number of independent observations for each bin is plotted in Fig. 6 for the experiment area. Most of the statistically reliable observations are within the surf zone for rip currents (yeardays 117, 124, and 125). When the wave energy decreases (yeardays 127 and 130), the flow pattern becomes more disorganized (decoupled from the morphology) and drifter observations are more spread out.

The velocity data are binned by location and averaged over the deployment duration, typically 3 h, for each day to obtain a synoptic view of the flow pattern (Fig. 7). For the first time, a synoptic circulation pattern of a rip current is observed in the field. Also shown in Fig. 7 is vorticity which is discussed below. Rip currents have a mean offshore flowing current located near the center of the shore-normal rip channel. Near the outer edge of the surf zone, the current turns in the alongshore direction, just shoreward of the breaker region. Near the center of the shore-connected shoal the current turns again and starts flowing shoreward. The onshore current turns parallel to the shoreline and then flows back towards the rip channel, completing a quasi-continuous loop. For an open coast rip-channeled beach, the rip current flow patterns represent surf zone eddies limited by the surfzone width and rip channel spacing. Faster velocities occur along the outer edges of the rotational elements, with the slowest velocities occurring near the eddy centers. As suggested by the spaghetti plots (Fig. 3a, b, and c), the eddies are coherent rotational elements and are contained within the surf zone, with the eddy centers located between $x = 77$–125. When the waves became smaller (Fig. 3d and e), the alongshore sinuous flow pattern is observed coupled to the underlying morphology. The large surf zone eddies no longer exist, but smaller rotational elements located near the edge of the rip channels are observed.

4.4. Drifter cross-shore velocity distribution

The average cross-shore distributions of cross-shore velocities obtained down the center of multiple rip channels for each drifter deployment are shown in Fig. 8 (top). The average of all rip current velocities within the surf zone is 0.3 m/s (solid black line) with peak velocities between 0.4 and 0.65 m/s. The strongest velocities are on yearday 127, which corresponds to the deployment at the lowest tide. The high tide deployments on yeardays 117 and 135 show the slowest velocities, with peak velocities of ~0.4 m/s, consistent with previous observations of rip current tidal modulation (Brander, 1999; amongst others). The velocities achieve a maximum in the middle of the surf zone and decay to the outer edge of the surf zone. Slightly seaward of the surf zone, negative velocities are indicated by occasional weak onshore drifter movement associated with Stokes drift near wave breaking. Seaward of the surf zone there are occasional large values of cross-shore velocity extending approximately two surf zone widths. Offshore, it is hypothesized that drifters that exit the surf zone are caught in rip current pulsations (or surf zone squirts, Smith and Largier, 1995; Reniers et al., 2007). These drifters exit the surf zone at approximately 0.2 m/s and move approximately two surf zone widths offshore. However, the low number of drifter observations per square-meter offshore of the surf zone (Fig. 8) reduces the significance of the offshore observations. The large number of drifter observations within the surf zone (Fig. 8) supports the notion that surf zone retention (of water, drifters, sediments, pollutants, humans, etc.) is high. The drifter numbers decrease at around 1.25 surf zone widths, which we believe is the true location of the outer boundary of the semi-enclosed system.

4.5. Lagrangian drifter mass balance

MacMahan et al. (2005) tried to evaluate the mass balance with a number of single-point Eulerian observations, which resulted in a large amount of scatter. The difficultly in this approach is related to the paucity of spatial coverage compared with the large rip current circulation shear (Fig. 7), potential rip current asymmetry (e.g. Figs. 4 and 7), and potential Eulerian and Lagrangian volume flux mis-matches (Kennedy and Thomas, 2004).

The cross-shore volume exchange of water is evaluated using the Lagrangian velocities in the middle of the surf zone. The Lagrangian volumetric flow rate Q for yearday 124 is computed for an alongshore transect as $Q = uh \cdot \Delta y$, where u is the cross-shore velocity for a bin, Δy

