Surf Zone Circulation and Transient Rip Currents on a Microtidal and Wave Dominated Open Coast Beach, Gold Coast, Australia

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Surf zone circulation and transient rip currents on a microtidal and wave dominated open coast beach, Gold Coast, Australia

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Abstract

Surf zone circulation patterns are recognised in the literature as having an important influence on cross- and alongshore exchange of water, sediment, and floatsam in the surf zone. Any study of surf zone circulation patterns therefore has implications for sediment transport, biological processes and beach safety, with the majority of studies focusing upon rip current circulation and rates of cross-shore exchange of drifters due to rip currents.

The aim of recent research has been to describe surf zone circulation patterns and retention of floatsam in the surf zone, with a major focus on informing rip current escape strategies and hazard mitigation. Previous studies have focused upon single bar embayed beaches in a microtidal environment or open coast beaches in a mesotidal or macrotidal environment, exposed to a generally shore-normal wave climate and displaying relatively stable bar morphology. This thesis explored surf zone circulation patterns and transient rip currents on the open beaches of the northern Gold Coast, Australia. These beaches are characterised as being microtidal and wave dominated, double bar, open coast beaches with no bounding headland morphology. The beaches are exposed to a highly variable wave climate, which is often bimodal and bidirectional and the dominant angle of wave approach is oblique to the shoreline. The double bar beach state combinations are complex and highly dynamic and sandbar and rip features are often skewed in response to the oblique angle of wave approach and prevailing longshore current.

This thesis highlights the variable nature of surf zone circulation patterns and transient rip currents on the Gold Coast open beaches through a Lagrangian drifter field study and a video-imaging study of transient rip currents. To date little research has focused upon transient rip currents due to their short-lived nature and the difficulties involved in predicting their location and occurrence.

GPS enabled Lagrangian drifters were deployed in the surf zone to measure the variability in surf zone circulation patterns on the Gold Coast open beaches and to quantify the retention of drifters entering a rip current under several different circulation regimes. As with previous Lagrangian drifter studies *rip current dominant* and

meandering current dominant circulation patterns were found to be characterised by large scale, semi-enclosed, surf zone eddies on the order of surf zone dimensions (~150 – 200 m). In contrast to recent studies however, these conditions observed moderate rates of drifters exiting the surf zone after entering a rip current (41%). During these conditions there were low rates (on average 15%) of drifter exchange alongshore between adjacent rip channel systems, indicating small exchange of water and sediment between nearby rip channels. *Alongshore current dominant* patterns were characterised by sinuous shore-parallel flowing drifter pathways. 3% of drifters deployed during these conditions exited offshore even when strong rip channel morphology existed, showing that the strong alongshore current was able to over-ride the offshore pulsing of rip currents. 100% of drifters deployed during *alongshore dominant* conditions passed through one or more adjacent rip channel systems, indicating a high exchange of water and sediment alongshore under these conditions. *Terrace beach* conditions did not display semi-enclosed surf zone eddies, with offshore directed currents (being generally obliquely angled) taking the form of mini rip currents and transient rip currents. The highest rates of drifters exiting the surf zone were observed during *terrace beach* conditions (56%). The angle of wave approach was observed to have a significant control on surf zone circulation on the Gold Coast open beaches, with oblique wave approach tending to generate *alongshore current dominant* conditions irrespective of the beach state. Conversely, *rip current dominant* circulation was observed to occur when wave approach angle was relatively shore-normal.

It is proposed that the interaction between the incoming wave climate and the underlying beach and bar morphology is the primary control of the retention of drifters under different circulation patterns. The drifter observations support the recent literature in suggesting potential non bathymetric, hydrodynamic controls that may influence the observed moderate exit rates of drifters under *rip current* and *meandering current* as well as *terrace beach* conditions. In summary these may include (but are not limited to): reduced morphodynamic coupling of the surf zone currents to the underlying morphology; presence of rip head bars; and low frequency pulsing of the wave-driven currents.

The remote-video study of transient rip currents presented novel video-imaging and statistical techniques for capturing and quantifying transient rip characteristics. The novel video approach to analysing transient rip currents allowed for the capture of 233 individual transient rip events from 1029 hours of video recording.

The results of the video-imaging analysis have particular implications for improving the overall understanding of transient rip current occurrence, geometry and growth rates. Rip growth rate is a measure of the seaward edge of the rip and is calculated to be the time taken from initiation to extend to the entire rip length (for the entire rip duration). The significant results of the study show that the transient rip current events are characteristically: short lived; infrequent in occurrence; random in location; have small spatial scales and low rates of rip growth. The novel video and statistical analysis supports the hypothesis that transient rip occurrence, length scales and behaviour are driven by localised hydrodynamic forcing at gravity wave to wave group frequencies. The observations of the study also support the hypothesis that transient rip currents observed on wave dominated, double bar, open coast beaches (e.g. present study) display length and time scales comparable to previous studies on single bar beaches.

The results presented in this thesis have inherent implications for beach safety in regards to the hazard rip currents present to bathers on wave dominated and microtidal open coast beaches. Overall the results suggest that different circulation patterns and rip current types will present a wide variety of hazards to bathers. When conditions are *alongshore current dominant* bathers are expected to float parallel to the shore-line and eventually end up on a shallow shoal or on the beach, with very little chance of being swept out to sea. Alternatively *rip current* and *meandering current dominant* conditions will see moderate rates of bathers caught in rip currents exiting the surf zone offshore. Under terrace beach conditions moderate to high rates of bathers being swept out to sea are expected when a bather enters a rip current. Whilst transient rip currents are generally small features with low rates of growth (i.e. low velocity) they present an additional hazard to bathers due to the lack of visual clues as to their occurrence. Instead of a single escape strategy safety message for all conditions, scenario-specific safety advice should be considered and communicated to the public. This sentiment is becoming increasingly supported in the literature.

Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Thomas Peter Murray
s2707183

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To my parents your love, support and financial backing is the only reason I've been able to continue living on the coast and complete my studies. You will never understand how grateful I am for everything you do for me.

Finally to all my other friends and family on the Gold Coast, Sydney and around the globe your friendship and support is the most important thing in the world to me. Thank you for always being there.

And as always Peace and Love!

Publications

MURRAY, T. P., CARTWRIGHT, N. & TOMLINSON, R. (2013) Video-imaging of transient rip currents on the Gold Coast open beaches. Journal of Coastal Research, SI65, 1809-1814.

MURRAY, T.P. (2012) Surf zone retention and exits on the Gold Coast open beaches, Australia, 2nd International Rip Current Symposium, 31st October – 1st November 2012, Sydney, Australia

MURRAY, T. P., CARTWRIGHT, N., STRAUSS, D. & TOMLINSON, R. (*in review*) Quantifying transient rip current characteristics using remote video imagery. *Paper submitted for review to Remote Sensing of the Environment on 20/11/2015*

Ethics Approval

During the candidature ethics approval was applied for and granted by the Griffith University Human Research Ethics Committee. The project undertaken is described here:

ENV/32/09/HREC

Title: "Real-time monitoring of beach hazards: an analysis of the nature, causes, occurrence and distribution of beach and surf zone hazards along a wave-dominated coastline."

Description: This project applied for the approval of 'human drifter floats' whereby humans were to be used as GPS drifters for measuring surf zone currents. Approval was granted to use swimmers in the surf zone. The ethics approval covers work carried out in Appendix A.1 (human drifter floats) and Chapter 4 (retrieval of GPS drifters by surfboard).

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List of Acronyms

General

ADCP	Acoustic Doppler Current Profiler
AHD	Australian Height Datum (≈ MSL)
GAM	Generalised Additive Model
GRIB	GRIdded Binary
IG	Infragravity
LCS	Lagrangian Coherent Structures
MWS	Mean Water Surface
NWW3	WaveWatch III
PVC	Polyvinyl Chloride
RA	Rip Activity
RTR	Relative Tidal Range
SWL	Still Water Level
SZE	Surf Zone Eddy
VLF	Very Low Frequency

Organisations

CoastalCOMS	Coastal Conditions Monitoring System
EPA	Environmental Protection Agency
NOAA	National Oceanic and Atmospheric Administration
NMEA	National Maine Electronics Association
SLSA	Surf Life Saving Australia

GPS related Acronyms

DGPS	Differential Global Positioning Systems
DOP	Dilution of Precision
GDA94	Geocentric Datum of Australia
GPS	Global Positioning Systems
HDOP	Horizontal Dilution of Precision
PDOP	Positional Dilution of Precision
RTK	Real-time Kinematic
SA	Selective Availability

SBAS	Satellite Based Augmentation System
VDOP	Vertical Dilution of Precision
WGS84	World Geodetic System 1984

Beach States (*note these can form combinations of inner / outer bar and transitional states)

LBT	Longshore Bar and Trough
RBB	Rhythmic Bar and Beach
TBR	Transverse Bar and Rip
eTBR	erosional Transverse Bar and Rip
rLTT	rhythmic Low Tide Terrace
LTT	Low Tide Terrace

List of Symbols

Roman symbols

C	speed of individual waves (or wave celerity) (m.s^{-1})
C_g	wave group velocity (or wave group celerity) (m.s^{-1})
E	total wave energy or energy density (N.m^{-2})
E_f	wave energy flux (W.m^{-1})
F_{br}	breaking force (N.m^{-1})
f	frequency (Hz)
g	gravity (m.s^{-2})
H	wave height (m)
H_a	horizontal angle (for theodolite measurements) (°)
H_b	breaker wave height (m)
H_{sig}	significant wave height (m)
H_{max}	maximum wave height (m)
H_{rms}	root mean square of wave height (m)
h	still water depth / mean water depth (depending on equation) (m)
k	wave number (m^{-1})
L	wave length (m)
	embayment length (m)
L_0	deepwater wave length (m)

n	n represents sample size for statistical analysis (-)
P	dominant peak wave direction (°)
S_m	momentum flux per unit length of wave crest (N.m^{-2})
S_p	excess pressure force compared to the still water situation (N.m^{-2})
S_{xx}	radiation stress (in the cross-shore direction) (N.m^{-2})
S_{yy}	radiation stress (in the longshore direction) (N.m^{-2})
S_{xy}	radiation stress (x-component acting parallel to the vertical plane and y-component acting parallel to the vertical plane) (N.m^{-2})
T	wave period (s)
T_p	peak wave period (s)
T_z	average wave period (s)
$\tan\beta$	beach slope (-)
u	cross-shore speed / velocity (m.s^{-1})
v	longshore current speed / velocity (m.s^{-1})
W_s	Sediment Fall Velocity (-)
ω	vorticity (radians.s^{-1})
X_s	surf zone width (m)
y_c	along-crest direction (m)

Greek Symbols

α_b	angle of wave breaking (°)
Ω	Dimensionless Fall Velocity parameter (-)
δ'	Embaymentisation parameter (-)
ξ	Iribarren number (-)
$\overline{\eta}$	mean water surface elevation (MWS) (m)
ρ	density of seawater (kg.m^{-3})
π	pi (e.g. 3.14$^{\bullet}$)
∇_{is}	gradient operator (-)

GAMs symbols

g	is a smoothing monotonic link function
y_i	is a selected response variable
x_i	is some predictor variable
z_i	is a parametric predictor variable
f_l	is a smooth function associated with the predictor x_i
ε_i	are independent error terms with a density function described by $N(0,\sigma^2)$

Chapter 1. Introduction

1.1. **Background**

The study of surf zone circulation patterns has received a high level of interest in the literature due to their importance in the cross- and longshore exchange of water, sediment, and floatsam in the surf zone. The study of surf zone circulation patterns therefore has implications for sediment transport, biological processes and beach safety, with many studies focusing upon rip current circulation and rates of cross-shore exchange due to rip currents.

Rip currents are offshore directed nearshore currents which are driven and controlled by a complex interaction between the wave climate, tides, winds and morphology. Rip currents have the ability to rapidly move a bather from shallow to deep water (Brander and MacMahan, 2011). Since recreational beach swimming became popular in the early 1900s, many unfortunate bathers have drowned in rip currents (Brander and MacMahan, 2011). As a result rip currents represent a serious public safety hazard with many local governments employing professional lifeguards to mitigate the associated risks.

Recent statistics have shown that rip currents are the major hazard to bathers at Australian and US beaches, where they are responsible for around 90% and 80% of all surf rescues respectively (Short, 2007; Brander and MacMahan, 2011). The 2006 National Surf Safety Report from Surf Life Saving Australia (SLSA) states that of the 98% of Australians who intend to visit the beach each summer, more than 70% do not know how to recognise a rip current by looking at the water (SLSA, 2006). It has recently been noted that rip currents are one of the most deadly natural hazards in Australia, resulting in the deaths of 21 people on average each year (for the period July 1, 2004 – June 20, 2011) (Brighton et al., 2013; Brander et al., 2013). Brander et al. (2013) however believe this number is most likely an underestimate as fatalities are only recorded as being rip current related when there is a witness present to state that the individual was caught in a rip current. It is important to note however that rip currents do not necessarily kill people, but rather people become exhausted once ‘caught’ in the rip and drown in them.

There are three main types of rip currents on an open coast beach: (1) permanent topographic rip currents (such as those that run along fixed coastal structures or features such as rock groynes or rocky headlands); (2) semi-permanent rip currents (such as those on sandy coastlines that exist whilst sand bars and channels are favourable but disappear, or move to another location, with changing morphology) (Short, 2006); and (3) transient rip currents (which are short lived and do not necessarily rely on topographic controls for their existence). A detailed description of each of these rip currents as well as other surf zone currents observed in nature are detailed in Chapter 2 (Section 2.4.3).

This thesis describes a study of surf zone circulation and transient rip currents on the Gold Coast, Australia, where the open beaches are characteristically wave dominated and are not controlled by headland morphology. A microtidal and wave dominated, double bar, open coast beach provides a dynamic environment with complex morphodynamic processes interacting to produce high variability in surf zone circulation patterns. This thesis explores this variability in surf zone circulation and in particular the retention of floatsam through a Lagrangian drifter study. In addition, the nature, behaviour and characteristics of transient rip currents are quantified via newly developed statistical and video-imaging techniques.

1.2. **Aims and Objectives**

The over-riding aim of the thesis is to qualitatively and quantitatively describe surf zone circulation patterns and transient rip current characteristics on the wave dominated, double bar open beaches of the Gold Coast, Australia using field observations. Results of the study will be compared and benchmarked against the literature to test the hypothesis that the rip current dynamics and circulation patterns will be different than on previously studied embayed, single bar beaches and open coast beaches in a meso- and macrotidal environment.

In terms of surf zone circulation patterns, the specific research objectives of the thesis are to:

(1) Characterise the various types and combinations of surf zone circulation patterns using GPS drifters;
(2) Test the hypothesis that due to the dominant oblique angle of wave approach as well as the complex and dynamic double bar beach state combinations, surf zone circulation patterns will differ to previous studies on single bar, embayed beaches and open coast beaches in a meso- and macrotidal environment;
(3) Quantify the cross-shore exchange of drifters (acting as a proxy for floatsam, e.g. bathers) entering a rip current under a variety of different surf zone circulation patterns;
(4) Test the hypothesis that surf zone retention will differ to previous studies on single bar, embayed beaches and open coast beaches in a meso- and macrotidal environment. It is hypothesised that surf zone retention rates will be influenced by: beach and surf zone morphology, wave climate and the angle of wave approach, and the presence of low frequency wave motions, leading to variability between different beach environments.
(5) Quantify cross-shore and longshore drifter velocities in the Lagrangian reference frame;

In relation to transient rip currents, the specific research objectives of the thesis are to utilise remote-video imagery to:

(6) Test new statistical and video techniques for measuring and analysing transient rip currents;
(7) Quantify transient rip activity and duration;
(8) Statistically test for transient rip occurrence against a range of environmental parameters in order to determine if there are any preferential environmental conditions for transient rip occurrence;
(9) Quantify transient rip current characteristics such as location, spacing, mobility, rip growth rate and geometry

Finally the results of the drifter and video imaging experiments will be discussed in the context of beach safety on wave dominated, double bar, open coast beaches.

1.3. **Outline of Thesis**

The outline for the thesis is as follows. Chapter 2 encompasses a literature review of surf zone hydrodynamics, focusing on wave-driven currents in the surf zone. Secondly, the chapter provides a more specific discussion of previous research into transient rip currents and their potential generation mechanisms. Chapter 3 describes the study site and the methods used throughout the thesis. Firstly, the design and validation of the GPS enabled Lagrangian drifters is presented followed by a description of the field experiments undertaken utilising these drifters to measure surf zone circulation. Lastly, the method of analysing remote-video imagery to quantify transient rip current characteristics is presented. Chapter 4 presents the results of the field study utilising the GPS enabled Lagrangian drifters to: quantitatively and qualitatively describe surf zone circulation patterns; and quantify cross-shore exchange rates of drifters under different circulation patterns surf zone retention. Chapter 5 presents the results of the remote-video study analysing the nature and behaviour of transient rip currents as well as quantifying their spatial and temporal characteristics. Both Chapters 4 and 5 also discuss the implications of the results in the context of beach safety. Finally Chapter 6 summarises the results and outcomes from the relevant chapters and places them in the context of the thesis as a whole. The main conclusions are highlighted and suggestions for future work are given.

Chapter 2. Literature Review

2.1. **Introduction**

The aim of this chapter is to provide some background on the relevant hydrodynamic and morphodynamic processes in the surf zone and then to provide a review of transient rip research. The chapter initially introduces the morphodynamics of wave dominated beaches. Next, the different types of currents observed in the surf zone are introduced and their behaviour briefly described. The chapter then describes hydrodynamic processes related to wave breaking and wave-driven currents in the surf zone. In doing so this chapter provides the background for the final section of the literature review on transient rip currents. Transient rip currents are a poorly understood surf zone phenomenon with previously limited research into their generation, behaviour and characteristics. The final section of this chapter aims to introduce the historical literature on transient rip currents and then explore potential generation mechanisms and observable manifestations of these temporary surf zone currents.

2.2. **Coastal Morphodynamics**

2.2.1. **Overview**

The study of beach morphodynamics has been in depth since the 1970's but with a strict focus on kinematics, physics and morphology (e.g. Wright and Thom, 1977; Wright and Short, 1984; deVriend, 1991; Cowell and Thom, 1994; Wright, 1995; Thom and Short, 2006). The term morphodynamics was introduced into the coastal literature by Wright and Thom (1977) and has been widely applied in studies of surf zones and beaches as well as to river mouths, inlets and estuaries (Wright, 1995; Short, 1999a). Wright and Thom (1977) defined morphodynamics as the 'mutual adjustment of topography and fluid dynamics involving sediment transport'. Beach morphodynamics involves the mutual interaction of waves, tides and currents with the beach topography, such that the wave processes modify the topography, which in turn will modify the waves and so on (Short, 1999a). The scale at which beaches can be studied, in terms of the 'morphodynamic approach,' ranges from instantaneous boundary layer dynamics through to Holocene barrier evolution (Cowell and Thom, 1994) (Figure 2.1). The theoretical aspect of the morphodynamic approach has been expanded and the approach has effectively utilised methodologies, such as GIS and video-image techniques, to expand the overall understanding of coastal topography and coastal processes over time (Thom and Short, 2006).

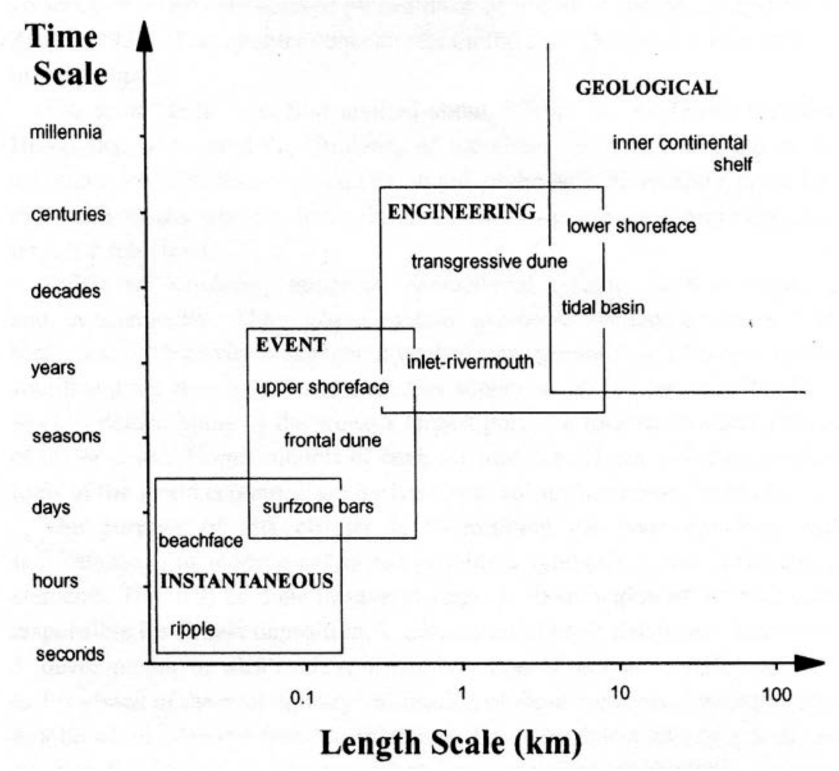


Figure 2.1: Definition of spatial and temporal scales involved in coastal evolution, with typical classes of sedimentary features. Source: Cowell and Thom (1994)

2.3. **Wave Dominated Beaches**

The Gold Coast beaches used as study sites in this thesis are considered wave dominated. This section describes the nature of this classification. Wave dominated beaches are usually classified using three parameters – breaker wave height (H_b), wave period (T) and sediment grain size (as defined by the sediment fall velocity - W_s) (Gibbs et al., 1971; Wright and Short, 1984). These three parameters are combined into the Dimensionless Fall Velocity parameter (equation 2.1), which is used to predict time-varying beach state (Wright and Short, 1984; Wright et al., 1987):

$$\Omega = H_b \,/\, (\, W_s\, T) \qquad (2.1)$$

The modal value and temporal variability of Ω depend on breaker wave height (H_b), which, in turn, depends on the deepwater wave climate and on nearshore modification of waves by shoaling, refraction and friction (Wright and Short, 1984). Wright and Short (1984) found that when $\Omega < 1$ beaches tended to be reflective, when $\Omega > 6$ they tended to be dissipative and in between ($\Omega = 1 - 6$) they behaved as intermediate beaches. Masselink and Short (1993) added the non-dimensional relative tidal range parameter (*RTR*) (equation 2.2) to beach models to discriminate wave dominated beach types from tide modified and tide dominated beach types (Short, 2006):

$$RTR = TR / H_b \tag{2.2}$$

where, TR = spring tide range and H_b = breaker wave height.

The Gold Coast has a maximum spring tidal range of 2.1 m and tides are semidiurnal (Short, 2000). As such all open ocean beaches on the Gold Coast are classified as wave dominated and microtidal (RTR <3). This study will therefore consider hydrodynamic and morphodynamic processes associated with wave dominated (microtidal) beaches.

Wright and Short (1984) present the most comprehensive classification model of wave dominated beaches to date. Beach classification is based on a series of characteristics, the most representative of which is bar morphology. The classification scheme consists of six beach types ranging from the highest energy Dissipative (D) to the lowest energy Reflective (R), with four intermediate beach types; Longshore Bar Trough (LBT), Rhythmic Bar and Beach (RBB), Transverse Bar and Rip (TBR), and Low Tide Terrace (LTT) (Figure 2.2). The Wright and Short (1984) beach model has been discussed in the literature.

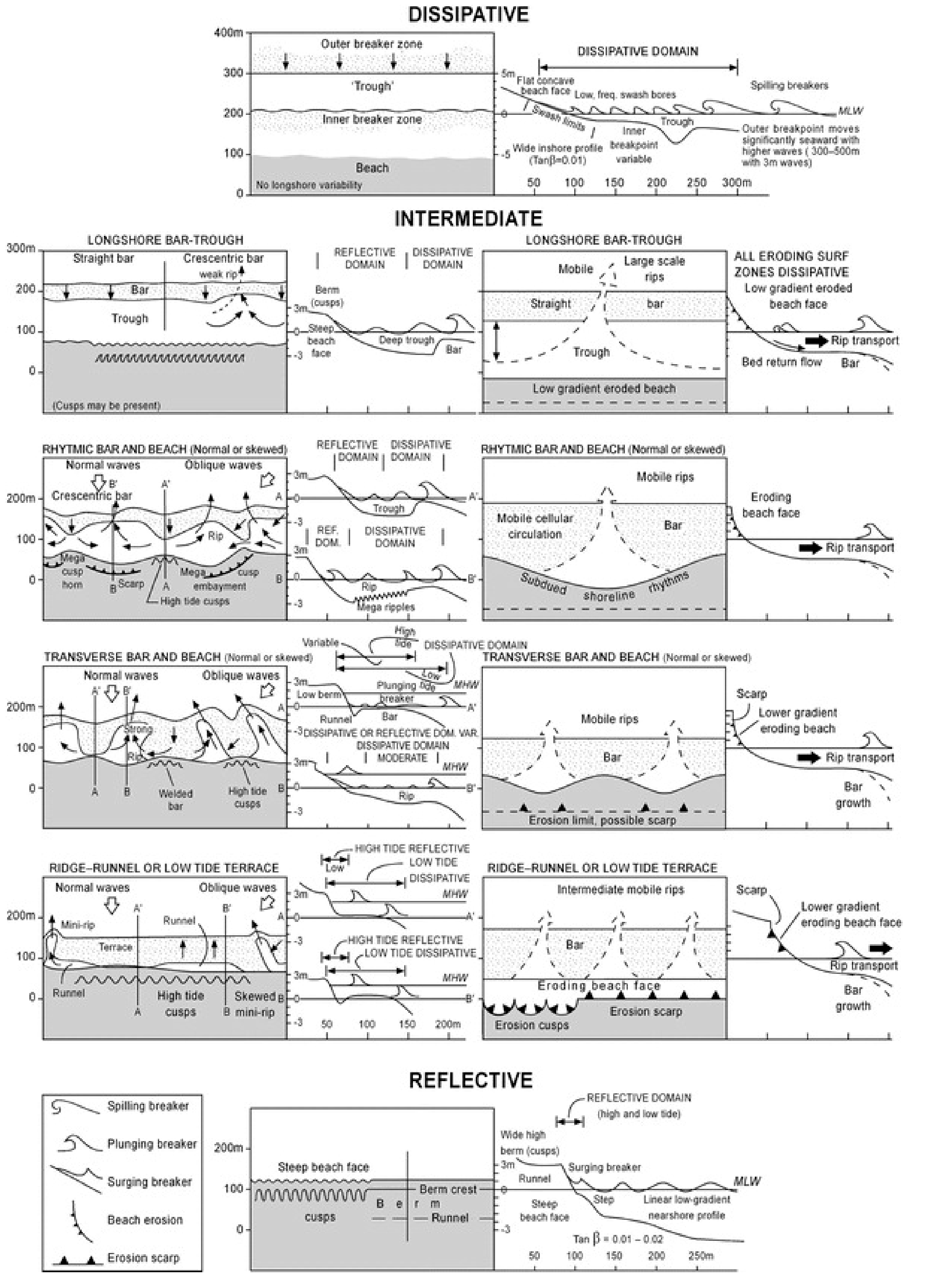


Figure 2.2: Wave dominated Beach Model (Wright and Short, 1984). Plan and profile configurations of the six major beach states. There are four intermediate beach types: Longshore Bar and Trough (LBT), Rhythmic Bar and Beach (RBB), Transverse Bar and Rip (TBR) and Low Tide Terrace (LTT). Beach states are presented in order of decreasing wave energy. Source: Short (1999b)

There are no modally *Dissipative* beaches in Queensland, as waves are not sufficiently high to form and maintain such beaches (Short, 2000). They can occur, however, for short periods of time during and immediately following periods of high cyclonic waves on exposed south east Queensland beaches (Short, 2000).

Intermediate beaches refer to those beach types that are intermediate between the lower energy reflective beaches and the highest energy dissipative beaches (Wright and Short, 1984). On the open southeast coast of Queensland 54 of the 73 wave dominated beaches are intermediate and they dominate the Gold Coast study site (Short, 2000). Their dominance is a result of the presence of the long exposed beaches, which are composed of fine to medium grained sand and receive waves between 0.5 and 1.5 m high all of which combine to generate rip dominated beach systems (Short, 2000).

On the Queensland coast, sandy beaches require waves to be less than 0.5 m to be classified as *reflective* and are a product of both coarse sand and lower waves (Short, 2000). None of the open beaches on the Gold Coast are classified as being modally reflective.

Many microtidal, wave dominated beaches have more than one bar, with two and occasionally three bars common on swell coasts, such as the Gold Coast (Figure 2.3). A study of a 9.3 year data set of ARGUS daily timex images of a 2 km stretch of Surfers Paradise beach was undertaken to analyse the temporal and spatial characteristics of the double bar system on the northern Gold Coast open beaches (Price and Ruessink, 2011; Price et al., 2011).

The outer bar was generally found to be in a more upstate (higher energy) morphology than the inner bar (Figure 2.3). For all intermediate outer bar states the inner bar was mostly a shore-attached terrace with some alongshore variability (Price and Ruessink, 2011). For linear outer bar states, however, the inner bar frequently separated from the shoreline and persistently developed rip channels (Price and Ruessink, 2011). Price and Ruessink (2011) found that the outer bar plays a significant role in governing the inner bar beach state. The most frequent combination of bar states was an outer TBR with an inner LTT (Figure 2.3).

