Rip Currents

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Abstract

Rip currents are fast-moving flows, traveling "outward almost at right angles to the shore" (Shepard 1936), creating a natural hazard for beachgoers, who suddenly find themselves in deep water. Field measurements and instrumentation, laboratory techniques, and numerical modeling have improved with time, enabling a more complete description of rip currents now. Surprisingly, there are many types of rip currents that can occur on beaches, and these currents are created by a wide variety of mechanisms that are presented here, along with numerical, physical, or field validation. We also show the potential for prediction schemes for use by lifeguards and beach managers.

1. INTRODUCTION

Rip currents, which are rapid offshore-directed jets of water that originate in the surf zone, are unfortunately one of the most lethal natural hazards worldwide, taking swimmers of all ability levels into deeper water within minutes. They can occur on many types of beaches under a variety of wave conditions and tidal levels. We show that there are many causes of rip currents and present an inventory of the different types, documenting the present understanding and gaps in our knowledge with the purpose of being able to forecast their appearance to help lifeguards and educate people to avoid rip current–related drownings.

Waves, incident from the ocean and carrying energy, mass, and momentum, dissipate across the surf zone by breaking, expending the last of their energy on the dry beach. Required mass and momentum balances force a complex hydrodynamic response in the nearshore, such as wave-induced increases in mean water level at the shoreline (setup) and wave-driven currents in the nearshore zone. This zone, including the surf zone and slightly farther offshore, encompasses all the nearshore current system, and typically can be one to two times wider than the width of the surf zone.

Rip currents consist of two hydrodynamic regimes: (*a*) the surf zone, which is the region of direct forcing by wave breaking, and (*b*) the inner shelf (outside the surf zone), which is the outer portion of the nearshore zone. The rip current flow behavior within the surf zone is often masked by breaking waves, whereas, offshore of the surf zone, the rip current jet moves into relatively quiescent waters, where the jet diffuses into a rip current head. Shepard et al. (1941) pointed out that rip currents are most visible on long sandy beaches, as the sediment- and bubble-laden rip currents exiting the surf zone are more easily identified (**Figure 1**). Inside the surf zone, the seaward-directed portion of the rip current circulation is often identified as occurring in the darker regions associated with deeper channels and nonbreaking waves located between shallower regions of intense wave breaking (**Figure 1*b*,*c***). Usually, rip currents are generated simply by alongshore variations in breaking wave heights (Bowen 1969), and the degree of the alongshore variation dictates their scales and magnitude: Usual ranges are 1–3 surf-zone widths in the offshore direction, 10–500 m in the alongshore direction, and 1–10 m in depth.

Beach type is a key component in rip current scale. Open-coast beaches that are far away from coastal structures or headlands have a plethora of rip current shapes. The two most commonly described are (*a*) an alongshore bar-trough beach that has an incised rip channel (**Figure 1*a***) and (*b*) a terraced beach with an incised rip channel, also referred to as a shore-connected shoal, or transverse bar system (**Figure 1*b***). Open-coast rip currents often occur quasi-periodically along a straight beach and are limited by the surf-zone width and rip-channel spacing. Near the end points of the beach, headlands may exist that deflect a surf-zone-generated alongshore current offshore. Rip currents are commonly found near coastal structures, such as groins or piers (**Figure 1*c***). If the end points of the beach are close together (referred to as an embayed or pocket beach), a large (mega-) rip current can form in the center of the beach that extends significantly farther offshore (on the order of 3–4 surf-zone widths) (**Figure 1*d***) than do open-coast rip currents. A commonly observed type of rip current is found in the center of beach cusps that are spaced O(10–20 m) on steep beaches, which are referred to as swash rips (**Figure 1*e***) because they are a part of the swash zone (wave run-up) processes. Swash rips, although hazardous to beachgoers, are not considered the same as the rip currents described above, which are described as surf-zone rip currents. Alternatively, an offshore hole, shoal, or offshore structure near the shoreline creates regions of wave focusing and higher mean water levels at the shoreline, leading to a rip current directly behind the object or two separated cells (not shown in the figure). The nature of the rip currents shown in **Figure 1*a–e*** is controlled by the bathymetry (morphologically controlled).

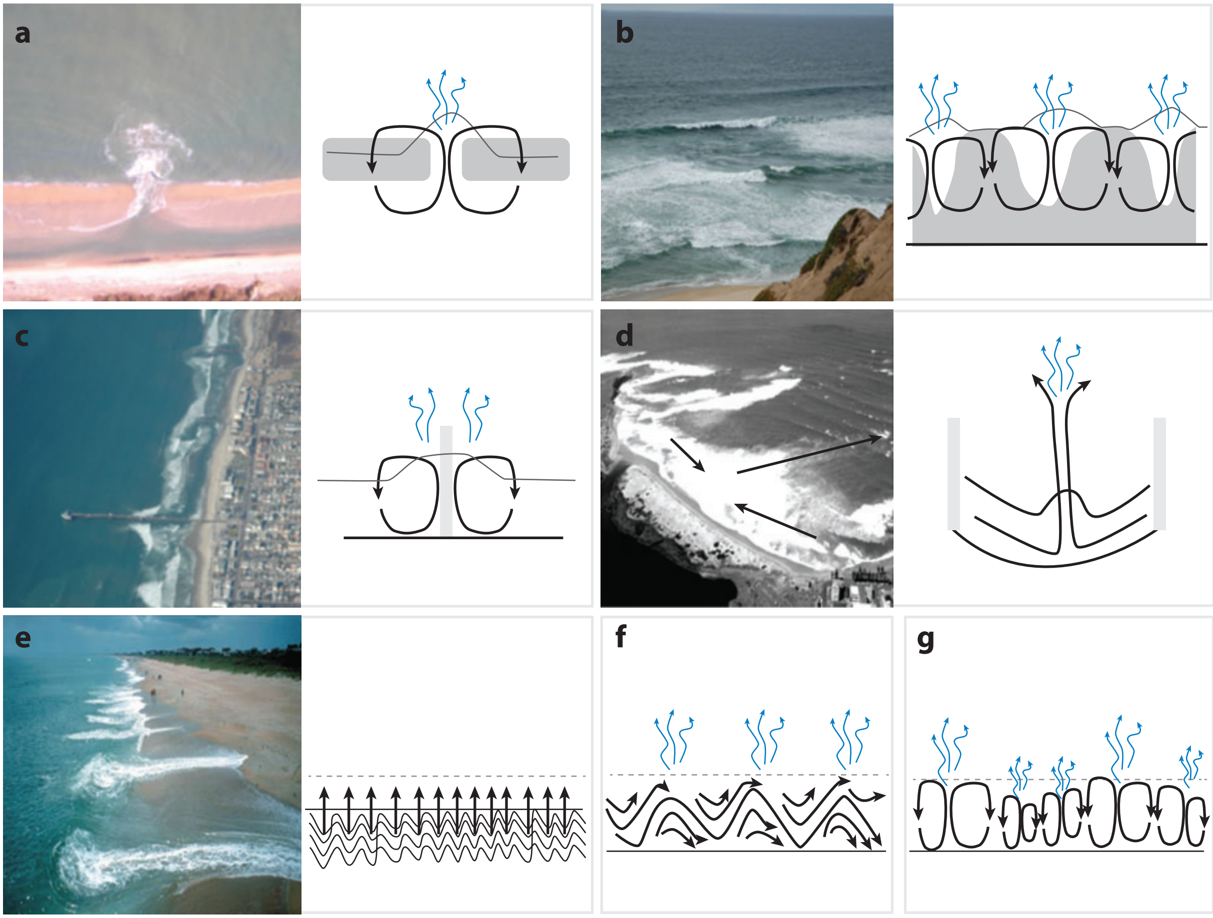

Figure 1

Snapshots and corresponding flow-behavior schematics of seven different types of rip currents. (*a*) Linear bar-trough rip current. (*b*) Semi-enclosed rip currents in Monterey, California, and corresponding flow schematic with the persistent surf-zone recirculation and occasional exit. (*c*) Rip current colocated with the pier. (*d*) Mega-rip current associated with a pocket beach. (*e*) Swash rip currents. (*f*) Obliquely incident wave angle (no corresponding snapshot provided). (*g*) Near-normally incident wave angle (no corresponding snapshot provided).

Another type of rip current, one that is not morphologically controlled and is known as a transient rip current, commonly exists on open-coast beaches. Transient rip currents are episodic (lasting on the order of 15 min) or quasi-periodic and tend to migrate along the beach. Transient rip currents can occur on beaches when the incident wave angle is oblique to the shoreline (**Figure 1*f***) or is near normal (**Figure 1*g***). Transient rip currents generally have smaller offshore flow and offshore extent than their bathymetrically controlled counterparts, but they still remain dangerous to beachgoers.

Figure 1 clearly shows that rip currents exhibit a wide range in dynamics, from semi-enclosed systems with limited offshore extent (**Figure 1*b*,*c***) to narrow offshore-directed rip jets extending well beyond the surf zone (**Figure 1*d***). These differences in the surf-zone circulation and offshore extent affect the allocation and redistribution of phytoplankton, nutrients, sediment, pollutants, and humans across the nearshore zone. On some beaches, pollution from storm runoff would accumulate within the surf zone without the assistance of rip currents.

GPS: global positioning system

Rip currents are not inherently dangerous, but a lack of education and awareness allows these important surf-zone circulations to become deadly. For example, surfers and lifeguards often utilize rip currents to expedite their journey across the surf zone.

In the following we start with an overview of observational and theoretical tools that are used to study rip current dynamics. Next a variety of mechanisms for rip current generation are discussed, including the processes responsible for their temporal variation and their potential coupling to bathymetry. A discussion is provided for the water exchange between the surf zone and the nearshore zone by rip currents and its implications. Finally we present an overview of the actions to take if involuntarily caught in a rip current.

2. MEASUREMENT AND ANALYSIS TOOLS

2.1. Field Measurement Techniques

For decades people have observed the nearshore circulation from the beach. Throwing nearly neutrally buoyant drifters, such as oranges, into the surf zone revealed the presence of rip currents and their flow speeds and directions (Huntley et al. 1988, Shepard & Inman 1950). Later, as technology advanced, fixed electromagnetic current meters were used in arrays to measure the alongshore variability of the nearshore circulation (Guza & Thornton 1989). Data-acquisition systems have significantly improved, becoming smaller and requiring less power. Now, small, portable, self-contained current meters exist, such as acoustic Doppler current profilers, that measure pressure and the three-velocity components over the water column. These new devices can be deployed more easily inside and outside the surf zone on simple tripods or on jetted poles and are used to measure nearshore currents and wave characteristics. This has reduced the manpower and vessels necessary to deploy instruments, as well as increased the number of deployable instruments.

Global positioning systems (GPSs) are now smaller, cheaper, and more accurate, which has allowed field experimenters to move away from bulky sleds or vehicles, such as the U.S. Army's large four-wheeled amphibious buggy, CRAB (Birkemeier & Mason 1984), for measuring nearshore bathymetry. For example, the development of GPS- and echosounder-equipped personal watercraft (MacMahan 2001) has allowed field experiments to be performed on beaches away from coastal infrastructure (such as the fixed pier at Duck, North Carolina, the site of many nearshore experiments and the CRAB). Now the use of more sophisticated drifters, with GPSs, for example (Johnson et al. 2003, MacMahan et al. 2009, Schmidt et al. 2003), allows for Lagrangian measurements and more extensive field experiments revealing more spatial details of rip currents.

Bathymetric measurements can also be inferred from video and radar systems, which view the beach and surf zone. Lippmann & Holman (1990) averaged video images of the surf zone taken over 10 min and observed unique patterns of wave breaking. Waves approaching the shoreline break at a particular depth and continue breaking over shallower depths, until the water gets deeper or the waves rush up the beach. White regions in time-averaged images corresponding to breaking waves highlight the presence of shallow bars and shoals, and darker regions represent deeper water depths, such as rip channels. Using image-processing techniques, video cameras also can provide information on wave height, period, direction, speed, and their run-up on the beach face (e.g., Stockdon & Holman 2000). In addition, nearshore currents can be estimated by using particle image velocimetry techniques with the video images (Chickadel et al. 2003). Owing to the inexpensive cost of video technology, systems have been deployed at a number of beaches over the world, obtaining near-continuous observations of surf-zone bar morphology for years.