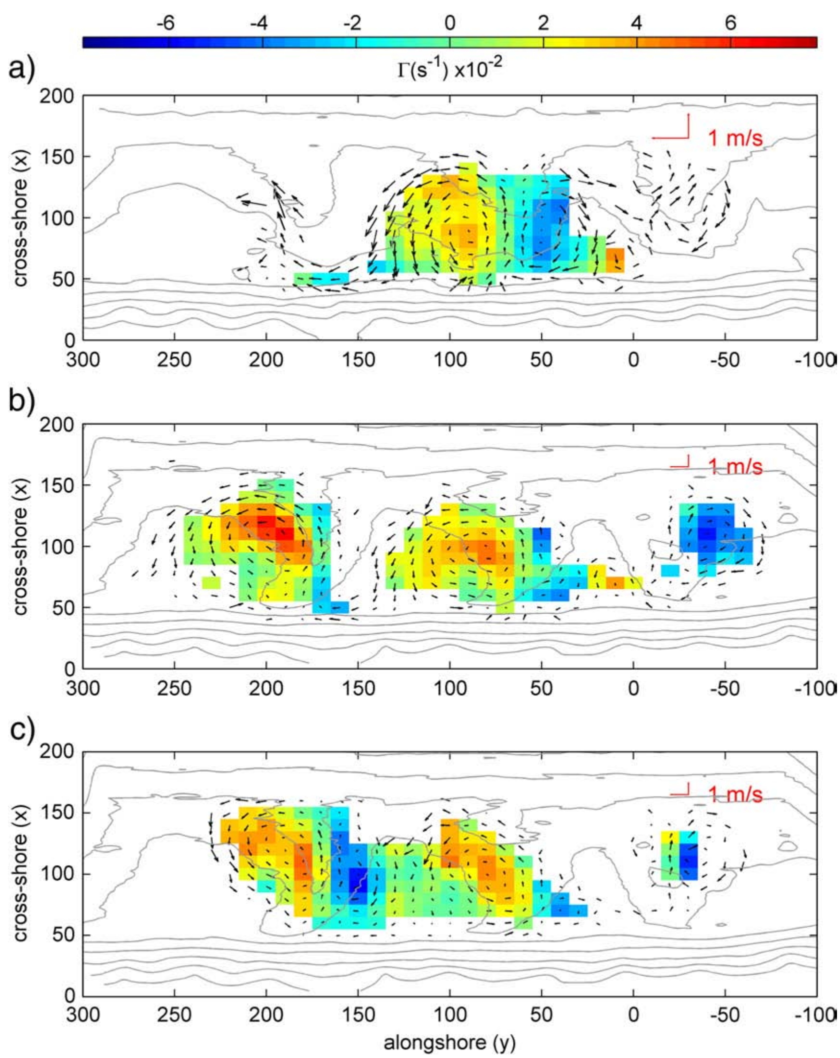

Fig. 7. Drifter velocity data are sorted into 10 m by 10 m bins and averaged over the deployment duration (~3 h) for yeardays 117 (a), 124 (b), 125 (c), 127 (d), 130 (e), 135 (f), and 139 (g). Vectors are shown only for bins with greater than five independent observations (Fig. 6). The red arrows in the upper right-hand corner provide vector scales. Color represents vorticity estimated from velocity observations. Bathymetric contours are plotted in the background in gray. Vorticity color scale plotted at the top the right. Note that there are different alongshore scales.

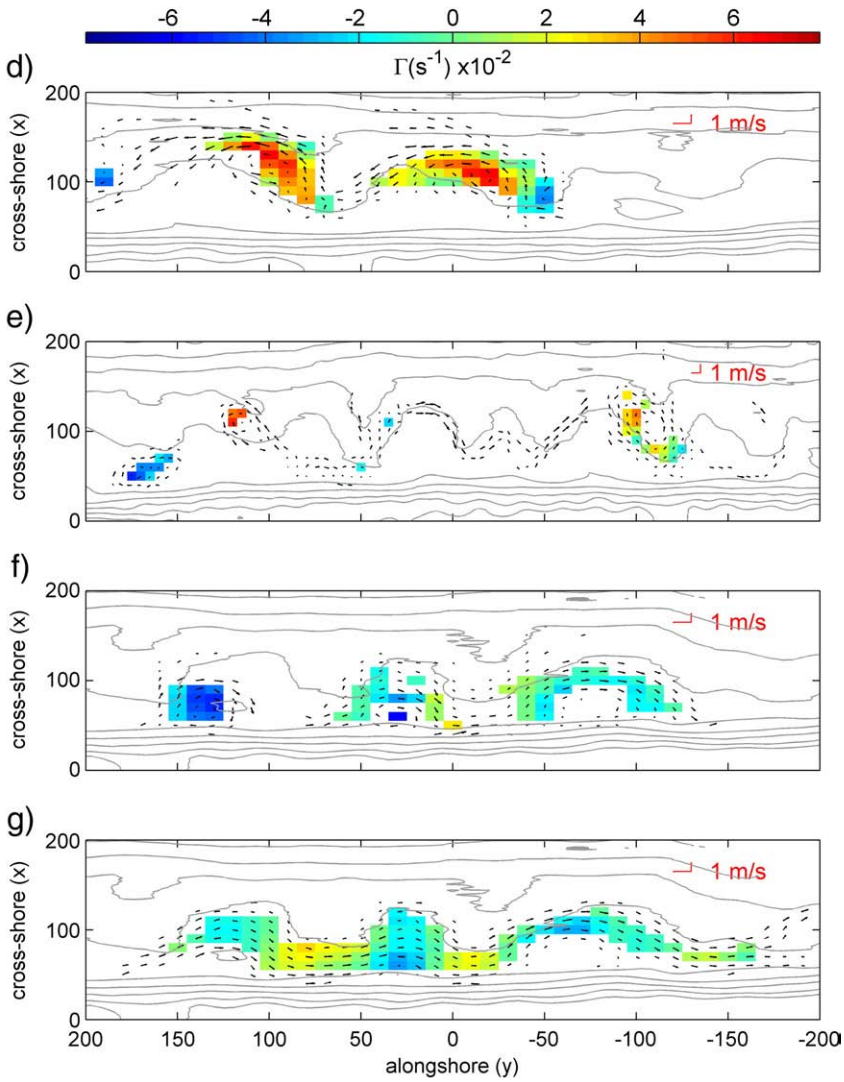

Fig. 7 (*continued*).