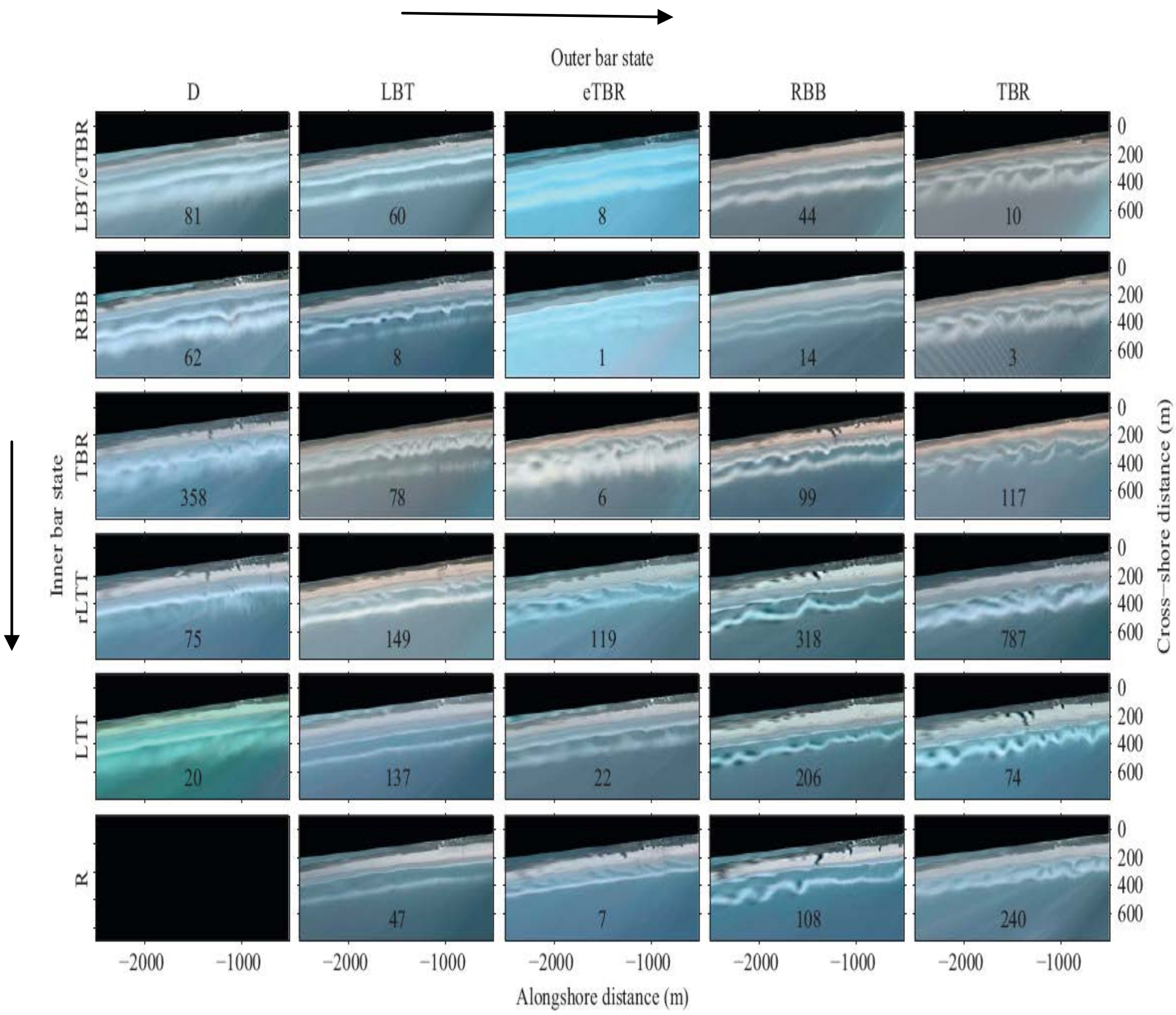


Figure 2.3: Observed combinations of the inner and outer bar states on the Gold Coast. The numbers at the bottom of each panel indicate the frequency (in days) of the observed combinations (3258 days in total). Arrows indicate downstate transitions of morphology (i.e. from highest energy to lowest energy). Source: Price and Ruessink (2011)

Price and Ruessink (2011) defined two additional beach states to the existing Wright and Short (1984) beach state classification system. These are displayed in Figure 2.3 as eTBR (erosional Transverse Bar and Rip) and rLTT (rhythmic Low Tide Terrace). The eTBR state occurs when the barline rapidly straightens and the trough continuity increases; with erosional rip channels also starting to develop (Price and Ruessink, 2011). As the bar is eroding, the eTBR morphology is considered an upstate transitioning beach state with the system heading back towards an LBT state (Price and Ruessink, 2011). The transition to an eTBR system is thought to be controlled by oblique wave incidence (Price and Ruessink, 2011). rLTT conditions occur when the Low Tide Terrace displays a quasi-rhythmic barline (Price and Ruessink, 2011).

2.4. Overview of Surf Zone Currents

Surf zone currents are ultimately driven by highly dynamic wave action which occurs over a wide range of frequencies (Figure 2.4). Unless otherwise stated, the surf zone currents discussed in this section are considered quasi-steady or mean current in that the current motion has been time-averaged over many wave cycles. It is important to note that surf zone currents are inherently unstable and will fluctuate on the time scales of infragravity and very low frequency (or far infragravity) (Figure 2.4).

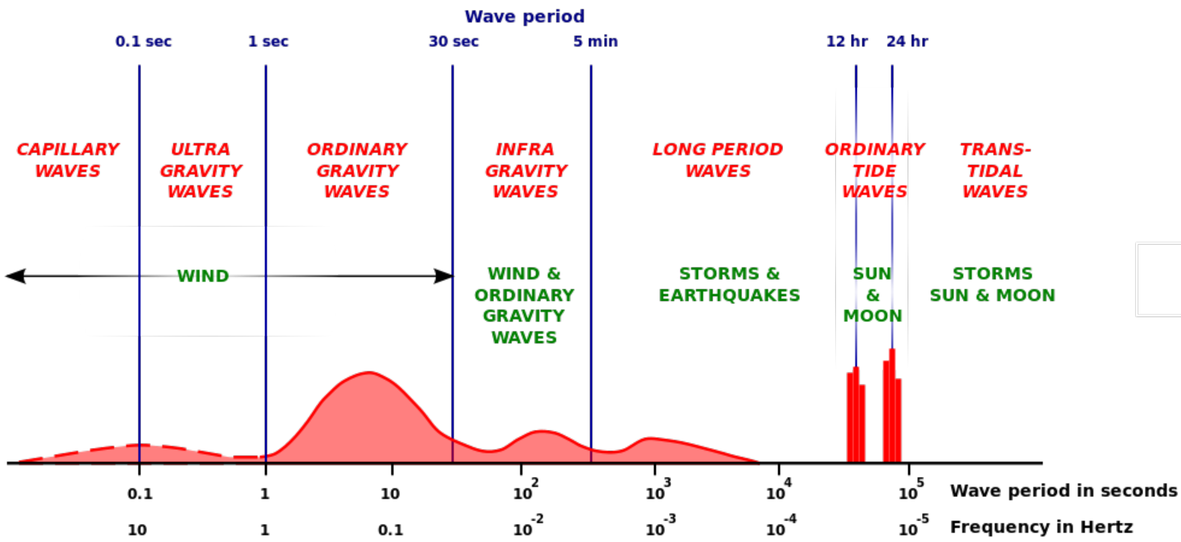


Figure 2.4: Classification of the frequency spectrum of ocean waves according to wave period. Modified from: Munk (1950)

2.4.1. Longshore currents

Longshore currents are time-averaged, shore-parallel flows within the surf zone which occur when the incident wave direction is at an angle to the coastline. These currents tend to meander in the direction of propagation rather than be constricted horizontal laminar flows (Figure 2.5). These currents may reach velocities exceeding 2 $m.s^{-1}$ and act as a powerful sediment/floatsam transport agent (Short, 2007; Brander and MacMahan, 2011). Meandering longshore currents also have the ability to rapidly move bathers around the surf zone and from shallow to deep water.

Figure 2.5: Longshore trough at Main Beach, Gold Coast (17/2/2015). Arrows represent the general meandering northerly longshore current flow on the Gold Coast. Rip currents are also identified as sandy plumes moving offshore from the outer sand bar. Source: CoGC skyepics (2015)

2.4.2. Bed return flow

Bed return flow or 'undertow' is a quasi-steady offshore directed current that exists below the trough level in the nearshore zone (Tang and Dalrymple, 1989). The bed return flow represents a mass conservation response, returning water seaward that was initially transported onshore in the upper water column due to broken wave motion.

Field measurements of bed return flow were initially explored on a dissipative beach by Wright et al. (1982) and early field studies of bed return flow suggested that the velocity of the 'undertow' current increased linearly with the incident wave height (Roelvink and Stive, 1989; Greenwood and Osborne, 1990; Hazen et al., 1990). Masselink and Black (1995) later showed a maximum offshore velocity of the current around the mid-surf zone, with a steep decrease in velocity toward the shoreline and a gradual decrease in bed return velocities in the offshore direction (from the mid surf zone) (Masselink and Black, 1995).

2.4.3. **Rip currents**

Rip currents are shore-normal (or shore-oblique), narrow, sea-wards flowing currents that originate within the surf zone, sometimes extend seaward of the breaking region and can obtain relatively high velocities (MacMahan et al., 2006). Traditional views of rip currents describe these flows as consisting of strong, narrow currents flowing seaward through topographic depressions in a bar and a weak net onshore flow due to mass transport in regions adjacent to the rip (e.g. Bowen, 1969) (Figure 2.6). This cell circulation is completed by longshore flows increasing towards and converging at the rips (Bowen, 1969) (Figure 2.6).

Rip currents are a function of both the prevailing and antecedent wave conditions and the rate of change in wave conditions (Short, 1985). Recent research has shown rip currents to often behave as semi-enclosed surf zone vortices with the rip current mostly confined to the surf zone (MacMahan et al., 2010a) (discussed further in Chapter 4). The strong seaward rip flow in often a deeper rip channel will transport seaward any buoyant object located in the flow, including flotsam and people (Short, 2007). The term ‘rips’ has become common place in the media as a shortened alternative to the term ‘rip currents’ and as such the two terms will be interchangeable throughout the rest of the thesis.

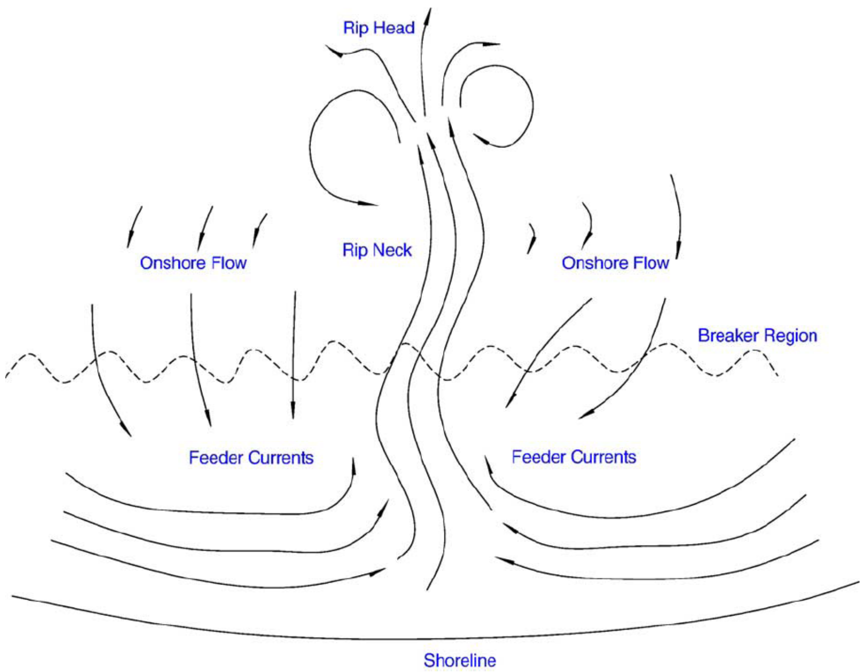


Figure 2.6: A schematic of the traditional definition of a rip current by Shepard et al. (1941). Source: MacMahan et al. (2006)

Rip currents are classified based on their morphological characteristics (e.g. topographically controlled versus non-topographically controlled) as well as the temporal characteristics of the rip hydrodynamics (i.e. quasi-steady versus transient). The following sections outline the various types of rip currents.

2.4.3.1. Semi-permanent, topographically controlled beach rip currents

Semi-permanent beach rip currents (Figure 2.7) are quasi-steady and have a temporarily fixed spatial structure associated with sandy beach and bar morphology (Short, 2007) that will evolve slowly over time (Johnson, 2004). These types of rip currents act as semi-enclosed vortices inside the surf zone, which can sometimes extend beyond the surf zone (MacMahan et al., 2010a; Austin et al., 2010; Winter et al., 2012; McCarroll et al., 2014a; McCarroll et al., 2014b; Scott et al., 2014; Winter et al., 2014). This idea will be explored in detail in Chapter 4 in the context of rip current retention.

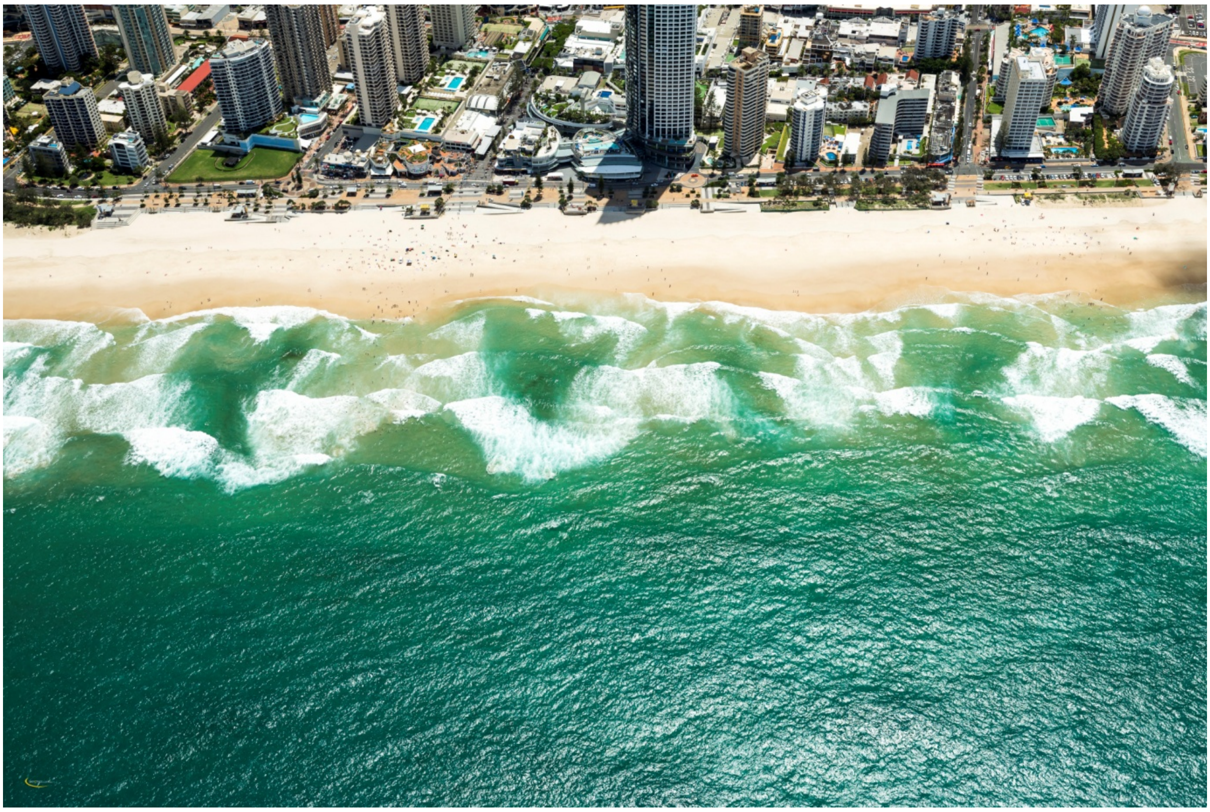


Figure 2.7: Semi-permanent beach rips at Surfers Paradise, Gold Coast (21/1/2015). Source: CoGC Skyepics (2015)

Semi-permanent beach rips may last on the order of days to weeks and have also been observed to migrate with changing beach morphology. Turner et al. (2007) conducted a three year study of semi-permanent beach rip channel behaviour using ARGUS technology along a 2 km stretch of Surfers Paradise Beach. The study observed that the majority of rips persisted for five or fewer days, but with a strongly skewed distribution resulting in an average of eight days and standard deviation of nine days. A small number of rip currents were observed to persist for up to 38 days (Turner et al., 2007). Approximately one third of beach rips observed were stationary and migration rates of those that did move varied from less than five metres per day to a maximum of around 50 m per day (Turner et al., 2007).

2.4.3.2. Permanent topographic rip currents

Topographic rip currents are quasi-steady currents associated with a fixed topographic boundary, such as headlands, rocks, reefs, or groynes (Short, 2006; Short, 2007) (Figure 2.8). Short (2007) suggests that topographic rip currents have stronger, more confined flows than semi-permanent beach rips and as a result it is traditionally believed these types of rip currents will carry flows (and therefore bathers) greater distances seaward than their beach rip counterparts. This is supported in a series of papers by McCarroll et al. (2013-2014), whom conducted Lagrangian drifter and human 'floater' studies on an embayed beach in NSW Australia and found that up to 80% of the time drifters entering a headland rip current may exit the surf zone. Conversely Pattiaratchi et al. (2009) observed rip cell re-circulation in the lee of a groyne (headland structure) at two beaches in Perth, Western Australia.

Figure 2.8: Topographic rip adjacent to the rock wall at the Gold Coast Seaway (17/2/2015). A less obvious topographic rip is also evident next to the sand pumping jetty. Source: CoGC skyepics (2015).

2.4.3.3. Mega rip currents

During storm wave conditions, topographically controlled rip currents increase in size and velocity and become *mega-rips*; that is a large scale topographic rip (Short, 2006) (Figure 2.9). These types of rip currents are the most energetic and difficult to study due to their large scale and relatively rare occurrence under high wave conditions. Mega-rip currents tend to occur when waves exceed ~ 3 m on embayed beaches of up to 3-4 km in length (Short, 2007). Due to the large length scales of mega-rip currents this generally results in only one or two rips along the entire embayment (Short, 2007). Mega-rips have been observed to have length scales of over 1 km and flows of up to 3 $m.s^{-1}$ and possibly more (Coutts-Smith, 2004).

Figure 2.9: Mega rip current located in the centre of Dee Why Beach, NSW, during 2-4 m swell conditions. Source: Short (2007)

2.4.3.4. Quasi-steady rip currents due to offshore bathymetric non-uniformities

Shepard and Inman (1950) were the first to propose the idea that wave refraction over offshore features may be a mechanism for the development of rip currents in the surf zone in the absence of nearshore bathymetry variations. Long and Özkan-Haller (2005) further investigated this theory using a numerical wave model and compared results of the model to field work undertaken during the Nearshore Canyon Experiment located along a section of coastline in La Jolla, California, stretching from Point La Jolla northward to Torrey Pines Beach. This region is characterised by an offshore submarine canyon that divides into two branches near the coast. The Long and Özkan-Haller (2005) model indicated that wave height variations associated with undulations in the canyon contours cause rip current circulation cells with an alongshore spacing of *O*(100m) even though the nearshore bathymetry displayed no variations at those length scales. These modelled results corresponded to observed rip currents during the Nearshore Canyon Experiment, indicating that offshore wave modification may lead to the generation of temporary or incipient (developing) rip currents and/or channels (Long and Özkan-Haller, 2005). They found the development of the rip currents to be controlled by the contour undulations rather than the presence of the submarine canyon itself. This suggests that rip currents could also be present for situations with undulating offshore contours that are, on average, parallel to the shoreline of an otherwise planar bathymetry (Long and Özkan-Haller, 2005). An example of this type of rip can be seen in the numerical modelling output displayed in Figure 2.10.

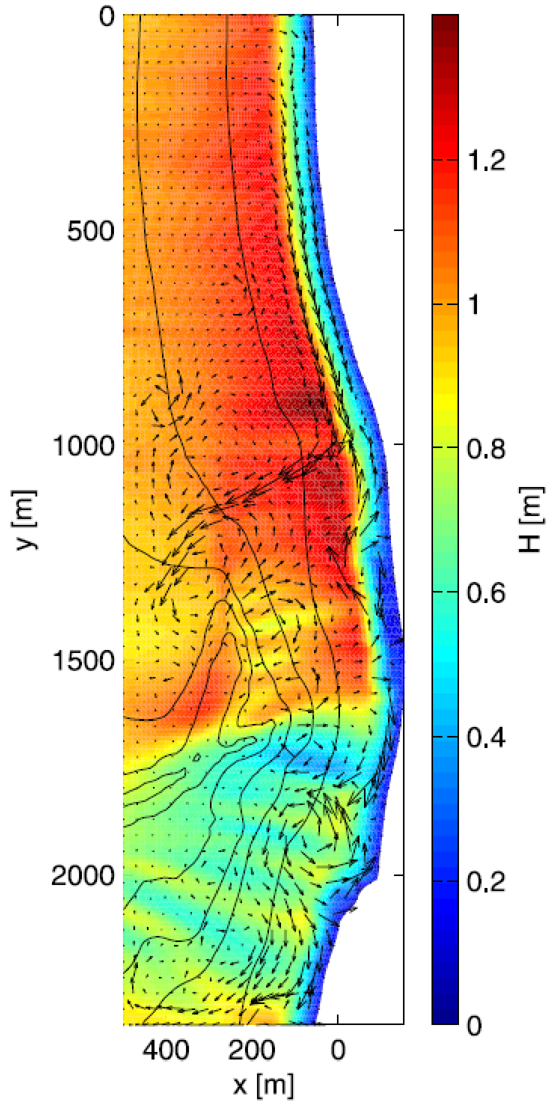


Figure 2.10: Numerical model output of predicted root-mean-square wave height (colour bar) and circulation patterns (black vectors). Presence of rip current between around (y)1000 m; (x) 0 m. Submarine canyon located offshore south of the rip current. Source: Long and Özkan-Haller (2005)

2.4.4. Non-topographically controlled transient rip currents

Transient rips currents (Figure 2.11), commonly known as 'Flash Rips', have received relatively little attention to date in the literature and as such they remain poorly understood. Transient rip currents have been described in the literature as episodic narrow offshore flows in the surf zone (Johnson and Pattiaratchi, 2006).

Like many topographically controlled rips, transient rip currents are quite often identified by a plume of sediment laden water or 'foamy' water, moving offshore (Figure 2.11) (Vos, 1976; Tang and Dalrymple, 1989; Murray et al., 2003; Murray, 2004; Slattery, 2010; Slattery et al., 2011). It is commonly accepted that transient rips vary in location and occurrence, have a short-lifespan and then decay (Murray et al., 2003; MacMahan et al., 2006; Johnson and Pattiaratchi, 2006). This results in the systems being particularly difficult to predict and measure in the field (Vos, 1976; Johnson and Pattiaratchi, 2004b; Johnson and Pattiaratchi, 2006; Slattery, 2010; Feddersen, 2013; Hally-Rosendahl et al., 2014). It is generally believed that they tend to occur on fairly uniform planar beaches with a Low Tide Terrace (LTT) beach state and a shore-attached bar. Transient rips are assumed to be hydrodynamically controlled, albeit they may be influenced by small bathymetric non-uniformities (cf. Section 2.8).

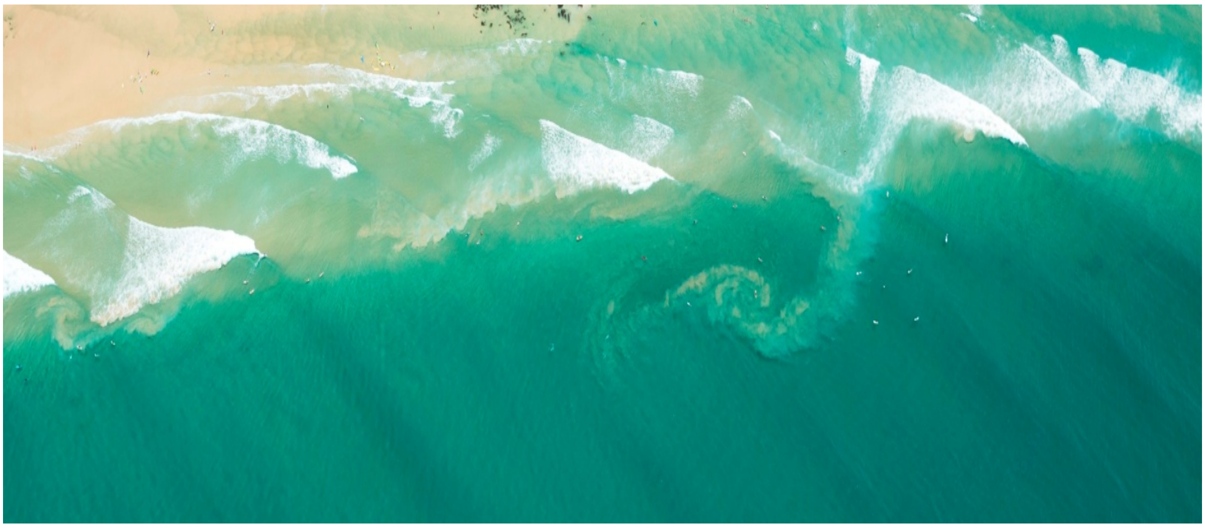


Figure 2.11: Transient Rip at Coolangatta Beach (17/2/2015) Source: CoGC skyepics (2015)

Johnson (2004) suggests that transient rip currents be classified as a *variable* current due to their formation being fundamentally driven by spatial variability in hydrodynamics rather than strong bathymetric control; which results in their formation being essentially “forced motions.” Johnson (2004) also argues that by definition transient rip currents possess a zero long-term mean flow. Transient rip currents in the literature and in this thesis have been recorded to persist on the order of tens of seconds to minutes, meaning that their lifespans persist over a number of wave cycles.

A major aim of this thesis is to improve the overall understanding of transient rip currents and where they fit into the overall hydrodynamic regime on the Gold Coast open beaches. As such a detailed review of the historical literature on transient rip currents and potential generation mechanisms is provided in Section 2.8.

2.4.5. **Swash rip currents**

Ephemeral currents may also be generated in the swash zone (Figure 2.12). Even if crests have not merged as they approach the shoreline there is a strong tendency for the swash resulting from successive waves to combine in the swash zone to give just one single swash from a wave group (Peregrine, 1998). This would lead to an increased runup and therefore setup on the beach (particularly on more reflective beach faces or high tide LTT beaches). The water then has to return seaward potentially causing temporary currents off the swash zone and/or inner bar into the deeper water immediately offshore (Figure 2.12). As noted in Dalrymple et al. (2011) swash rips are not discussed as surf zone currents as they occur in the swash zone.

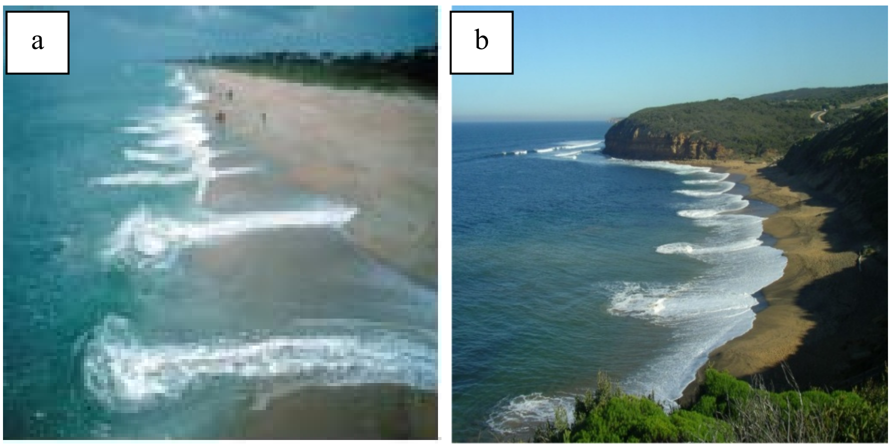


Figure 2.12: Examples of swash rips: (a) Source: Dalrymple et al. (2011); (b) Source: Castelle (2012)

2.5. Surf Zone Circulation

The traditional view of surf zone and in particular rip current circulation was based on early work of Shepard et al. (1941), Shepard and Inman (1950), Bowen (1969) and summarised by Komar (1998). Traditionally it was accepted that there are two wave-induced current systems in the nearshore that dominate water movements: (i) a cell-circulation system consisting of rip currents and associated longshore currents and (ii) longshore currents generated by an oblique wave approach to the shoreline (Komar, 1998). When waves break with their crests effectively parallel to the shoreline the generated currents take the form of rip cell-circulation (Figure 2.13A). With highly oblique wave angle approach, longshore currents are generated and on barred beaches are often confined to a nearshore trough (Figure 2.13C). In natural systems, a combination of these two current systems exist (Figure 2.13B). The intermediate scenario commonly occurs when waves break at small angles to the shoreline or where there is a strong control by bar and beach topography on the pattern of nearshore currents (Komar, 1998).

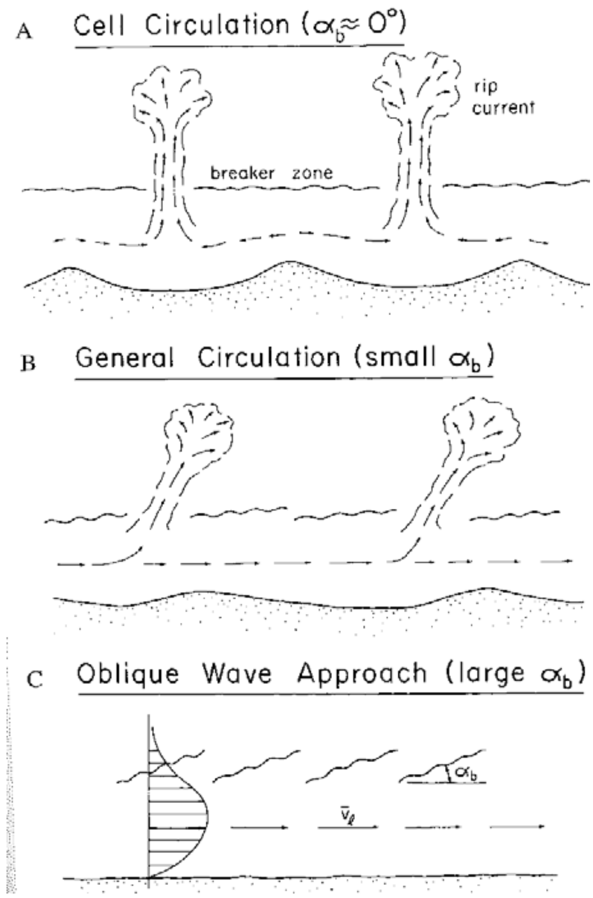


Figure 2.13: Typical patterns of surf zone currents observed, largely dependent upon the angle of wave breaking (α_b). Source: Komar (1998)

The recent use of Lagrangian drifter technology (cf. Chapter 4) and modelling experiments of rip current circulation have brought about a new thinking on surf zone circulation. MacMahan et al. (2010a) provided a simplified description of the different types of surf zone circulation expected on a barred beach and described a fourth circulation pattern, *Meandering*, which is a combination of rip current circulation and sinuous alongshore current (circulation patterns summarised in Figure 2.14). It is now generally accepted that rip current flow fields consist of semi-enclosed, large scale vortices (on the order of surf zone width) with the flow occasionally extending offshore beyond the edge of the surf zone (MacMahan et al., 2010a; Reniers et al., 2010; Castelle et al., 2011; Castelle et al., 2013; Castelle et al., 2014b).

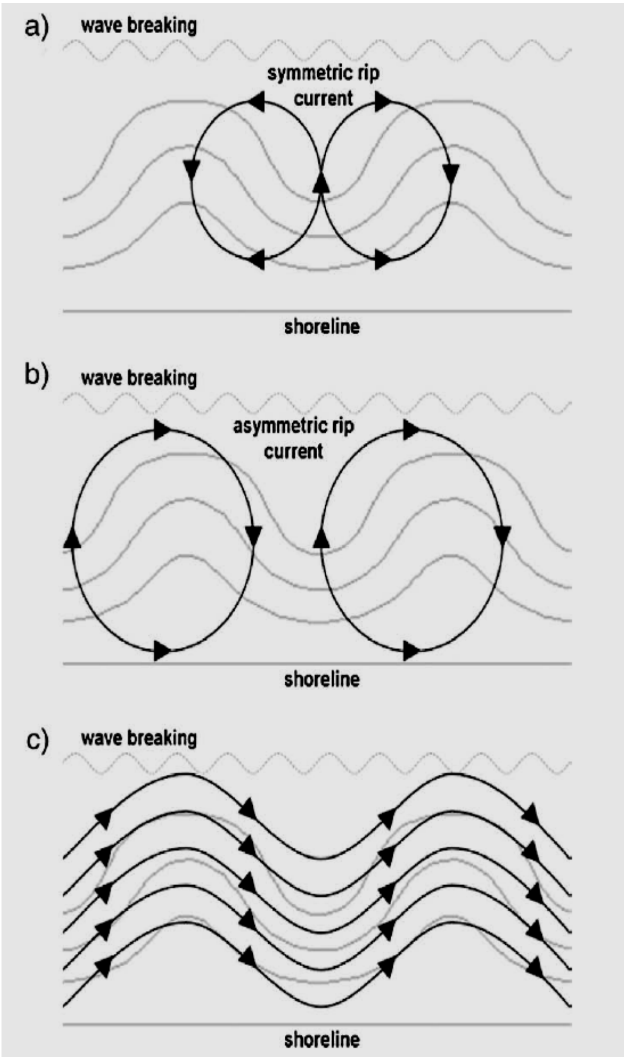


Figure 2.14: Conceptual circulation patterns for an open coast rip-channelled beach for (a) a symmetric rip current, (b) an asymmetric rip current, and (c) sinuous alongshore current. Black lines represent the velocity flow field, gray lines are the bathymetric contours, and gray sine wave is location of the surf zone where wave breaking begins. Figure and caption sourced from MacMahan et al. (2010a)

To date very little quantitative information exists on circulation patterns on planar terrace beaches and correspondingly transient rip current circulation. Dalrymple et al. (2011) provide a simple conceptual model of transient rip current circulation (Figure 2.15). Circulation patterns on a planar terrace beach are discussed further in Chapter 4.