VIDEO IMAGING THE NEARSHORE ZONE

Video cameras provide a convenient tool for examining coastal processes and particularly the changes in beach stages with time. The first system of this type was the ARGUS video camera imaging system (Holman et al. 2006, Holman & Stanley 2007), which uses time averaging of video images to discern the areal extent of breaking waves, which are a proxy for the presence of bars and the inner surf zone. A spectacular video of 4 years of the shoreline evolution of Palm Beach Australia (available at **http://www.planetargus.com**) shows the full menagerie of bar shapes that can occur on this beach.

Marine radar systems have also been used to infer surf-zone bathymetry and wave properties (Farquharson et al. 2005, McGregor et al. 1998, van Dongeren et al. 2008). They have the advantage of a large field of view when compared to video; however, the technology is not as fully developed, and the costs are much higher.

2.2. Laboratory Measurements

In the laboratory, there are wave basins with fixed beds used to study the wave-induced nearshore circulation only (e.g., Haas & Svendsen 2002, Haller et al. 1998, Kennedy & Dalrymple 2001, Kennedy & Thomas 2004, Reniers et al. 1997) or moveable beds (e.g., Castelle et al. 2009, Dalrymple & Lanan 1976, Komar 1971) to examine the interaction of the hydrodynamics and the bathymetry (morphodynamics). Wave tanks, although much narrower than a wave basin, have also been used to examine rip current behavior (Dean & Oh 1995, Drønen et al. 2002).

The advantages of a wave basin or tank are that the wave climate is controllable and measurements are easy to take. The disadvantages can be that important physical phenomena, infragravity waves, for example, can be neglected and that results have to be scaled to prototype conditions.

2.3. Theory

As waves from the open ocean approach the surf zone, they undergo refraction and shoaling as a result of varying water depths. At the offshore edge of the surf zone, they steepen and break, and then propagate across the surf zone and run up the beach. The breaking process causes an energy loss and a consequent reduction in the wave momentum flux (radiation stresses). To balance this change in shoreward and/or alongshore directed momentum flux, forces are needed. These primarily arise from a wave-induced change in the mean water level at the shoreline, which provides a hydrostatic force, or a bottom friction force, due to wave-induced currents.

Bowen (1969) and Sonu (1972) were the first to point out the role of nearshore bathymetry and the radiation stresses in driving alongshore and rip currents. A relatively robust set of equations exists for the nearshore circulation based on equations of motion and conservation of mass. These equations are usually vertically averaged (as they are used in shallow water) and then time averaged, usually over the wave period, but sometimes at the wave-group timescale. This is similar to Reynolds averaging, leading to the radiation stress terms introduced by Longuet-Higgins & Stewart (1961), which represent the momentum flux of the waves. These two-dimensional equations are basically the nonlinear shallow-water equations augmented by the radiation stress terms. These equations are coupled with equations for the wave motion, which provide the input to the radiation stress terms.

Simple solutions of these equations can be obtained by linearizing the nonlinear terms and utilizing assumptions about the breaking waves in the surf zone [e.g., Bowen (1969), who developed a linear equation for potential vorticity].

An alternative approach to rip currents has been to examine the circulation and vorticity in the surf zone directly, following Peregrine (1998), who pointed out that rip currents and longshore currents can have the features of coherent turbulent structures. In some circumstances, the flow in the surf zone can be considered as a kind of forced wall-bounded turbulent boundary layer. Peregrine argued that wave breaking does not occur simultaneously along a wave front, but rather in sections. Tracing a complete horizontal circuit on the water surface that intersects the section of breaking wave crest and passes around the nonbreaking end of the wave front shows that the circulation increases with time proportionally to the square of the wave height (Brocchini et al. 2004, Kennedy 2003). Using this approach, Terrile & Brocchini (2007) described the generation of rip currents on a linear bar-trough beach intersected by rip channels by summing interacting point vortices generated by a sequence of breaking waves.

2.4. Numerical Models

Numerical models of the nearshore circulation solve (typically) the time- and depth-averaged equations of motion and conservation of mass. Two different models are usually needed: the wave driver to compute the wave field and the corresponding radiation stresses and the flow model to compute the mean flows induced by the wave field.

The interaction of the waves with the current is achieved by repetitively recalculating the wave field over the evolving flow field (e.g., Haas et al. 2003, Yu & Slinn 2003). Although these models usually do not account for wave-group-related motions, they can be modified to include infragravity waves and wave-group-induced vortical motions that constitute a significant part of the temporal variability of the rip current flows (e.g., Long & Özkan-Haller 2009, Reniers et al. 2004, Roelvink et al. 2009, van Dongeren et al. 2003).

Another wave model for use as a wave driver, based on the time-dependent Boussinesq equations for variable depth (Peregrine 1967), describes waves in shallow water and includes both frequency and amplitude dispersion. These time-domain equations have been extended for greater applicability by Nwogu (1993), who introduced a modified depth, which gives better frequency dispersion than the usual formulations that use the bottom or the still-water elevation; by Madsen et al. (1991), who introduced new terms to allow the model to be used in deeper water; and by Wei et al. (1995), who added additional abilities to model more nonlinear (higher) waves. Corresponding numerical models of these equations have been developed that show that they can accurately describe the waves offshore and within the surf zone when (perforce) empirical relationships are used for wave breaking (e.g., Chen et al. 2000, Kennedy et al. 2000).

Sørensen et al. (1998) found the surprising result that the Boussinesq wave model also predicts the mean water-level changes and wave-induced flows, like alongshore currents, when the time-varying model results are wave averaged, obviating the need for solving the time-averaged hydrodynamics equations. Using the open-source FUNWAVE model (Wei & Kirby 1995), Chen et al. (1999) modeled the Haller laboratory rip current experiment mentioned above with Boussinesq wave theory. We use this model to illustrate some mechanisms for rip current generation.

Morphodynamic models are used to model the shoreline change in response to the wave forcing. These models include the features of the hydrodynamic models, but then also have equations for sediment transport and sediment mass conservation to allow the bathymetry to respond to the waves and currents.

3. MECHANISMS FOR RIP CURRENT GENERATION

The occurrence, size, and strength of rip currents are determined by the beach bathymetry, the wave climate (wave height, period, and direction), the tide level, and, to a much lesser extent, the

MORPHODYNAMIC PROCESS MODELING

Morphodynamic process models attempt to predict the evolution of the nearshore bathymetry subject to changing wave and tide conditions. Two decades of field measurements and video-based observations have shown extremely rich morphodynamic behavior of the nearshore bottom features. Timescales and processes during storm conditions, responsible for the reset of the bathymetry to the offshore bar stage, are quite different than for moderate conditions, during which alongshore variability of the bottom emerges and evolves. This modeling requires, in addition to a detailed description of the hydrodynamics, a sediment transport formulation with great dynamic range and accuracy, as a mismatch in the sediment transport rates will result in a rapid diversion of the model results. Furthermore, the model predictions are dependent on the initial bathymetry and, because the presence of rip channels along an open coast starting from a reset event cannot be predicted in a deterministic sense, there are at best only qualitative agreements with the field data at present.

wind and the composition of the beach. Here we examine the various mechanisms that can create rip currents, beginning with the most common.

3.1. Bathymetric Variations

From extensive field measurements, Wright & Short (1984), and then Lippmann & Holman (1990), showed that nearshore bathymetry tends to follow a progression of stages, from an eroded stage during a storm to a post-storm recovered beach condition, shown schematically in **Figure 2**. In a storm, waves carry sand offshore to create long linear offshore bars. Wright & Short referred to this stage as a dissipative beach, as there is a wide surf zone with many waves contained within it. The ultimate stage occurs when the bar moves back onshore, finally reattaching to the shoreline. They referred to this last stage as a reflective beach, as the beach face has a steeper slope and just few waves within the surf zone. The progression from the storm-induced linear bar stage to the reflective beach takes place in weeks or months. Within days after a storm, the sand bar of the dissipative beach becomes quasi-sinusoidal in planform, which then evolves to a more pronounced crescentic sand bar, with the horns of the crescents facing the shoreline. [This stage has been observed around the world's shorelines (van Enckevort et al. 2003).] The next stage occurs when the horns attach to the beach, creating transverse bars, with incised rip channels and embayments, until finally the bar begins to weld back onto the beach (see **Figure 3**). As this welding processes occurs, a ridge and runnel system develops with an alongshore trough between the bar and the beach face that channels the flow toward an offshore-directed channel. This too can be classified as a rip current system, despite the channelization of the flow by the beach topography.

Rip currents are present during all the evolving beach stages with the current intensity depending on the alongshore variability of the bathymetry. Observations of the changes in the nearshore morphology from the storm-induced linear bars to the final reflective beach condition show that, for a majority of the time, the offshore bathymetry is characterized by crescentic or transverse bars, and only at the initial stages do we have the situation of a linear bar incised with rip channels.

For this initial state, Dalrymple (1978) proposed a model in which the mean water-level setup behind the bar due to the wave breaking on the bar was nonuniform, decreasing from a maximum at the alongshore centerline of the bar to a minimum at the ends of the bar, at which no breaking would take place in the deeper rip channels. The on/offshore momentum balance was achieved by both the mean water-level setup, wave reflection from the bar, and by friction of the onshore flows over the bar. Finally, the alongshore gradient in setup provides the driving force for alongshore currents toward the rip channel. A stagnation point at the shoreward end of the rip channel due to the alongshore flows from each alongshore direction provides the offshore head to drive the rip current. A similar model has been proposed by Belloti (2004), with simpler assumptions about the water-level variation behind the bar.

A laboratory wave-basin experiment of a fixed planar beach with a linear alongshore prismatic sand bar with two rip channels, conducted at the University of Delaware (Haller et al. 2002), showed that this mechanism is basically correct, but that surprisingly the rip current migrated back and forth in the rip channel. This experiment also measured some of the key momentum terms described by Bowen (1969).