is the alongshore bin spacing, and h is the water depth at the bin center. A spatially averaged alongshore transect of the cross-shore velocities is computed for a given y and averaged from $x = 80$ m and $x = 110$ m, which are used for a volumetric flow calculation. The constraint of 5 independent observations is relaxed so that a quasi-continuous alongshore velocity profile can be computed. The computation was performed for 220 m$>y>-$30 m, a region that spans three rip channels (Fig. 9). The onshore velocity over the shoals is of similar magnitude to the offshore velocity in the rip channels, whereas the volumetric transport per unit width is 3 times larger in the rip channel owing to its deeper depth (Fig. 9). The net discharge summed over the alongshore transect is near zero, with an error of less than 5% of the gross discharge (117 m^3/s). Similar results were attained for yeardays 117, 125, and 127 supporting coherent rip current circulations patterns with an average imbalance of about 5%. If the vertical structure of the flow field is uniform, then it would be expected that the currents measured at the surface by the drifters represent the total flow field and the conservation of mass would require that there be a mass balance. The fact that the measured mass balance is near zero suggests that there is only weak vertical flow structure and that the drifters represent the flow field within the surf zone well. Furthermore, the surprisingly low imbalance suggests that exchange of water between the surf zone and inner-shelf is small.

4.6. Rip current vorticity

To date comprehensive kinematic fluid characteristics of the surfzone motions are non-existent owing to the lack of synoptically observed flow fields. The present data set allows us to examine these characteristics in detail. Vorticity is a measure of velocity shear or parcel orientation change without change of parcel area and shape (Molinari and Kirwan, 1975). In addition, this higher order flow estimate is useful for evaluating nearshore numerical model results. The vorticity, Γ, defined as:

$$\Gamma = \frac{dv}{dx} - \frac{du}{dy} \tag{5}$$

is calculated in discrete form using a weighted central-difference method defined by:

$$\begin{aligned}\Gamma_{i,j} = {} & \frac{1}{\Delta x}[\theta(v_{i+1,j+1} - v_{i-1,j+1}) + (1-2\theta)(v_{i+1,j} - v_{i-1,j}) \\ & + \theta(v_{i+1,j-1} - v_{i-1,j-1})] - \frac{1}{\Delta y}[\theta(u_{i+1,j+1} - u_{i+1,j-1}) \\ & + (1-2\theta)(u_{i,j+1} - u_{i,j-1}) + \theta(u_{i-1,j+1} - u_{i-1,j-1})]\end{aligned} \tag{6}$$