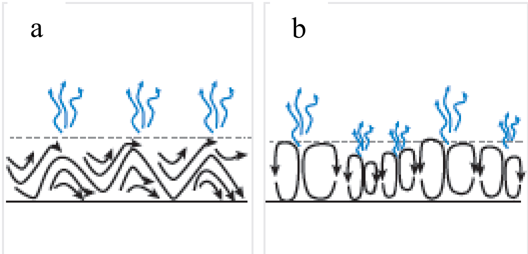


Figure 2.15: Flow behaviour schematics of the two types of transient rip currents proposed by Dalrymple et al. (2011). Transient rips generated by an oblique incident wave angle (a) and near normal wave angle (b) are shown (modified from Dalrymple et al., 2011).

2.6. Introduction to the Beach Rip Hazard

Any study concerned with surf zone currents and in particular rip currents will have inherent implications for beach safety and hazard management. Brander and MacMahan (2011) summarised the complexity of the problem with educating beach goers as to the inherent risks of rip currents and strategies to employ if 'caught' in a rip. They argue that whilst traditionally educational material has suggested that swimmers would not be able to swim against rip currents of speeds 1 $m.s^{-1}$ in fact most average swimmers may be able to swim at these velocities. It is therefore assumed that capable swimmers may be able to swim against low to moderate rip currents and make their way back to shore or to an adjacent shallow sand bar over short distances (Brander and MacMahan, 2011). It is therefore obvious that the greatest risk is presented to poor or inexperienced swimmers (Brander and MacMahan, 2011; McCarroll et al., 2014a). Brander and MacMahan (2011) suggest that surf zone currents may briefly pulse at velocities greater than 2 $m.s^{-1}$ and these rip current pulsations are considered the major causes of mass rescue events and events where average or experienced swimmers are carried offshore into deeper waters. Finally it is important to remember that swimmer behaviour is important for bathers 'caught' in a rip current as even strong swimmers may panic when being carried out to sea in a rip current (Brander and MacMahan, 2011; Miloshis and Stephenson, 2011; McCarroll et al., 2014a).

Traditionally the education material has suggested that once caught in a rip current, bathers attempt to swim parallel to the beach towards the breaking waves, where a shallower sand shoal should exist, or until the bather escapes the rip current and may proceed to make their way back toward shore. As recent research has suggested rip currents are composed of semi-enclosed vortices in the surf zone (e.g. MacMahan et al., 2010a), the alongshore feeder currents may be as strong as the rip current itself and be difficult for a bather to swim against. It has recently been suggested that swimming parallel in the wrong direction (i.e. against the feeder current) could be hazardous (MacMahan et al., 2010a; McCarroll et al., 2014a). As a result two studies have used human drifters performing various actions to test rip current 'escape strategies' (Miloshis and Stephenson, 2011; McCarroll et al., 2014a). Due to the complexity of surf zone circulation and the dynamic nature of the beach and surf zone morphology and hydrodynamics the debate continues as to what to do when caught in a rip current. This debate is covered in detail in Miloshis and Stephenson (2011), Brander and McMahan (2011) and McCarroll et al. (2014a).

2.7. Surf Zone Hydrodynamics Overview

The surf zone is characterised by a complex mixture of wave and current motions operating over a wide range of frequencies and magnitudes (Figure 2.4). These motions are related to the breaking of incident waves and consist of high frequency turbulence, incident gravity, infragravity and very low frequency (VLF) wave motion, and wave driven mean currents (Aagaard and Masselink, 1999). This section introduces key concepts and processes which are central to the theory of wave-generated currents in the surf zone.

2.7.1. Wave radiation stress

One of the most important fundamental concepts involved in the generation of time-averaged nearshore currents is the wave radiation stress. The concept of wave radiation stress was first introduced in a series of papers by Longuett-Higgins and Stewart (1960-1964) and is defined as the momentum flux due to the presence of waves only. This momentum flux consists of two components namely the momentum flux per unit length of wave crest (S_m) and the excess pressure force compared to the still water situation

(S_p). The time-averaged radiation stress is given by the sum of these two components (e.g. Svendsen, 2006),

$$\overline{S = S_m + S_p = \int_{-h}^{\bar{\eta}} (\rho u^2) dz + \int_{-h}^{\bar{\eta}} p dz} - \frac{1}{2}\rho g h^2 \tag{2.3}$$

where, ρ is density, g is gravitational acceleration, h is the still water depth $\bar{\eta}$ is water surface elevation relative to still water level. The second term denotes the total pressure force over the water depth and the third term denotes the hydrostatic pressure force due to the still water level so subtracting the latter from the former leaves the excess pressure force due to the waves only.

Insertion of linear wave theory into equation (2.3) yields the following solutions for the magnitude of the radiation stress (e.g. Svendsen, 2006),

$$S_m = \frac{1}{16}\rho g H^2 (1 + G) \tag{2.4}$$

$$S_p = \frac{1}{16}\rho g H^2 G \tag{2.5}$$

where, H is the wave height and,

$$G = \frac{2kh}{\sinh 2kh} \tag{2.6}$$

with $k = 2\pi/L$ the wave number and L the wavelength.

For wave crests propagating at an angle α to a horizontal (x,y) coordinate system, the different components of the wave radiation stress are as follows (Svendsen, 2006):

The x-component acting normal the vertical plane x = constant is,

$$S_{xx} = \frac{1}{16}\rho g H^2 [(1 + G)\cos^2\alpha + G] \tag{2.7}$$

The y-component acting normal the vertical plane y = constant is,

$$S_{yy} = \frac{1}{16}\rho g H^2 [(1 + G)\sin^2\alpha + G] \tag{2.8}$$

The x-component acting parallel to the vertical plane x = constant (S_{xy}) and the y-component acting parallel to the vertical plane y = constant (S_{yx}) are equal and are given by,

$$S_{xy} = S_{yx} = \frac{1}{16}\rho g H^2 \cos\alpha \sin\alpha (1 + G) \quad (2.9)$$

These results show the dependence of the radiation stress on the wave height ($S \propto H^2$).

Now considering a steady force balance and, for illustrative purposes, neglecting lateral mixing and other forcing terms (e.g. bottom friction and wind shear stress), Newton's second law yields the following general relationship between radiation stress gradients and mean water level gradients (e.g. Svendsen, 2006; Nielsen, 2009),

$$\nabla \bar{\eta} \propto -\nabla S \quad (2.10)$$

where, ∇ is the gradient operator and $\bar{\eta}$ is the elevation of the mean water level. That is, positive radiation stress gradients result in negative mean water level gradients and vice versa.

Therefore wave height variability in the cross-shore and longshore directions (induced by transformation processes such as refraction, shoaling, breaking and wave-current interactions) set up spatial gradients in the radiation stress which in turn are balanced by the mean water level gradient which ultimately drive surf zone currents.

2.7.2. Surf zone vorticity

Forcing of surf zone motions is usually assigned to gradients of radiation stress (cf. Section 2.7.1) leading to a view of the surf zone with emphasis on the gradients of surface elevation driving currents (Peregrine, 1998). Peregrine (1998) suggests that because in other areas of fluid dynamics it is useful to study a flow's vorticity; it is only natural to review the vorticity associated with surf zone currents.

This additional approach to explaining the manifestation of both topographically and hydrodynamically controlled rip currents was outlined by Peregrine (1998) and theoretically investigated further by Bühler and Jacobson (2001); Johnson and Pattiaratchi (2006); Terrile and Bocchini (2007); Long and Özkan-Haller (2009); Clark et al. (2010-2012); and Feddersen (2014). Peregrine (1998) argued that as wave breaking (typically) does not occur simultaneously along a wave front, differential wave breaking generates circulation and vorticity in the wave-averaged flow. Whilst this theory tends to favour occurrence on barred beaches, as this promotes wave breaking in sections (Bühler and Jacobson, 2001); vortical motions and occasional very low frequency (VLF) motions manifesting themselves as offshore 'squirts' have been observed on planar, alongshore uniform beaches (Murray et al., 2003; Johnson and Pattiaratchi, 2004b; Johnson and Pattiaratchi, 2006; Spydell et al., 2007; MacMahan et al., 2010a; Feddersen, 2014; Hally-Rosendahl et al., 2014).

Up until recently studies of surf zone vorticity have been generally model based (Özkan-Haller and Kirby, 1999; Johnson and Pattiaratchi, 2006; Terrile and Brocchini, 2007; Reniers et al., 2007; Long and Özkan-Haller, 2009; Bonneton et al., 2010). Recent field studies using Lagrangian techniques have been able to observe and quantify surf zone vortices (Schmidt et al., 2003; Johnson and Pattiaratchi, 2004b; Schmidt et al., 2005; Spydell et al., 2007; Spydell et al., 2009; MacMahan et al., 2010a; Feddersen, 2014; Hally-Rosendahl et al., 2014). Whilst some vortical motions may be related to shear instabilities of the mean longshore current (Section 2.7.3), energetic-vortical surf zone motions that predominantly reside within the very-low-frequency band, when the alongshore currents are minimal, have been found (MacMahan et al., 2010b; Clark et al., 2010; Clark et al., 2011; Clark et al., 2012; Feddersen, 2014).

Recent model simulations also suggest that the VLF vortical motions may persist for durations of up to 25 min (Johnson and Pattiaratchi, 2006; Reniers et al., 2007) even though the wave group time scales are much shorter (Long and Özkan-Haller, 2009). This long life span allows these vortices to potentially trigger incipient sediment motion leading to the formation of bathymetric features such as rip channels (Reniers et al., 2007; Long and Özkan-Haller, 2009).

2.7.3. **Shear waves**

Shear waves with typical periods of 100 to 1000 s were first observed by Bowen and Holman (1989) and Oltman-Shay et al. (1989) and described as originating from shear instabilities in the alongshore current.

In the absence of longshore variations in the bathymetry; a stationary, long-crested wave field approaching the shore at an oblique angle generates a longshore directed current and a setup of the mean water level (Özkan-Haller and Kirby, 1999). As the mean longshore current is only weakly depth dependent it can be assumed to be (as with rip currents) a two-dimensional (2D) flow. This 2D flow is inherently unstable and Oltman-Shay et al. (1989) first noted that the meandering of the longshore current in the direction of the current flow did not satisfy gravity wave dynamics. As a result Bowen and Holman (1989) introduced the concept of an instability of the mean longshore current into nearshore oceanography (previously had been well studied in deeper oceanography) (Özkan-Haller and Kirby, 1999).

Field studies have observed significant meandering of strong alongshore currents; driven by obliquely incident waves (Oltman-Shay et al., 1989; Özkan-Haller and Kirby, 1999; Noyes et al., 2004; Dalrymple et al., 2011). Nonlinear numerical modelling by Allen et al. (1996) and Özkan-Haller and Kirby (1999) showed that for strong shear the meanders can grow eddies that either move along with the alongshore current or are ejected from the surf zone, forming transient whirlpool like flows (Dalrymple et al., 2011).

Unlike gravity and infragravity waves the restoring mechanism for these shear waves, is potential vorticity, where the background vorticity is supplied by the shear structure of the mean longshore current in analogy to the effect of the Earth’s rotation in larger-scale oceanographic flows (Feddersen, 2014). In other words a perturbation across the background potential vorticity will be balanced by a relative vorticity in the water column which acts as a restoring force (Bowen and Holman, 1989).

The mechanism of shear instabilities in the longshore current shows that these types of currents can be unstable and that the longshore current can act as a strong mechanism for cross-shore mixing in the surf zone (Bowen and Holman, 1989). These shear instabilities in the longshore current will be examined further in 2.8.5.1 as potential drivers of transient rip currents.

2.7.4. **Surf zone eddies**

Surf zone eddies (SZEs) as defined by Feddersen (2014) are temporary, time-dependent motions in the surf zone of which transient rip currents are a signature, as opposed to mean surf zone circulation patterns such as semi-permanent rip currents. These two-dimensional (2D) horizontal turbulent eddies exist in the surf zone with length-scales greater than the water depth (Feddersen, 2014). As the length-scales of SZE's are much larger than the water depth, the dynamics of the SZE's are likely to follow those of 2D turbulence (Feddersen, 2014). These eddies have rotational (as opposed to irrotational) velocities, which are associated with vertical vorticity (Feddersen, 2014). The rotational vortices have difficulty mixing together to form an irrotational flow as they are essentially 2D structures trying to act in the third dimension, but struggle to do so (Feddersen, 2014).

SZE's were first identified by Oltman-Shay et al. (1989) as occurring at the VLF wave spectrum. These low frequency surf zone eddies are thought to be the primary process that disperse tracers in the surf zone on alongshore uniform beaches, but the mechanisms that generate these eddies are not well understood (Spydell and Feddersen, 2009; Clark et al., 2010; Clark et al., 2011; Clark et al., 2012; Feddersen, 2014).

It has recently been hypothesised the mechanisms that transfer energy from incident swell and sea waves to lower frequency eddies may include:

- short-crested breaking-wave vorticity forcing due to along-crest variation in wave dissipation (Peregrine, 1998; Bühler and Jacobson, 2001; Bonneton et al., 2010; Clark et al., 2012; Feddersen, 2014);
- shear instabilities in the alongshore current (Oltman-Shay et al., 1989; Noyes et al., 2004);
- alongshore variation in bathymetrically-controlled wave breaking (Kennedy et al., 2006; Castelle et al., 2010) and;
- wave-groups (Long and Özkan-Haller, 2009).

Recent research suggests that these 2D turbulent SZE's are primarily generated through external forcing by short-crested wave breaking or intrinsically through an instability mechanism (i.e. "shear waves") (Feddersen, 2013). This has significant implications for transient rip generation and will be discussed further in Sections 2.8.5.1 - 2.8.5.3.

2.7.5. Tidal modulation

A secondary process that modulates beach and surf zone behaviour is ocean tides (Figure 2.4). Tides are the periodic rise and fall in the ocean surface, due to the gravitational force of the moon and the sun acting on a rotating earth (Masselink and Turner, 1999). The tidal rise and fall of the ocean surface is barely noticeable in deep oceanic waters, however on shallow continental shelves, along coastlines, and within estuaries, tidal processes may play a primary or key subordinate role in 'shaping' morphology and influencing surf zone currents (Masselink and Hughes, 2003).

Whilst the Gold Coast beaches are classified as microtidal (cf. Section 2.3), the natural fluctuation of the tide will have a significant impact on wave and current processes within the surf zone, primarily through changes in the water depth. On microtidal beaches surf zone morphodynamics may depend on the stage of the tidal cycle, with waves breaking further onshore, and which may break on the beach face, under high water conditions (Masselink and Turner, 1999). Rip currents may also increase during low water conditions due to nearshore bar morphology becoming increasingly shallow and offshore flows being confined to rip channels (Aagaard et al., 1997; Brander, 1999; Brander and Short, 2001; MacMahan et al., 2005; Austin et al., 2010; McCarroll et al., 2014b; Winter et al., 2014).

2.8. Transient Rip Currents

Despite a recent review by Dalrymple et al. (2011) of the possible causes or types of transient rip currents in the surf zone, there is still no consensus on the definition of a transient rip current in the literature or the professional world (i.e. lifeguards and beach managers). Section 2.8.1 identifies the limited literature on transient rip currents undertaken to date. Sections 2.8.1 - 2.8.4 provide a qualitative description of transient rip currents from the literature, professional lifeguards and coastal academics and outline some common assumptions about their formation. Section 2.8.5 proposes two possible generation mechanisms for the formation of the 'idealised' transient rip current (i.e. rip currents occurring on a planar beach devoid of clear bathymetric non-uniformities), drawing upon the fundamental principles of surf zone vorticity outlined earlier in this chapter. Section 2.8.5.3 also briefly describes how these currents are identified in the surf zone. Section 2.8.6 then briefly describes the suggested temporal length scales of these 'idealised' transient rip currents. As the surf zone is an inherently noisy and chaotic environment it is suggested that several other processes might aid in transient rip generation and evolution. This is discussed in Section 2.8.7. The chapter also briefly describes the transition of transient rip currents to semi-permanent beach rip currents (2.8.8).

2.8.1. **Overview of transient rip current studies**

Due to their elusive nature only five research groups have attempted to specifically tackle the transient rip current phenomenon in any sort of detail (Table 2.1). Three recent studies (Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014) focusing on surf zone vortices and cross-shore exchange of water and tracers (i.e. sediment / dye) have proposed the fundamental causes of transient rip currents in the surf zone (Section 2.8.5). Whilst these recent studies have identified possible driving mechanisms of transient rip systems, Hally-Rosendahl et al. (2014) note that their time and length scales are not well understood.

Table 2.1: Historical literature investigating transient rip currents

Literature	Brief Description
Vos (1976)	Observational study describing transient rip formation
Murray et al. (2001, 2003, 2004)	Field observations and a numerical model to test a hypothesis for transient rip current generation based on feedback mechanisms from (at the time) a newly hypothesised wave-current interaction
Johnson and Pattiaratchi (2004, 2006)	Lagrangian drifter field study (2004) and Boussinesq modelling study (2006) of transient rip currents, quantifying transient rip behaviour and proposing possible generation mechanism / manifestation of the currents
Slattery et al. (2010, 2011)	Remote-video study assessing the nature and activity of transient rip currents
Castelle et al. (2014)	Remote-video and Lagrangian human drifter study undertaken to measure transient rip currents on a Low Tide Terrace, wave dominated open coast beach

2.8.2. **Vos' description of transient rip formation**

Vos (1976) conducted a purely observational study of the formation and location of transient rip currents on a high energy, wave-dominated beach. The study provided the first description of transient rip formation and behaviour on open coast beaches away from the influence of headlands and groynes. Vos (1976) observed that transient rip currents tend to form when there is a build up of larger 'set' waves (Figure 2.16I). Vos (1976) argues that the "sucking and erosive" effects of the larger breaking waves initiate a seaward current in a scoured breaker zone, at the same time that water is accumulating inside the breakers (Figure 2.16I-III). Accumulated water inside the breakers then begins to drain seaward, feeding the embryonic rip current, which then develops into a mature current (Figure 2.16 IV-VI).

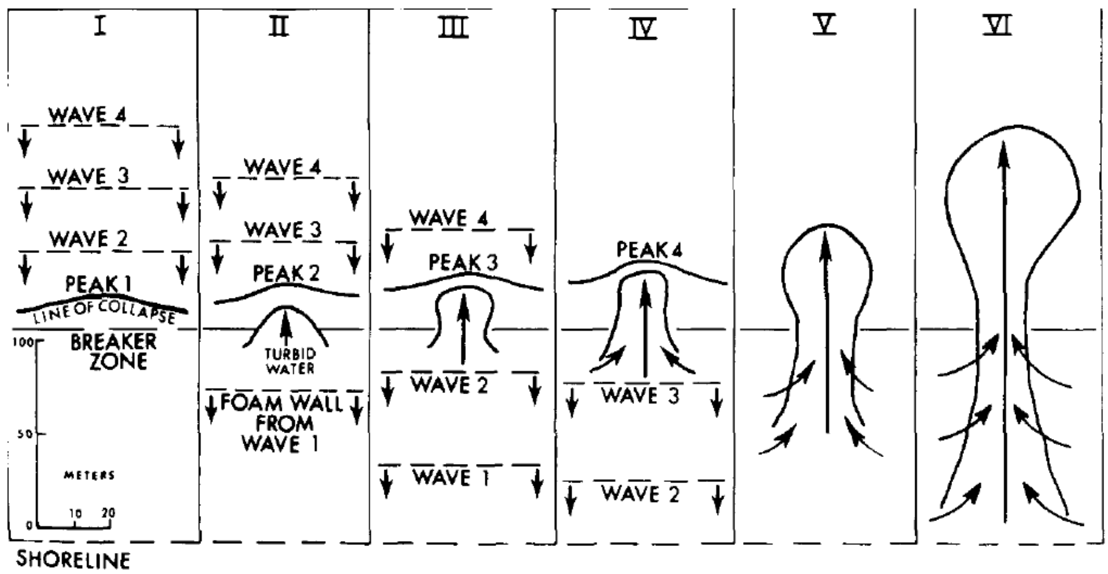


Figure 2.16: Schematic illustration of the sequence of events controlling the initial formation and the location of a transient rip current. Source: Vos (1976)

2.8.3. **Perspectives from professional lifeguards**

In November, 2009 the researcher spent two days with the Surfers Paradise lifeguards, identifying physical surf zone hazards with a focus on transient rip currents. The lifeguard's qualitative description of transient rips is quite similar to that outlined in Vos (1976) (Figure 2.16 & Figure 2.17). The lifeguards stated that transient rips occur when there is a build-up of larger than the average waves, favouring plunging wave conditions. Waves coming out of deep water break on the edge of the bar then continue on shoaling, but a plume of sandy/ green water, flashes (hence the name 'flash rips') back out to sea before dissipating rapidly (Figure 2.17). The transient rip may travel parallel to the shore with the alongshore current (known colloquially as ‘sweep’) until it finds a weak part (i.e. deformation) of the bar to travel out in. Lifeguards acknowledged that transient rip currents tend to form and pulse quickly then dissipate rapidly, whilst moving people from shallow to deep water suddenly. Lifeguards are concerned with transient rip currents that occur with wave heights generally < 1 m as with bigger seas the ocean tends to become self mitigating, with respect to beach hazard and risk.

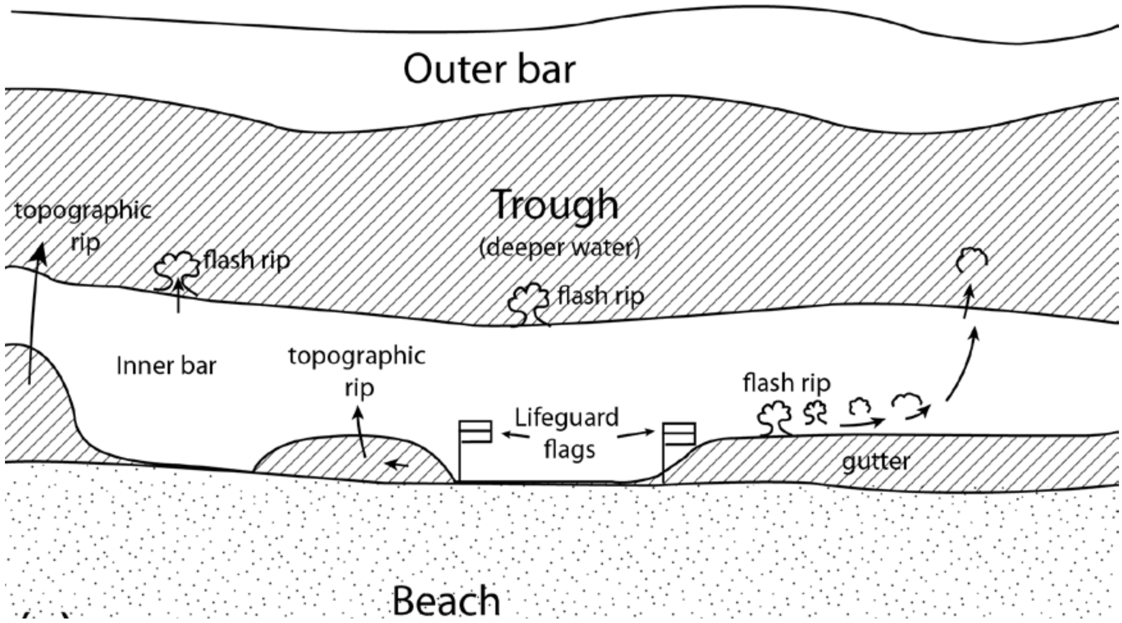


Figure 2.17: Schematic illustration of transient rip (flash rip) occurrence / behaviour on November 5, 2009 (lifeguard observations). There was a weak N to S longshore current on the day with transient rips migrating south with the current (Note: figure not to scale)

2.8.4. **Perspectives from coastal academics**

In 2011 an informal email survey asked four well respected coastal geomorphologists to provide the author with a “classification of transient rip systems and an explanation of how these differ from the more morphologically controlled beach rip currents.” The survey returned little consensus on a classification for transient rips, other than transient rip currents generally occur on alongshore uniform sections of beach (Table 2.2).

Table 2.2: Informal transient rip classifications from four coastal experts (2011). Identities have been kept anonymous but country of origin is noted to give a worldwide perspective

Coastal Expert ID	Transient rip classification
AUS1	*"I don't have a classification of transient rips and in fact one doesn't exist in the literature. The best description of transient / flash / high-energy rips is really by Short (2007) and are analogous to erosional rips"*
AUS2	*"Transient rips have no defined rip channel, are variable in location, can occur on flat featureless Low Tide Terrace. So a definition would be a rip current that occurs periodically at variable locations where waves are breaking across a uniform surface. They have a finite life span usually related to one rip pulse"*
US	*"This is great topic, but a tough one. Basically, you need to convince folks that the apparent transient rip current is not related to any bathymetric feature. It has been found that rip currents can develop with very subtle bathymetric relief"*
FRANCE	*"(1) for near shore-normal waves, sometimes exited by two distinct wave peak directions, the beach must be rather alongshore-uniform with plunging breakers (2) Other flash rips can be observed for reasonably high-angled waves through shear instability of the longshore current. * In both cases the surf zone sandbars have to be rather alongshore-uniform"*

2.8.5. Fundamental drivers for the generation of transient rip currents

Rip currents can be created on beaches that have no alongshore bathymetric variation. To date very little work has focused on the drivers of transient rip currents, with no studies dealing specifically with the topic. Recent research (Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014) has proposed two possible generation mechanisms for the idealised transient rip current (i.e. rip currents occurring on a planar beach devoid of clear bathymetric non-uniformities) formation:

1) Shear instabilities in the longshore current (first observed by Bowen and Holman (1989) and Oltman-Shay et al. (1989) and more recently explored by: Allen et al. (1996); Özkan-Haller and Kirby (1999); Noyes et al. (2004); Clark et al. (2010-2012), and Feddersen (2014)

2) Short-crested breaking wave vorticity forcing due to along-crest variation in wave dissipation: first introduced by Peregrine (1998) and more recently explored by Johnson and Pattiaratchi (2006); Terrile and Bocchini (2007); Long and Özkan-Haller (2009); Clark et al. (2010-2012), and Feddersen (2014)

As mentioned in Sections 2.7.2 - 2.7.4 these two types of surf zone motion tend to drive 2D horizontal surf zone eddies (Section 2.7.4) that behave similar to 2D turbulence and fluctuate at frequencies lower than normal incident waves. Feddersen (2013) argues that transient rip currents are a signature of these 2D surf zone eddies and are easily visualised by surf zone tracers such as sediment and dye (cf. Section 2.8.5.3). These 2D eddies can exist in the absence of any mean cross-shore flow (V). On rip-channeled beaches both the 2D eddies and mean circulation features can be responsible for cross-shore diffusivity of water and sediment. The following three sections (2.8.5.1 - 2.8.5.3) will argue for the ability of the shear instability mechanism and short-crested wave breaking to drive these surf zone vortices, which may evolve into transient rip currents on alongshore uniform beaches.

2.8.5.1. Shear instabilities in the longshore current

It is proposed that transient rip currents can be observed for reasonably high-angle waves through shear instability of the longshore current. The presence of strong shear in the alongshore current cross-shore profile can lead to shear instability and the meandering of the alongshore current in the cross-shore direction (Bowen and Holman, 1989; Allen et al., 1996; Özkan-Haller and Kirby, 1999; Noyes et al., 2004; Dalrymple et al., 2011) (Figure 2.18). Oltman-Shay (1989) observed a meandering in the alongshore current over timescales of up to *O*(1000 s) and showed that these motions have much shorter wave lengths than edge waves at similar frequencies.

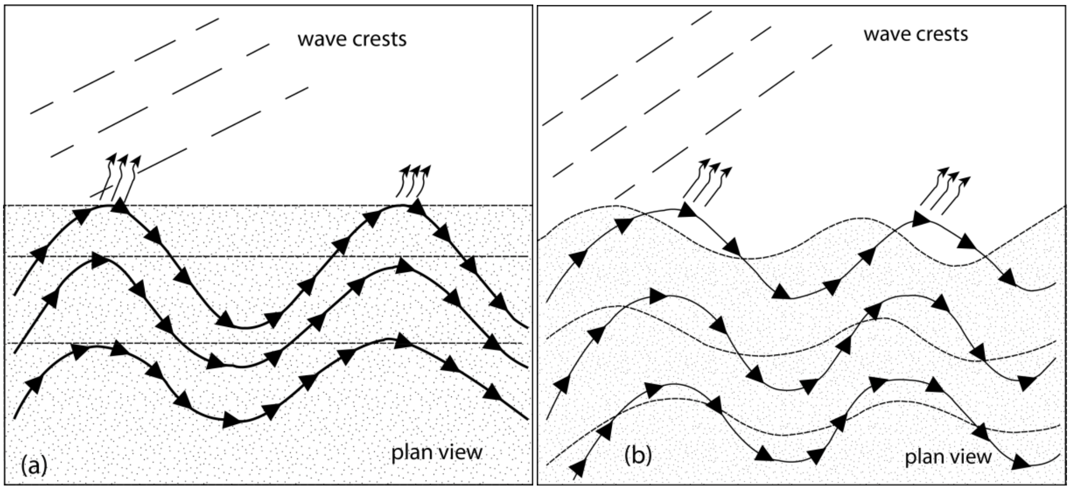


Figure 2.18: Shear instabilities of a meandering longshore current, manifesting themselves as offshore ejections out of the surf zone (a) planar beach (b) barred beach (plan view).

As with the interacting surf zone eddies (cf. Section 2.8.5.2) vortex pairs, created by the shear instability, may also shed creating strong offshore flows (i.e. rip currents) (Peregrine, 1998; Peregrine and Bokhove, 1998; Özkan-Haller and Kirby, 1999; Johnson and Pattiaratchi, 2006; Dalrymple et al., 2011). Theoretically this may occur on planar, alongshore uniform beaches, whereby the cross-shore flows manifest themselves as spatially and temporally variable transient rip currents (Figure 2.18a; Figure 2.19). The process of vortex pairing is described further in Section 2.8.5.3.