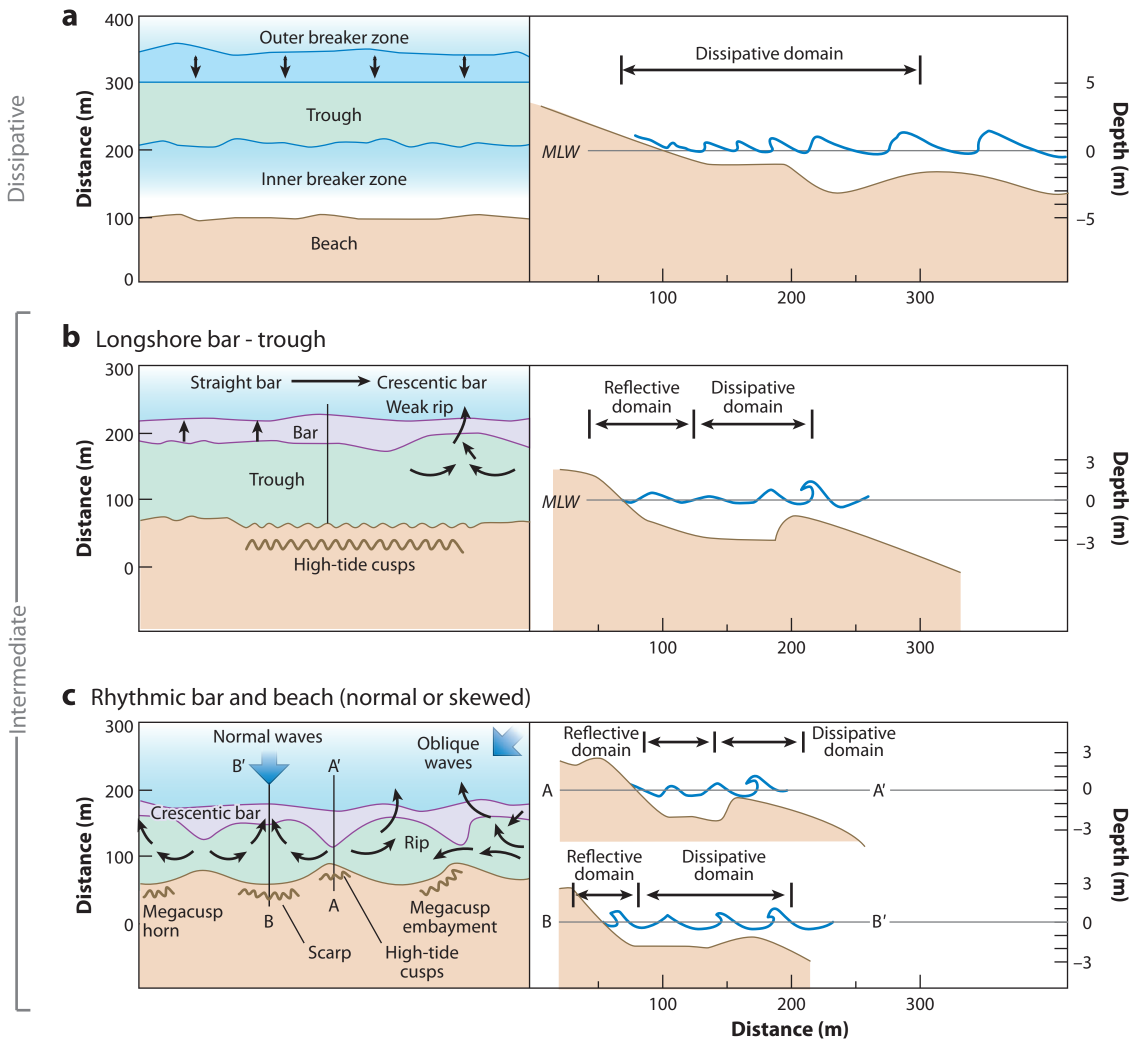

Figure 2

Wright & Short's beach classification by stages as modified by Short (1985). The progression from a prestorm condition to the post-storm welding of the offshore bar to the beach goes from top to bottom.

Most field experiments have been performed on transverse barred beaches (e.g., Brander 1999, MacMahan et al. 2005, Shepard et al. 1941, Sonu 1972; see **Figure 1*b*** and **Figure 2*d***). The mechanisms to drive the nearshore flows on beaches with transverse bars are similar to those for an alongshore bar system as described above, but there are some important, yet subtle, differences in flow response. The rip current flow behavior for Haller et al. (2002) and Kennedy & Thomas (2004) in the laboratory on an alongshore bar system shows that the mean rip circulation patterns are cells that occupy regions both inside and outside the surf zone. The rip current circulation cells for MacMahan et al. (2010b) and Reniers et al. (2009) in the field show that they are located solely within the surf zone, except for episodic squirts. Furthermore, feeder channels or troughs on transverse barred beach systems are substantially smaller and shorter than alongshore troughs. The velocities tend to be largest in the alongshore trough and rip channels on alongshore-bar

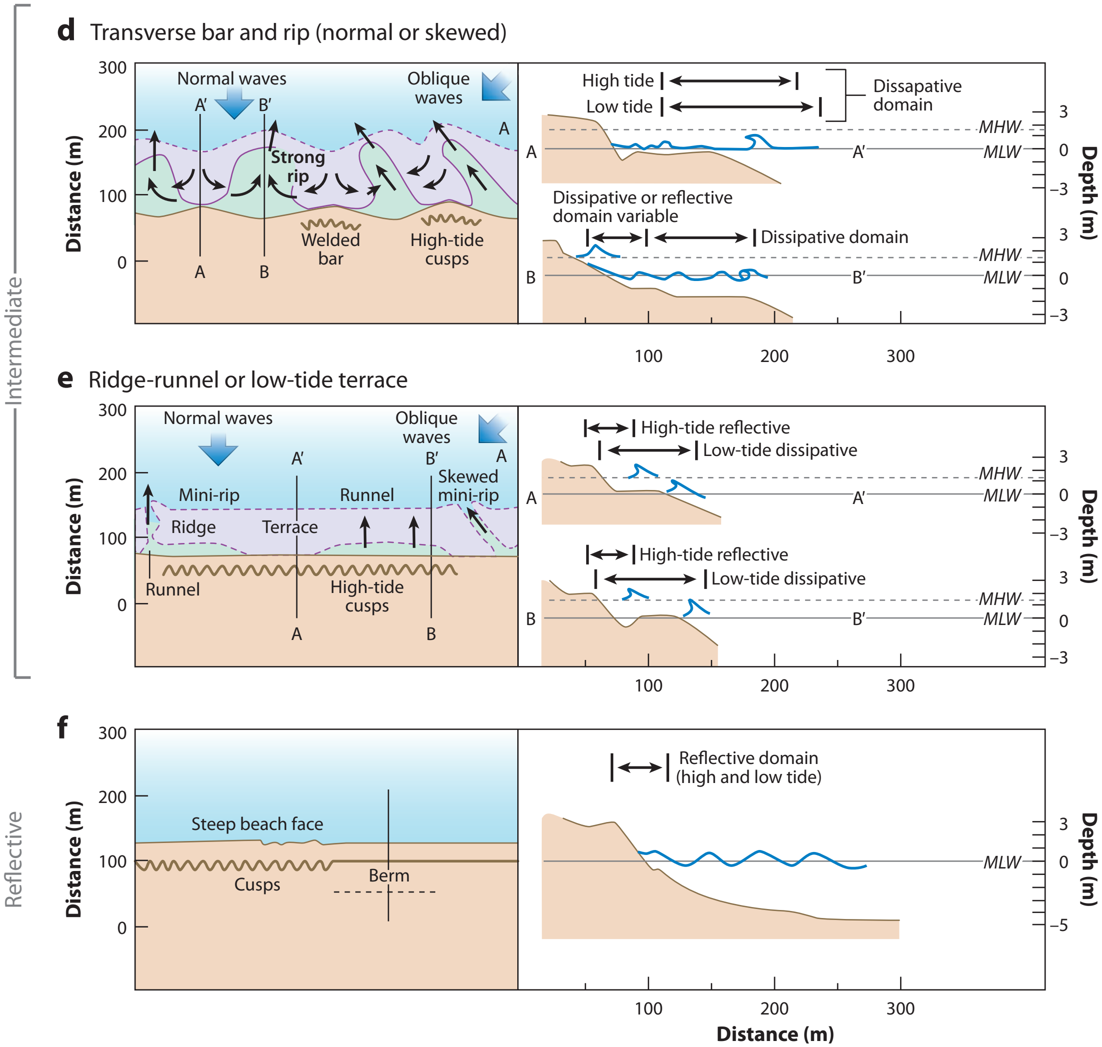

Figure 2

(*Continued*)

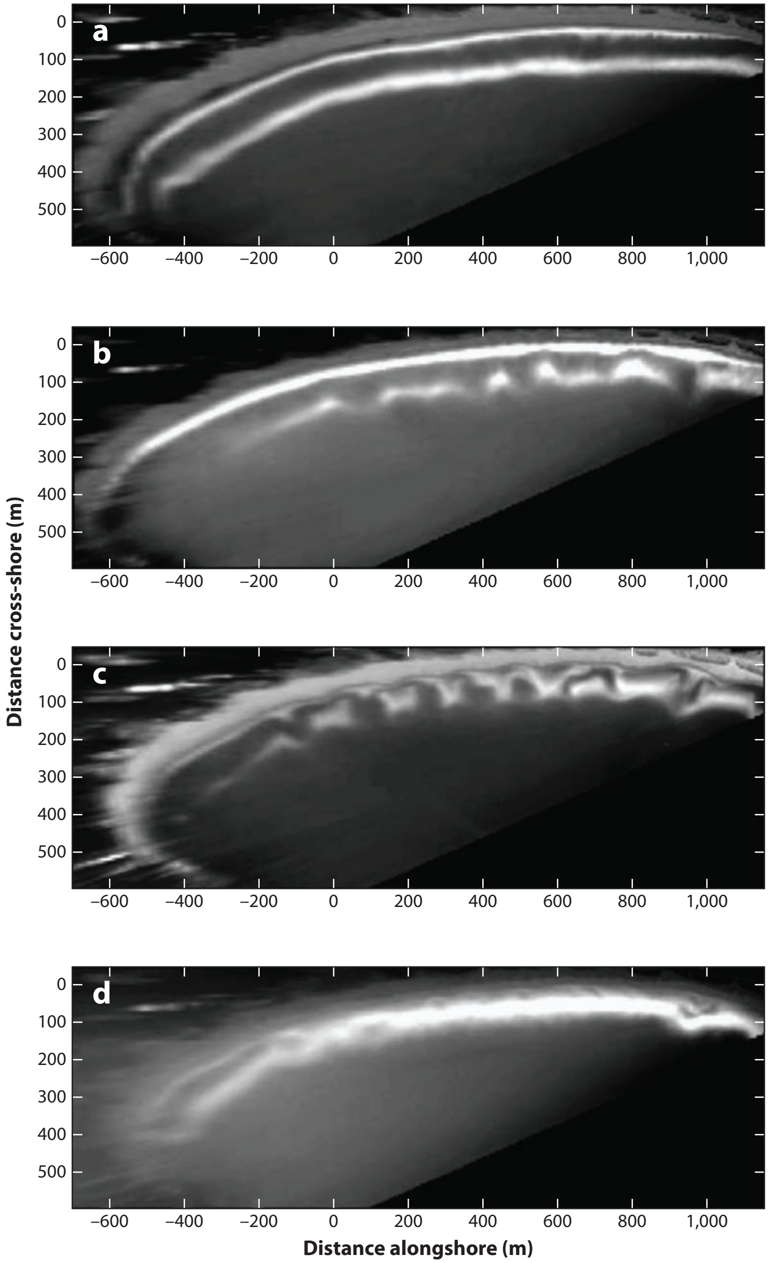

Figure 3

Four beach stages from Palm Beach, Australia, showing the transition of the offshore sand bar with time post-storm. The images come from an Argus video system. Figure taken from Ranasinghe et al. (2004).

beaches, whereas the velocities tend to be largest over the shoals on transverse beaches, which can partially be described by mass conservation arguments. In addition, at extremely low tides, waves pump water across the alongshore bar, which continues to support the existence of a rip current, whereas on transverse bars the rip current diminishes.

Bathymetric alongshore variability leading to rip currents can be subtle. At Torrey Pines, California, a low-energy rip current system fortuitously migrated through an array of stationary pressure and current meters (MacMahan et al. 2008). The alongshore rip-channel slope was approximately 1:300, yet this supported a 0.5 m s^{-1} rip current at low tides. Low-energy rip currents may be the most hazardous of the rip currents owing to their lack of strong visual cues. As subtle alongshore bathymetric variations can induce rip currents, it is believed that most beaches support rip currents, because no beach is completely alongshore uniform.

3.1.1. Cusped beaches. Cook (1970) observed that small periodically spaced cusps on the beach face (scalloping of the beach with horns toward the sea) on the order of 10–20 m in length have flows that run offshore in the middle of the cusp. These small-scale circulations are driven by the local cusp bathymetry as the waves rush up and divide on the horns of the cusps and unite and flow seaward in the cusp bay. Thornton et al. (2007) and MacMahan et al. (2005), among others, noted that megacusps, on the order of 100–200 m in length, had rip currents located in the cusp bay. On the contrary, Komar (1971) noted that wave basins with sandy beaches developed rip currents and cusps, such that the rip occurred on the horns of the cusps, similar to Dalrymple & Lanan's (1976) intersecting wave cusps. Whether the rip emanates from the bay of the cusp or the horns probably depends on the relative importance of wave refraction.