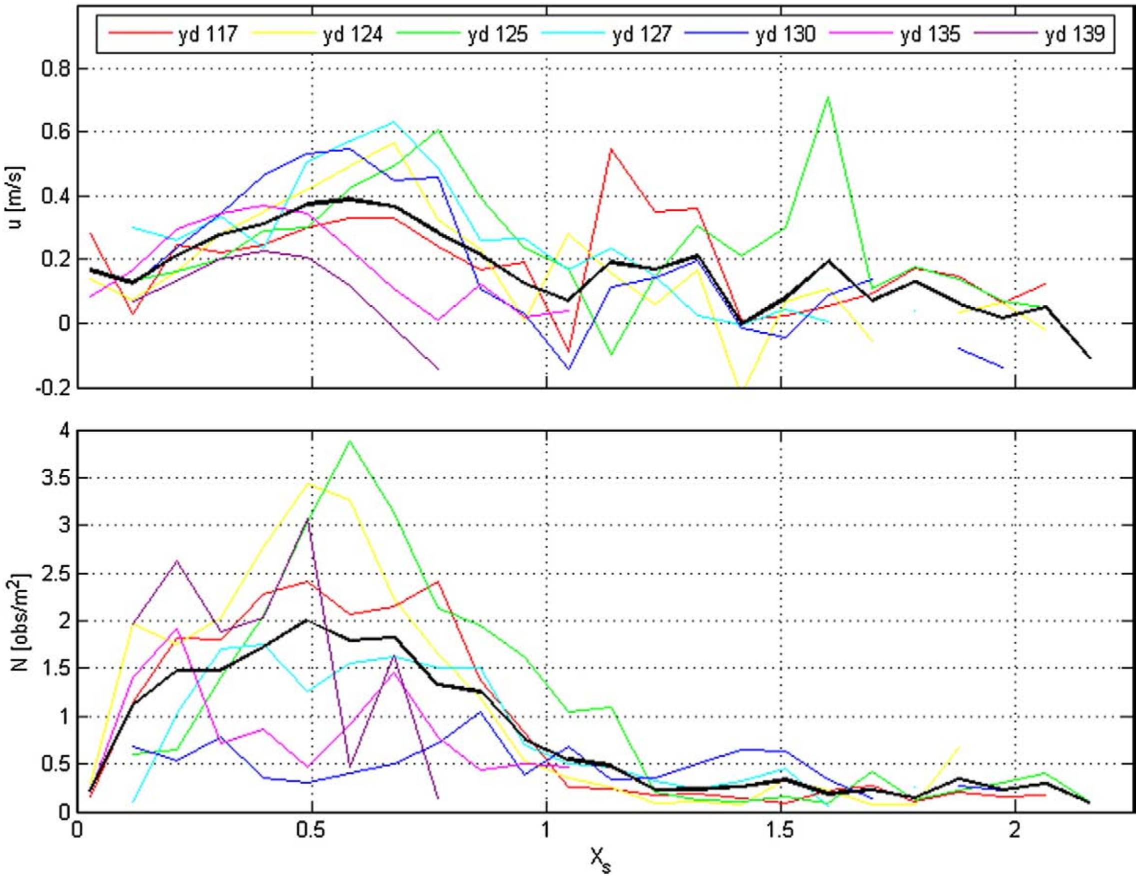

Fig. 8. Cross-shore distribution of cross-shore velocities averaged for three rip channels (top) and corresponding drifter density (bottom) plotted versus cross-shore position normalized by surf zone width.

where $u_{i,j}$ and $v_{i,j}$ represent the cross-shore and alongshore velocities at point (x_i,y_j) with $x_i = i\Delta x$, $y_j = j\Delta y$, where $\Delta x,\Delta y = 10$ and $\theta = 1/3$. The statistics of velocity are understood, but the statistics on the gradients in velocity that compose the vorticity calculation are not known. Therefore, owing to the statistical uncertainty of the spatially-weighted central-difference kinematic estimate of vorticity, a Monte Carlo simulation is performed using the measured mean velocity field and randomizing the variations about the mean based on the velocity standard deviation for each grid cell for yearday 124 (Fig. 10). Two simulations were performed. The first simulation calculates the vorticity 123 times, which was the average number of independent observations that composed the nine velocity components for yearday 124 and the second simulation is performed 2000 times. The mean standard deviations on the vorticity are the same 0.019 s^{-1} for both Monte Carlo simulations, which indicates the measured vorticity had sufficient degrees of freedom. The hot and cold mean vorticity estimates are generally larger than the standard deviation.

For rip currents occurring on yeardays 117 (Fig. 7a), 124 (Fig. 7b) and 125 (Fig. 7c), the double rip current cell structure is observed, with the two well-defined cells centered on the main rip channel and rotating in opposing directions (warm and cool colors). Maximum absolute vorticity occurs in the center of the rip current cells. The meandering rip currents on yeardays 127 (Fig. 7d) and 130 (Fig. 7e) result in the drifters moving over a larger area decreasing the number of bins with adequate significant independent observation, but vorticity patterns are consistent with the rip current cases.

4.7. Beach safety

The observed semi-enclosed surf zone circulation patterns have significant importance to the lifeguard community and to beach-goers with regard to beach safety. During our rip current drifter deployments, swimmers were caught in the rip current while releasing the drifters. Swimmers would float and ride the circulation pattern back to wading depths on the shore-connected shoal, mimicking the drifter response. Thus, the drifters can be considered proxies for floating humans. During one of the rip current circulation pattern deployments (yearday 124), GPS units were placed on several swimmers and they freely floated in the rip current system. An example of one person who floated around a rip current for two revolutions is shown in Fig. 11. The average swimmer revolution was approximately 7 min, similar to average drifter revolution and dye revolutions (MacMahan et al., 2009). In general, beach-goers are told to “swim parallel” or along the shoreline when pulled into a rip current (www.usla.org). However, the alongshore currents feeding the rip current can be as strong as the rip current, which can make swimming parallel difficult (Fig. 11). Furthermore, the rip current circulations patterns tend to be biased to one direction indicating that swimming parallel in the wrong direction could be hazardous. These results suggest that if the swimmer remains calm and afloat, they will be returned to wading depths within a few minutes. The percentage associated with the likelihood that a person would be swept seaward of the breakers was computed by estimating the number of drifters entering the rip current relative to the number of drifters exiting the surf zone. A drifter could enter a rip current either by deployment or re-entering the rip current after completing a revolution. It was found to be 10% drifters that entered a rip current exited the surf zone (Table 1). This is different than the percentage of drifters that exits per hour (Section 4.2). There are times, though infrequent (10%), that swimmers may exit the surf zone. No swimmer exited the surf zone during the experiment.