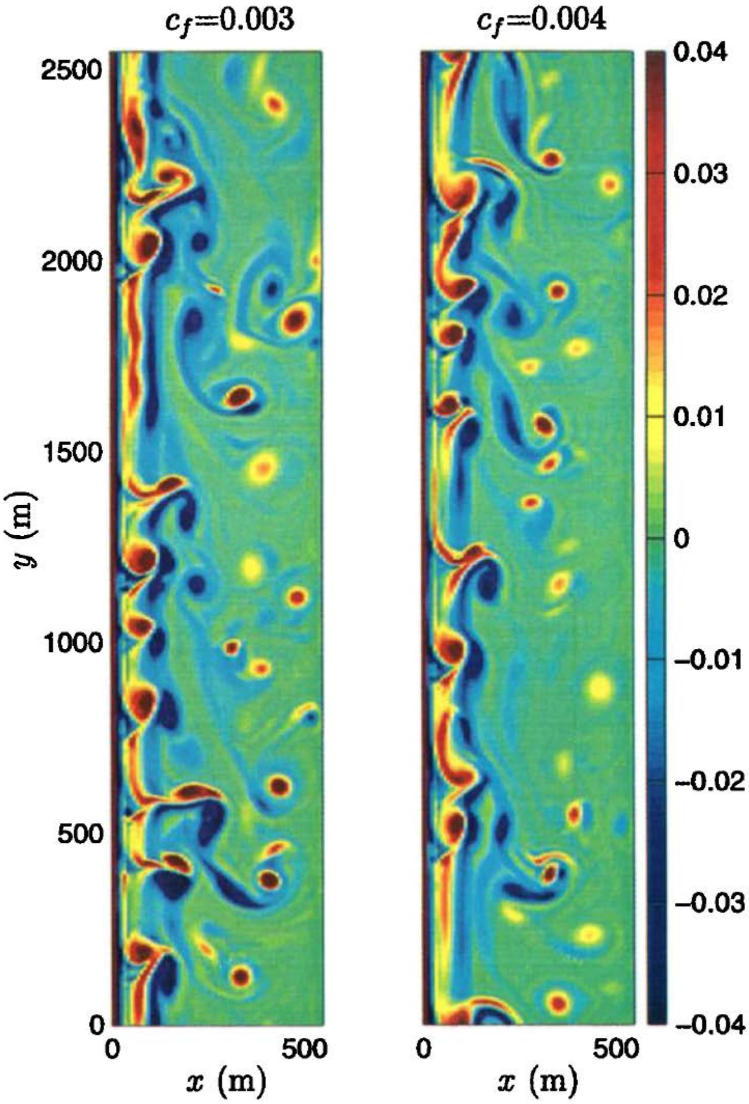


Figure 2.19: Example of (simulated) contour plots of vorticity generated by shear instabilities in the alongshore current. Source: Özkan-Haller and Kirby (1999)

It has been visually observed but not quantified that in the case of transient rips generated by shear instability of the alongshore current, rips can migrate alongshore (B Castelle, personal communication, 8 June 2011). Migration of transient rips with the longshore current has also been observed and identified by Gold Coast professional lifeguards (cf. Section 2.8.3).

Numerical models and corresponding field studies have found that in most natural surf zones the shear instability eddy generation mechanism is negligible relative to the breaking-wave forcing of surf zone eddies / vortices, with the possible exceptions for very narrow-banded, highly oblique, large incident waves (Spydell et al., 2009; Spydell and Feddersen, 2009; Clark et al., 2010; Clark et al., 2011; Clark et al., 2012; Spydell and Feddersen, 2012; Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014). As a result it is believed that transient rip currents will be most commonly driven by short-crested breaking wave vorticity forcing due to along-crest variation in wave dissipation (see the following section).

2.8.5.2. Wave vorticity due to along-crest variation in wave breaking

As well as the *intrinsic* mechanism of shear instability in the alongshore current, vorticity associated with the small scale 2D surf zone eddies are believed to be generated through the *extrinsic* mechanism of short-crested breaking-wave vorticity forcing due to along-crest variation in wave dissipation (Peregrine, 1998; Peregrine and Bokhove, 1998; Clark et al., 2012; Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014).

Clark et al. (2012) were the first to measure wave-generated vertical vorticity (e.g., horizontal eddies) in the field. They found that individual short-crested breaking waves generate significant vorticity [$O(0.01\ s^{-1})$] in the surf zone (Figure 2.20 and Figure 2.21). Clark et al. (2012) provide the best summary of this hypothesised process:

> *"the instantaneous forcing is composed of individual breaking waves that often are short-crested owing to the directional spread of the wave field (Longuet-Higgins, 1957), with crests from different directions interacting to create alongshore varying wave amplitudes. Thus, the wave field is spatially inhomogeneous over wave time and spatial scales, with the largest amplitude section of the wave breaking first, resulting in a breaking region with a finite alongshore extent (Clark et al., 2012, pp. 1)(Figure 2.20)"*

Figure 2.20: Photograph of breaking waves (propagating toward the shore from lower-right to upper-left) showing the triangular patches ('wedge formation') of residual white foam marking the location where breaking occurred. As the waves break, they transfer momentum to the water column and generate vorticity. The initially small breaking region on the lower right expands as the wave moves toward shore on the upper left. This pattern is typical in the surf zone, with the shape of the triangle varying with wave conditions and bathymetry. Yellow circles represent wave crest ends. Figure and Caption modified from: Clark et al. (2012)

On alongshore uniform beaches it is argued that a directionally spread breaking wave field (i.e. incoming waves with a variety of angles) is required for finite breaking crest-lengths (Johnson and Pattiaratchi, 2006; Spydell and Feddersen, 2009; Feddersen, 2014). On natural, more irregular beaches several possibilities are hypothesised to be responsible for causing finite breaking crest-lengths (Johnson and Pattiaratchi, 2006; Clark et al., 2012), including:

- variations in alongshore bathymetry;
- the inherent spatial variability of the incident (short) wave field (i.e. wave-wave interactions and / or multiple wave sources);
- interaction of the incident wave field and the wave-averaged mean current (i.e. incident wave-current interactions);
- offshore wave modifications;
- interaction of the incident wave field with lower frequency waves (i.e. long waves)

It is hypothesised that non-uniform vorticity ω about a vertical axis (termed "vorticity" by Clark et al. 2012) is generated by along-crest variations in the breaking force (Clark et al., 2012):

$$\frac{d\omega}{dt} = -\frac{dF_{br}}{d_{yc}} \tag{2.11}$$

where t is time, F_{br} is the breaking force, and y_c is the along-crest direction (Peregrine, 1998; Peregrine, 1999; Bühler and Jacobson, 2001; Bonneton et al., 2010; Clark et al., 2012).

Clark et al. (2012) explains that the maximum vorticity generation is likely to occur at the crest end $y_c = 0$, where adjacent regions of breaking and non-breaking wave crest are assumed to form a large differential in forcing (Figure 2.21). Using a novel circular array of current metres Clark et al. (2012) measured the vorticity generated by short-crested breaking waves in the surf zone. Video observations were also used to identify times when short-crested breaking occurred within or near the array. Clark et al. (2012) observed the change in vorticity (i.e. generated vorticity) to be positive for left-handed (Figure 2.21A) and negative for right-handed (Figure 2.21B) wave ends. This finding supports the theory first described by Peregrine (1998; 1999). Johnson and Pattiaratchi (2006) suggest that as the incident wave forcing is the largest in the inner surf zone (i.e. where almost 100% of waves are broken) and decreases offshore, it is reasonable to assume that the main vorticity input from the incident wave field occurs in the inner surf zone.

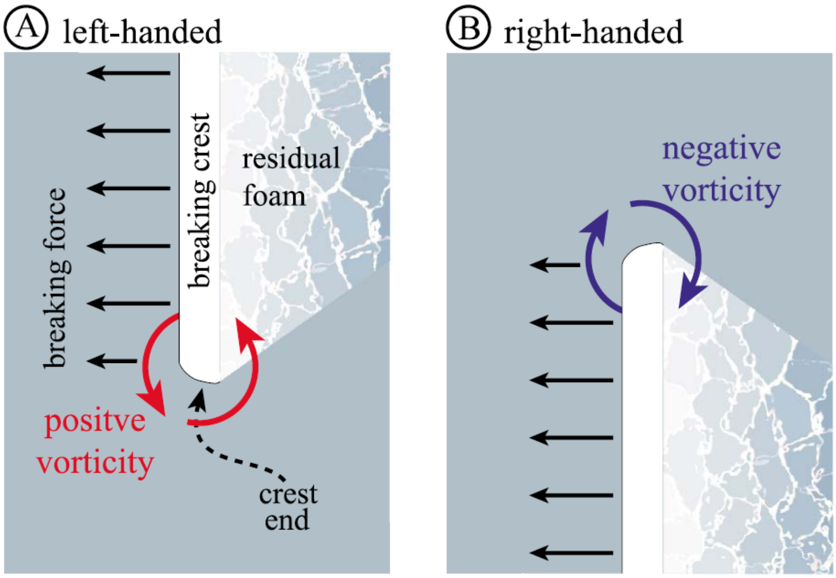


Figure 2.21: Schematic (looking down from above) of negative and positive vorticity generated by (A) left- and (B) right-handed ends of breaking waves. Solid black arrows indicate the instantaneous forcing (owing to breaking) on the water column in the direction of wave propagation, and the curved arrows indicate the direction of fluid rotation for the resulting positive (red) and negative (blue) vorticity. Figure and Caption sourced from: Clark et al. (2012)

The field study of Clark et al. (2012) backs up numerical modeling simulations that also suggest short-crested breaking waves can generate vorticity and cross-shore dispersion of currents and sediment in the surf zone (Bühler and Jacobson, 2001; Johnson and Pattiaratchi, 2006; Bruneau et al., 2011).

Feddersen (2014) found that the majority (> 80%) of surf zone vorticity occurs at alongshore scales < 20 m, which is similar to transient rip scales. This finding indicates that short-crested wave breaking is also dominant over wave group forcing in generating surf zone eddies and that eddy energy is cascaded to longer length scales (i.e. smaller wave number k_y), through nonlinear interactions as in 2D turbulence (Feddersen, 2014). Observations and model results have also found that in the mean-squared perturbation vorticity budget, the breaking-wave vorticity forcing term was generally orders of magnitude larger than the shear-instability generation term (Johnson and Pattiaratchi, 2006; Spydell and Feddersen, 2009; Feddersen, 2014). As a result it is believed that the short-crested breaking wave vorticity forcing due to along-crest variation in wave dissipation is the most common driver of surf zone vorticity and in turn transient rip currents.

2.8.5.3. Vortex coupling

Under conditions where short-crested breaking wave vorticity is generated, some vortex pairs (of opposite signs) can manifest themselves as transient rip currents on planar beaches (Johnson, 2004; Johnson and Pattiaratchi, 2004b; Johnson and Pattiaratchi, 2006; Long and Özkan-Haller, 2009; Spydell and Feddersen, 2009; Clark et al., 2012; Feddersen, 2014).

Johnson and Pattiaratchi (2006) present a conceptual model for transient rip formation, by offshore propagation of turbulent vortex pairs (Figure 2.22). In the initial stages of rip generation Johnson and Pattiaratchi (2006) modelled individual vortices to propagate alongshore often resulting in two patches of opposite signed (i.e. positive and negative) vorticity being driven together. As the vortex pair moves offshore, conservation of potential vorticity results in streamlines being squeezed together (Figure 2.22). This has been proposed as the reason for offshore intensification of rip neck flow (Arthur, 1962; Johnson and Pattiaratchi, 2006; Feddersen, 2014).

Johnson and Pattiaratchi (2004b; 2006) observed and modelled transient rip currents to appear as narrow regions of offshore flow which penetrate offshore and are associated with a vortex pair in the head (Figure 2.22 & Figure 2.23). The rip currents observed in their studies were oriented at varying angles to the shore but were always composed of opposite regions of vorticity along the rip neck and a vortex pair in the head region.

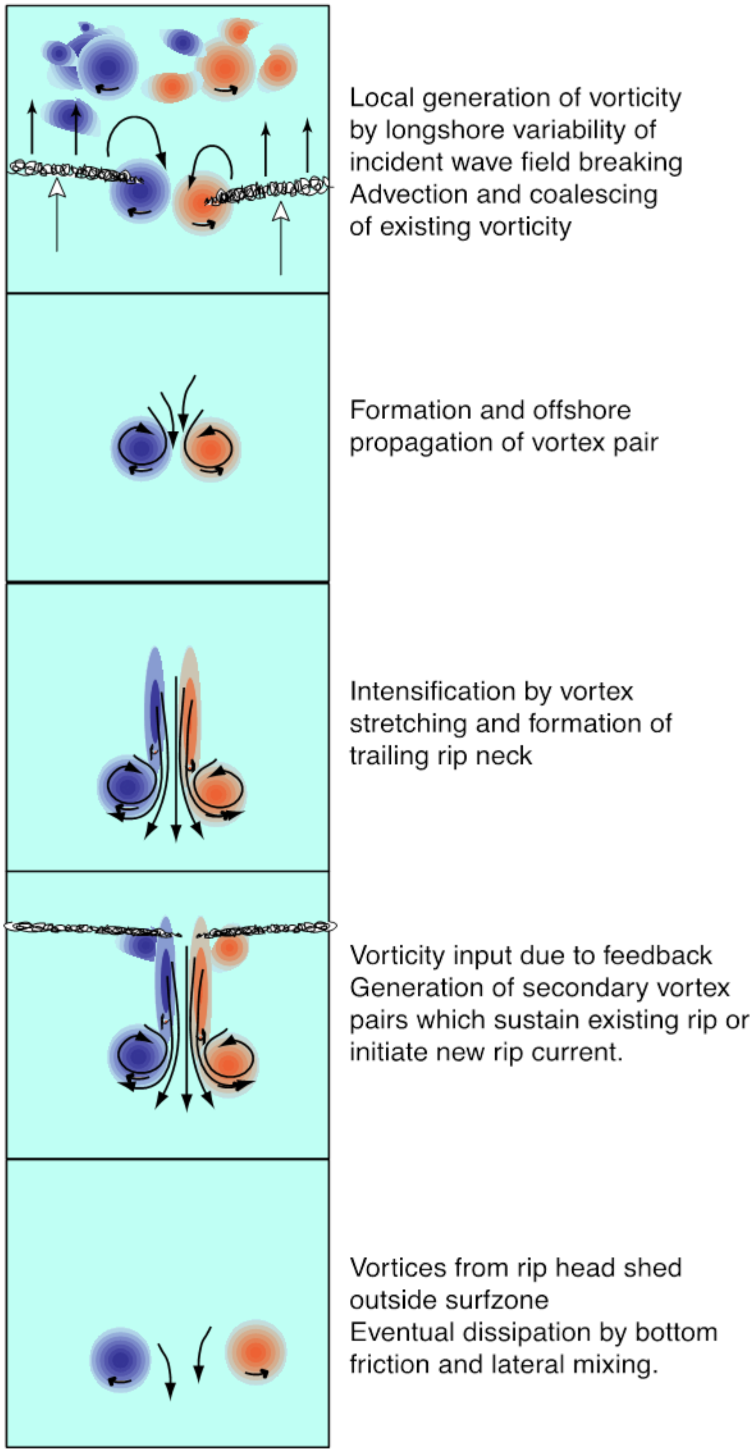


Figure 2.22: Conceptual model of transient rip generation. Source: Johnson and Pattiaratchi (2006)

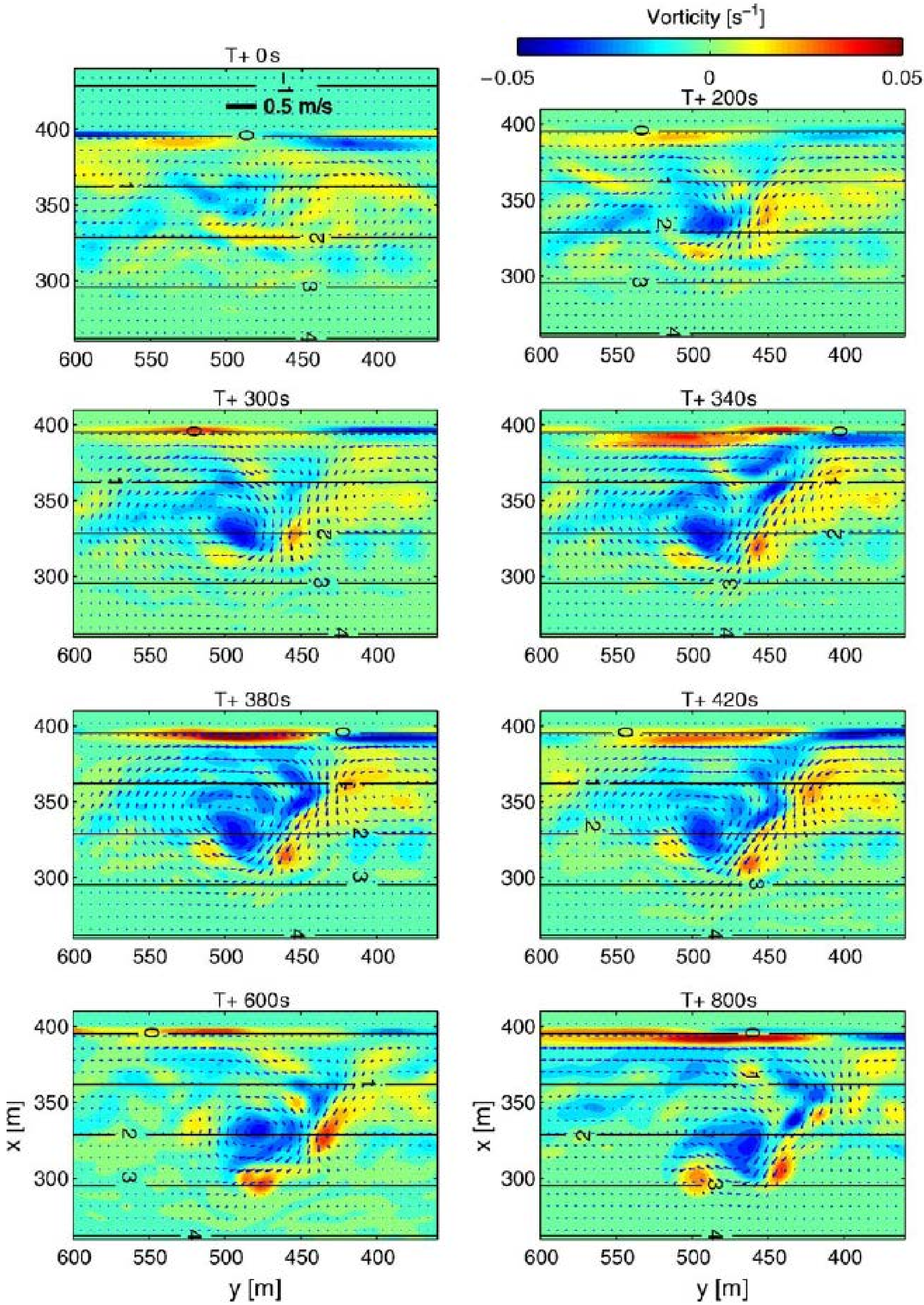


Figure 2.23: Example of modelled velocity and vorticity field, showing the development of transient rip currents. Source: Johnson and Pattiaratchi (2006)

Peregrine (1998) argues that whilst visual observation of the velocity field in the surf zone is difficult, there is one type of occasion when the surf zone eddies may become clearly visible (Figure 2.24). Sometimes the strength of the breakers means that there is substantial suspension of sediment in the surf zone, but not outside the surf zone. This means that when a surf zone eddy propagates outside the surf zone, the eddy cores transport sediment laden water out into clear water (Figure 2.24).

Figure 2.24: Aerial photograph of rip dye experiment at the alongshore uniform Imperial Beach, California. Transient rip currents obvious in the dye and sediment tracer with rip head representative of a vortex couple. Source: Feddersen (2013)

Often these features can manifest themselves as 'mushroom cloud-like' plumes of sand-laden water (Figure 2.11 & Figure 2.24). As the seaward directed jet expands laterally, a mushroom-shaped structure (vortex pair) develops at the head, with counter-rotating eddies that may or may not be of equal size (Smith and Largier, 1995). This vortex pair may detach from the stem of the rip current, as the root dissipates, and carry a patch of surf zone water offshore (Smith and Largier, 1995). These are some of the most obvious visual clues of transient rip currents on an alongshore uniform beach and have been observed in the field by Vos (1976), Murray et al. (2003), Johnson and Pattiaratchi (2004b), Feddersen (2013, 2014) and Hally-Rosendahl et al. (2014). These 'mushroom cloud' features are also commonly observed over the inner Low Tide Terrace bar along the Gold Coast open beaches. This scenario supports the theory that offshore propagation of turbulent vortex pairs may be a manifestation of transient rip currents on a planar beach.

2.8.6. **Temporal scales over which transient rip forcing occurs**

Johnson and Pattiaratchi (2006) suggest that the vorticity field of the wave-averaged transient rip currents generated by short-crested wave breaking display vortices and vorticity gradients at a range of scales and there are similarities with the rotational (in the sense of possessing vertical vorticity) flow seen in nonlinear simulations of longshore current instabilities. MacMahan et al. (2010b) further argue that the frequent co-existence and potential interaction of shear instabilities and wave breaking induced vortices may mask the VLF response to the grouped incident waves. The influence of wave groups on transient rip generation will be addressed in Section 2.8.7.2.2.

2.8.7. **Generation of transient rips in natural surf zones**

Section 2.8.5 discusses what are believed to be the fundamental drivers of 'idealised' transient rip currents on alongshore uniform beaches and surf zones. In reality the beach and surf zone topography is rarely alongshore uniform and more commonly a mixture of rip current (and other surf zone current) types exist in nature. Transient rip currents may additionally be driven by a combination of the following surf zone mechanisms / interactions and it is an understanding of the respective contributions of each mechanism / interaction that is difficult to assess in field studies and numerical models.

2.8.7.1. Multiple wave sources – directionally spread wave field

Generally open ocean beaches are exposed to a combination of sea/swell sources arriving at the coastline at the same time. A directionally spread wave field is hypothesised to be the major cause of short-crested wave breaking vorticity (cf. Section 2.8.5) leading to transient rip currents (Johnson and Pattiaratchi, 2006; Spydell and

Feddersen, 2009; Clark et al., 2012; Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014). Several studies have shown that random sea state (i.e. with stochastic wave group forcing) can lead to the formation of transient rip currents (Johnson and Pattiaratchi, 2004b; Reniers et al., 2004; MacMahan et al., 2004b; Dalrymple et al., 2011; Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014). In other words a wave-wave interaction in the gravity wave frequency band can lead to along-crest variability in wave breaking, which has been shown to drive surf zone vorticity (Section 2.8.5.2). Whilst this forcing can give rise to transient rip events there is some contention in the literature as to whether vorticity and transient rip generation is increased under a directionally spread or narrow wave field.

Modelling by Spydell and Feddersen (2009) suggest that for constant incident wave energy, the surf zone averaged root mean square vorticity increases with increasing wave directional spread. This increase in vorticity would coincide with an increase in transient rip occurrence. The Clark et al. (2012) field study supports this model result with vorticity generated by short-crested breaking waves observed where the bathymetry was alongshore uniform and the alongshore locations of wave breaking were not bathymetrically controlled. The waves measured during the field experiment were normally incident and directionally spread and the wave conditions seaward of the surf zone were defined as nearly constant (Clark et al., 2012).

In contrast to the findings Spydell and Feddersen (2009) and Clark et al. (2012), Murray et al. (2003) and Johnson and Pattiaratchi (2006) found an obvious increase in the duration and strength of transient rip currents for long period, narrow spread waves. For shorter period waves with wide directional spreading, there was a decrease in rip frequency, strength and duration. Johnson and Pattiaratchi (2006) do argue however that a certain amount of directional spreading, and the associated spatial gradients in forcing of the wave-averaged current, is required to provide sufficient vorticity to initiate the rip generation process.

2.8.7.2. Interaction of the incident wave field with Low Frequency Waves

It is proposed that the interaction of incident waves with infragravity (0.004 Hz < f < 0.04 Hz) and very low frequency (< 0.004 Hz) motions may lead to spatially and temporally variable currents in the surf zone, irrespective of the nature of the bathymetry.

2.8.7.2.1. Edge Waves

Edge waves are free waves that travel along the beach and are trapped in the nearshore by reflection and refraction. They are standing in the cross-shore direction but may also be standing in the longshore direction. It is proposed that the simultaneous occurrence of incident ocean waves along with edge waves of the same frequency will lead to a superposition of these two types of waves that gives a periodic alongshore variation in breaking wave height (Dalrymple et al., 2011). This may lead to the short-crested wave induced vorticity described in Section 2.8.5.2.

2.8.7.2.2. Wave Groups (bound long waves)

The interaction of wave groups is also believed to create incipient flows in the surf zone. Whilst these motions tend to modulate at the infragravity time scale (30 s – 5 min) they may also occur at Very Low Frequencies (VLF's) (4 min to 30 min) (MacMahan et al., 2004b; MacMahan et al., 2004a; MacMahan et al., 2010b). As the sea state in the nearshore zone 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 (Long and Özkan-Haller, 2009; Dalrymple et al., 2011). As the groups encounter the surf zone there are alongshore variations in the wave radiation stress which are balanced by water level gradients, that can lead to transient alongshore currents and transient rip currents (Dalrymple et al., 2011).

2.8.7.3. Wave-current interactions

Several studies have argued that the wave-current interaction has minimal effect on wave height, but can play an important role in modifying wave direction and directional spreading (Herbers et al., 1999; Henderson et al., 2006; MacMahan et al., 2008).

Herbers et al. (1999) and MacMahan et al. (2008) suggest that directional spreading of the wave field in the surf zone on an alongshore uniform beach is often related to rip currents and in particular rip current pulsations. It is hypothesised that rip currents and rip current pulsations on a fairly planar beach could lead to an increased variability in the incoming local wave field, which increases the directional spreading, providing a further feedback mechanism for the generation of variability in the alongshore wave breaking (Herbers et al., 1999; MacMahan et al., 2008). It is also proposed that offshore current fluctuations of shear instabilities and wave group forced VLF motions can increase the directional spreading of the incident wave field (Herbers et al., 1999; Henderson et al., 2006; MacMahan et al., 2008).

A series of papers by Brad Murray, (Murray and Reydellet, 2001; e.g. Murray et al., 2003; Murray, 2004) utilised field observations and a numerical model to propose an alternate model for transient rip current generation by wave-current interactions on a planar, alongshore uniform beach. Their theory involves alongshore variations in setup but the variations in wave setup need not be attributed to the incident wave patterns or bathymetry.

Murray and Reydellet (2001) observed that waves are dissipated more rapidly in a rip current than wave breaking alone would cause. The waves travelling shoreward in these areas are not generally larger when they reach the shore than waves in adjacent areas, suggesting some mechanism other than wave breaking occurs in the rip current (Murray and Reydellet, 2001; Murray et al., 2003).

It is commonly recognised that for non-bathymetrically controlled rips (i.e. no rip channel present) that waves tend to steepen and increase in height as they enter an opposing current. This is believed to be due to the refraction of wave crests by the current causing an energy focus leading to an increase in wave height (Murray and Reydellet, 2001; Murray et al., 2003). The opposing current also shortens incoming wave length, which is analogous to wave shoaling (i.e. the opposing current is analogous to shallower water), influencing the incoming wave field and spatial variations in the radiation stress gradients and water level (Murray and Reydellet, 2001; Murray et al., 2003).

Murray and Reydellet (2001) argue that they have observed a weak offshore flow to decrease wave heights locally, which allows the offshore slope to accelerate the current as the radiation stress gradient no longer balances the setup (Figure 2.25a). They suggest that the increased current would in turn decrease incoming wave heights further, which would reinforce the acceleration of the current. The removal of water from the surf zone locally creates alongshore surface slopes that drive alongshore currents feeding the transient rip current (Figure 2.25b) (Murray and Reydellet, 2001; Murray et al., 2003). If the waves replenish the water in the region from which the alongshore currents are feeding the transient rip current, at a similar rate to the rip current removing water from the surf zone, the current may attain a steady state (Murray and Reydellet, 2001). However, if the current(s) are too wide or closely spaced, surface elevations in the surf zone are lowered regionally, decreasing the offshore surface slope, making it more likely that the rip will decelerate (Figure 2.25c) (Murray and Reydellet, 2001; Murray et al., 2003). This allows wave heights to increase locally, causing further deceleration and possible termination of the current (Murray and Reydellet, 2001; Murray et al., 2003).

(a)

(b)

(c)

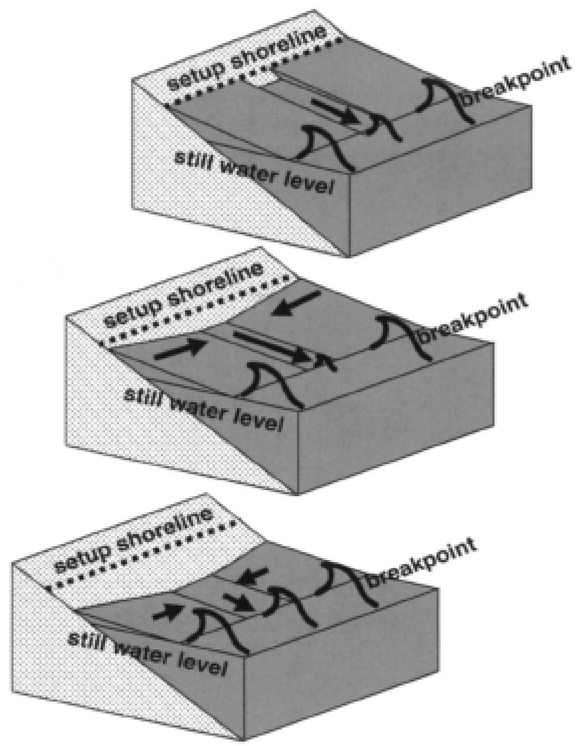


Figure 2.25: Schematic illustration of hypothesised interactions, leading to the generation, reinforcement and decay of rip currents on planar, uniform bar / beach morphology. Source: Murray and Reydellet (2001)

Model results (Murray and Reydellet, 2001) and field observations (Murray et al., 2003) indicate that interactions and feedbacks between these processes offer a plausible explanation for why transient rip currents are often narrow and jet-like while also widely spaced, why they can occur on planar beaches as well those with alongshore bathymetric variations and; why they are generally dynamic rather than steady state phenomena.

2.8.7.4. Transient rip currents caused by small bathymetric perturbations in a fairly uniform alongshore bar/beach morphology

A relatively unexplored theory of transient rip formation and behaviour is that these spatially and temporally variable processes are in fact influenced by small bathymetric perturbations; not well-developed or obvious enough depressions to be classified as topographically controlled beach rips. These small non-uniformities appear on mostly alongshore planar beach and bar morphology (Low Tide Terrace) and may take the form of holes, mega-ripples, relic rip channels or any other kind of shallow (gradient) topographic depression in an otherwise mostly alongshore uniform morphology. This is opposed to clearly developed rip channels seen in Transverse Bar Rip and Rhythmic Bar Beach morphology or the occasionally well-cut mini-rips that can occur on a Low Tide Terrace Beach.

It has long been theorised that non-uniformities of the bathymetry can induce alongshore variations in radiation stresses and pressure gradients to drive circulation (Bowen, 1969; Dalrymple, 1978). These small non-uniformities in the alongshore bathymetry may also generate variations in along-crest wave breaking leading to short-crested wave breaking vorticity. As mentioned in Section 2.8.5 these short scale (i.e. < 20 m) surf zone vortices may evolve into transient rip currents.

Until recently however, the role of surf zone bathymetric non-uniformities on the generation of rip currents was unproven (MacMahan et al., 2008). MacMahan et al. (2008) showed for the first time that subtle alongshore bathymetric variations (1 in 300 alongshore variation) (depth variation across the rip channel was ~0.25 m in 75 m alongshore) and low-energy waves can in fact induce a quasi-periodic transient rip current system (i.e. not an idealised non-bathymetrically controlled one).