Figure 4 illustrates waves over a cuspate beach modeled with FUNWAVE. There is a slight refraction of the incident waves over the horns of the cusp, creating a higher mean water level there. The flow divides at the horns and flows into the bay of the cusp, creating a strong offshore flow. In this case, size matters. For small cusps, the flow would not go far offshore, being mostly confined to the beach face. For megacusps, however, the offshore flow is significant and can be called a rip current.

3.1.2. Offshore morphology-induced rip currents. The presence of offshore holes or dredge pits in shallow water creates regions of strong local refraction, with the waves refracted away from the center of the hole (Hartog et al. 2008). If the hole is near the surf zone, then there is a reduction of wave height shoreward of the hole and hence less setup. Here we consider a hole in a planar beach with normal wave incidence. Near the edges of the hole, the refracted waves intersect the normally incident waves, resulting in a larger mean water level at those locations. There are now two competing forces: the refracted waves tending to drive alongshore currents away from the hole-beach centerline and the large mean water levels behind the edges of the hole driving alongshore currents both away from the hole and toward the hole. If the hole is small, then the alongshore hydrostatic gradient due to the two setups is large, and there are alongshore currents directed to the hole centerline. As a result, there is a rip current located at the centerline of the hole. If the hole is elongated in the alongshore direction, then there are rip currents at the ends of the hole, as the refraction-forced alongshore current overpowers the alongshore pressure gradient. Peltz (2004) examined the effects of holes in an otherwise planar beach with normal wave incidence. The presence of the hole causes waves to refract away from the hole, leaving a shadow area on the shoreline. Where the refracted waves enter the surf zone, they reinforce the normally incident waves.

Figure 5 shows waves normally incident over an offshore hole, along with the refraction-induced mean water level, the rip current that flows seaward over the hole, and the vorticity of the flow. The region of high mean water level on the beach is similar to that of a rip current,

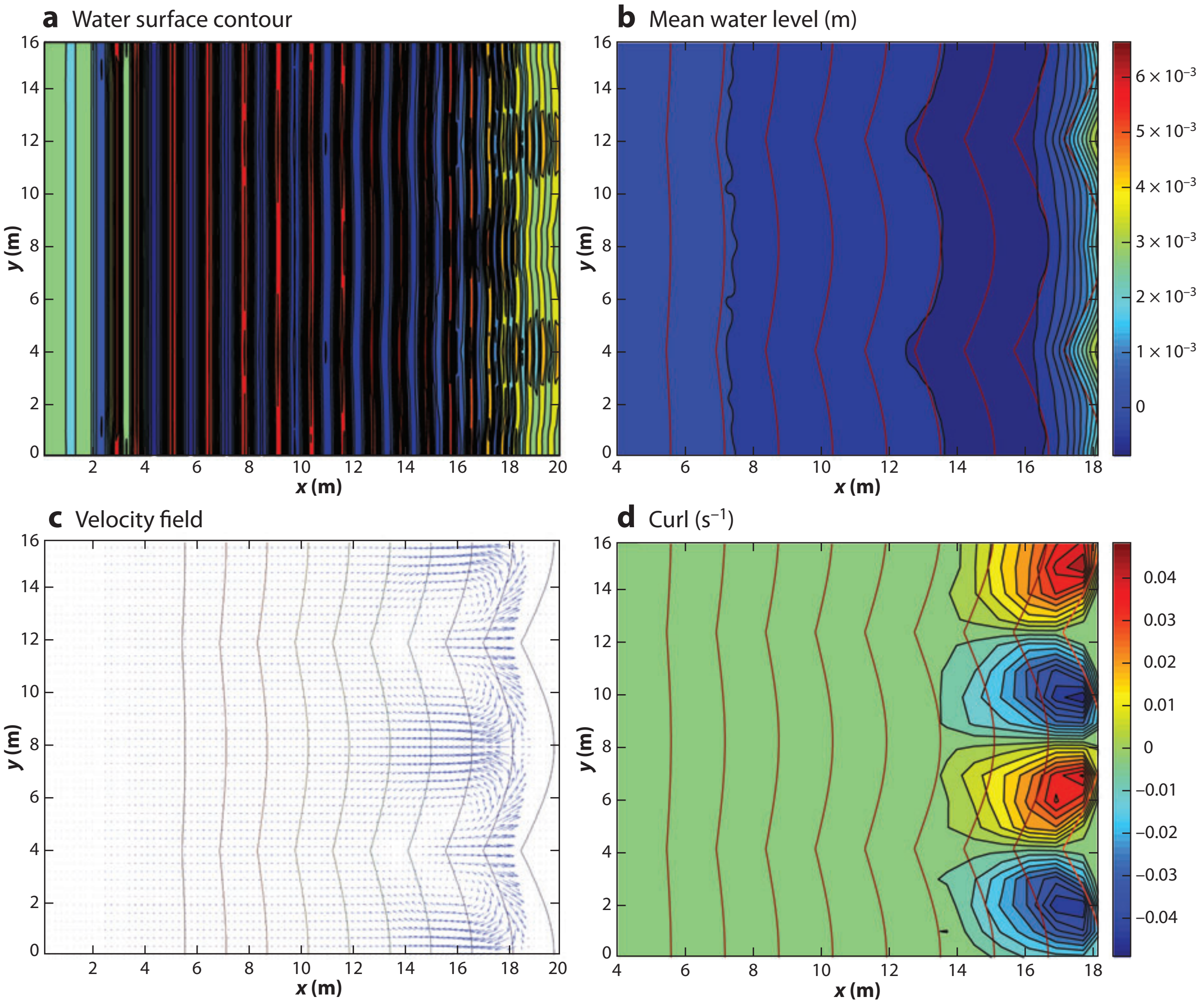

Figure 4

Boussinesq FUNWAVE model of rip currents on a periodic cusped shoreline, with a cusp wave length of 8 m: (*a*) wave refraction for a 1.0-s wave, (*b*) mean water-level contours, (*c*) velocity vectors, $\mathbf{u}_\alpha$, and (*d*) the vorticity. Bottom contours are also shown in the figure.

except that the sign of the vorticity is changed. Here there is an inflow to the higher mean water level from the sea and alongshore currents directed away from this area—just the opposite of a rip current.

A submarine canyon, which is a large offshore hole, can generate large (mega-) rip currents. The Scripps and La Jolla submarine canyons produce rip currents, which can extend well beyond the surf zone (Long & Özkan-Haller 2005, Shepard & Inman 1950). Waves refract over the canyons and generate regional alongshore variations in wave energy, without the requirement of surf-zone rip-channel morphology.

Alternatively, offshore shoals, offshore shore-parallel breakwaters, or an island near the shoreline creates regions of wave focusing and higher mean water levels at the beach, which then lead to a rip current directly behind the object or two separated cells (e.g., see Brocchini et al. 2004).

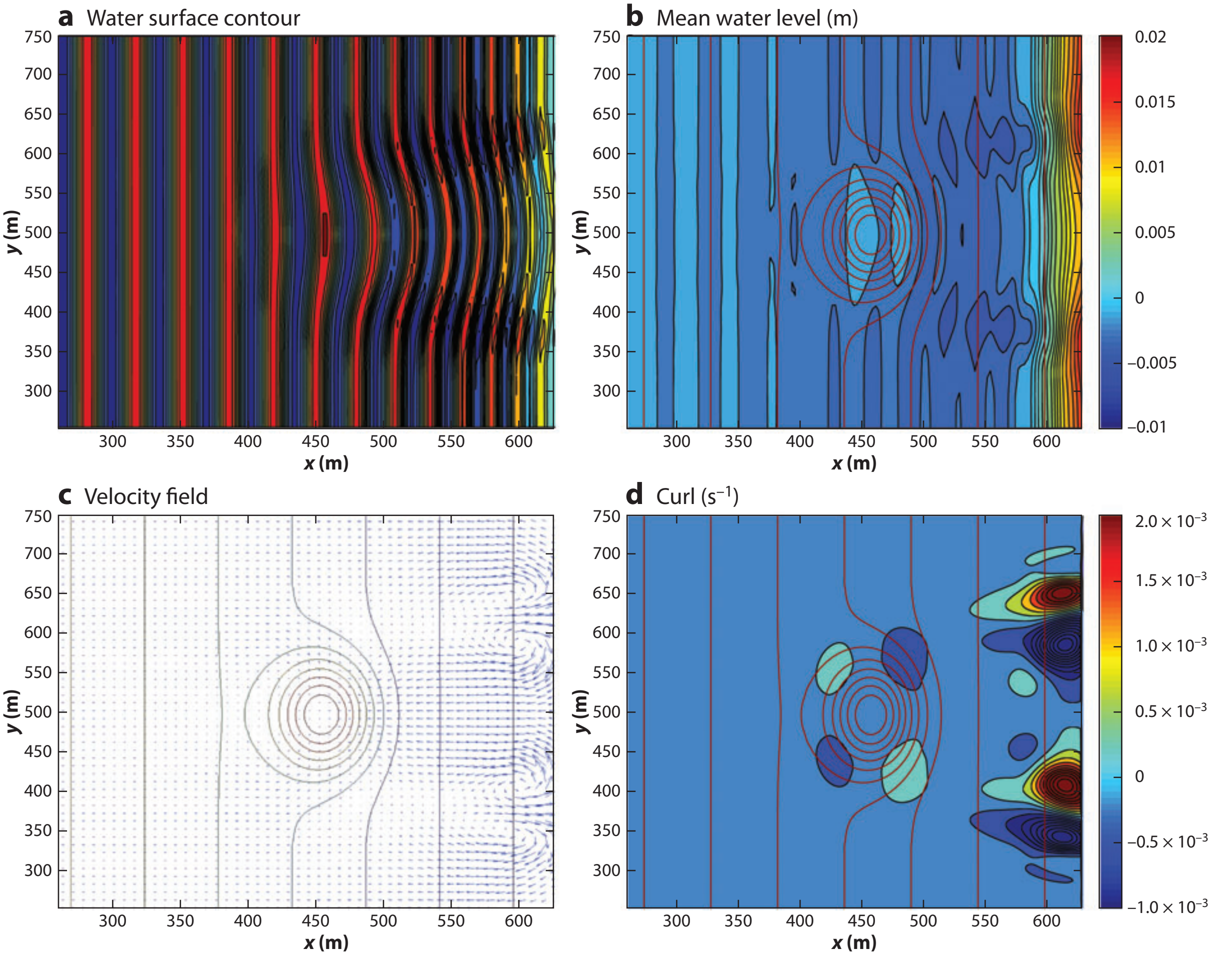

Figure 5

Boussinesq FUNWAVE model of a rip current over an offshore hole located 200 m from the shoreline: (*a*) wave refraction for a 5.0-s wave, (*b*) mean water-level contours, (*c*) velocity vectors, $\mathbf{u}_{\alpha}$, and (*d*) the vorticity. Bottom contours are also shown in the figure.

3.1.3. Structure-induced rip currents. Obliquely incident waves and the presence of coastal structures on the beach lead to rip currents when the structure obstructs the alongshore current (e.g., Dalrymple et al. 1977, Mizumura 1979, Shepard et al. 1941, Wind & Vreugdenhil 1986). The obliquely incidence waves create an alongshore forcing across the surf zone that is balanced by the bottom friction acting on the wave-induced alongshore current. As the alongshore current slows in the vicinity of, say, a groin (a shore-perpendicular rock or timber structure), which acts like a dam, an additional alongshore hydrostatic force develops, creating a higher mean water level at the groin—the stagnation point. This increased mean water level results in a cross-shore gradient in the mean water level and the hydraulic head necessary to drive the offshore rip current.