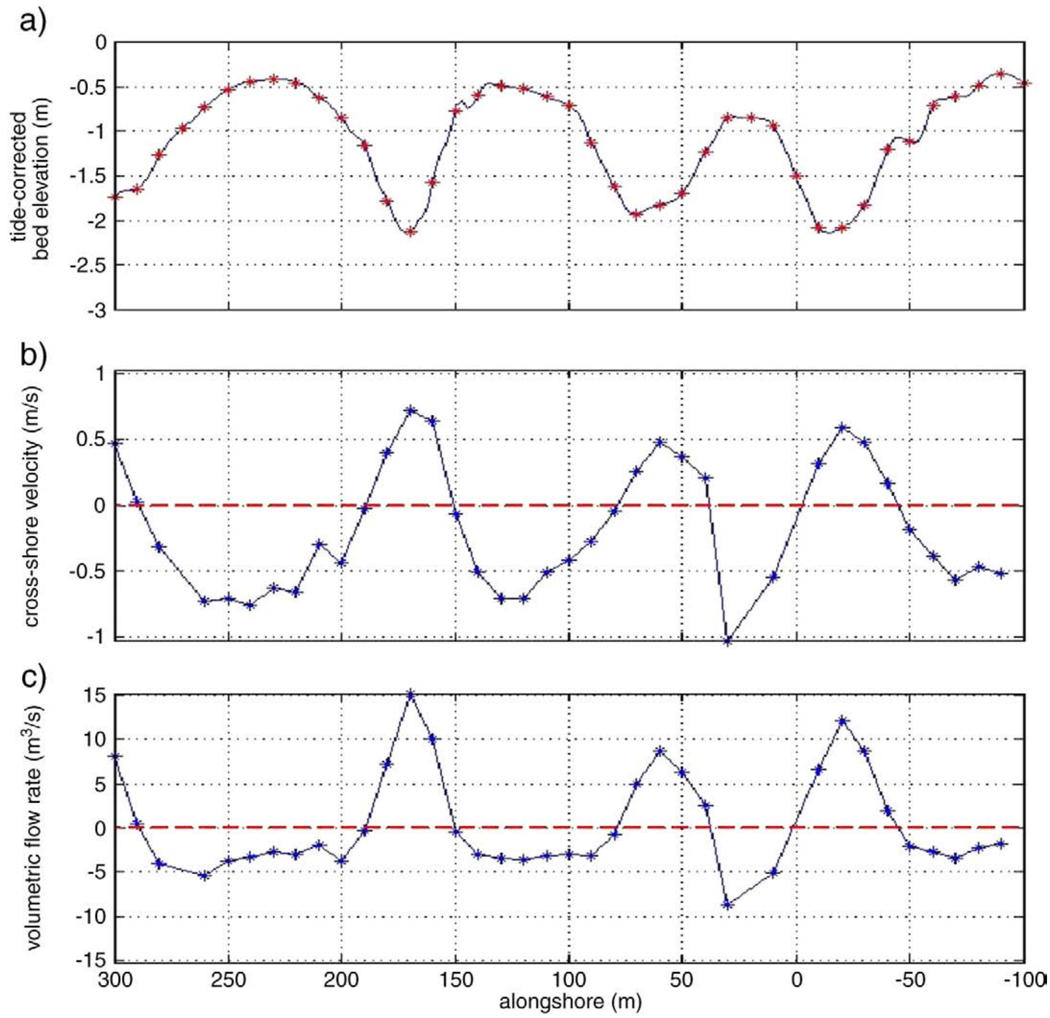

Fig. 9. Alongshore bed elevation (a), drifter averaged cross-shore velocities (b), and volumetric flow rate (c) averaged from $x=80$ to 110 m for yearday 124 and $\Delta y=10$ m.

5. Discussion and conclusions

During this study, Lagrangian rip current circulation patterns are quantitatively documented in the field. These Lagrangian observations provide new insights about the behavior of rip currents and surfzone exchange for open coast rip-channeled beaches. The observed beach rip current circulation pattern consisted of semi-enclosed vortices that retained material within the vortex center and remained within the surf zone. The number of drifters increased toward the center of the rip current vortices for energetic conditions when the circulation pattern was well organized (Fig. 6). Talbot and Bate (1987) found surfzone diatom blooms were correlated with larger breaking waves and rip current events, and the largest concentrations of surfzone diatoms were observed near the center of rip current vortices. Our drifter results support their findings and indicate that despite the large velocities in the rip channel, diatoms, pollution, and other floating material are only rarely transported offshore and are instead retained and concentrated within the rip current vortices inside of the surf zone. Unlike large-scale open ocean vortices that trap and then transport material, the rip current vortex is fixed in one location, as it is coupled to the surfzone morphology, and tends to retain material and does not transport it.