MacMahan et al. (2008) found the presence of a mild-sloped topographic depression to induce statistically significant alongshore variations in H_{rms}, wave direction, directional spreading, infragravity waves, and very low frequency motions. In terms of H_{rms}, this indicates that the alongshore pressure and radiation stress gradients are important even though the alongshore variability in the seabed is small (MacMahan et al., 2008). Very low frequency pulsations influenced by the presence of the bathymetric non-uniformity, create current fluctuations which increase the variability of local wave directions, which increases directional spreading of the wave field (MacMahan et al., 2008). This form of directional spreading was found to increase on the low tide as the influence of the small bathymetric perturbation became more pronounced (MacMahan et al., 2008). This finding backs up previous work of Herbers et al. (1999) who also observed directional spreading of the surf zone wave field to increase on the low tide on an alongshore uniform beach.

Additionally MacMahan et al. (2008) found the small bathymetric depression to be tidally modulated, having little effect on surf zone circulation on the high tide but during the low tide rip current cell circulation formed. This supports the 'classic' view of a Low Tide Terrace beach state, which tends to be reflective on the high tide and cut by mini-rips (irrespective of whether rip channels are present or not) on the low tide.

The occurrence of this type of non-idealised transient rip current may be quasi-periodic, particularly on coasts with narrow directional wave-group spreading and longer peak wave period, due to interactions of the incoming wave groups with the small non-uniformities in the topography (Reniers et al., 2004; MacMahan et al., 2004a; MacMahan et al., 2006; Dalrymple et al., 2011). Small bathymetric perturbations may also be in the form of 'relic' rip channels that have infilled during accretionary conditions, but still maintain some sort of topographic non-uniformity. From a hazard perspective these low-energy rip currents become difficult for lifesavers to mitigate and hazardous to bathers, due to their lack of visual clues (Dalrymple et al., 2011).

2.8.7.5. Low energy Low Tide Terrace transient rip currents

A new scenario explaining the formation of transient rip currents is proposed in the following section. This scenario is based on qualitative observations by professional lifeguards and a small amount of literature (Vos, 1976; Johnson and Pattiaratchi, 2004b; Slattery et al., 2011) which have observed spatially and temporally variable currents generated on moderately steep Low Tide Terrace (LTT) beaches, flowing off the shore-attached inner bar into a deeper inshore trough (cf. Sections 2.8.2 & 2.8.3). At a fundamental level these types of transient flows are thought to be related to radiation stress gradients and variations in the Mean Water Surface (MWS) in the inner surf zone (wave setup and setdown) and on a beach (wave runup).

On Low Tide Terrace beaches at high tide when waves are less than 1 m, they may pass right over the bar and not break until the beach face, behaving much like a reflective beach (Short, 1996). On the low tide plunging waves may break heavily on the outer edge of the bar, with deep water beyond (Short, 1996). Increased setup or wave run up under these conditions can lead to transient currents forming and scouring of the edge of the inner bar, with weak plumes of sediment laden water ejecting (relatively short distances) offshore into deeper water. For example: as incoming waves shoal over the deeper water (seaward of the bar/beach where breaking occurs) there is setdown. As waves begin to break over the inner bar/beach there is setup of the mean water surface due to balancing forces in the radiation stress gradients (cf. Section 2.7.1). A further increase in setup in the breaker zone would theoretically occur with an increase in localised wave heights, or a localised increase in the number of breaking waves in a short-time period (increase in wave groupiness). This would reinforce a temporary steeper water level gradient between the breaker zone and shoaling zone located immediately offshore and thus the water rushes out of the breaker zone into the deeper water, for a short-period of time until the short-wave climate (or wave groupiness) settles down and there is a decrease in the radiation stress gradients (cf. Section 2.7.1). In other words a transient rip current may form, pulse and then decay.

These low energy, ephemeral type rip currents are usually identified by a plume of sand-laden water and often have the appearance of a narrow rip neck and 'mushroom cloud' shaped rip head (cf. Section 2.8.5.3). This suggests that some turbulent vortex motion may be associated with the formation of these currents.

2.8.7.6. Offshore wave modification

Offshore-shoals and reefs near the shoreline may create localised regions of directionally spread waves, which may generate along-crest variation in wave breaking, leading to the formation of surf zone vortices (on smaller spatial scales i.e. O(< 20 m)) and transient rip currents on alongshore uniform beaches (Section 2.8.5.2). A double bar system characterises the Gold Coast open beaches and is present at the northern beaches study site (cf. Section 3.2.2). This has important implications for the generation of transient rip currents on the inner bar / beach as the offshore storm bar can alter the local wave field even without causing breaking before the waves reach the inner bar/beach and break. Once again the alongshore variability in wave dissipation due to wave refraction and shoaling by the offshore sand bar may lead to short-crested wave induced vorticity, which has been proposed to be the fundamental driver of transient rip currents (Section 2.8.5.2).

2.8.8. **Transitions of transient rips to semi-permanent or permanent rips**

Johnson and Pattiaratchi (2006) observed transient rip currents to often re-emerge from the same place as the previously observed rip. They attributed this re-occurrence of transient rip currents in a similar location to feedback mechanisms on the incident wave field and the remnants of previous vortex pair shedding. Whilst Johnson and Pattiaratchi (2006) did not investigate the effects of topography; rips occurring in the same location leads to an erosion of the seabed, leading to a depression in the topography and further erosion of the developing trough due to positive feedback of the water flow. The end result being a semi-permanent rip embayment forming in the surf zone. Therefore it is hypothesised that transient rip currents may play a key role in controlling beach morphology and stability, in particular the initial development of rip embayments and more topographically controlled rip current systems (Reniers et al., 2004; Murray, 2004; Johnson and Pattiaratchi, 2006). This is explored further in Chapter 5.

2.9. Summary

The Gold Coast open beaches present a microtidal and wave dominated environment, which cycle through all of the Price and Ruessink (2011) beach state combinations. Surf zone circulations on ocean beaches consist of a complex mix of motions where surf zone currents can be characterised as quasi-steady or transient:

- Quasi-steady or mean current systems: longshore currents; topographic rip currents; semi-permanent beach rip currents; mega rip currents; swash rip currents; quasi-steady rip currents due to offshore bathymetric non-uniformities; and bed return flow
- Transient current systems: transient rip currents

Time-averaged nearshore currents are fundamentally generated by mean water surface gradients which are balanced by radiation stress gradients. Transient rip currents and rotational surf zone motions (i.e. shear waves and 2D turbulent surf zone eddies) can be described in terms of surf zone vorticity. Transient rip currents have been described as being a signal of 2D turbulent surf zone eddies driven by: (i) the *intrinsic* mechanism of shear instability in the alongshore current and; (ii) through the *extrinsic* mechanism of short-crested wave breaking vorticity forcing due to along-crest variation in wave dissipation (i.e. wave breaking). A review of the literature suggests that the formation of 'idealised' transient rip currents (i.e. rip currents occurring on a planar beach devoid of clear bathymetric non-uniformities) is generally due to the latter forcing mechanism described here. In reality the beach and surf zone topography is rarely alongshore uniform and more commonly a mixture of rip current (and other surf zone current) types exist in nature. It is therefore hypothesised that on natural, more irregular beaches several complex surf zone interactions are likely to be responsible for causing finite breaking crest-lengths and generation of transient rip currents.

Chapter 3. Study Site and Methodology

3.1. Overview

This chapter provides a description of the study site and methodologies used in the field and video-imaging experiments for assessing surf zone current dynamics on the Gold Coast open beaches. A validation for the use of low cost non-differential GPS units in Lagrangian drifter studies is initially provided before a description of the Lagrangian drifter study methodologies for measuring surf zone circulation and retention of drifters entering a rip current on an open coast double bar beach. A remote-video study of transient rip currents on the Gold Coast open beaches was undertaken in order to quantify transient rip occurrence, activity as well as spatial and temporal characteristics. This chapter presents the video-imaging and statistical analysis methodologies used to measure the spatial and temporal length scales of transient rip currents.

3.2. Study Site

3.2.1. Gold Coast overview

The City of Gold Coast has 52 km of open coast beach and is located on the East Coast of Australia around 28º S (Figure 3.1). The Gold Coast is Australia's premier coastal tourist destination and as such the beaches present a hazardous environment to large numbers of bathers lacking experience with moderate to high energy surf zones. The typical open ocean Gold Coast beach is microtidal, exposed to a highly variable wave climate and typically presents a double-barred system with bar and trough topography (Strauss et al., 2006). The double bar beach state cycles through all of the Price and Ruessink (2011) beach state morphologies (cf. Section 2.3). Moreover, the wave climate is dominated by ocean swell, primarily incident from the south east (Short, 2000). Average deep-water significant wave heights on the Gold Coast generally range from 0.8 – 1.4 m with mean periods of 7 – 9 seconds (Jackson et al., 1997). As a result of the prevailing swell direction and the narrow continental shelf the wave approach angle is often oblique in the surf zone resulting in a net northward littoral drift (Strauss et al., 2006).

The longest beach on the Gold Coast is the straight stretch of sand that runs for 16 km from the Nerang entrance south to the small Nobby headland (Short, 2000). This stretch of beach is classified here as the Gold Coast (northern) open beaches (Figure 3.1) and contains the study site for field measurements (cf. Chapter 4 & Chapter 5). Currigee Beach on south Stradbroke Island, located ~2 km north of the Gold Coast Seaway (Figure 3.1) was utilised as a secondary study site and as such is also analogous to a northern Gold Coast open beach. The Gold Coast (northern) open beaches (Figure 3.1) are composed of relatively uniform fine sand (d_{50} = 200 – 250 µm) that results in a wide, low gradient high tide beach fronted by a 150 to 200 m wide surf zone (Short, 2000). Palm Beach, Burleigh Heads and Currumbin (Figure 3.1) are the study site for the preliminary field experiments validating the use of the GPS enabled Lagrangian drifters (cf. Appendix A.1). These study sites display identical sediment grain size, beach and surf zone morphology and are exposed to the same deep water wave climate as the Gold Coast open beaches. They do however have the added complexity of bounding headland morphology and an adjacent coastal inlet.

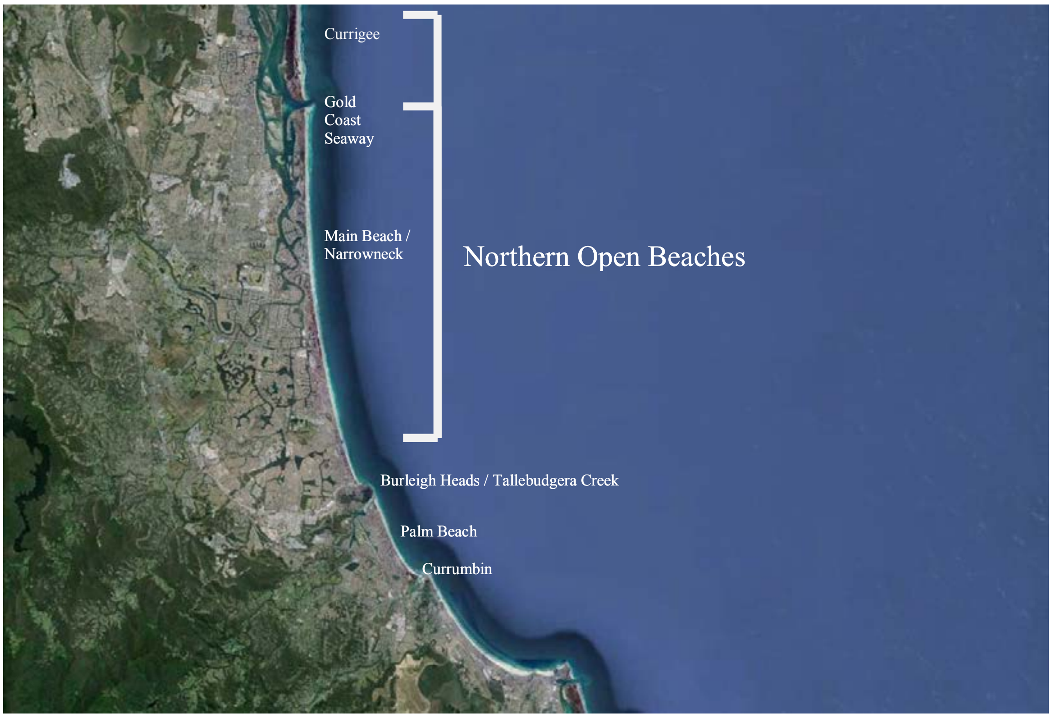


Figure 3.1: Gold Coast Study Site

3.2.2. **Northern beaches study site (Chapter 4 & Chapter 5)**

The stretch of open beach between Main Beach and Narrowneck was chosen as the primary study site for the phase one Lagrangian drifter experiment on surf zone circulation (Chapter 4) as well as the video-imaging experiment on transient rip currents (Chapter 5).

The Main Beach - Narrowneck study site (Figure 3.1 - Figure 3.3) is characterised by double bar morphology and high energy wave conditions (Strauss et al., 2006). Modal beach state conditions at the study site are: a Low Tide Terrace (LTT) / Transverse Bar Rip (TBR) inner bar and a Rhythmic Bar Beach (RBB) outer bar (Short, 2000).

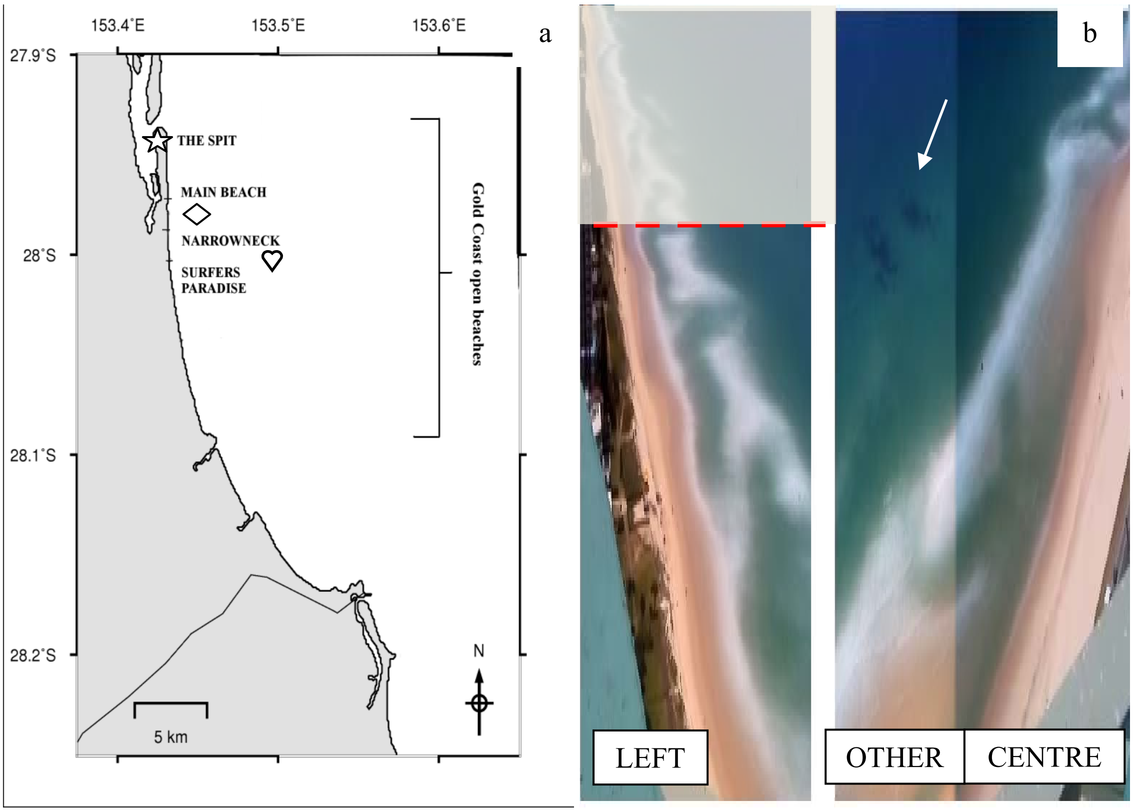


Figure 3.2: Study site: (a) Map of the Gold Coast open beaches. Wind data collected from a weather station at The Spit (i.e. Gold Coast Seaway) (*star*), Gold Coast directional wave buoy data collected in 16 m of water (diamond), NWW3 GRIB point (*heart*); (b) Camera views for the Main Beach to Narrowneck study site (*labelled LEFT, OTHER, CENTRE)*. There is an approximate 400 m black spot directly below the camera, displayed by the white gap. The dashed red line indicates the northward limit of the study area (~500 m north of the camera). The white arrow indicates the Narrowneck artificial reef.

At the southern end of the study site (~ 27º59’14.50” S – 27º59’09.70” S) is an artificial reef, which was completed in December 2000 (Figure 3.2b). The Narrowneck reef consists of two underwater ridges that sit side by side and are aligned shore-normal, extending approximately 100 – 300 m from the shoreline. The reef sits in approximately 4 to 6 m water depth and plays a role in modifying the local morphodynamics of the beach and surf zone. Whilst it is hypothesised that the reefs influence on the incoming wave field may have an impact on the inner surf zone and beach morphodynamics (cf. Section 2.8.7.6) its role in the nearshore processes is ignored for this study as transient rip currents occur along the entire stretch of the Gold Coast open beaches, with or without the presence of an offshore submerged structure.

In August 2015, the University obtained and mobilised a Differential GPS and echo-sounder equipped Personal Water Craft (PWC) and an RTK-GPS equipped All Terrain Vehicle (ATV) to undertake surf zone and beach survey respectively. The introduction of these two vehicles allowed for an increased number of drifter releases and retrieval as well as detailed topographic mapping of the beach and surf zone. Due to logistical and local government restrictions on the use of this type of equipment in public areas, a secondary study site was chosen for conducting an additional phase two GPS Lagrangian drifter study.

The secondary study site chosen for this additional field work was an approximate 1.5 km stretch of coast known as Currigee Beach on South Stradbroke Island, located (~2 km) north of the Gold Coast Seaway and approximately 9 km north of the original study site (Figure 3.3). The study site has the same characteristics as the Main Beach – Narrowneck study site described above with a double bar morphology that cycles through all the beach states outlined in Price and Ruessink (2011) (cf. Section 2.3) and an identical wave climate with a dominant net northerly longshore current.

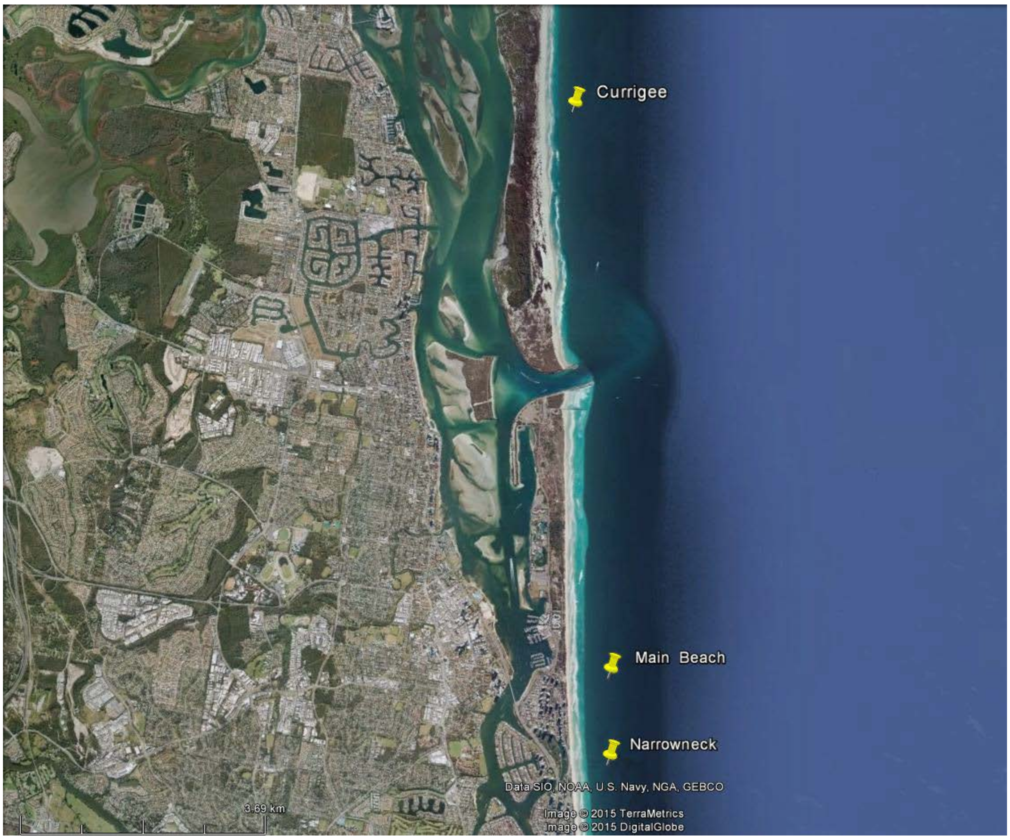


Figure 3.3: Study sites for Lagrangian Drifter Experiments (Currigee Beach, South Stradbroke Island; and Main Beach-Narrowneck). Source: Google Earth®

3.3. GPS Drifter Development and Validation

3.3.1. Overview of Lagrangian drifters

Traditional field studies have generally focused on Eulerian measurements of surf zone currents, using an array of current meters which only give a limited, spatially fixed view of the surf zone dynamics and current flow. Until recently Lagrangian field data of current systems in the surf zone were rare, but deemed to be valuable for understanding the detailed structure of surf zone currents, confirming model predictions and making estimates of dispersion (Spydell et al., 2007; Spydell and Feddersen, 2009; Spydell et al., 2009; MacMahan et al., 2010a; Feddersen, 2014; Hally-Rosendahl et al., 2014). In the past dye tracer studies and theodolite tracking of drifters have been conducted to give estimations of Lagrangian rip current velocity and surf zone circulation (cf. Appendix A.1).

Recent studies have begun to use more sophisticated GPS drifter techniques to quantify surf zone currents and reveal a greater understanding of the spatial and temporal characteristics of surf zone current circulation (e.g. Schmidt et al., 2003; Johnson et al., 2003; Johnson and Pattiaratchi, 2004b; Spydell et al., 2007; Bruneau et al., 2009a; Bruneau et al., 2009b; MacMahan et al., 2009; Spydell and Feddersen, 2009; Spydell et al., 2009; Austin et al., 2010; MacMahan et al., 2010a; Bruneau et al., 2011; Sabet and Barani, 2011; Spydell and Feddersen, 2012; Winter et al., 2012; Austin et al., 2013; McCarroll et al., 2013a; McCarroll et al., 2013b; Austin et al., 2014; Castelle et al., 2014a; McCarroll et al., 2014a; McCarroll et al., 2014b; Scott et al., 2014; Winter et al., 2014). The accuracy of cheap, consumer grade GPS systems continues to improve and the size of the units are decreasing as new technologies are developed. This has allowed for surf zone drifters to incorporate GPS receivers and loggers to measure surf zone currents.

As an understanding of the hazardous nature of surf zone currents is important, GPS units have also been attached to 'human floaters' to further understand the nature of surf zone currents and assess 'escape strategies' from rip currents (Miloshis and Stephenson, 2011; McCarroll et al., 2013a; McCarroll et al., 2013b; McCarroll et al., 2014a). A brief description of the importance of these types of Lagrangian studies is provided in Appendix A.1. The present Gold Coast study conducted a preliminary 'human floater' experiment comparing traditional theodolite techniques to more recent GPS techniques for mapping surf zone currents. The preliminary study found that non-differential GPS will give a reasonable estimate of surf zone current velocities and drifter tracks. The full details of this preliminary experiment are presented in Appendix A.1.

3.3.2. **GPS validation**

3.3.2.1. AMOD AGL 3080 receiver chip and manufacture specifications

The AMOD AGL 3080 GPS unit used in the present study is a combined receiver/logger and is small enough to fit in the surf zone drifter housing (cf. Section 3.3.3). The SiRF III Chip, installed in the AMOD AGL3080, is a relatively new and accurate GPS receiver chip at the low-cost consumer grade. The receiver chip of the AMOD AGL3080 is identical to the receiver chip used in McCarroll's (2014b) GPS drifter study. As the accuracy of these receiver chips has also been quantitatively tested in Sabet and Barani (2011) and McCarroll et al. (2014b) similar accuracies in the present Gold Coast data set are expected. It is still prudent however to test the accuracy of the AMOD AGL 3080 units in this thesis (cf. Section 3.3.2.2).

GPS is accurate for determination of velocity (about 10 times more accurate than a car odometer) when moving at relatively constant speed (Witte and Wilson, 2004). Manufactures tend to report velocity accuracies of 0.1 – 0.2 $m.s^{-1}$. These values would be acceptable errors for estimating surf zone current velocities over the entire deployment or when averaging velocity over longer time periods (e.g. 30 seconds). For lower velocities the error would become significant. The manufacturer of the AMOD AGL3080 claims velocity accuracies on the order of 0.1 $m.s^{-1}$ with 'Selective Availability' removed (Table 3.1).

Table 3.1: AMOD AGL3080 accuracy and SiRF III Chip Statistics (from the manufacturer)

Positional accuracy	10 m (2D RMS), 5 m (2D RMS, with WAAS correction), and < 5 m (50%, with DGPS correction) without SA
Velocity accuracy	0.1 $m.s^{-1}$ without SA
Re-acquisition time	0.1 s average

3.3.2.2. GPS position errors

The *relative* error, which is an apparent change of position relative to an arbitrary datum that is not due to real motion (i.e. experienced by a stationary receiver), contaminates any calculations of the velocity and a moving receiver (Johnson and Pattiaratchi, 2004a). *Relative* error of the stationary units (i.e. Drifters) is therefore examined to show that non-differential fixing position is sufficient for measuring surf zone motions up to 1 Hz.

A 50 minute stationary test of the AMOD AGL3080 GPS was undertaken on an open field with a clear view of the sky, on a sunny day with little cloud cover.

Two GPS units were placed on a metal plate (0.5m x 0.5m), one metre off the ground, to reduce the effects of satellite signal multi-pathing. Positional data was collected at 1 Hz. The change of *relative* positional error was estimated from the 50 minute stationary test. *Relative* positional error was achieved by subtracting each data point from the average position recorded in the stationary experiment. This methodology is consistent with that used in Johnson (2004) and Sabet and Barani (2011) and comparable to those of MacMahan et al. (2009) and McCarroll et al. (2014b).

The standard deviation of displacement for Drifter 1 at 1 Hz is 1.63 m and 1.87 m in Eastings and Northings respectively. The standard deviation of displacement for Drifter 2 at 1 Hz is 1.40 m and 2.69 m in Eastings and Northings respectively. The maximum displacement from the mean position for both drifters was 5.05 m (Drifter 1) and 5.76 m (Drifter 2) in Eastings and Northings respectively. All these values are standard errors for non-differential GPS units and similar values have been calculated in other stationary tests of non-differential GPS units (Johnson et al., 2003; MacMahan et al., 2009; Sabet and Barani, 2011; McCarroll et al., 2014b). As a result the AMOD AGL 3080 GPs data logger is used for the Lagrangian drifter study (Chapter 4). Further validation of the functional accuracy of the GPS units is outlined in Appendix A.1(iii).

3.3.3. **Drifter design and validation**

Drifter design was based as closely as possible on those of Schmidt et al. (2003) and MacMahan et al. (2009), with low-cost materials used. The GPS drifter (Figure 3.4 & Figure 3.5) has four primary components: an instrument housing and casing (approximately 160 mm in diameter and 140 mm in length); an AMOD AGL3080 GPS receiver and data logger; a ballasted submerged body to allow the drifter to float neutrally buoyant and minimise surfing; and a flag rod for visualisation (approximately 650 mm in length). The submerged body of the drifter is made up of three parts: an impact resistant central body of tubular polyvinyl chloride (PVC) (approximately 100 mm in diameter and 400 mm in length) that is filled with concrete and foam to make the drifter neutrally buoyant; a dampening disc (approximately 300 mm in diameter) attached to the bottom of the PVC tube, made of polypropylene plastic (corflute) to prevent surfing; and three corflute fins (approximately 320 mm in length) arranged around the side of the PVC tube for stability. The drifter is painted for visibility and waterproofed.

Drifters have a foam buoy on top of the PVC tube to enhance visibility and to house the waterproof containers, which hold the GPS units. A wooden rod is attached to each drifter and ribbons attached to the top of the rod to enhance visibility in the surf zone. As mentioned in Schmidt et al. (2003) and MacMahan et al. (2009) windage effects on a drifter within an energetic surf zone are unknown. MacMahan assumes an estimated bias error in wind slippage to be 0.01 $m.s^{-1}$ per $m.s^{-1}$ of wind. As the drifter design is based heavily on those of MacMahan et al. (2009) negligible wind slippage errors are also assumed for these drifters.

Figure 3.4: GPS Drifter

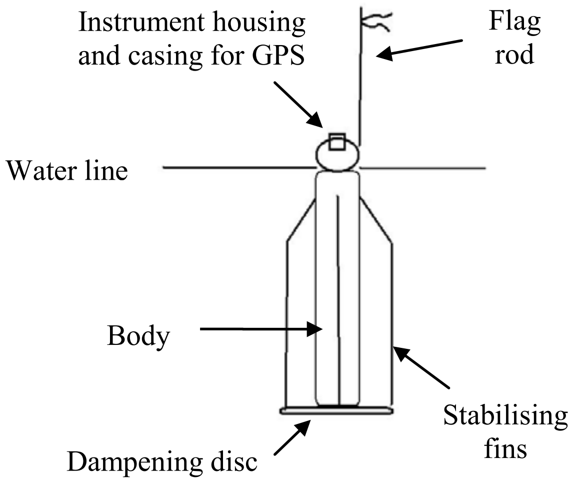


Figure 3.5: GPS drifter and components

GPS drifters were tested for efficacy, in the surf zone, around headlands and in the creeks at Currumbin and Tallebudgera-Burleigh Heads on six days in May – June, 2011. Two examples of Lagrangian drifter data collected are displayed in Figure 3.6 & Figure 3.7. Drifters were deployed under a variety of tidal, wind and wave conditions, with the full dataset displayed in Appendix A.1(v).

Figure 3.6 & Figure 3.7 and Appendix A.1(v) show the individual drifters follow similar trajectories based on wave, current and tidal conditions on the days of sampling. Both examples show drifters exiting the surf zone, which indicated they have overcome any issues of surfing due to breaking waves. It was also visually observed for drifters to travel with the currents against the prevailing wind. This confirms that the drifter design is adequate for measuring surf zone currents, with minimal influence of wave and windage effects.

Figure 3.6: Drifter tracks overlayed in Google Earth® (Currumbin 18 May 2011, ebb tide)

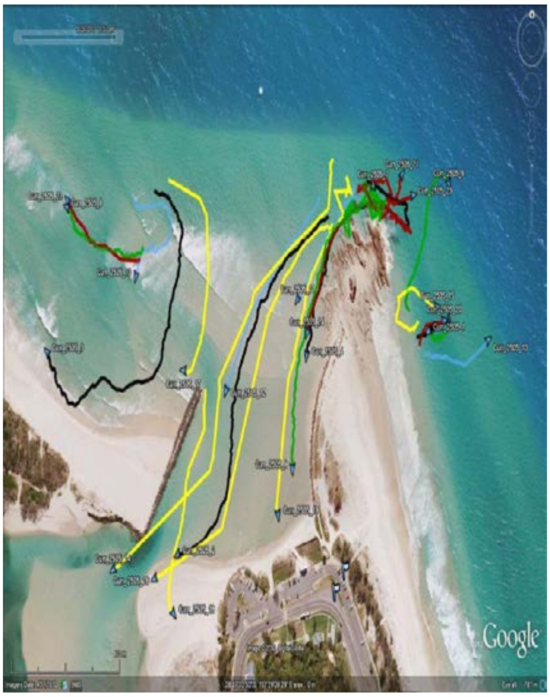


Figure 3.7: Drifter tracks overlayed in Google Earth® (Currumbin 25 May 2011, flood tide)

Finally a comparison of design and building costs for some recently used GPS drifter studies are outlined in Table 3.2. The GPS enabled drifters designed and built by Griffith Centre for Coastal Management (Table 3.2) are used for the Lagrangian surf zone study in Chapter 4.