Wave shadowing behind the structure can result in an eddy that gives an additional offshore flow at the downwave side of the groin. Using GPS-equipped drifters in the field, Pattiaratchi et al. (2009) observed a closed-circulation eddy in the lee of a groin, which produced a rip current adjacent to the groin. This eddy (and rip current) was a function of the wave characteristics (height, incident angle, and period).

Headlands on an embayed beach act like both sides of a groin. At the upwave end of the embayment, the headland shadows the beach, leading to an eddy. At the other end of the beach, the headland acts as the upwave side of a groin, supporting a rip current at that site.

Piers at the coastline, consisting of rows of piling supporting the deck, often are associated with rip currents that flow seaward under the pier. These currents could be a result of the wave dissipation on the piling, resulting in lower wave heights at the shoreline, or a result of the deepening of the bathymetry under the pier by scouring at the piles.

In some cases structures are meant to generate rip currents, as is the case with artificial surfing reefs, to assist the surfers in getting out of the surf zone (Black & Andrews 2001, Cáceres et al. 2010), although they may lead to erosion of the shoreline (Ranasinghe et al. 2006).

3.2. Wave-Wave Interaction Models

Rip currents can also be created on beaches that have no bathymetric variation or coastal structures by the interaction of different types of waves. Edge waves, directional sea states, and wave groups are all possible generation mechanisms for rip currents.

3.2.1. Edge waves. One of the first alternative mechanisms for rip current genesis, which did not require alongshore bathymetric variability for the variation in the alongshore wave height, was the assumption of the simultaneous occurrence of incident ocean waves along with edge waves of the same frequency, which are waves that are trapped at the shoreline and travel along it (Lamb 1945). The superposition of these two types of waves gives a periodic alongshore variation in breaking wave height, as verified by theory and laboratory (Bowen & Inman 1969). However, according to Guza & Inman (1975), synchronous edge waves would only exist on a highly reflective beach; otherwise the presence of breaking waves would rule out the existence of the synchronous edge wave.

3.2.2. Wave-group-forced rip currents. Dalrymple (1975) noticed that two intersecting trains of waves of the same wave period but different directions would create straight nodal lines of zero wave amplitude, which do not move with time. For wave trains of equal and opposite angle to the shore normal, these nodal lines are perpendicular to the shoreline at a predictable periodic alongshore spacing. These lines of zero wave amplitude are the location of the rip currents, which are forced by the high mean water level that occurs where the incident waves reinforce in the surf zone. **Figure 6** shows the FUNWAVE model results for two synchronous intersecting wave trains, including the instantaneous water surface, the mean water level, the wave-induced mean velocities at Nwogu's modified depth ($\mathbf{u}_\alpha$), and the mean vorticity. For this case, the offshore flowing rip current shows a sinuous shear instability, as discovered by Haller & Dalrymple (2001). This current, flowing seaward along the nodal line, affects the incoming wave through wave-current interactions, such that nodal line is not clear through the surf zone in **Figure 6*a***. In a laboratory model with a sandy beach, Dalrymple & Lanan (1976) showed that the intersecting waves and rip currents created beach cusps, with the waves rushing up the bays and flowing seaward on the cusps. This is the opposite flow circulation that occurs on a cusped shoreline with normal wave incidence, as shown in **Figure 4**.

Hammack et al. (1990) examined the nonlinear version of this case, showing in the laboratory that intersecting nonlinear shallow-water waves, described by the Kadomtsev-Petviashvili

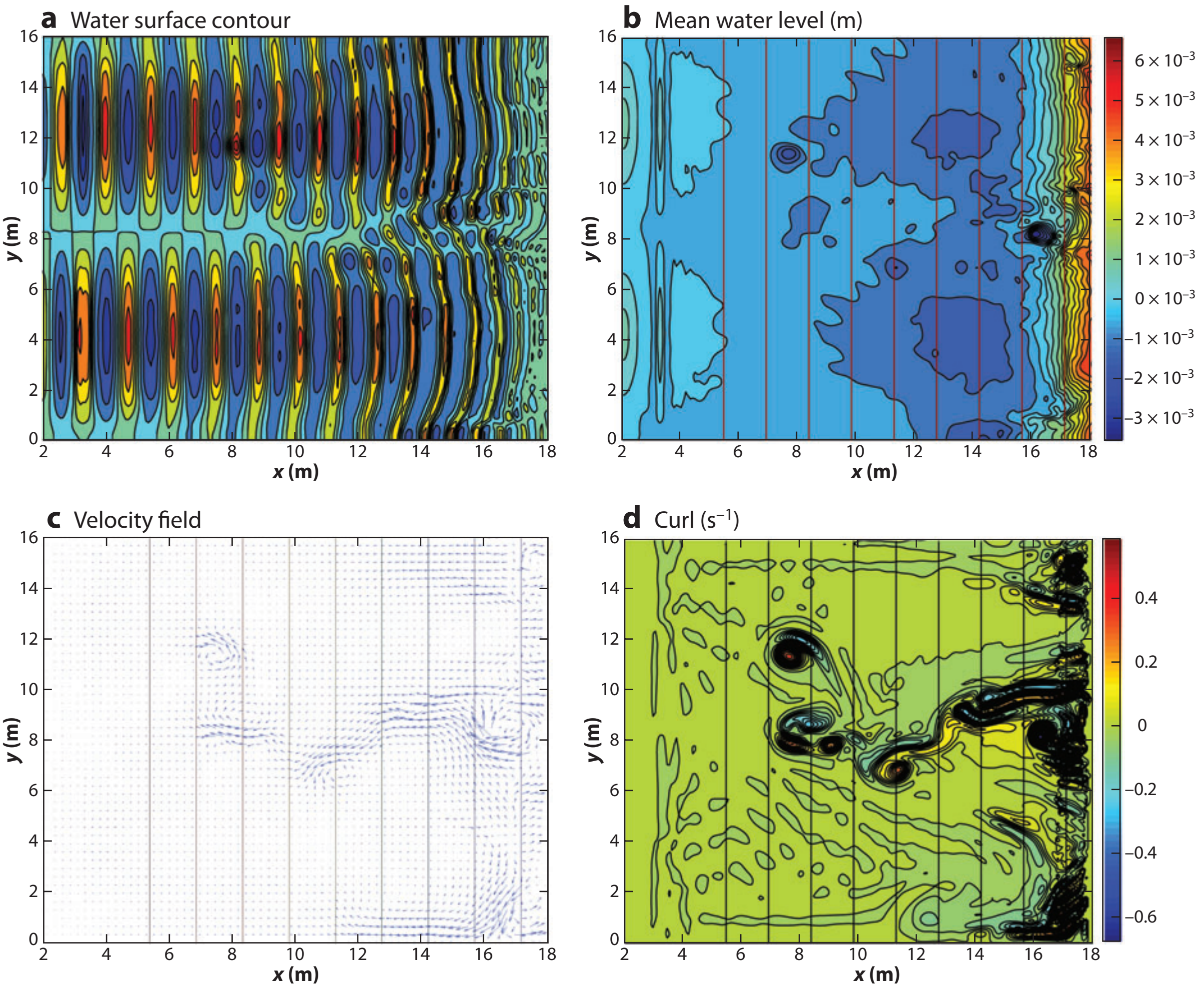

Figure 6

Boussinesq model of a rip current created by two synchronous wave trains: (*a*) contour of the free surface, showing the shore-normal nodal line, for a 5.0-s wave, (*b*) mean water-level contours, (*c*) velocity vectors, $\mathbf{u}_\alpha$, and (*d*) the vorticity. Bottom contours are also shown in the figure.

equation, develop a honeycomb pattern of wave crests and corresponding hexagonal nodal lines and that the rip currents follow the nodal lines offshore.

As a part of a major field experiment (Seymour 1989) at Torrey Pines Beach, California, Tang & Dalrymple (1989) examined the relationship between the offshore wave groups (measured with an offshore linear array of pressure sensors and using a square law detector to determine the wave envelopes) and slowly migrating rip currents as measured by a linear array of 10 electromagnetic current meters in the surf zone (Guza & Thornton 1989). One of the tools they used was a frequency–alongshore wave number ($f - k_y$) spectrum, as used by Huntley et al. (1981) for edge waves. Using a canonical correlation analysis, they found that there was a correlation between the offshore wave groups and the migrating rip current system at the beach at very low frequencies (VLFs), less than 0.0015 Hz.

As the sea state in the nearshore is usually a combination of waves from many different sources, waves tend to be groupy in nature, which means that the wave groups have a spatial and temporal variability in wave height (depending on their frequency-directional spectral distribution). As the groups encounter the surf zone, there are alongshore variations of the waves at the breaker line that can engender alongshore and rip currents.

One of the first laboratory approaches to wave groups was by Fowler & Dalrymple (1990), who created bichromatic groups in a wave basin by superposing two wave trains from different directions with slightly different wave periods. The superposition of the two wave trains created nodal lines that migrated along the shoreline. As long as the migration speed was low, rips flowed seaward along the moving nodal lines. If the frequency difference between the wave trains is zero, the rip currents are stationary, as shown in the laboratory by Dalrymple & Lanan (1976).

Ryrie (1983) showed that a narrow single wave group can generate a surf-zone eddy that persists long after the wave group has been dissipated by breaking. For more realistic alongshore length scales of the group, two counter-rotating eddies are generated. Eddy-eddy interactions can then lead to significant mixing of the alongshore current or potentially even a displacement of the alongshore current maximum from the bar to the trough (Bühler & Jacobson 2001).

In the case of a random sea state (i.e., with stochastic wave-group forcing), these interactions between the individual eddies (**Figure 7*b***) created by each of the ever-changing wave groups entering the surf zone (**Figure 7*a***) can result in transient rip currents (**Figure 7*b*,*c***) (Johnson & Pattiaratchi 2004, MacMahan et al. 2010a, Reniers et al. 2004). The timescales of the transient rips are primarily determined by the constructive/destructive interference with eddies generated by subsequently arriving wave groups, as demonstrated by Long & Özkan-Haller (2009).

3.3. Strong Alongshore Currents and Shear Instabilities

For most models of rip currents, the rips are the major circulation feature, and the incident waves approach at angles nearly normal to the beach. In a surprising field experiment characterized by waves approaching the surf zone with large angles of incidence, Oltman-Shay et al. (1989) discovered that strong alongshore currents driven by the obliquely incident waves can meander wildly. As explained by Bowen & Holman (1989), the presence of strong shear in the alongshore current cross-shore profile leads to a shear instability and the meandering of the alongshore current in the cross-shore direction. A laboratory verification was shown by Reniers et al. (1997). Nonlinear numerical modeling by Allen et al. (1996) and Özkan-Haller & Kirby (1999) showed that for strong shear the meanders can grow and form eddies that either move along with the alongshore current or are ejected from the surf zone, forming transient whirlpool-like flows. When paired up, these eddies can create strong flows (i.e., rip currents) (Peregrine 1998).

In addition, the coexistence and potential interaction of shear instabilities and wave-group breaking-induced vortices may exist, according to Haller et al. (1999), who used field data from the U.S. Army pier at Duck, North Carolina, to show that, for obliquely incident waves, the modulation of short-wave forcing by groups sometimes occurs at the time and spatial scales of free shear instabilities, potentially leading to explosive growth of the shear instabilities (Shrira et al. 1997). However, in many cases, they failed to find coherent modulation of short-wave forcing due to its broad distribution in k_y space.