During RCEX, drifters exited the surf zone infrequently, often one at a time, so statistically significant rip current kinematic estimates about a jet could not be determined. Smith and Largier (1995) concluded that rip current pulsating jets (exits) were the primary mechanism for surf zone/inner-shelf exchange. They estimated that it took approximately 3 h to flush the entire surf zone. Assuming an exponential auto-correlation function for rip current velocities, the overall average drifter exit rate of 17% found for the three beaches studied here, corresponds to a relaxation (e-folding) time of 9.5 h. Thus, after 9.5 h, approximately 30% of the initially present drifters are still present in the surf zone and 70% have exited, assuming no drifters returned to the surfzone from offshore. These results are consistent with numerical model results of drifter exits that incorporate Stokes drift (Reniers et al., 2009). The potential onshore surfzone flux was not estimated with these observations.

Rip current velocities are modulated at the tidal frequency, which is a dominant temporal signal (Brander, 1999; MacMahan et al., 2006, amongst others), because the tidal elevation modifies the cross- and alongshore location of wave breaking. This alongshore variability of wave breaking associated with the variability of the alongshore morphology is also modified by the amplitude of the incident short-waves changing the flow patterns and rip current velocity (MacMahan et al., 2006). There appears to be a crude morphodynamic threshold for rip current cross-shore exchange. It was found that for larger waves, intense wave breaking occurred farther offshore in the rip channel inducing coherent vortices on the order of surfzone dimensions, which retained material within the surf zone and toward the center of the vortices. As the morphodynamic coupling decreased

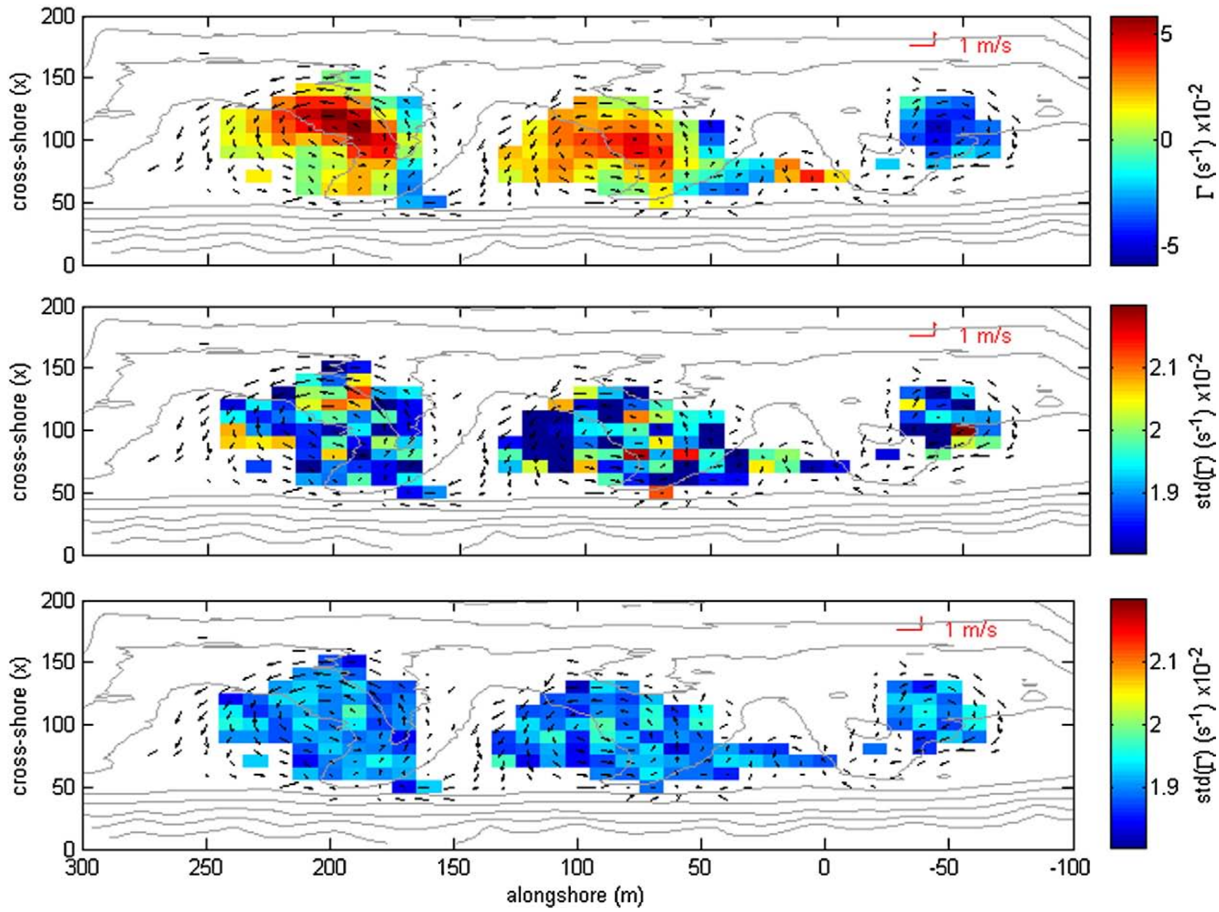

Fig. 10. Monte Carlo vorticity simulations showing (top) mean vorticity, (middle) standard deviation for 123 runs, which represent the average number of observations composing a vorticity estimate for yearday 124, and (bottom) standard deviation for 2000 runs (mean std is 0.019). Vectors represent deployment averaged velocities (as in Fig. 7). The red arrows in the upper right-hand corner provide vector scales. Bathymetric contours are plotted in the background in gray. Vorticity color bar plotted at the right.