Table 3.2: Comparison of GPS drifter systems and cost (from most expensive to least expensive)

	Type of GPS (+ cost per unit)	Type of antenna	Recording Frequency (Hz)	Data output format	Cost per drifter ($)	Post-processing
Schmidt et al. (2003)	Differential GPS with base station (see cost per drifter)	External	• 0.1 Hz for DGPS • 1 Hz for internally logged data for post-processing	• Real-time DGPS tracking data • Carrier phase and pseudo-range information internally recorded	~ US $3000 (including GPS and antenna set up; not including base station)	• Pseudo-range and carrier phase data post processed for high accuracy of absolute position
Johnson and Pattiaratchi (2003)	• Garmin GPS 36 receiver/antenna • DGPS-XM data logger (see cost per drifter)	Internal antenna	1 Hz	• NMEA 0183 format • WAAS enabled (questionable in Australia)	~ AUD $750 per unit including GPS and data logger	• Low pass filtering of the data to remove noise at higher frequencies (> 0.5 Hz) • Differential methods used to reduce relative RMS error for accurate positioning for motions at frequencies of 1 Hz.
MacMahan et al. (2009)	Earthmate Bluelogger (US $150) • WAAS enabled • RINEX data recorded • US $150 Earthmate Bluelogger post-processing software OR Expensive survey grade software (~ US $12,000)	External patch antenna	• 0.5 Hz recording of pseudo-range data for post-processing	• WAAS enabled • RINEX data produced – carrier phase and pseudo-range information	~ US $213	• Pseudo-range and carrier phase data post processed for high accuracy of absolute position
McCarroll et al. (2014b)	Locosys Technology Genie GT-31 (~ AUD $200-250)	Internal patch antenna	1 Hz	• NMEA 0183 format	Unknown cost but most likely similar to MacMahan et al. (2009)	• 'Surfing' events removed • zero-phase 5th degree Butterworth filter was applied to raw GPS data • 0.04 Hz (25s) low pass cut-off filter applied to raw GPS data
Sabet and Barani (2011)	Garmin e-trex (non-differential) (~ US $100 - $150)	Internal patch antenna	1 Hz	• NMEA 0183 format	~ US $150 (labour unknown)	• Tracks averaged over 10 s to reduce noise and increase accuracy
Griffith Centre for Coastal Management (GCCM)	**AMOD AGL3080 (non-differential) (~ AUD $50-60)**	**Internal patch antenna**	**1 Hz**	**• NMEA 0183 format • WAAS enabled (questionable in Australia)**	**~ AUD $150 (with labour)**	**• 30 s moving average filter applied to raw GPS data**

3.4. **Lagrangian Surf Zone Current Drifter Experiment on an Open Coast Beach**

3.4.1. **Lagrangian GPS field experiments**

The Lagrangian drifter studies were conducted in two phases. Phase one consisted of GPS enabled drifter experiments carried out in the inner bar region of the Main Beach-Narrowneck study site on seven separate days between September 30, 2011 and July 18, 2012. The seven separate days were chosen in order to measure surf zone circulations in a range of different morphodynamic and hydrodynamic regimes. Phase one drifter release and retrieval was undertaken manually by a small research team, using surf craft.

A secondary phase of drifter experiments was undertaken on two additional days, September 1, 2015 and October 16, 2015. This phase utilised the power craft described in Section 3.2.2 which enabled a larger number of individual drifter releases per day. It is noted that the general findings obtained in phase one and two were found to be consistent with each other (cf. Chapter 4).

3.4.1.1. Drifter deployment and retrieval

A total of 254 individual deployments were undertaken providing approximately 55 hours of Lagrangian GPS data (Table 3.3). Typical deployments for the phase one study were around 2 – 3 hours with the Phase Two studies conducted for a longer period of the tidal cycle, 4 hours (Table 3.3). This strategy is consistent with existing studies which will be discussed in detail in Chapter 4.

Table 3.3: Drifter deployment and time statistics from release to retrieval / beaching. Tidal stage information during sampling is also provided.

Experiment Phase	Date	Total number of individual drifter deployments	Maximum duration for individual drifter (min)	Min duration for individual drifter (min)	Average duration for individual drifter (min)	Standard Deviation (min)	Total time of drifter recordings (hr:min:ss)	Period of tide during sampling	High tide (m / time (24h))	Low tide (m / time (24h))
PHASE ONE	30/09/2011	21	25:20	01:48	11:40	06:55	4:26:28	Ebb – high to mid	1.62 @ 10:07	0.04 @ 16:21
	02/11/2011	22	25:19	05:07	10:45	04:02	3:56:28	Flood – mid to high	1.35 @ 13:36	0.34 @ 06:34
	29/11/2011	16	20:44	07:01	15:26	04:28	4:06:56	Ebb – mid to low	1.59 @ 11:14	0.13 @ 17:51
	22/02/2012	24	16:36	01:41	08:54	03:36	4:26:47	Ebb – mid to low	1.61 @ 08:39	0.10 @ 14:52
	26/04/2012	25	24:55	02:58	12:04	06:20	4:51:16	Ebb – mid to low	1.04 @ 11:06	0.38 @ 16:43
	24/05/2012	25	21:05	03:29	12:55	04:36	5:30:58	Ebb – mid to low	1.09 @ 10:07	0.29 @ 15:43
	18/07/2012	16	36:33	03:24	16:44	11:31	4:27:49	Ebb/Flood- either side of low tide	1.09 @ 07:35	0.15 @ 13:15
PHASE TWO	01/09/2015	50	36:47	04:07	15:06	07:41	12:35:18	Ebb – mid high to mid low	1.48 @ 09:59	-0.01 @15:54
	16/10/2015	55	42:58	02:22	12:56	09:15	10:34:01	Ebb – high to mid low	1.45@ 09:39	0.20 @ 16:00

The typical extent of the drifter deployment region was ~800 – 900 m in the longshore and ~ 200 - 300 m in the cross-shore. Sampling days (Table 3.3) were chosen to reflect a variety of tidal, wave and morphology conditions (discussed in detail in Chapter 4) in order to capture a variety of surf zone circulation patterns (cf. Sections 2.5 & 4.1). The majority of deployments were conducted on the ebb tide, around the low tide when the rip currents are most active. This was also done in order to conduct low tide surveys of the beach and inner surf zone bar (cf. Section 3.4.2). Generally low to moderate wave conditions were favoured due to the difficulties and risks involved with highly energetic surf zone experiments.

Two techniques for drifter release were used. These techniques were chosen to map surf zone circulation and estimate current velocities:

i) Cluster release: Up to seven drifters were deployed simultaneously depending on availability of researchers and drifters. The cluster release technique was favoured for the phase one study in order to improve the sampling density of drifters. The cluster release is consistent with methodologies applied in Johnson and Pattiaratchi (2004b); Austin et al. (2009); MacMahan et al. (2010a) and (Winter et al., 2014) (cf. Table 4.1).

ii) Seeded release: Drifters deployed in a staggered release to measure the current motions through time and space. This technique was favoured for the phase two study in order to continuously sample a rip current over the majority of a tidal cycle. The seeded release is consistent with methodologies applied in Austin et al. (2009); Austin et al. (2013); Scott et al. (2014) and McCarroll et al. (2014b) (cf. Table 4.1). Whilst this technique may have an increased chance of capturing a greater number of transient rips through opportunistic occurrences (i.e. chance), this method was not utilised for measuring transient rip currents. On the *terrace beach / inner bar* day (Julian Day 61 – cf. Chapter 4) it was decided to spot the transient current first then release a 'cluster of drifters' into the rip in order to be certain of capturing these temporary features.

Drifters were deployed preferentially into rip channels and rip feeder channels, and were also walked out to the middle of shoals by the small research team. In the phase one study drifters were released and retrieved by researchers (one researcher per drifter and were retrieved by hand / surf craft). The number of individual drifters released during the phase one study was similar to that of Johnson and Pattiaratchi (2004b). The phase two study increased the number of individual releases per day with the aid of power craft. 50 and 56 individual drifter deployments were undertaken on Julian Days 1433 and 1478 respectively (Table 3.3). The number of individual drifter releases in this phase two study is similar to that of Austin et al. (2009) and Winter et al. (2014) but limited when compared with the more detailed studies of MacMahan et al. (2010a), Austin et al. (2013), McCarroll et al. (2014b) and Scott et al. (2014).

This study focuses on the inner surf zone bar/beach as it is interested in circulation patterns that may affect bathers. As such the outer bar is ignored and drifter exits are classified as those moving beyond the edge of the inner bar which is consistent with methods used in Austin et al. (2013) for measuring surf zone retention. Drifters either exited the surf zone beyond the edge of the inner bar, beached or were retrieved if they came too close to the 'flagged' swimming area.

3.4.1.1.1. Post-processing of GPS data

GPS data is recorded by the AMOD AGL3080 units in the World Geodetic System 1984 (WGS84) reference frame. Easting and Northing positions were sampled at a rate of 1 Hz. As surf zone currents are time-averaged currents over a series of waves, a moving average filter of 30 seconds was applied to the raw position data in order to smooth out noise and remove outliers. A forward differencing scheme was then used to post-process the filtered GPS data for velocity (consistent with MacMahan et al. (2010a). Cross-shore and longshore components of drifter speed were analysed separately and general trends in drifter velocity were described. Multiple drifters for each section of the surf zone circulation were used to validate current speeds and improve accuracy of results / obtain averages.

3.4.1.1.2. GPS accuracy (estimating surf zone current velocities)

The overall velocity error was estimated based on the maximum standard deviation of relative positional accuracy of ±3.3 m per length (distance) of drift (cf. Section 3.3.2.2). Based on the surf zone drifter durations and corresponding distances travelled error values in the overall GPS magnitude speed recording were on the order of 0.01 $m.s^{-1}$. These are deemed acceptable in this experiment and are consistent with those of Johnson et al. (2003); MacMahan et al. (2009); Sabet and Barani (2011); McCarroll et al. (2014b).

3.4.2. **Beach and surf zone bathymetry survey**

In the phase one drifter study low tide surveys of the beach and inner bar were conducted on each day of sampling using a Real-time kinematic (RTK) GPS to resolve inshore conditions and map beach and inner bar topography out to wading depth. The RTK GPS has an accuracy of ±0.02 m in three dimensions (i.e. x,y,z) and is referenced to the Geocentric Datum of Australia (GDA94). Topographic data is mainly used as a visual tool in displaying bar and trough / rip channel topography and quantifying the number of drifters entering a rip channel(s) on days when the study was conducted outside the view of the CoastalCOMS high camera (Section 3.4.3).

The phase two drifter study was undertaken at a remote location and detailed mapping of the beach and surf zone was undertaken. Bathymetric surveys were conducted around the high tide on days of drifter release and following consecutive days using a Differential GPS and echosounder equipped PWC (Julian Days 1433 and 1478). Surveys on the sub-aerial beach were conducted around the low tide on the same days as bathymetric surveys using an RTK-GPS equipped ATV. Sub-aerial beach survey lines were conducted at approximately 5 m spacing. Bathymetric surf zone survey lines were conducted at approximately 20 m spacing, with finer detail (~5 m) in areas where important features, such as rip channels, were observed. Echosounder recordings were sampled at 5 Hz and GPS position both in the surf zone and on land were sampled at 1 Hz. Surf zone survey data were interpolated to an ~8 x 10 m grid for Julian Day 1433 and ~10 x 10 m grid for Julian Day 1478. Grid cell averaging was undertaken in Delft3D® using the *Shepard* method which is a weighted averaging method, with weights depending on the reciprocal of the squared distance between the grid point and the surrounding samples:

$$\bar{s} = \frac{\sum_{i=1}^{N} \frac{s_i}{d_i^2}}{\sum_{i=1}^{N} \frac{1}{d_i^2}} \tag{3.1}$$

with,

$\bar{s}$ = averaged value

N = number of samples within the polygon

d_i = distance between grid point and sample point i

s_i = value of sample point i

GPS drifter tracks were overlayed onto bathymetric contour plots on each day of sampling to aid in visualisation of surf zone circulation patterns.

3.4.3. **Camera deployment**

Remote-video of the beach and surf zone was acquired from a vertical camera located approximately 100 m above mean sea level at Narrowneck, Gold Coast, Australia (Figure 3.2). Video and images are downloaded from the Coastal Conditions Monitoring System (CoastalCOMS) network. The CoastalCOMS network of cameras is an automated observation system for coastal monitoring developed by Griffith University and Coastalwatch Holdings Pty Ltd (Splinter et al., 2011). The camera provides three separate views for analysis, giving an almost 180º view of a 1.1 km stretch of coast (Figure 3.2b). Remote-video data was used in the phase one drifter study to classify morphology (Chapter 4) and the remote-video monitoring of transient rip currents (Chapter 5). The remote-video imaging techniques are explained further in Sections 3.5.2 - 3.5.4.

3.4.4. **Beach state conditions and surf zone width**

A qualitative description of beach state conditions was obtained on all days of sampling. Time exposure (timex) images from the Narrowneck High Camera were collected for analysis on each day of sampling at high tide, mean sea level and low tide. Beach state is derived from timex images and visual observations at the study site. The dimensionless fall velocity (Ω) equation (cf. Section 2.3) was used to quantify beach state on each day of sampling.

Narrowneck high camera images were rectified (cf. Section 3.5.4) to calculate surf zone width. The surf zone width was approximated as the high water mark to the seaward edge of the inner bar, taken from the rectified images. On days where field work was conducted in the camera blackspot the surf zone width was estimated from the inner bar in the nearest camera images and the bathymetric surveys.

3.4.5. **Overlaying drifter tracks onto rectified timex images (phase one study)**

Mapping of the inner bar during the phase one study was limited to wading depth. This technique has been used in previous studies such as Murray (2004) and Castelle et al. (2014a). To try to tackle this limitation, where possible drifter releases in the phase one study were undertaken within the view of the CoastalCOMS high camera, in order to resolve beach morphology and plot drifter tracks over rectified timex imagery of the surf zone. The timex images of breaking wave patterns were used to infer beach and surf zone morphology and used to display variations in bathymetry (i.e. bar-rip morphology. On three of the seven phase one days of sampling (*Julian Days 1, 61 & 239*) the area of interest for the field work was conducted outside the camera field of view.

3.4.6. **Quantification of surf zone retention and exits**

McCarroll et al. (2014b) suggest that rates of cross-shore exchange can be estimated from the proportion of Lagrangian drifters that are transported by currents from within the surf zone to beyond the extent of breaking waves, either per deployment per hour (MacMahan et al., 2010a), per rip entry (Scott et al., 2014), or by the exchange rates of simulated drifting particles in numerical models (Reniers et al., 2009). McCarroll et al. (2014b) argue that the different techniques may be compared for estimating the cross-shore exchange rate and that Lagrangian drifters may be used as a proxy for bathers (ignoring swimmer behaviour) floating in the surf zone. This thesis supports this sentiment and as such the percentage of drifter exits were calculated per rip entry.

When discussing surf zone retention and exits, each individual drifter entering each individual rip current was classified as a separate rip entry. So if a drifter entered more than one rip current during any deployment, this was recorded. The rip exit percentage was calculated as the number of drifters exiting the surf zone relative to the number of drifters entering the rip current (i.e. drifters exiting the surf zone ÷ drifters entering the rip current (%). This is consistent with methodologies used in Castelle and Coco (2013) and Scott et al. (2014).

3.4.7. Environmental parameters

Half hourly wave data was obtained from a nearby directional waverider (Figure 3.2) and the average wave conditions for each sampling period are presented in Table 4.2 (Chapter 4). Tidal predictions were collected from the Bureau of Meteorology tidal predictions, at the entrance to the Gold Coast Seaway (The Spit) (Figure 3.2). A summary of tidal conditions during days of sampling is displayed in Table 3.3.

3.5. Video-imaging of Transient Rip Currents Experiment Methodology

3.5.1. Challenges associated with studying transient rip currents in the surf zone

There are several logistical difficulties in studying transient rip currents instrumentally (particularly in the Eulerian reference frame) in the surf zone, as they are generally short-lived, do not occur in predictable locations and can migrate. A fixed array of Eulerian current meters is both difficult and expensive to deploy and may not capture these motions, due to the geographical limitations of having fixed instruments. Transient rip measurements by GPS Lagrangian drifters are generally opportunistic and rare due to the difficulty in being in the right place at the right time. This adds support for the use of remote-video techniques for quantifying these temporary phenomena in the surf zone.

The use of remote-video imagery taken from a high (vertical) positioned camera with a large view of the beach and surf zone has become increasingly important in the study of surf zone morphodynamics in the last 20 years. The strong visual clues (i.e. sediment laden plumes of water heading offshore on a relatively planar beach) of transient rip currents make them readily accessible for study by camera techniques.

Due to the high spatial and temporal variability of transient rip currents to date their temporal and spatial scales are poorly understood (Johnson and Pattiaratchi, 2006; Hally-Rosendahl et al., 2014). Johnson and Pattiaratchi (2004b) present the only field study to date specifically focusing on the spatial and temporal length scales of transient rip currents, whilst Slattery (2010) used video-imaging techniques to measure their temporal activity. Model results of Johnson and Pattiaratchi (2006) provide additional information for transient rip length scales. These results will be discussed further in Chapter 5. The current Gold Coast open beaches study aims to quantify transient rip current spatial and temporal scales primarily through remote-video techniques (Chapter 5).

3.5.2. **Video imaging**

Transient rip currents were identified from a vertical camera located approximately 100 m above mean sea level at Narrowneck, Gold Coast, Australia (Figure 3.2, cf. Section 3.4.3). The camera records continuous video imagery at a rate of 15.9 frames per second. The transient rip current signal was sampled from the video imagery at ~3 Hz.

Video was obtained from a 588 day sample period between February 14, 2011 and September 23, 2012. The video sampling was undertaken for days where transient rip formation was expected, based on knowledge from the literature, professional lifeguards and coastal geomorphologists (cf. Section 2.8). Days when the inner bar-beach was shore-attached and / or in a terrace state were favoured, with high energy wave conditions and prolonged periods of well-developed TBR morphology generally ignored.

A total of 1029 hours of video were analysed which consisted of 799 hours of daily and 230 hours of five minute recordings from select days (Table 3.4). 233 individual transient rip currents were identified and rip occurrence, activity, geometry, rip growth rate, spacing and migration quantified. A summary of the different video datasets is displayed in Table 3.4.

217 individual rips were identified from the 799 hours of daily video footage, for rip occurrence. However of those 217, 24 (11%) were associated with a small bathymetric non-uniformity and as such were ignored from the analysis. Two of the transient rips were forming as the camera view changed so an accurate analysis of duration for these two rips is unattainable (Table 3.4). An additional 42 individual transient rips were identified in the extra 230 hours of 5 minute video recordings for duration analysis (Table 3.4).

Table 3.4: Summary of video datasets

Rip parameters identified in video	Sample period	Total hours of recording	Type of footage (i.e. continuous daily or 5-minute recordings	Number of transient rip currents identified
Rip occurrence and spacing	20/11/2011 – 23/09/2012	799	Continuous daily footage (10-12 hours/day)	193
Rip duration, rip growth and geometry	14/11/2011 – 23/09/2012	1029	Continuous daily footage (10-12 hours/day) 5-minute recordings	233

3.5.3. **Transient rip identification and analysis**

Transient rip currents were identified as plumes of sediment laden and / or foamy water extending offshore of the planar terrace beach, in the absence of any obvious bathymetric non-uniformity (e.g. holes, mega-ripples, relic rip channels) (cf. Section 2.8.5.3) (Figure 3.8). The general rules used for distinguishing transient rip currents from other breaking wave signals in the video were: (i) their duration had to last for a minimum of 20 seconds and; (ii) they had to have an obvious rip neck that developed as the sediment plume headed cross-shore, generally ending in an established rip head. Transient rips were differentiated from semi-permanent topographic rips using low tide timex-imaging of the beach which reveal the presence of rip channels. Transient rip current termination was defined as: the rip head detaching from the rip neck, shedding further offshore and dissipating, with termination proposed to be induced by bottom friction and lateral mixing (Figure 3.9).

Evolution of the observed transient rip currents was found to be similar to that qualitatively described by Vos (1976) (cf. Section 2.8.2) and was consistent with Johnson and Pattiaratchi (2006) conceptual model of transient rip formation (cf. Section 2.8.5.3).

Figure 3.8: Transient rip formation. Displaying 'classic' rip neck and rip head behaviour

Figure 3.9: Transient Rip termination

3.5.4. **Image rectification**

To analyse transient rip spacing, geometry (i.e. cross-shore and longshore extent) and speed/velocity, accurate measurements of the currents (signal) on the XY-T (space-time) plane are required. The use of geo-referenced and rectified photo and video imagery has been increasingly employed in the study and management of coastal zones in the last 20 years. For the most part this new technology has been used to analyse and measure beach state and other large scale topographic features on the beach and within the surf zone (Lippmann and Holman, 1989; Lippmann and Holman, 1990; Turner et al., 2004; Wijnberg and Holman, 2007; Price and Ruessink, 2011). Recent studies have looked into using rectified video-images to analyse surf zone hydrodynamics such as waves (Aouad, 2004), longshore currents (Cohen, 2003) and swash zone dynamics (Power et al., 2011). This study will be the first of its kind to use rectified geo-referenced video imagery to analyse transient rip dynamics in the Lagrangian reference frame.

Relevant image frames were extracted from the video and imported into Matlab®. Each image was geo-referenced with real world ground control points established using a Real Time Kinematic Global Positioning System (RTK-GPS) with an accuracy of ±0.02 m in three dimensions (i.e. x,y,z). Pixel coordinates were matched to each ground control point (GCP) and a rectification of each image was performed using the Matlab® Image Processing Toolbox (Figure 3.10 and Figure 3.11). Images were rectified following methodologies first developed by Lippmann and Holman (1989; 1990) and Aagaard and Holm (1989) and further refined by Power et al. (2011), using two transform types: *Affine* and *Projective* (Figure 3.10). The *Affine* transform keeps parallel lines parallel but causes shearing of the image, turning squares into parallelograms (Figure 3.11b). This transform is useful for aligning and scaling pixels along the x-axis of the image, corresponding to cross-shore distance in the real world. The *Projective* transform causes the image to merge to a vanishing point, thus stretching pixels along the y-axis (Figure 3.11c). Figure 3.11d displays the final plan view with each pixel coordinate having a real world Universal Transverse Mercator (UTM) projection horizontal position equivalent. The full Matlab coding methodology is presented in Appendix A.2.

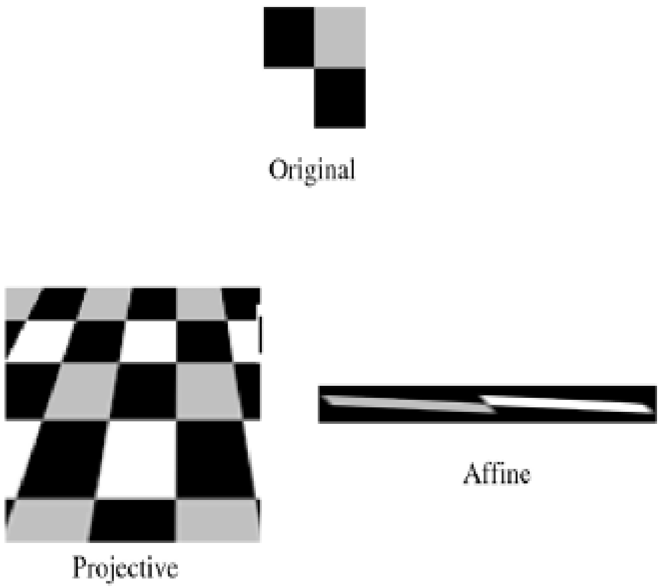


Figure 3.10: Matlab® transform types. The original checkerboard is transformed by projective and affine transforms Source: Aouad (2004).

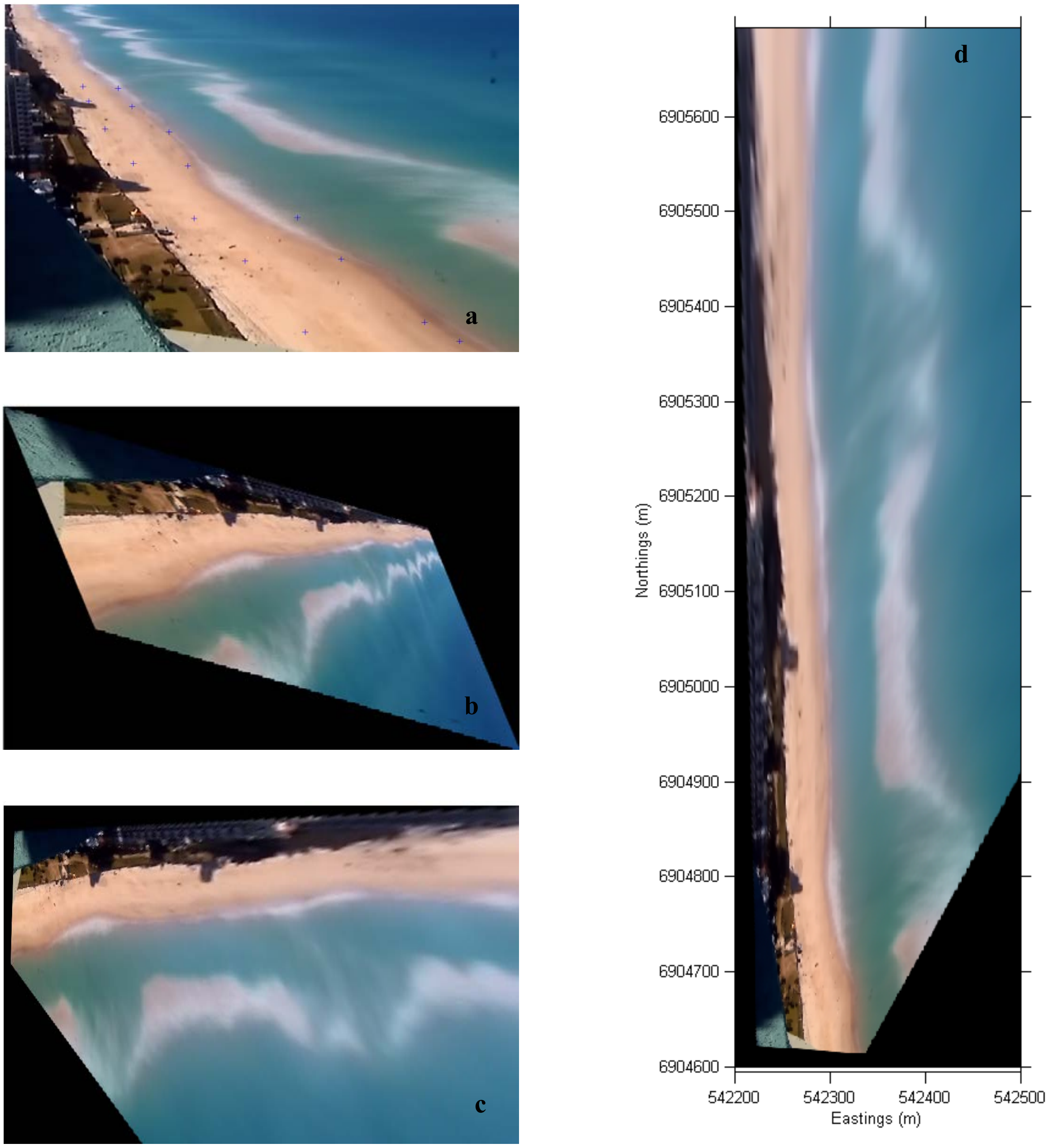


Figure 3.11: Example of the image rectification process of a low-tide timex image: (a) original image (Left view) from CoastalCOMS high camera, displaying GCPs (*blue crosses*); (b) image after the *affine* transformation has been applied; (c) image after the *projective* transformation has been applied; (d) final rectified plan view

The precision of the rectification process was determined by the spatial dimensions each pixel represented in the final rectified image (Table 3.5). As with the ARGUS system at the same study site (Turner et al., 2007) the accuracy of the transformation process is typically one image pixel. Pixel dimensions were calculated to be approximately one metre per pixel in both the cross-shore and longshore direction in the final rectified images (Table 3.5). This is slightly more accurate than the ARGUS system, which covers a larger area and has pixel precision of approximately 0.5 m and 5 m in the cross-shore and alongshore directions respectively (Turner et al., 2007). The accuracy of the rectification was determined by comparing the change in location of real world pixel coordinates (scaled down) between the original image and the final rectified image (Table 3.5). Due to the high elevation of the camera, spatial errors are small. Due to the obliquity of the camera views, accuracy is generally decreased with increased distance from the camera. As the errors are relative for each camera view, real world coordinates that occur in several views cannot be compared between images. For example transient rip features that persist through the OTHER and CENTRE views (Figure 3.2b) will not be measured between the two views as accuracy of pixel coordinates between the two views is poor. An approximated measurement of error between coordinates in the OTHER and CENTRE views was estimated to be roughly ± 10 m.

Table 3.5: Spatial errors and precision of the rectification methodology

Camera View	GCP	Cross-shore (m)	Longshore (m)	Precision (pixel size) cross-shore by longshore
Left	1	± 0.11	± 3.73	
	2	± 0.25	± 7.03	
	3	± 0.10	± 1.84	
	4	± 0.24	± 8.85	
	5	± 0.22	± 0.55	
	6	± 0.24	± 1.11	
	7	± 0.18	± 0.50	
	8	± 0.15	± 3.86	1.01 m by 1.00 m
	9	± 0.45	± 1.70	
	10	± 0.04	± 0.23	
	11	± 0.06	± 0.73	
	12	± 0.46	± 0.66	
	13	± 0.07	± 0.57	
	14	± 0.50	± 0.26	
	15	± 0.54	± 1.60	
Centre	1	± 0.96	± 0.38	
	2	± 0.16	± 0.03	
	3	± 0.20	± 0.41	
	4	± 0.26	± 0.23	
	5	± 0.02	± 0.15	
	6	± 0.34	± 0.25	
	7	± 0.25	± 0.24	
	8	± 1.01	± 1.00	0.98 m by 1.00 m
	9	± 1.22	± 1.65	
	10	± 0.55	± 1.54	
	11	± 0.73	± 0.77	
	12	± 0.20	± 1.32	
	13	± 1.05	± 3.76	
	14	± 1.59	± 5.50	
	15	± 1.58	± 4.20	
Other	1	± 0.50	± 0.16	
	2	± 0.25	± 0.11	
	3	± 0.76	± 0.43	
	4	± 0.09	± 0.09	
	5	± 0.19	± 0.04	0.99 m by 1.00 m
	6	± 0.16	± 0.03	
	7	± 0.10	± 0.66	
	8	± 0.27	± 0.02	
	9	± 0.29	± 0.49	

3.5.5. **Environmental data**

3.5.5.1. Basic parameters

Half hourly wave data was obtained from a nearby directional waverider (Figure 3.2a). Half hourly average wind data was obtained from a nearby automatic weather station (Figure 3.2a). Tidal predictions are collected from the Bureau of Meteorology tidal predictions, at the entrance to the Gold Coast Seaway (The Spit) (Figure 3.2a). Environmental parameters were compared and correlated with the continuous daily video footage (Table 3.4) to produce statistics on transient rip occurrence.