3.4. Instability Models

For a prismatic beach profile (that is, no alongshore variation in bathymetry), there is no alongshore variation in wave refraction, so that there are no alongshore variations in wave breaking. For normal

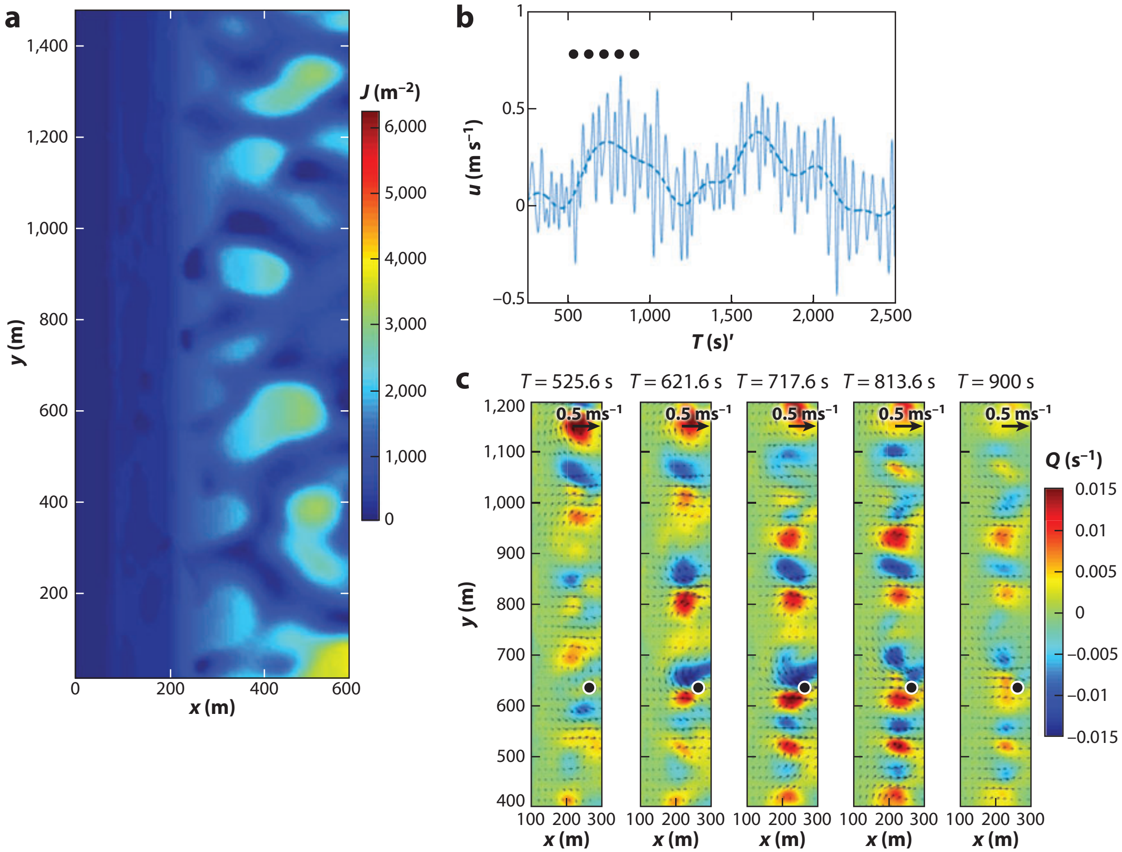

Figure 7

Calculated very-low-frequency (VLF) response over alongshore uniform bathymetry showing transient rips forced by wave groups made up of a random sea state with directional spreading. (*a*) Snapshot of spatial variability of wave energy with dissipation on the bar and near the shoreline. (*b*) Velocity time series within the surf zone (corresponding to the *black dot* in panel *c*), showing mean, VLF, and infragravity motions (*solid line*) and mean and VLF only (*dashed line*). (*c*) Snapshots (at times indicated in panel *b*) of the VLF-vorticity and accompanying velocity field showing the presence of transient rip currents.

wave incidence, there also would be no alongshore current. The decreasing momentum flux of the incident breaking waves gives rise (in the onshore direction) to an alongshore-uniform wave setup. In a certain sense, this is analogous to applying a load to a top edge of a vertical plate. For small loads, the plate remains planar, whereas, for larger loads, a perturbation of the plate leads to buckling.

3.4.1. Theoretical stability models. An approach to the rip current problem in this case is to consider a modal or a stability analysis, using linearized forms of the equations for conservation of mass, momentum, and wave energy. Here there is a basic equilibrium state, consisting of normally incident waves and a breaking-induced equilibrium wave setup. There is no mean depth-averaged flow (as the shoreline represents a nonflow boundary condition). For the case of a nonerodible bed, Dalrymple & Lozano (1978) and Falqués et al. (1999) show that, if wave refraction on currents is included in the model by adding another equation, there is a mode of nearshore circulation that consists of seaward-flowing rip currents that create wave refraction, which drive local longshore currents that feed the rip current. [Laboratory experiments (Dean & Oh 1995) in a narrow wave tank with a steep erodible beach showed that the offshore flow in the rip current steepened the incoming waves sufficiently and the refraction effect was not observed; the beach may have been too steep.]

Hino (1974) was the first to include an erodible bed in a stability model on an initially planar beach. Additional equations were necessary to account for the sediment transport by waves and currents and a conservation of sediment, so that the bathymetry changes with the erosion or deposition. He obtained a solution that consisted of circulation cells and a periodically cusped shoreline. Other studies include Deigaard et al. (1999), Falqués et al. (1999, 2007), and Damgaard et al. (2002).

3.4.2. Morphodynamic numerical models. Linear stability models provide insight into the most likely patterns to initially emerge from an alongshore uniform equilibrium state and steady forcing. In reality, the wave forcing changes continuously, and the bathymetry is never truly uniform. In addition, because the morphodynamic timescales are significantly longer than the hydrodynamic timescales, the beach is rarely, if at all, in equilibrium. To account for these effects, morphodynamic numerical models have been developed, which include the feedback between the hydrodynamic forcing and the evolving bathymetry. These models are capable of predicting the generation of nonlinear nearshore morphodynamics, including the realistic quasi-regular distribution of rip channels and shoals (Calvete et al. 2005, Castelle & Bonneton 2006, Damgaard et al. 2002, Drønen & Deigaard 2007, Reniers et al. 2004, Smit et al. 2008) and corresponding rip current circulations.

At present, comparisons of morphodynamic models with observations have mostly been qualitative. Comparisons of length scales of bar-shoal patterns with video-based observations and quantitative comparisons of the generation and evolution of rip channels are recent developments (Bruneau et al. 2009, Smit et al. 2008). It will take some time before a satisfactory agreement is obtained. Nevertheless, the future of rip current prediction might include real-time simulation of the nearshore hydro- and morphodynamics on a given beach, using meteorological and wave data from offshore, to drive numerical models including the assimilation of bathymetric observations (van Dongeren et al. 2008).

4. TEMPORAL MODULATIONS AND BEACH SAFETY

Rip currents fluctuate on various temporal scales, from minutes to weeks, which has importance for beach safety. Rip current strength increases with increasing wave height. Thus the frequency of storms (on the order of days to weeks) can affect the hazardous nature of rip currents. Even though the rip current velocity increases with increasing wave height, there is a drop-off in rip current related rescues, as beachgoers tend not to enter the ocean when there are large waves.

4.1. Tides

Tides long have been known to affect the strength of rip currents (e.g., Aagaard et al. 1997, Brander & Short 2001, Shepard & Inman 1950, Sonu 1972) with the primary effect usually being that the rip currents intensify as the tide level falls. Therefore, low tides, and in particular spring low tides, can be the most dangerous. The temporal variations associated with storms and tides are quite predictable, and most beachgoers and lifeguards can determine the times of the most hazardous rip currents.

An example of tidal variation is shown in **Figure 8**. One explanation is that the effect of the falling tide is to emphasize the bathymetric effects. Increased breaking over bars, a wider surf zone, and a relatively more pronounced rip channel would all be responsible for increasing rip intensity. Moreover, as the water level falls even further, sand bars can become intermittently exposed, further channelizing the flow behind the bar.

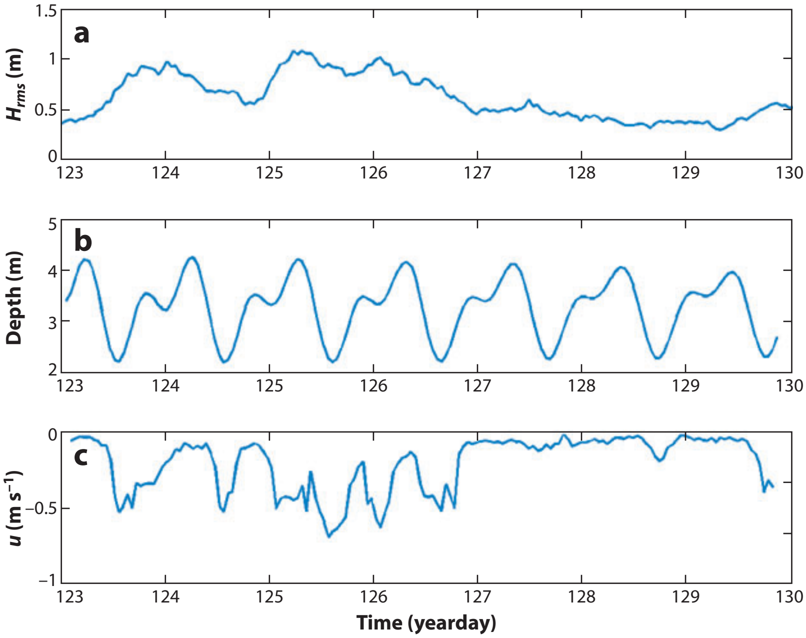

Figure 8

Hourly significant wave height, mean water depth, and depth-averaged cross-shore rip current velocity for an upward-facing acoustic Doppler current profiler deployed in 3-m water depth in the throat of a rip current at Sand City, Monterey, California, during Rip Current EXperiment (RCEX) in 2007.

Interestingly, on some beaches, the surf-zone bathymetry may support the development of stronger rip currents near high tide. Again this is associated with the conditions that support the maximum alongshore variations in wave breaking. One example of this case is a cusped shoreline, and another was observed at Truc Vert, France. An evolution of flow behavior as a function of tidal elevation is shown in **Figure 9**. The beach system has an offshore (storm-generated) crescentic bar system. It is hypothesized that the crescentic bar dissipates the wave energy at low tides, affecting the high-tide morphodynamics.

An interesting flow evolution was observed over a tidal cycle and for different wave energy on a beach characterized by transverse bars (J.A. Brown, J. MacMahan, A. Reniers, J.W. Brown, E. Thornton & T. Stanton, unpublished manuscript). At low tides or for large waves, a rip current was present (**Figure 10**), but as the tidal level increased or storm energy decreased, the local hydrodynamic coupling with the surf-zone rip morphology became less significant. This resulted in a meandering flow field, which was in between a rip current and alongshore sinuous flow pattern. As the tide increased or wave energy decreased further, the meandering current adjusted into a sinuous alongshore current that was coupled to the underlying morphology. Thus, within a few short hours, a range of flow patterns can exist on a beach where strong bathymetric rip current morphology exists.