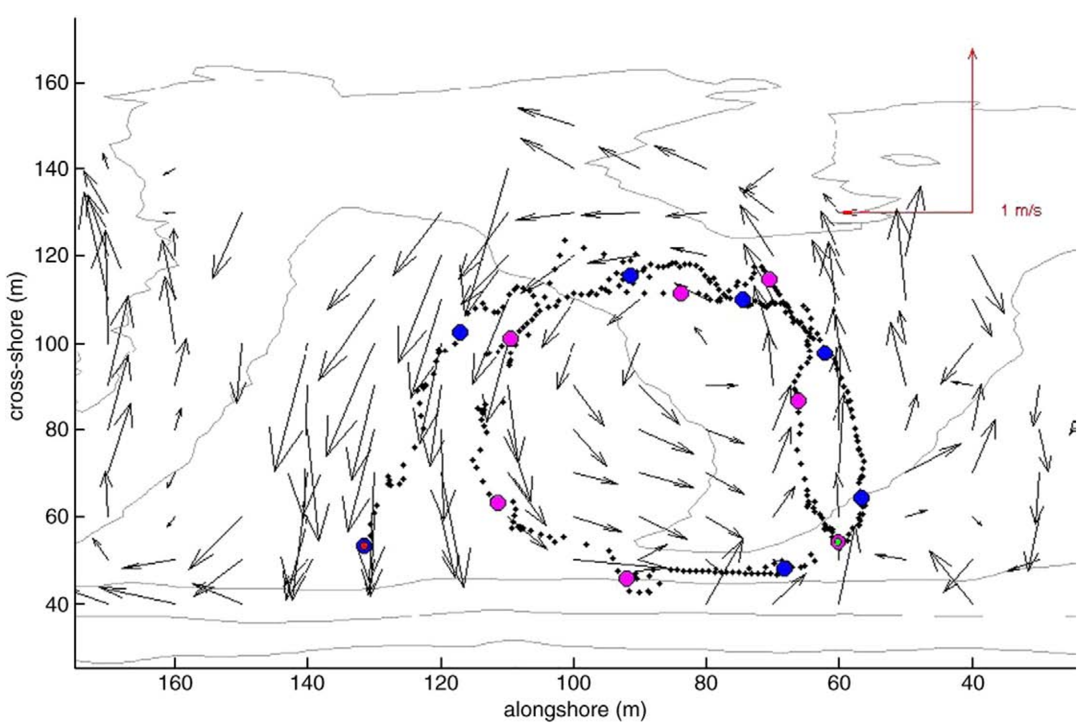

Fig. 11. The dotted line represents the track of a human drifter (floating with the current and tracked with a GPS) on yearday 124 (Table 1). The circles on the dotted line represent location at each 1 min interval starting at zero (green) and ending at 14 (red). The human drifter made two revolutions, the first is shown in magenta and the second is shown in blue. Vectors represent deployment averaged velocities (as in Fig. 7). The red arrows in the upper right-hand corner provide vector scales. Bathymetric contours are plotted in the background in gray.