3.5.5.2. WaveWatch III data: a proxy for 'sea state'

WaveWatch III data was used as a proxy for 'sea state' to assess transient rip formation under different wave conditions including: wind wave dominant conditions, swell dominant conditions and equal swell and wind wave conditions. WaveWatch III (NWW3) is a third generation spectral wave model operated by NOAA's National Centers for Environmental Prediction (Tolman, 2002). An automated data collection system has been developed to archive forecast and hindcast data from the NWW3 model. The automated system accesses the output GRIB (GRIdded Binary) data four times daily at 00z, 06z, 12z and 18z and extracts the records for: wind speed ($m.s^{-1}$), wind direction (º) and both the u and v vector components of wind ($m.s^{-1}$), primary swell H_{sig} (m), secondary swell H_{sig} (m), wind wave H_{sig} (m), wave direction of primary swell (°), secondary swell and wind waves (º) mean wave period primary swell (s), secondary swell and wind waves (s), and H_{sig} of combined primary and secondary swell and wind wave heights (m).

The NWW3 GRIB point chosen for analysis is approximately 6.7 km offshore of Surfers Paradise at the location -28ºS, 153.5º E (Figure 3.2a). The GRIB point is protected from direct exposure to south swell by the presence of Point Danger, Cook Island and adjacent reefs and shoals to the south and southeast. The EPA directional waverider buoy is inshore of the GRIB point and as such the influence of exposure to south swell on estimated and recorded wave heights is expected to be similar.

Sea state was classified in two ways: (i) number of swells / wave sources in the water (i.e. the greater the number of wave sources the 'messier' (i.e. more stochastic) the sea state; and (ii) by calculating the ratio of swell wave height to wind wave height (equation 3.2) to determine wave source dominant conditions:

$$\frac{primary\ swell\ height + secondary\ swell\ height}{wind\ wave\ height} \qquad (3.2)$$

if; > 1 the sea state is classified as 'swell dominant', < 1 'wind wave dominant', and = 1 'equal swell and wind wave conditions.'

Whilst this method provides a good proxy for sea state it has a fundamental flaw as it does not take into account wind speed and direction which may have an effect on creating 'messier' or 'smoother' surface conditions.

To assess the accuracy of the NWW3 hindcast data, the NWW3 combined significant wave height model results were plotted against half-hour averaged Main Beach waverider buoy readings (Figure 3.2a). As the two datasets are recorded at slightly different times / time intervals a linear regression plot was not possible to produce. The correlation between the two datasets is reasonable and as such NWW3 data can be used for analysis (Figure 3.12).

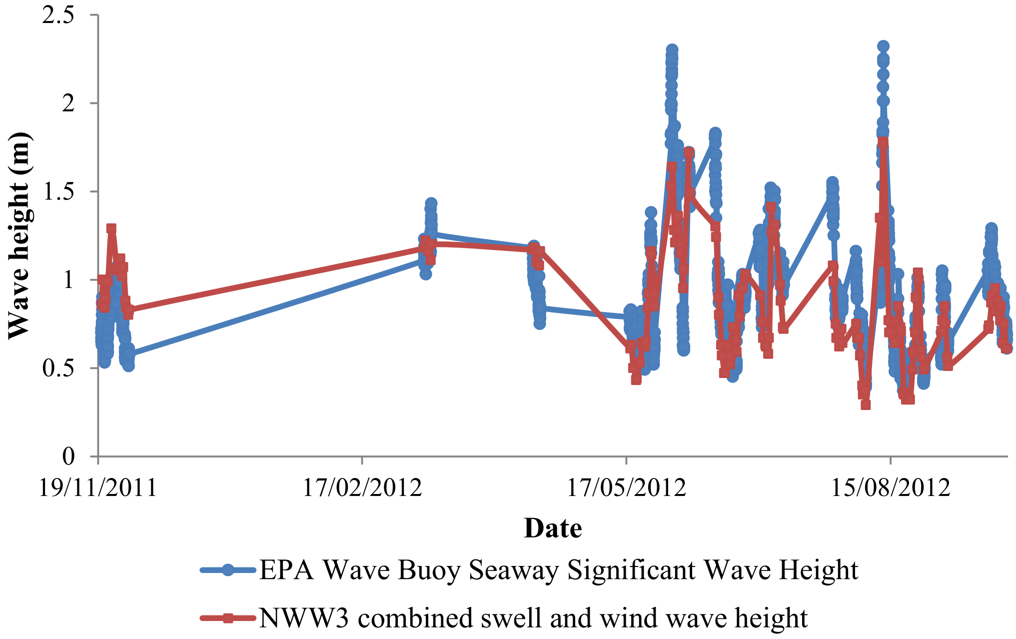


Figure 3.12: Comparison of half-hourly averaged significant wave height readings from the Gold Coast EPA waverider buoy and combined swell and wind wave height from the NWW3 hindcast model.

3.5.6. **Transient rip parameter analysis**

3.5.6.1. Rip activity, occurrence and duration

Rip duration was calculated from the time the rip head or (if absent) the rip neck formed until the temporary current dissipated, with sediment settling out in the water column and evidence of the current signal in the video ceasing. Transient rip occurrence, duration (approximated to the nearest second) and flow behaviour were identified from the video and occurrence was compared to different morphodynamic and hydrodynamic conditions, which incorporated beach state, wave, tide and wind characteristics. When comparing beach state, breaker type, and number of swell sources to transient rip occurrence statistics are weighted by the percentage of each parameters occurrence.

The parameter 'rip activity' (RA) was calculated to compare to Slattery's (2010) results from Long Island, New York. Rip activity (RA) was defined to be the sum of rip current duration (hr) per length of shoreline (km) divided by the total time of observation (hr).

3.5.6.2. Rip geometry: length and width

The spatial extents of rip geometry including rip neck width and rip length were quantified through analysis of the rectified images (Figure 3.13). The rip neck width was approximated by measuring across the rip neck at the widest point. Rip length was classified as the maximum distance the rip covered and approximated from the shoreward extent of the rip neck to the maximum offshore extent of the rip head. From a hazard perspective, distance offshore is important and as such the total cross-shore extent was estimated in this way (Figure 3.13). Rip length scales were simplified to distances travelled in the x-y plane (i.e. cross-shore and alongshore respectively). After quality assurance of the data, 233 rips were identified for rip neck analysis and 182 individual rips analysed for rip length.

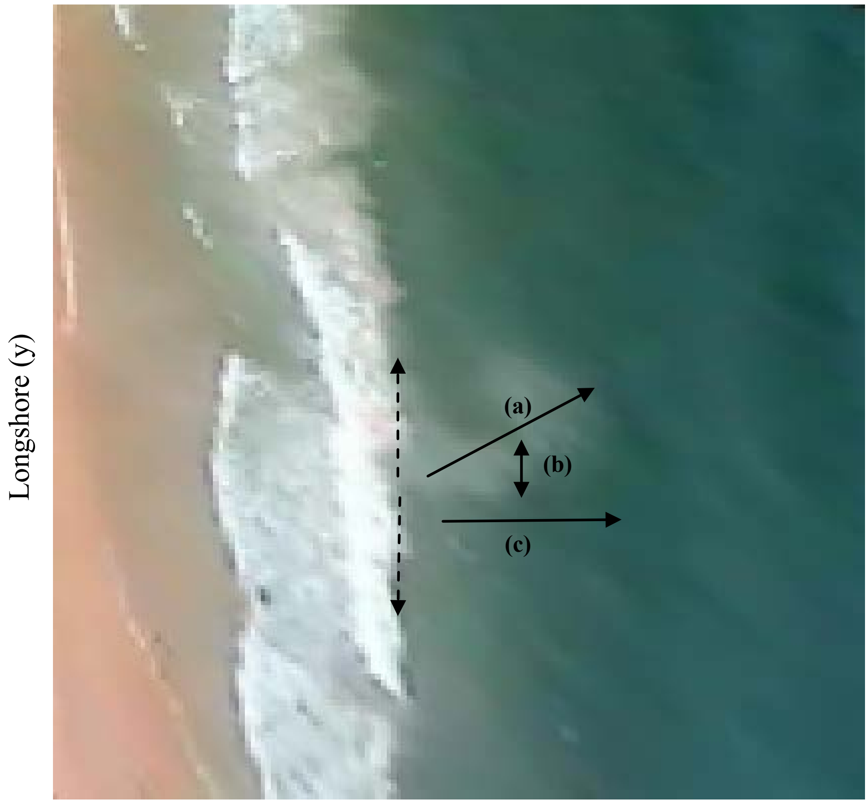


Figure 3.13: Rip length scales: (a) rip length; (b) rip neck width; (c) cross-shore extent of rip. Dashed arrows indicate the potential migration of the rip current with the alongshore current in the y-direction

3.5.6.3. Rip location and spacing

The location of rip formation was estimated from the middle of the rip neck at the shoreward limit of the rip neck. Formation points were recorded and overlayed on rectified low tide timex images (or MSL timex images where the low tide image was unavailable) for each day of recording to determine whether there was a preference of cross-shore (x) location for rip formation. Transient rip occurrence was sorted longshore into 20 m bins (consistent with the alongshore spatial scale of the rips) and a frequency histogram was plotted adjacent to rip initiation position. Rip spacing was measured alongshore (y) between the formation points of each individual rip current. Only rips forming in the daily video footage (Table 3.4) were analysed for formation and spacing as there was greater chance of capturing several rips in each view for a full days video worth as opposed to the five minute recordings. Rip spacing was measured alongshore between the start points of each individual rip.

Temporal rip spacing was measured for each day and the overall statistics are discussed in Section 5.3.3. Temporal spacing of transient rip occurrence was measured between the origin (time) of one rip to the origin (time) of the succeeding rip.

3.5.6.4. Rip growth rate

Average rip growth rate was also quantified through analysis of rectified images. The rip growth rate is a measure of the speed of the seaward edge of the rip head. The measure of rip growth rate acts as a proxy for the average speed of the rip for the lifespan of the current and is therefore different from actual rip neck speeds. The rip growth rate was estimated to be the length of the rip / duration of the rip (i.e. length / time). After quality assurance of the data 182 individual rip currents were analysed for rip growth rate. Rate of rip growth was also analysed in the x-y plane to explore the cross-shore and longshore components of the current.

3.5.7. **Statistical analysis of transient rip current occurrence data**

3.5.7.1. Parametric statistics

An initial univariate, parametric analysis was conducted between transient rip occurrence (count) and environmental factors (average wave and wind, tide and beach state) assuming a normally distributed data set. A linear correlation between transient rip occurrence (count) and environmental factors including: H_{max}, H_{sig}, T_p, T_z, peak wave direction, wind speed and wind direction was conducted. Additionally wave steepness, wave energy flux (hereafter referred to as wave power) and Iribarren number were calculated and a linear regression analysis between these three parameters and transient rip occurrence was conducted. A Log10 transformation of all the statistical occurrence data was applied to satisfy the assumption of normality and reduce the chance of a Type I or Type II error (De Veaux et al., 2008).

Wave steepness as defined by Austin et al. (2009) was calculated as H_{sig} / T_p and used as a proxy for sea state with steeper waves indicating more stormy conditions (windswell) or plunging breakers and less steep waves indicating longer period swell conditions or more spilling or surging breakers.

Wave power (energy flux) was calculated using the equation:

$$E_f = E_{c_g} \tag{3.3}$$

where, E_f = Energy density (W/m^2) and c_g = the group velocity (m.s^{-1});

$$c_g = c\frac{1}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right) \tag{3.4}$$

where, k is a dimensionless parameter $2\pi / L$; with L = wave length and h = water depth

Wave breaker type (i.e. spilling, plunging or collapsing / surging) was determined using the Iribarren number to determine breaker type conditions for transient rip occurrence from the 799 hour daily video footage study. Transient rip occurrence for each beach state was weighted by the percentage of breaker type occurrence.

The Iribarren number was calculated for each half hour recording to represent wave breaker type (Battjes, 1974):

$$\xi = \frac{tan\beta}{\sqrt{\frac{H_b}{L_0}}} \tag{3.5}$$

where, $tan\ \beta$ = beach slope, H_b = breaker wave height, and L_0 = deepwater wave length.

For each 30 minute buoy reading, shoaling only H_b was calculated using an empirical method for estimating surf heights from deep water significant wave heights and peak periods in coastal zones (Komar and Gaughan, 1973; Caldwell and Aucan, 2007):

$$H_b = H_{sig^{4/5}} \left[\left(\frac{1}{\sqrt{g}}\right) \times \left(\frac{gP}{4\pi}\right)\right]^{2/5} \tag{3.6}$$

where, H_b = shoaling only breaker wave height, H_{sig} = significant wave height, P = dominant peak wave period and g = gravity.

Bed slope for calculating the Iribarren number was taken from the average Narrowneck profile for the years 1987 to 2010 in the inner bar zone between -1 m AHD and – 4 m AHD. Deepwater wave length in metres was estimated using the equation:

$$L_o = \frac{{T_p}^2}{2\pi} \quad (3.7)$$

An independent (two-sample) t-test was conducted for tidal stage (ebb vs. flood); and outer bar activity (i.e. whether there was wave breaking or no wave breaking on the outer bar) to determine whether there was a significant difference in mean transient rip occurrence under different conditions. For this statistical test, transient rips occurring under shore-attached terrace beach states (LTT and LTT/TBR transitional states) and bar-trough beach conditions (LBT, RBB and RBB/TBR transitional states) were also analysed separately to determine whether or not there was a difference in behaviour of occurrence under different beach state conditions.

The data for these independent t-tests was collected randomly under the various conditions to satisfy the independence assumption of the statistical test (De Veaux et al., 2008). Sample sizes (n values) were randomly made equal in both tests (i.e. outer bar activity and tidal stage) to allow for robustness of the independent t-test, as variance was found to be heterogeneous in both tests. Studies have shown that the t-test in the case of equal sample sizes is robust against variance heterogeneity (Posten et al., 1982; Posten, 1992; Guiard and Rasch, 2004). It has also been shown that the t-test is extremely robust against non-normality under large sample sizes (i.e. $n > 30$) (De Veaux et al., 2008).

The effect of tide on transient rip occurrence was further explored by analysing the tidal stage, at which transient rips were preferentially observed, for both terrace state and shore-detached bar conditions.

3.5.7.2. Generalised Additive Model (GAM) analysis

Generalised Additive Models (GAMs) were used to support the univariate (i.e. linear regression and two sample t tests) statistical tests and further explore the effect of a suite of predictor variables (the independent variables) potentially influencing the response variable (the dependent variable, which here is the transient rip current occurrence or 'count'). GAMs enable flexible specification of the dependence of a response variable on the predictor variables without having to specify the model in terms of detailed parametric relationships (i.e. there is no assumption of a normally distributed data set) (Wood, 2006). This is done through specifying smooth functions on some, or all, of the unknown predictor parameters. The GAM analysis is used to provide a multivariate assessment of transient rip occurrence whilst also accounting for potential nonlinearity in the physical relationships. The GAM provides a more sophisticated statistical interpretation of the data than simple parametric analysis. The GAMs analysis was conducted based on parameters estimated from the 799 hours of daily video footage data (Table 3.4).

The form of a GAM follows the structure shown in (equation 3.8).

$$g(E(Y)) = f_1(x) + f_2(z) + \varepsilon_i \tag{3.8}$$

where:

- $E(Y)$ is an estimation of the response variable set (y_1, y_2, $y_3 \ldots y_n$),
- g is a smoothing monotonic link function that describes how E(Y) depends on the linear predictor
- x and z are predictor variables
- f_1 *and f2* are the smooth functions associated with predictors x and z.
- ε_i represents is an independent error term that is the difference between the estimated (E(Y)) and actual (Y) values of the response variable has a density function described by $N(0,\sigma^2)$

Equation 3.8 allows for flexible specification of the dependence of some response variable (in our case transient rip occurrence) on a set of predictor variables (cf. Equation 3.9) in terms of smooth functions (Wood, 2006).

The formation of the initial GAM used in this study is specified in equation 3.9 (see Table 3.6 for definitions of the predictor variables used). Note that equation 3.9 includes non-parametric: (*Julian_Day*, H_{sig}, T_p, *peak wave direction*, *wind direction [vector]*, *windspeed*) and parametric (*Tide_Stage_EBB1_Flood2*, *Outer_bar_active_N_1_Y_2*) predictors. The GAM methodology enables the combining of parametric and non-parametric predictors in the same model.

It is important to note that equation 3.9 is based on current understanding about the expected dominant physical influences on wave-driven currents in the surf zone. By starting with an appropriate model structure, the GAM facilitates meaningful results from the model-fitting process and also reduces the likelihood of model concurvity (Lefkaditou et al., 2008; Wood, 2008). Model concurvity can lead to underestimation of variance and inflated type I errors (Ramsay et al., 2003), which is especially relevant if using backfitting to fit the model rather than a direct GAM-fitting approach (Wood, 2008) as is used here.

TR count = f(Julian_Day) + f(Hsig) + f(Tp) + f(peak wave direction) + f(wind x-vector, wind y-vector) +f(windspeed) + as.factor(Tide_Stage_EBB1_Flood2) + as.factor (Outer_bar_active_N_1_Y_2)) (3.9)

In GAMs, the response variable (TR count) is drawn from a specified distribution from the exponential family. In this assessment, the Poisson distribution was selected because it represents the probability of a number of events (counts) occurring over a fixed interval of time (Wood, 2008). The use of a Poisson distribution highlights a restriction of linear modelling (e.g. $y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$) and affirms the selection of a generalised modelling approach (i.e. GAM) for this regression assessment. Linear modelling has an underlying assumption of homoscedasticity (i.e. constant variance). However, this assumption does not account for scenarios when the response variable follows a distribution other than the normal distribution (e.g. Poisson, binomial, gamma). GAM (and generalised linear modelling) allows the variance of the response variable to be specified as a function of its mean. In this study, the variance was specified as proportional to the mean (E(Y)) for all models. A logarithmic link function was specified to ensure positive predictions.

Equations 3.8 and 3.9 show how smooth functions are used to relate the predictors to the response. There are various options on how these smooth functions can be represented in the model. In this assessment, thin plate regression splines (TPRS) were used for all nonparametric predictors. The use of TPRS addresses shortcomings of other smoothing options (P-splines, cubic smoothing splines, cubic regression splines), specifically its ability to be applied to multiple predictors and the location of ‘knots’ (the points where components of the spline interconnects) are automatically computed (Wood, 2006).

The significance of the nonparametric and parametric coefficients are assessed by whether their respective p-values were less than 0.05 (significant) or not (not significant).

The model was implemented using the mgcv package (Wood, 2006) in the open source software R (Ihaka and Gentleman, 1996). A GAMs analysis will be the first of its kind on analysing transient rip occurrence. The results of the GAMs analysis are explained in Section 5.3.10.

Table 3.6: Summary of predictor variables used in the GAM assessment (response variable: transient rip count)

Predictor	Description
Julian day	Time-referenced to 20 Nov 2011 (day 1)
Significant wave height (H_{sig}) (m)	Half hour averaged (16 m water depth)
Peak wave direction (º)	Half hour averaged (16 m water depth)
Peak wave period (T_p) (s)	Half hour averaged (16 m water depth)
Wind x-component (knots)	Vector incorporating wind speed and direction (half hour averaged)
Wind y-component (knots)	Vector incorporating wind speed and direction (half hour averaged)
Outer bar activity	Wave breaking on outer bar = active; No wave breaking on outer bar = inactive (described in model as a factor variable)
Tide Stage	Tidal stage separated into ebb and flood tides disregarding still water (described in model as a factor variable)

3.5.7.3. Disclaimer about the use of statistical analysis

A criticism of statistical assessments is that they are driven by the data rather than the understanding of the processes involved. Both the univariate and multivariate statistical analysis are data based and therefore only as good as the data collected. Whilst these statistical analyses attempt to quantify certain conditions under which transient rip current formation may thrive or favour, further processed based studies such as those conducted by Clark et al. (2010; 2012) and Feddersen (2013; 2014) are necessary for assessing the actual forcing mechanisms of transient rip currents.

3.6. Summary

A description of the study site and methodologies used in this thesis was presented. It was shown that non-differential GPS units may be used with reasonable accuracy in Lagrangian drifter studies on an open coast beach. This is consistent with recent literature, e.g. McCarroll et al. (2014b). The Lagrangian drifter field experiment methodologies were described with a focus on characterising surf zone circulation and discussing retention of drifters entering a rip current under different morphodynamic and hydrodynamic conditions. As transient rip currents are relatively rare in the surf zone, a detailed remote-video analysis of transient rip current occurrence and spatial and temporal length scales is undertaken. A combination of univariate and multivariate statistics are used to make inferences about transient rip occurrence.

Chapter 4. Surf zone circulation on the Gold Coast beaches: a Lagrangian drifter study

4.1. **Introduction**

MacMahan et al. (2010a) presents a conceptual model (Section 2.5) of four different idealised surf zone circulation patterns observed on a single barred beach. To improve on the overall understanding of surf zone circulation patterns and to compare surf zone retention rates between different beach environments a simplified classification scheme of surf zone circulation may be utilised (e.g. Section 2.5). This conceptual model provides the basis for the discussion of surf zone circulation patterns on the Gold Coast open beaches in this thesis.

Castelle and Coco (2012) further classified surf zone circulation by considering the influence of embaymentisation (i.e. headland control). The degree of headland control on surf zone circulation has be characterised into three embayed beach states (Masselink and Short, 1993; Castelle and Coco, 2012): (i) cellular circulation — occurring with high waves and/or a short beach, under strong geological control, where one rip (mid-beach) or two rip channels (at headlands) drain the beach; (ii) intermediate circulation — moderate geological control, with wider rip channel spacing and headland rip currents; and (iii) normal circulation — low waves and/or a long beach, with no geological control away from the vicinity of headlands, and many open beach rips occurring that behave hydrodynamically as per open coast rips (McCarroll et al., 2014b). Castelle and Coco (2012) revised the embaymentisation parameter δ' to classify each of the above circulation patterns based upon headland control:

$$\delta' = \frac{L}{X_s} \qquad 4.1$$

Where X_s = surf zone width and L = embayment length. Castelle and Coco (2012) classified cellular circulation as $\delta' \leq 9$, intermediate circulation as $9 < \delta' \leq 16$, and normal circulation as $\delta' \geq 16$. As the Gold Coast northern open beaches sit within a 16 km embayment (and Currigee ~20 km embayment on South Stradbroke Island) and inner bar surf zone widths were calculated to be on the order of 80 – 200 m (Table 4.2), normal circulation is expected (i.e. $\delta' \approx 80 \geq 16$). Incorporating the whole surf zone with (inner and outer bar) the δ' parameter still remains greater than 16 (i.e. $\delta' \approx 50 \geq 16$).

Although these classification models have identified these kinds of behaviour, observational evidence is limited. Lagrangian drifters are a new technology that has the capability of providing evidence for these simplified models and to further qualitatively and quantitatively analyse surf zone circulation patterns and retention of floatsam in rip currents. The present study, as well as those of the literature (Table 4.1), combines to improve the overall understanding of variability in surf zone circulation patterns in different beach environments. Table 4.1 provides a summary of previous GPS Lagrangian drifter studies (human drifter and physical and numerical modelling experiments excluded) and the conditions under which they were conducted.

The majority of drifter studies in the literature have been undertaken on open coast, meso-macrotidal beaches, with relatively stable beach morphology (Transverse Bar and Rip inner bar state) and shore normal wave approach (Table 4.1). Two previous drifter field studies have been undertaken on single bar microtidal beaches: the first on an open coast, low energy terrace beach (Johnson and Pattiaratchi, 2004b); and the second on an embayed intermediate wave dominated beach (McCarroll et al., 2014b). The present study presents the first in a microtidal, double bar environment exposed to a highly dynamic wave climate, with a dominant oblique angle of wave approach and characteristic longshore drift (cf. Section 3.2). The inner and outer bar beach state combinations are also highly dynamic and the interaction between the incoming wave climate and morphology is expected to produce different rates of retention and circulation patterns to those previously studied in the literature. Only Winter et al. (2014) conducted a similar open beach drifter study observing both shore normal and shore oblique wave approach, but their study was conducted in a mesotidal environment with relatively constant TBR inner bar morphology and a low energy wind-sea dominated wave climate.

Table 4.1: Summary of the most relevant GPS Lagrangian drifter field studies on surf zone circulation and rip current retention to date (in chronological order)

Study	Location	No. drifters	No. days	Tidal regime	Wave climate	Types of rips	Morphology	Embayment index (δ′)
Johnson and Pattiaratchi (2004b)	Perth, Australia	53	3	Microtidal	H_{sig} = 0.86 – 1.16; T_p = 3 – 5s; shore-normal and shore-oblique wave approach (northerly longshore current)	Transient rips	Single bar: low energy terrace beach	Normal circulation (δ′ ≥16)
Austin et al. (2009)	Perranporth, UK	Total no. not reported but drifters released in clusters of 4 for ~3 hr periods	10	Macrotidal	H_{sig} = 1 – 2 m; T_p = 7 - 12s; shore-normal wave approach	Semi-permanent beach rips	Double bar: falls at the transition between the low tide bar/rip and dissipative morphological states (all Perranporth rip circulation studies undertaken under low tide bar/rip conditions)	Normal circulation (δ′ ≥ 16)
MacMahan et al. (2010a)	Monterey, US;	Total no. not reported but likely > 100 at each of the three study sites, on each day of sampling	7	Mesotidal	H_{sig} = 0.5 – 1.6 m; T_{mean} = 6.0 – 13.9 s; shore-normal wave approach	Semi-permanent beach rips	Single bar: characteristic TBR	Normal circulation (δ′ ≥ 16)
	Truc Vert, France;			Meso-macrotidal	H_{sig} = 0.9 – 2.1 m; T_{mean} = 10.1 – 15.0 s; shore-normal wave approach	Semi-permanent beach rips	Double bar: characteristic outer RBB (mostly inactive) characteristic inner TBR	Normal circulation (δ′ ≥ 16)
	Perranporth, UK			Macrotidal	H_{sig} = 0.8 – 1.3 m; T_{mean} = 8.3 – 9.1 s; shore-normal wave approach	Semi-permanent beach rips	Double bar: low tide bar/rip	Normal circulation (δ′ ≥ 16)

Study	Location	No. drifters	No. days	Tidal regime	Wave climate	Types of rips	Morphology	Embayment index (δ′)
Austin et al. (2013)	Perranporth, UK	Total no. not reported but likely > 100 each day of sampling	25	Macrotidal	H_{sig} = 0.6 – 2.1 m; T_p = 4 – 13 s; shore-normal wave approach	Semi-permanent beach rips	Double bar: low tide bar/rip	Normal circulation (δ′ ≥ 16)
Scott et al. (2014)	Same data set as Austin et al. (2013)							
McCarroll et al. (2014b)	Sydney, Australia	293	1	Microtidal	H_{sig} = 0.8 – 0.9 m; T_p = 12 – 14 s; oblique wave approach (northerly longshore current)	Semi-permanent beach rips; transient rips topographic headland rips	Single bar: TBR mid beach; terrace beach mid-northern end	Cellular circulation (δ′ ≤ 9)
Winter et al. (2014)	Egmond aan Zee, Netherlands	Total no. not reported but any given day between ~40 – 75	5	Mesotidal	H_{sig} = 0.35 – 0.7m; T_p = 2 – 6 s; shore-normal and shore-oblique wave approach	Semi-permanent beach rips	Double bar: linear outer bar; inner bar: TBR	Normal circulation (δ′ ≥ 16)
Present Gold Coast Study(2011 – 2015)	***Gold Coast, Australia***	***254***	***9***	***Microtidal***	***H_{sig} = 0.57 – 1.23 m; T_p = 4.7 – 16.0 s; shore-normal and shore-oblique wave approach (both southerly and northerly longshore current observed)***	***Semi-permanent beach rips; mini rips; transient rips***	***Double bar: range of intermediate wave dominated beach states for both inner and outer bar***	***Normal circulation (δ′ ≥ 16)***

Note: human drifter studies and physical and numerical modelling studies are ignored from this table but discussed throughout the chapter

McCarroll et al. (2014b) presents the first comprehensive measurements of nearshore current patterns across the entire extent of an embayed beach bounded by headland rip currents. They assessed cross-shore exchange of Lagrangian drifters for the following different surf zone circulation patterns / currents including: (i) semi-permanent bathymetrically controlled beach rip currents; (ii) headland topographically controlled rip currents; (iii) alongshore currents forced by oblique waves; (iv) transient currents on near planar topography resulting from hydrodynamic interaction; and (v) nearshore currents resulting from cross-shore exchange with the surf zone.

Other Lagrangian drifter studies (including numerical and human floater experiments) have been more specifically focused upon semi-permanent beach rips (Reniers et al., 2009; MacMahan et al., 2010a; Austin et al., 2013; Castelle and Coco, 2013; Castelle et al., 2013; Castelle et al., 2014b; Scott et al., 2014; Winter et al., 2014); headland rips (Castelle and Coco, 2013); and alongshore currents forced by oblique waves (MacMahan et al., 2010a; Austin et al., 2013; Scott et al., 2014; Winter et al., 2014).

Recent research has focused on the cross-shore exchange of Lagrangian drifters in rip currents, with direct implications for sediment transport and beach safety (Bruneau et al., 2009b; Reniers et al., 2009; MacMahan et al., 2010a; Austin et al., 2013; Castelle and Coco, 2013; Castelle et al., 2013; Castelle et al., 2014b; Scott et al., 2014; McCarroll et al., 2014b; Winter et al., 2014). Field studies as well as physical and numerical modelling studies have found rip current flow fields to consist of semi-enclosed, large scale vortices (on the order of surf zone width) that retain floating material at a rate of about 80-90% (MacMahan et al., 2010a; Reniers et al., 2010; Castelle et al., 2011; Castelle et al., 2013; Castelle et al., 2014b). This high rate of surf zone retention is thought to be the product of morphodynamic coupling of the currents to the underlying morphology (MacMahan et al., 2010a; Austin et al., 2013; Scott et al., 2014). Previous studies undertaken on open coast beaches have been characterised by shore-normal wave approach and relatively stable TBR inner bar morphology (Table 4.1). It is proposed that the shore normal wave approach and stable TBR morphology leads to strong morphodynamic coupling of the surf zone currents to the underlying morphology and therefore high rates of retention of drifters/floatsam.

As the worldwide database continues to grow, studies are beginning to show that surf zone retention is not necessarily high or low due to rip current circulation but will vary due to a variety of wave, tide, wind and morphological parameters (Castelle et al., 2011; Scott et al., 2014; Winter et al., 2014; McCarroll et al., 2014b). McCarroll et al. (2014b) (Table 4.1) observed that flow behaviour and exchange rates can vary along the length of an embayed beach due to geological control. Along the 600 m long embayed beach there was an increase in surf zone exit rates by drifters observed from south (upwave) to north (downwave), with exit rates per drifter deployment of 22% at the south headland rip, 65% at the mid-beach open rip, and 80% at the north headland rip. The high rate of drifter exits contrasts with the earlier observations on open coast beaches and supports a study conducted on a wave-dominated, macrotidal beach by Scott et al. (2014) (e.g. highest rate observed = 73% of drifters exiting the surf zone per rip entry) and a study conducted on a wind-sea dominated, mesotidal beach by Winter et al., (2012, 2014) (i.e. drifter exits were the dominant behaviour, over recirculation and alongshore drifting). It is also important to note that all three of the above mentioned studies observed a range of cross-shore exchange rates and retention rates of drifters under a variety of wind, wave, tide and morphological conditions (Table 4.1).