4.2. Very-Low-Frequency Motions

Haller et al.'s (2002) laboratory wave-basin experiment of a linear alongshore prismatic sand bar with two rip channels exhibited the surprising result that, although the rip current occurred in the provided rip channels, the offshore rip flow was unstable and oscillating from side to side in

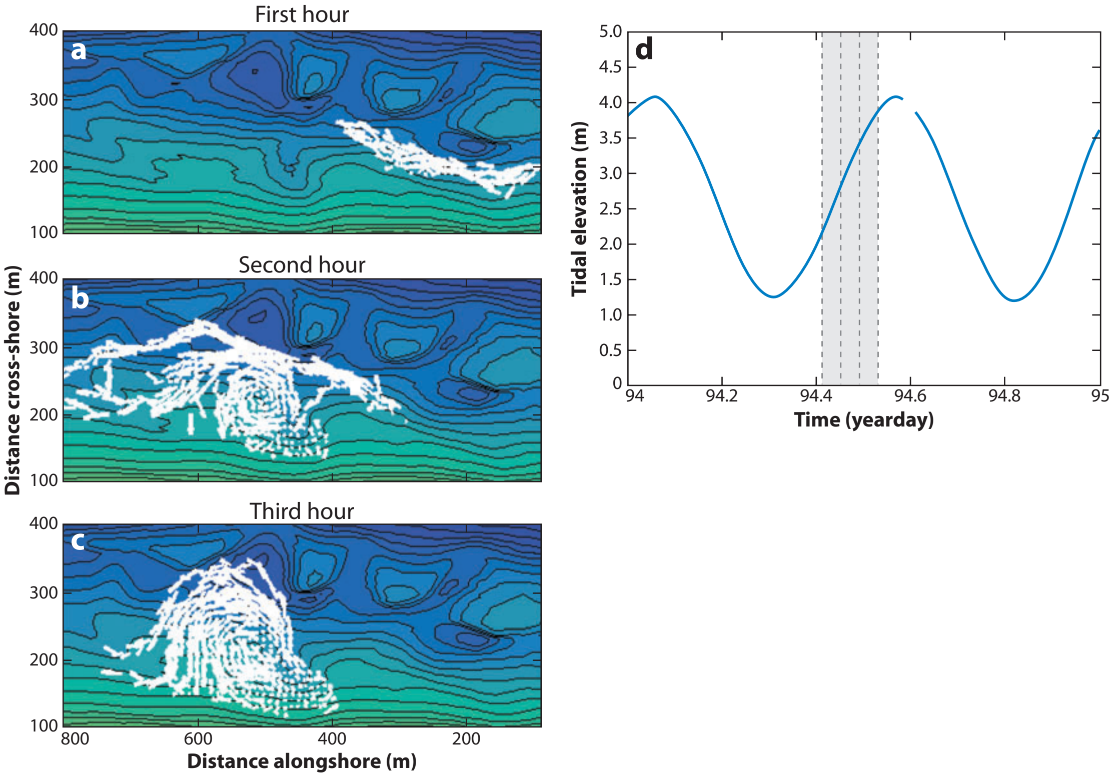

Figure 9

Drifter velocity data sorted into 10 m × 10 m bins, hourly averaged, and plotted for three different tidal elevations for Truc Vert, France, in 2008 (*a–c*). Bathymetric contours are plotted in the background of the drifter plots. (*d*) The tidal elevation is shown with time, along with three time-averaging bins (*shown in gray*).

the rip channels (which were wider than the jet widths). Haller & Dalrymple (2001) argued that the cause was shear instabilities, which are to be expected when a jet encounters quiescent fluid and which have lower frequencies than the incident waves. These instabilities (both sinuous and varicose) thus provide another mechanism for temporal variations in rip currents. Kennedy & Zhang (2008) postulated that the entire nearshore circulation system can be unstable, based on an eigenfunction analysis.

MacMahan et al. (2004b) found in the field, using $f - k_y$ spectral analysis, that the rip current cells oscillated primarily in the cross-shore at frequencies less than 0.004 Hz. These surf-zone motions were referred to as VLFs and decayed rapidly beyond the surf zone. In line with the results by Reniers (2007), Yu & Slinn (2003) numerically found that monochromatic waves generated a rip current jet that extend well beyond the surf zone, and the associated VLFs had a maxima outside the surf zone differing from the field observations. These calculations were based on a synthetic smooth rip-channeled bathymetry. However, when a realistic bathymetry was used, the offshore extent of the rip currents changed dramatically (compare panels in **Figure 11**), with rip currents mostly contained to the surf zone. For this case rip current instabilities were present in the modeling results; however, their cross-shore distribution was incompatible with the observations. Only when a realistic directionally broad spectrum was used as the boundary condition were the VLF maxima largest in the surf zone, similar to the field observations. This suggests

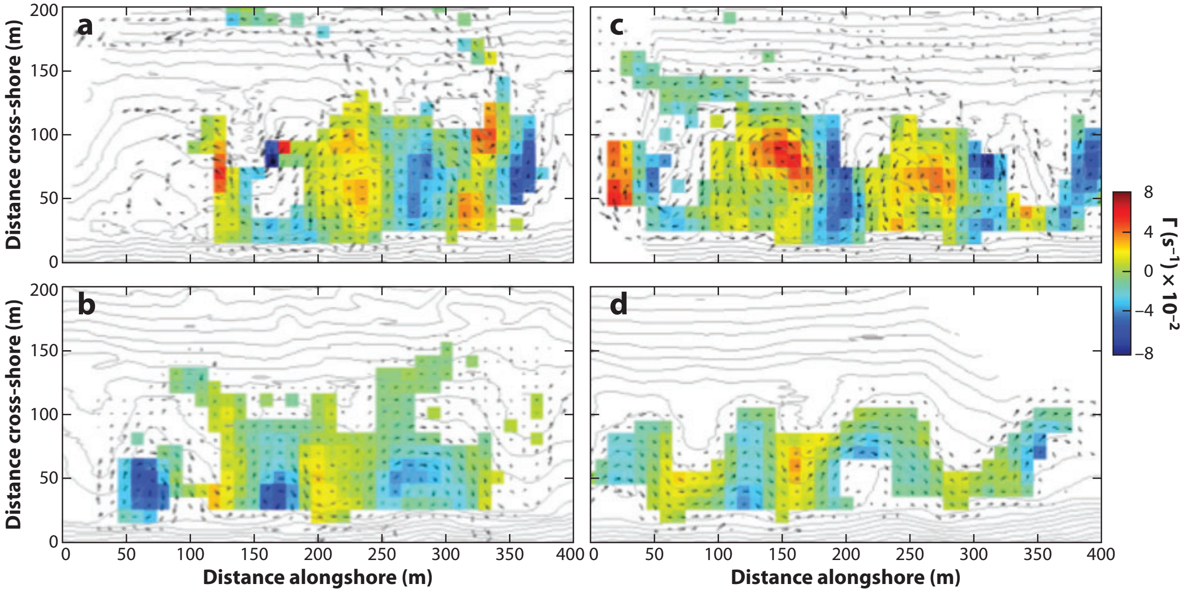

Figure 10

Drifter velocity data sorted into 10 m × 10 m bins and averaged over the deployment duration (3 h) for Sand City, Monterey, California, during Rip Current EXperiment (RCEX) in 2007. Shown are a (*a*) symmetric, (*b*) asymmetric, (*c*) meandering, and (*d*) sinuous drifter-derived flow field. The color scale represents vorticity estimated from velocity observations. Bathymetric contours are plotted in the background in gray.

that the presence of relatively small bathymetric variations can have a profound effect on the rip current circulation, which is typically not accounted for in laboratory experiments in which an idealized bathymetry is often used. An important exception to this are the recent experiments by Castelle et al. (2009), who used a mobile sandy bed to allow the generation of rip channels and concurrent rip currents. Their findings support the containment of the rip circulations within the surf zone, consistent with the numerical model results depicted in the right column of **Figure 11**, with the occasional squirts related to VLF motions. Note that these VLF motions have also been observed on planar beaches (MacMahan et al. 2010a), i.e., in the absence of alongshore bathymetric variability, and as such can lead to transient rips (Johnson & Pattiaratchi 2004).

4.3. Infragravity (Wave-Group) Pulsations

That ocean waves often arrive in sets of waves (or wave groups) has been long known as the cause of fluctuations in the strength of rip currents and the nearshore circulation system (Shepard et al. 1941, Shepard & Inman 1950, Smith & Largier 1995, Sonu 1972).

Kennedy & Dalrymple (2001) used normally incident wave groups in the wave-basin setup of Haller et al. (2002), with a planar beach and an alongshore sand bar with two incised channels, finding that the rip currents pulsate with the wave groups. Furthermore, the bigger the waves are in the group, the faster the response of the rip current velocity is to the arrival of the bigger waves. Large pulsations in rip current strength clearly present a bathing hazard as the nearshore currents intensify during periods of large waves.

VLF: very low frequency

MacMahan et al. (2004a) tested two infragravity rip current pulsation hypotheses. The first hypothesis was that the rip current pulsations result from infragravity motions associated with the

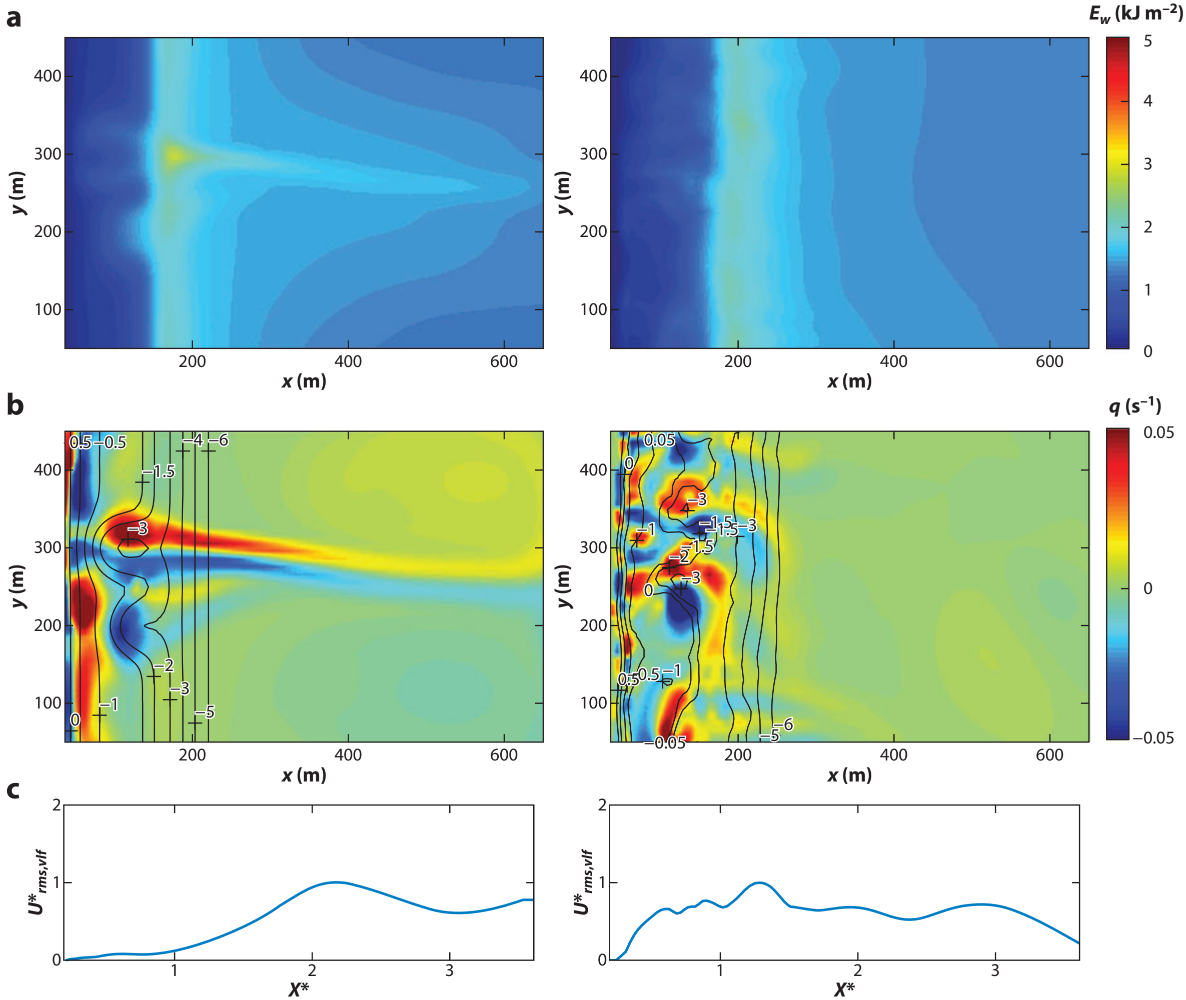

Figure 11

(*Left column*) Snapshot of wave energy (*a*), corresponding vorticity (*b*), and normalized alongshore-averaged very-low-frequency (VLF) intensity (*c*), $U^*_{rms,vlf}$, as a function of the normalized cross-shore distance, X^*, for regular waves with $H = 1$ m and $T = 10$ s, normally incident on a coast with two asymmetric rip channels (with an offset in the cross-shore direction). (*Right column*) Similar to that presented in the left column, but for the case of the actual bathymetry. Figure taken from Reniers (2007).

wave groups, such as the bound long waves (Longuet-Higgins & Stewart 1964, Masselink 1995). The second hypothesis was that the mass transport and wave setup produced by the higher waves within wave groups force significant amounts of water into the surf zone. During the subsequent wave height minima in the short-wave groups, the now excess water returns outside the surf zone through the rip channels, which are hydraulically more efficient (Munk 1949, Shepard & Inman 1950). The first hypothesis was found to represent the rip current pulsations on two beaches (Monterey, California, and Torrey Pines, California). Because the infragravity wave is 180° out of phase with the wave group, the maximum offshore current occurs during the maximum in the wave group. This is hazardous to bathers, because the larger waves in the wave group tend to lift bathers off the seabed, and the combination of the rip current and infragravity pulsation leads to a large offshore current. Infragravity pulsations can be as fast or faster than the mean rip current velocity.