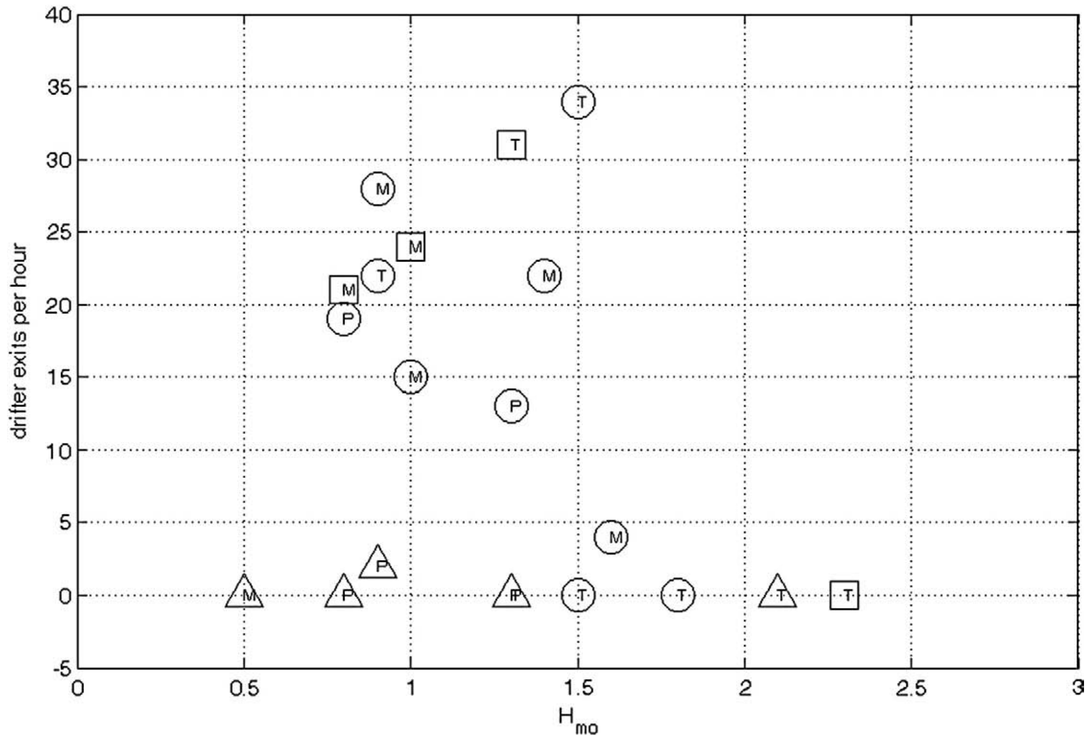

Fig. 12. Surfzone drifter exits for rip current (circles), meandering currents (squares), and alongshore currents (triangles) as a function of significant wave height for Monterey, CA (M), Truc Vert, France (T), and Perranporth, United Kingdom (P).

with decreasing wave height, cross- and alongshore exchange increased. As wave energy continued to decrease and the surf zone narrowed, the flow field became less energetic and floating material was retained in the surf zone and only exchanged in the alongshore.

An attempt was made to correlate the percent of drifter exits with the independent forcing variables of H_{mo}, T_{mo}, h, and combinations of these variables, including Ω. The only representation that seemed meaningful is relating drifter exists to wave height (Fig. 12), which showed drifter exits are smallest for the largest waves, increasing for moderate waves, and decreasing again for small waves. Attempts have been made to relate rip current length scales to wave forcing, sediment characteristics and tidal elevation (Huntley and Short, 1992; Short and Brander, 1999), but most have failed to find meaningful correlations. Although the wave height parameterization allows a qualitative description of the processes within a bounded framework, there was no significant correlation found with these parameters suggesting more complex relations.

Talbot and Bate (1987) tracked dye concentration plumes and diatoms and found that the offshore rip current flux and surf zone flushing varied for different rip current systems. They qualitatively observed rip current systems that supported cross-shore exchange and those that did not and they classified rip currents based on their cross-shore exchange. A modified version of their rip current cross-shore exchange classification system is provided combined with the rip current classification by Short (2007) based on the twenty, approximately 3 h, surfzone drifter deployments for three different beaches described above (Fig. 13). The classification qualitatively describes the potential for rip current exchange for various rip current

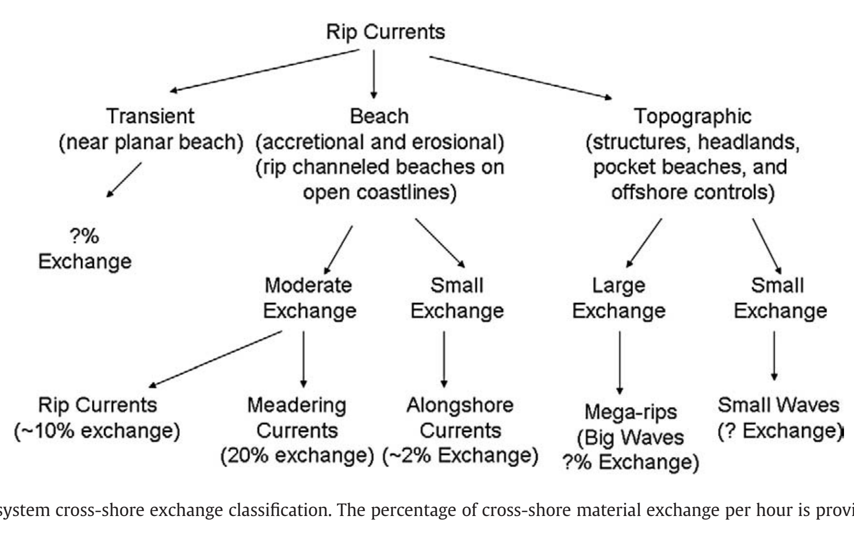

Fig. 13. Rip current system cross-shore exchange classification. The percentage of cross-shore material exchange per hour is provided for each system.

morphologies. There are still many unknowns associated with topographic rip currents and behavior on near planar beaches that include transient motions and undertow.

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