Based on the authors' field observations during rip activity, the mean rip current velocity is approximately 0.5 m s^{-1}. Infragravity pulsations can be on the order of 0.5 m s^{-1} and fluctuate between 30 s and 5 min. This results in a rip current velocity of 0 m s^{-1} for part of the infragravity wave cycle and 1 m s^{-1} for the other part of the cycle. In addition, VLF motions fluctuate on the order of 5–30 min. As a result two people swimming in a rip current within 10 min of each other can experience a dramatically different response.

5. RIP CURRENT WATER EXCHANGE

Rip currents are generally viewed as a conduit for transporting material out of the surf zone and into the inner shelf region (Clarke et al. 2007, Grant et al. 2005, Inman & Brush 1973, MacMahan et al. 2010b, Reniers et al. 2009, Smith & Largier 1995). Yet, even though rip currents can be efficient at mixing (Brown et al. 2009), the largest concentrations of surf-zone diatoms (Talbot & Bate 1987) and drifters (MacMahan et al. 2010b) were observed near the center of rip current vortices on beaches with semi-enclosed rip circulations. This is similar to large-scale open-ocean vortices that trap and then transport material, whereas the rip current vortex is fixed in one location, as it is coupled to the surf-zone morphology, and tends to retain material within the surf zone.

A. Kennedy (personal conversation) found that a large number of drifters exited the surf zone in the laboratory experiments described by Kennedy & Thomas (2004). It is thus likely that linear bar-trough systems with rip channels have a higher exchange than observed on beaches with transverse bars (Castelle et al. 2009, MacMahan et al. 2010b).

Whether there is mixing has implications for the dispersal of pollutants from the surf zone, including those that are washed from the beach (Boehm et al. 2002, Yamahara et al. 2007) or are transported to the surf zone by land runoff.

Only a few studies exist that evaluate the flushing rate of the surf zone via rip currents. Surprisingly, this rate is less than previously thought. Smith & Largier (1995) estimated that it would take approximately 3 h to flush the surf zone by rip current pulsations. MacMahan et al. (2010b) and Reniers et al. (2009) also found similar flushing times using different approaches. Drifters deployed in the surf zone for three different beaches had a 20% hourly exit rate. Reniers et al. (2009) numerically simulated these patterns and found that the exit rate varied from 10% to 30% per hour, as it is a function of surf-zone width, wave height, and wave period. Castelle et al. (2009) observed in the wave basin that the laboratory drifter exit rate was similar to the field observations and that asymmetric rip currents resulted in most surf-zone exits.

Numerical simulations using Lagrangian coherent structures indicate that the primary exit mechanism of floating surf-zone material in the case of semi-enclosed rip circulations is associated with VLFs representing detaching eddies from the main rip current (Reniers et al. 2010). Although this cannot readily be inferred from snapshots of the instantaneous velocity field, it can be visualized by estimating the trajectories of virtual particles over a limited duration (**Figure 12**). The gyres at either side of the rip current trap surface floating material, as can be inferred from the large collection of virtual drifters at these locations, in line with the observations of both Talbot & Bate (1987) and MacMahan et al. (2010b). In conclusion, rip currents are one of the primary mechanisms for flushing the surf zone, but the flushing rate is lower than previously thought on beaches with semi-closed nearshore circulation.

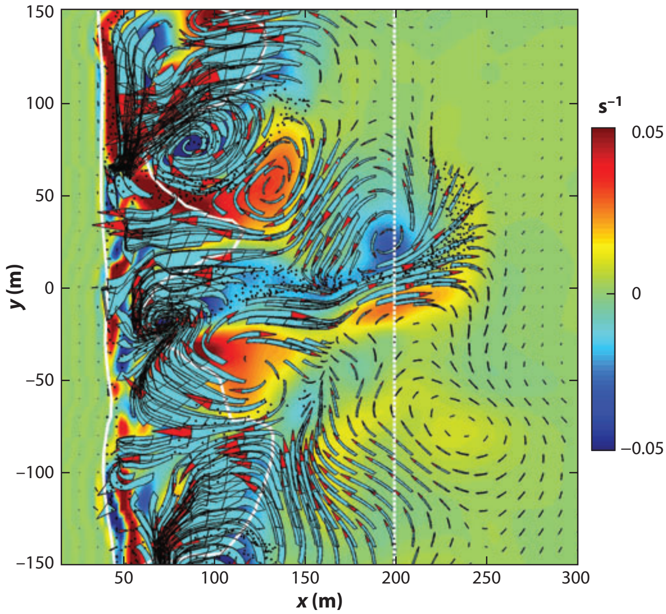

Figure 12

Virtual particle trajectories calculated for a 100-s interval from a velocity snapshot. Underlying vorticity field in s^{-1} indicated by the color bar in the upper-right corner in which warm (cold) colors correspond to clockwise (counterclockwise) rotation. The width of arrows corresponds to velocity magnitude, and the red tip indicates direction. Corresponding computed virtual drifter positions are indicated by the black dots. The approximate surf-zone edge is indicated by the dashed white line and bottom contours by the solid white lines.

6. PREDICTIONS OF RIP CURRENTS

Because bathymetrically controlled rip currents occur post-storm as the storm-built bar migrates landward, the stage of the beach is a key indicator of rip currents. Wright & Short (1984) relate the beach stage to the Dean number, $\Omega = H_b/(wT)$, where H_b is the breaking wave height, w is the sediment fall velocity, and T is the incident wave period. For values of $\Omega = 6$, the storm bar exists. As the wave climate decreases post-storm, Ω drops toward unity. It is likely that there are other parameters that also can provide an estimate of beach stage.

The U.S. National Weather Service is now predicting rip currents at beaches all around the United States as part of their surf-zone forecasts. These forecasts provide an estimate of the risk of rip currents to the general public and lifeguards in the following categories: low risk, moderate risk, and high risk. Moderate risk implies that wave and wind conditions support the occurrence of rip currents, whereas high risk means that dangerous and life-threatening rip currents are predicted (**http://www.ripcurrents.noaa.gov/forecasts.shtml**). In the Balearic Islands of Spain, meteorological data are included in the predictions (Alvarez-Ellacuria et al. 2009), and hazard levels are transmitted to the lifeguards. It is important that the rip current forecasts be accurate as high-risk forecasts could reduce attendance at the beach, which has economic implications, whereas a false low-risk forecast endangers swimmers.

Ideally, available meteorological, tide, and offshore wave data would be correlated to the presence of rip currents. Because historically it has been difficult to measure rip currents, lifeguard rescues have served as a proxy for the occurrence of rip currents as most rescues are rip current related. The obvious difficulties with this data are that the numbers of swimmers on the beach vary with the season and the day of the week. Furthermore, there are few swimmers on stormy days when rips are likely to be present.

Originally, Lushine (1991) correlated wind direction, wind velocity, swell height, and time of low tide to rescues at a beach in southeast Florida to develop the Lushine Rip Current Scale (LURCS). The technique is based on giving a score to each of these factors and summing the scores linearly. Appropriately high scores mean higher risk of rip currents. Later, Lascody (1998) modified the LURCS technique for east central Florida beaches (ECFL LURCS), based on the observation that the wave climate is more severe on this portion of the Florida coast and that wave period should play a greater role.

LURCS: Lushine Rip Current Scale

ECFL LURCS: Lushine Rip Current Scale modified for the east coast of Florida

Engle (2003) analyzed the effect of wind, waves, and tide to rip current occurrence for Daytona Beach and New Smyrna Beach in Florida to assess the accuracy of the ECFL LURCS. He included the tide effect on increasing the intensity of the rip currents that has been discussed earlier and removed the wind factors. Engle also found that the direction of the incident waves was correlated with rip current rescues. Again, the modified ECFL rip current prediction scheme involved a linear combination of factors that are summed to determine the risk.

Schrader (2004) examined the use of the Engle-modified ECFL LURCS at two additional Florida beaches, including one on the Gulf of Mexico. Although he noticed that there are some site-specific factors for rip current prediction (e.g., tides are not as important in the Gulf of Mexico), the ECFL LURCS did pretty well. He found a relationship between rip current occurrence and the presence of frontal systems that are accompanied by strong winds and larger waves with long periods. Note that decreasing wave height was considered to be a factor in rip currents, implying that post-storm periods are conducive to rip currents (as in Wright & Short's beach stages).

Using rescue data at Ocean City, Maryland, Nelko & Dalrymple (2008) show that the ECFL LURCS was not that successful. From these last three investigations, it is clear that local conditions dictate the rip current occurrences on beaches, and empirical techniques such as the LURCS and its derivatives need to be calibrated locally.

Nelko & Dalrymple (2008) also show that the use of beach stages, in addition to other meteorological data, is important for rip-channel prediction. Beach stage was determined from time-averaged video from three video cameras mounted atop a beachfront hotel in Ocean City, Maryland. A procedure for a predictive rip current scheme was presented.

In addition to calibrated empirical correlations, the future of rip current prediction might include real-time simulation of the nearshore hydrodynamics and morphodynamics on a given beach, using meteorological and wave data from offshore, to drive numerical models. (Already in the United States, there are real-time wave and surf forecasts, e.g., the Coastal Data Information Program of Scripps Institution of Oceanography for California.) These nearshore current models would then provide lifeguards with appropriate information as to the occurrence and location of the rip currents as they form.

7. CONCLUSIONS

Beaches are highly variable in planform and bathymetry as is the wave climate impinging on them. As a result, the nearshore circulation is also quite variable. It is likely that the most common type of rip current is one that is forced by wave refraction over irregular bathymetry. This means that beach stage (Wright & Short 1984) plays an important role in the occurrence and prediction of rip currents.

There are a large number of additional mechanisms that are capable of generating rip currents, falling into the categories of wave-structure interactions, wave-wave interaction models, shear instabilities of strong alongshore currents, and hydrodynamic and morphodynamic instability models. Models for rip current prediction will need to incorporate a variety of these mechanisms. Nevertheless, it is likely that real-time forecasting of rip currents is not too far in the future.

From the public health standpoint, reducing risk at the shoreline means educating beachgoers, so that they know to swim at guarded beaches and/or enter the ocean with buoyancy (such as a surfboard).

Finally, if you are ever caught in a rip, despite all that you have read above, then there are several approaches to getting out safely. An analogy to being in a rip current is swimming in a river; as you float downstream you do not notice anything unusual. However, if you overshoot your destination, you need to swim upstream and only then do you notice that you are not making much progress against the current. This is usually when panic occurs. In a river, you can swim to the closest bank and walk back to your destination. However, for rip currents, you are moving away from the shoreline, and the tendency is to swim onshore, which is the incorrect procedure. New results associated with the GPS-equipped drifters suggest that, if you are within the surf zone, you should worry simply about staying afloat as you may remain within the surf zone in a circulation cell or, if you are outside of the surf zone, then you should swim parallel to the beach until you are out of the rip current.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Contents

Indexes

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