4.1.1. **Aims**

The research aims of the GPS drifter experiments presented in this chapter are:

(1) To quantify the cross-shore exchange rate of drifters (acting as a proxy for floatsam, e.g. bathers) entering a rip current under a variety of surf zone circulation patterns observed on an open coast beach;

(2) Test the hypothesis that due to the dominant oblique angle of wave approach as well as the complex and dynamic double bar beach state combinations, surf zone circulation patterns and hence floatsam retention in the surf zone will differ to previous studies on single bar, embayed beaches and open coast beaches in a meso- and macrotidal environment;

(3) Estimate Lagrangian surf zone drifter (i.e. wave and current) velocities;

(4) Discuss the impact of the Lagrangian drifter experiment findings in the context of beach safety on wave dominated, double bar, open coast beaches.

4.1.2. Chapter Outline

The following chapter is structured as follows. Firstly the approach undertaken for the Lagrangian drifter study is outlined followed by a brief recount of the study site (with a previous detailed description in Section 3.2). Secondly a summary of the drifter observations and morphodynamic and wave climate conditions on each day of sampling is provided. The chapter then discusses the four general surf zone circulation patterns as defined in Section 4.2 (further background in Section 2.5) and the cross-shore exchange rate of drifters under each of those circulation patterns. The drifter retention and exit statistics are then discussed with inferences made as to the possible controls on retention of floatsam in the surf zone. This section relies heavily upon comparing the present data set with previous field observations in the literature. The cross-shore and longshore components of the current speed are then discussed. This leads into a section quantifying the surf zone exit behaviour and analysis of current speeds during drifter exits and beyond the surf zone. Finally the results are discussed in terms of their implications for beach safety.

4.2. Approach

4.2.1. Overview

For the first time on a microtidal, wave dominated, double bar, open coast beach with no bounding headland morphology, drifter pathways (i.e. surf zone circulation patterns) and cross-shore exchange of drifters is described. This chapter focuses upon cross-shore exchange in surf zone circulation patterns / currents types (i - iv) described by below (conceptual diagrams in Section 2.5). For the present Gold Coast study a total of 254 drifters were released over a total of nine days which is comparable with other studies as shown in Table 4.1. Daily average significant wave height conditions ranged from 0.57 – 1.23 m, and average daily peak wave periods ranged from 4.7 – 16 s (Table 4.1). The angle of wave approach varied from shore oblique to fairly shore normal with northerly and southerly flowing longshore currents observed as well as negligible longshore drift on different days of sampling (cf. Sections 4.3 & 4.4). Each of the nine days of sampling represented a different morphological state (cf. Sections 4.3 & 4.4).

Surf zone circulation patterns are mapped and qualitatively described utilising GPS Lagrangian drifter track data. For characterisation, surf zone circulation patterns on the Gold Coast were simplified to four classifications for discussion:

(i) *Alongshore current dominant* (cf. Figure 2.14); which can occur under a variety of beach state conditions from straight bar trough morphology to attached transverse bar rip morphology.
(ii) *Rip current dominant*; with potential for both symmetric and asymmetric circulation patterns (cf. Figure 2.14). Symmetric rips are comprised of two opposing circulation cells that equally occupy half of the shore-connected shoal and rip channel, whilst asymmetric rips occupy one rip channel and one shore-connected shoal (MacMahan et al., 2010a) (cf. Figure 2.14).
(iii) *Meandering*; a combination of rip current and sinuous alongshore current.
(iv) *Terrace beach / inner bar conditions* (cf. Figure 2.15); which occur during the quieter swell months (in particular July – November). On these days there was an increased prevalence of transient rips occurring (Chapter 5).

The first three surf zone circulation patterns are primarily based upon those outlined in MacMahan et al. (2010a) (cf. Figure 2.14). In the present study *rip current dominant* and *meandering current dominant* circulation conditions are analysed (grouped) together. The prevalent longshore current that exists on the Gold Coast open beaches, generally results in a mixture of *meandering current* and *rip current dominant* circulation patterns occurring simultaneously. Mapping of surf zone circulation under Low Tide Terrace Beach conditions accounts for circulation patterns on a mostly planar beach.

The surf zone is inherently complex due to varying morphological and hydrodynamic conditions and as such surf zone circulation is also complex. Days where the circulation patterns do not adhere to the well-defined classifications detailed above will be highlighted and described accordingly.

4.2.2. **Study sites**

The Main Beach – Narrowneck study site was utilised for the phase one surf zone drifter study (cf. Section 3.2.2). In terms of assessing surf zone circulation and surf zone current hazards the study site was chosen as it is representative of an open ocean coastline, not bounded by headland morphology. The study site was also chosen due to its close proximity to the CoastalCOMS high camera at Narrowneck (cf. Section 3.2.2), which allows for the quantification of beach morphology and aids in the displaying of drifter data over timex images where possible.

Currigee Beach on South Stradbroke Island was chosen for the phase two drifter study for logistical reasons outlined in Section 3.2.2. This study site is 9 km north of the Main Beach – Narrowneck site and displays the same characteristic morphology, wave climate, net northerly longshore current and tidal regime.

4.3. **Summary of Drifter Observations**

Results from the nine days of sampling have shown that surf zone circulation on the Gold Coast open beaches is complex and due to differing morphodynamic and hydrodynamic conditions a wide range of surf zone retention rates were observed (Table 4.2). The nature of surf zone circulation and surf zone retention of drifters under different circulation patterns will be explored in detail in Section 4.4. Examples of each surf zone circulation pattern are provided in the form of drifter pathways, with a full qualitative description of surf zone morphodynamics and hydrodynamics on each day of sampling presented in Appendix B.1.

Table 4.2 highlights the high level of variability in beach state combinations with no two days exhibiting the same morphological conditions. Rip current dominant conditions generally occurred when the inner bar was in a Transverse Bar and Rip state (Table 4.2). Alongshore current dominant conditions occurred under a variety of beach state conditions, suggesting that wave approach angle is more important for controlling the general circulation pattern than the underlying morphology under these conditions (Table 4.2). One day of Low Tide Terrace beach conditions was observed and two days of complex circulation patterns were observed (Julian Days 239 and 1478) (Table 4.2). The dimensionless fall velocity parameter Ω parameter ranged between 2 – 3 (Table 4.2).

Table 4.2: A summary of daily drifter observations, which include: 1) drifter deployment duration; 2) observed circulation pattern; 3) direction of longshore drift; 4) percentage drifter exits per drifters entering a rip current; 5) average daily significant wave height; 6) average daily peak wave period; 7) average daily peak wave direction; 8) dimensionless fall velocity; 9) outer and inner bar beach state; and 10) surf zone width.

Date *(Julian Day)*	Drifter duration (h)	Circulation pattern	Longshore drift direction	Exits S_{exit} / R_{in} (%)	H_{sig} (m)	T_p (s)	Peak wave direction (ºN)	Ω	Beach state (outer bar: inner bar)	Surf zone width (approx) (inner bar)
30/09/2011 *(1)*	2.7	Combination of meandering and rip current dominant (asymmetric rip currents)	Northward	46	0.84	11.7	105 (ESE)	2	No breaking: LTT/TBR	150 m
02/11/2011 *(34)*	3.2	Alongshore current dominant	Northward	0	1.16	10.9	103 (ESE)	2	LBT: RBB/TBR	100 m
29/11/2011 *(61)*	2.2	Terrace conditions (mini rip dominant and transient rips present)	Southward (weak)	56	0.57	8.0	108 (ESE)	2	No breaking: LTT	80 m
22/02/2012 *(146)*	2.5	Alongshore current dominant	Northward	6	0.84	8.4	109 (ESE)	2	No breaking: RBB/TBR	150 m
26/04/2012 *(210)*	2.0	Rip current dominant (asymmetric skewed rip currents) – progressing to meandering through the day	Northward	33	1.23	10.5	90 (E)	3	RBB: LTT/TBR	150 m
24/05/2012 *(239)*	2.5	Complex circulation: combination of alongshore current dominant and weak rip current forcing	Southward	0	0.94	4.7	70 (ENE)	3	No breaking: TBR/LTT	180 m
18/07/2012 *(293)*	2.7	Rip current dominant (asymmetric skewed rip currents)	Negligible	29	1.23	16.0	90 (E)	2	LBT/RBB: TBR	200 m
01/09/2015 *(1433)*	4.0	Rip current dominant (asymmetric rip currents)	Northward	55	0.80	11.4	99 (E)	2	No breaking: TBR	180 m
16/10/2015 *(1478)*	4.0	Complex circulation: combination of alongshore current dominant and weak rip current forcing on the falling tide (dominant wave breaking over a wide linear, eTBR bar, restricting circulation to shore-adjacent trough)	Northward	0	1.08	10.6	98 (E); Secondary ESE swell (115°)	2	No breaking: eTBR	200 m

4.4. **Surf Zone Circulation Patterns and Retention**

This section provides a description of Gold Coast surf zone circulation patterns in the context of the four different circulation pattern classifications outlined in Sections 2.5 & 4.2. Similar to Table 4.2, Table 4.3 summarises the GPS drifter data but in this case the data has been grouped based on circulation pattern. On Julian Days 239 and 1478 complex circulation was observed where the circulation patterns did not adhere to the well-defined classifications (Table 4.3). These two days will be discussed at the end of this section.

Table 4.3: Summary of drifter data for each different surf zone circulation pattern. Drifter exit rates are calculated as Exits = S_{exit} / R_{in} (%) for every drifter entering a rip current under the corresponding circulation patterns

General circulation pattern	No. of days observed	Total no. drifters	Average daily H_{sig} (m)	Average daily T_p (s)	Average daily peak wave dir (°N)	Exits S_{exit} / R_{in} (%)
Alongshore current dominant	2	46	0.84–1.16	8.4-10.9	103-109	3
Rip current & meandering current dominant	4	112	0.80-1.23	10.5–16.0	90-105	41
Terrace beach conditions	1	16	0.57	8.0	108	56
Complex circulation	2	80	0.94-1.08	4.7-10.6	70-98	0

4.4.1. Alongshore current dominant conditions

Alongshore current dominant conditions were observed on two out of the nine days when peak wave angle was oblique to the coast, irrespective of H_{sig} and T_p (Table 4.3). Strauss and Tomlinson (2009) noted that incoming wave angle plays a major role in surf zone circulation and beach state transitions on the Gold Coast open beaches, regardless of wave height and period, with strongly oblique wave angle leading to *alongshore current dominant* conditions and the straightening of the bar and beach. On the two days of sampling where the surf zone circulation pattern was clearly *alongshore current dominant*, peak wave directions out of the ESE were observed (Table 4.3).

An example of 24 individual drifter pathways under *alongshore dominant* conditions is presented in Figure 4.1 with daily qualitative descriptions in Appendix B.1. Under these conditions, even when strong rip channel morphology is evident (e.g. Figure 4.1) the drifters entering a rip current almost never exit the surf zone beyond the edge of the inner bar, with an overall 97% retention observed (Table 4.3). This is consistent with field studies conducted by MacMahan et al. (2010a) who studied three open coast beaches in a meso-macrotidal environment (Table 4.1) and found 94 - 100% of drifters entering a rip current were retained in the surf zone under *alongshore current dominant* conditions. Offshore movement of the drifters in well-defined rip channels was observed on these days, but the longshore current remained dominant therefore limiting the number of drifter exits.

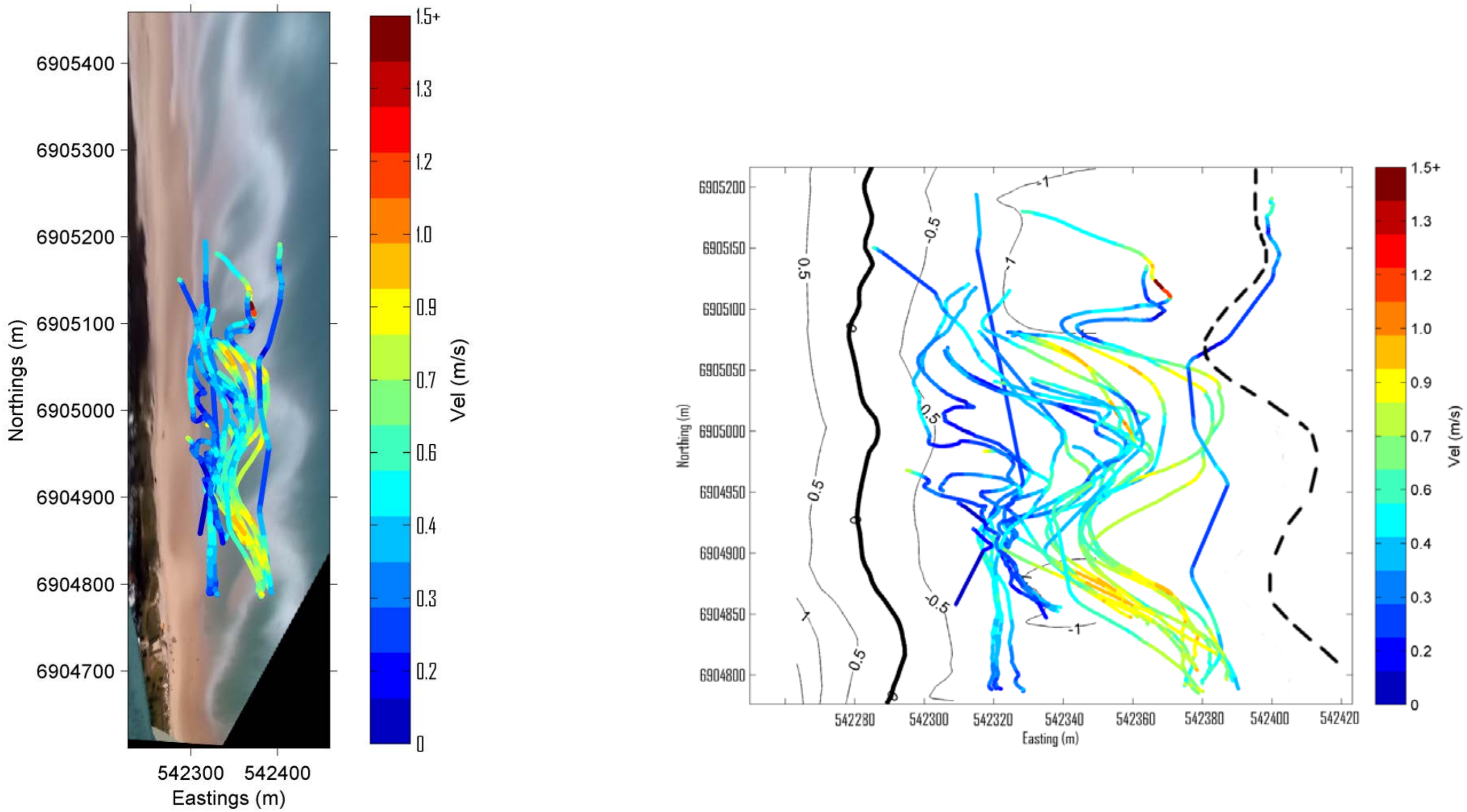


Figure 4.1: Drifter position and speed tracks for drifter deployments on Julian Day 146 at Main Beach – Narrowneck study site. (a) Overlayed on rectified timex image of the study site; (b) Corresponding contour plot. Bathymetric contours are plotted in the background in gray (solid black 0 m AHD contour; dashed line approximate edge of inner bar). The colour bar represents drifter speed ($m.s^{-1}$)

4.4.2. Rip current circulation and meandering circulation

Skewed bar and rip morphology was prevalent on the Gold Coast open beaches, with asymmetric rip circulation observed on half of the sampled days (Table 4.2). This is the result of the prevailing longshore current observed on the open beaches, with rip current circulation generally occurring in combination with *meandering current* patterns. Rip current and meandering circulation conditions occurred through a range of significant wave heights, peak wave periods and peak wave directions (Table 4.2 & Table 4.3). Rip current circulation did however become more prevalent with a more shore-normal (easterly) wave angle approach (Table 4.2 & Table 4.3), which is consistent with the recent literature in terms of beach state and bar morphology for the Gold Coast (Strauss et al., 2006; Garnier et al., 2009; Strauss and Tomlinson, 2009; Price and Ruessink, 2011). These studies found that with a more shore-normal wave direction, the resulting beach state favoured rhythmic bars, separated by rip channels. Alternatively for a more oblique wave approach the beach state tended to straighten out into a more linear bar / trough morphology. An example of 50 individual drifter pathways under *rip current dominant* conditions is presented in Figure 4.2 with daily qualitative descriptions in Appendix B.1.

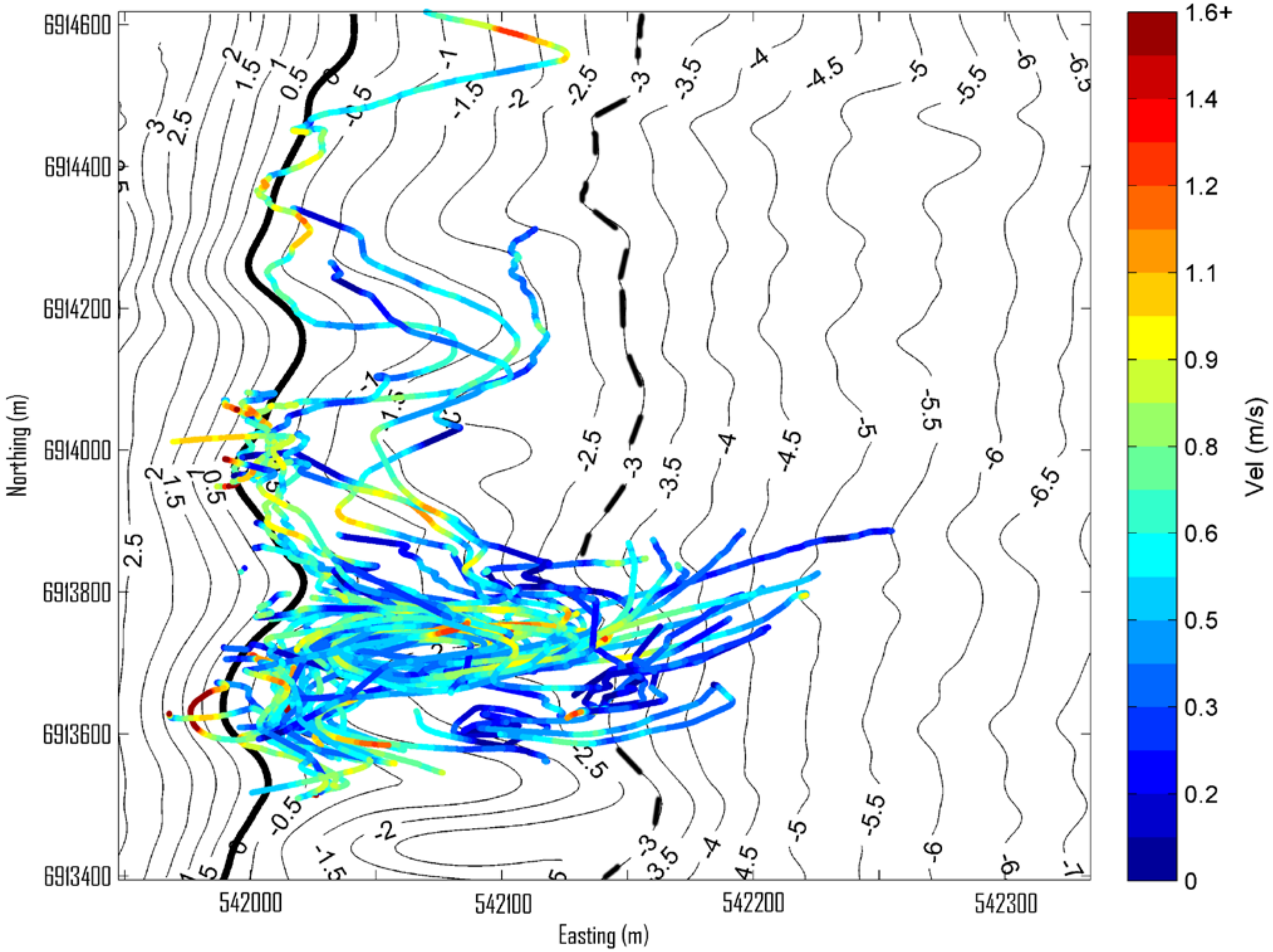


Figure 4.2: Drifter position and speed tracks for drifter deployments on Julian Day 1433 at Currigee Beach (South Stradbroke Island). Bathymetric contours are plotted in the background in gray (solid black 0 m AHD contour; dashed line approximate edge of inner bar). The colour bar represents drifter speed (m.s^{-1}). *Note: rectified timex image unavailable (study site outside camera field of view)*

There was an increased percentage of drifters exiting the inner bar system under *rip dominant* and *meandering dominant* conditions when compared with *alongshore current dominant* conditions (Table 4.3). Under these conditions, 41% of drifters entering rip channels exited the inner bar region giving an overall retention rate of 59%. This is a significantly lower retention rate than was measured (i.e. 80 - 90%) in the early Lagrangian field, physical modelling and numerical modelling studies (Reniers et al., 2009; MacMahan et al., 2010a; Castelle et al., 2011; Castelle et al., 2013). This rate of retention is however consistent with the physical modelling results of Castelle et al. (2011), where approximately 30 – 45% of drifters entering an asymmetric rip current to exit the surf zone (i.e. retention rate of 55 – 70%). It is also comparable to the overall mean exit rate across all sectors and time blocks in McCarroll et al. (2014b) study: 46% exits/h.

When compared to the literature (cf. Section 4.1), surf zone retention rates on the Gold Coast open beaches under a mix of *rip current dominant* with *meandering* current conditions can be classified as moderate (i.e. 59% retention) with previous studies observing both high, e.g. MacMahan et al. (2010a) and low e.g. McCarroll et al. (2014b) rates of drifter retention (cf. Section 4.1). As daily offshore exchange of drifters is at a maximum of 55% (Table 4.2) and overall exit rates were 41% (Table 4.3) under *rip dominant* and *meandering* dominant circulation conditions it is suggested that overall, the inner bar retention of drifters entering a rip current, is still the dominant observation.

Based on a sample of 112 individual drifter deployments (Table 4.3) rip current and meandering current dominant conditions on the Gold Coast open beaches (double bar, microtidal environment) are characterised by large scale, semi-enclosed, surf zone eddies on the order of surf zone dimensions. This is consistent with studies conducted on other open coast beaches in a meso-macrotidal environment (Bruneau et al., 2009b; Reniers et al., 2009; MacMahan et al., 2010a; Austin et al., 2013; Castelle and Coco, 2013; Castelle et al., 2013; Castelle et al., 2014b; Scott et al., 2014; McCarroll et al., 2014b; Winter et al., 2014).

4.4.3. **Terrace beach / inner bar conditions**

On Julian Day 61 (Table 4.2) the morphology was characterised as a (near) alongshore, planar beach with the cross-shore movement of drifters primarily controlled by a small mini rip and transient rip currents present in the surf zone (cf. Appendix B.1; Chapter 5). This beach condition is rare on the Gold Coast open beaches (Price and Ruessink, 2011) and was only sampled on a single day in this study set. For the days of sampling during the experiment, lowest significant wave heights were observed on Julian Day 61 (Table 4.2). Julian Day 61 also recorded the highest percentage of drifter exits per drifters entering a (mini) rip current (or transient rip current) (Table 4.2 & Table 4.3). Drifter tracks for this day of sampling are presented in Figure 4.3.

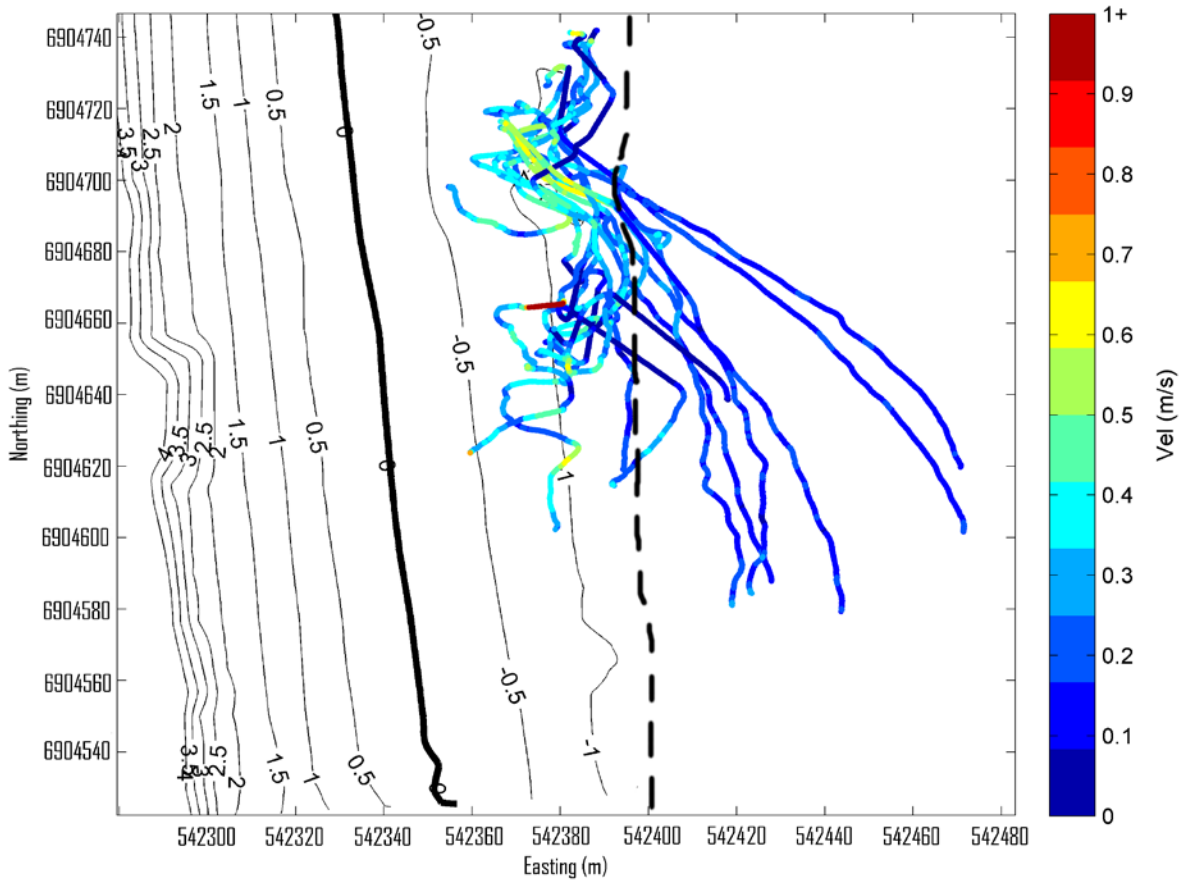


Figure 4.3: Drifter position and speed tracks for drifter deployments on Julian Day 61 at Main Beach – Narrowneck study site. Bathymetric contours are plotted in the background in gray (solid black 0 m AHD contour; dashed line approximate edge of inner bar). The colour bar represents drifter speed ($m.s^{-1}$). *Note: rectified timex image unavailable (study site outside camera field of view)*

In the present Gold Coast study, the highest percentage of drifters exiting the surf zone after entering a rip current occurred under *terrace beach / inner bar dominant* conditions (Table 4.3). The majority of drifter exits under *terrace beach / inner bar dominant* conditions occurred out of a small bathymetric perturbation in the inner bar terrace. It is noted that two drifters captured transient rip currents moving offshore of a planar section of the inner bar terrace (Figure 4.3). Low wave heights, a narrow surf zone and a lack of strong morphodynamic coupling of the rip current circulation to the underlying morphology are the likely reasons for the highest number of exits occurring under these conditions (cf. Section 4.5).

McCarroll et al. (2014) also observed transient rip currents occurring on an alongshore planar section of beach (~200 m) in their study of a microtidal and wave dominated, single barred embayed beach. Transient rip currents were identified in this section of beach with drifters displaying higher than average velocities and exiting the surf zone at a rate of 21% (per sector entry), lower than observed in the present Gold Coast study. This lower drifter exit rate observed in McCarroll et al. (2014b) is possibly due to transient rip current forcing not being the dominant circulation pattern on the beach on the day of sampling. The increased influence of headland control on surf zone circulation ($\delta' \leq 9$ – cf. Section 4.1) on this beach and presence of well defined semi-permanent beach rip morphology is expected to dominate the circulation over transient rip forcing. It is interesting to note however that transient rip currents can and do form concurrently with other beach rip types and will lead to a degree of cross-shore exchange of water, sediment and floatsam. This supports findings of the remote-video study conducted for this thesis which is presented in Chapter 5.

One transient rip event was identified and captured by the GPS drifters, with two individual drifter tracks pulsing offshore in the absence of any topographic non-uniformity (Figure 4.3). Both drifters underwent a small looped motion in the track before the exit, with a localised vortex pair shedding offshore which has previously been associated with transient rip formation (Johnson and Pattiaratchi, 2006; Clark et al., 2012; Feddersen, 2014; Hally-Rosendahl et al., 2014) (cf. Section 2.8.5.3). These vortex features are believed to be caused by rotational flow in the infragravity and VLF wave field with vorticity introduced by along-crest variation in wave breaking (Johnson, 2004; Johnson and Pattiaratchi, 2006; Clark et al., 2012; Feddersen, 2014; Hally-

Rosendahl et al., 2014) (cf. Section 2.8.5). Low frequency waves will modulate the relative vortices by vortex stretching, which may cause a pumping mechanism to enhance offshore propagation of the current (Johnson, 2004). The longshore current on the day of sampling was weak (approx. average longshore current speed 0.1 $m.s^{-1}$ – cf. Section 4.6.1), suggesting shear instabilities in the longshore current did not play a role in the transient rip forcing. Castelle et al. (2014a) also observed transient rip currents to occur in the absence of a strong longshore current on an open wave dominated and microtidal beach with modal Low Tide Terrace morphology.

4.4.4. **Complex circulation patterns**

Two of the sampling days did not adhere to the simplified circulation classification scheme outlined in Sections 2.5 & 4.1. As such these days were classified as having complex circulation (Table 4.2 & Table 4.3). Both days were characterised by drifters travelling shore-parallel in a longshore current and cross-shore under weak rip current forcing (Table 4.2). In saying this surf zone circulation patterns were very different on the two days of sampling due to a range of morphodynamic and hydrodynamic factors (Table 4.2, cf. Appendix B.1). Both days observed a 100% retention rate of drifters entering a rip current (Figure 4.4 & Figure 4.5).

On Julian Day 239 (Table 4.2), when circulation patterns were a combination of *alongshore current dominant* and *weak rip current forcing*, the average peak wave direction for the day of sampling was out of the ENE (Table 4.2) and the net longshore current was in a north to south direction (Figure 4.4), opposite to the predominant south to north direction. Offshore movement of drifters in deeper rip channels, adjacent to the exposed low tide transverse bars occurred (Figure 4.4; Appendix B.1). As the tide receded the drifters were observed to be ‘lifted’ onto the shallow transverse bar as the water was draining on and off the bar. The drifters were then pushed shoreward, via wave activity and southward in the longshore current (Figure 4.4). The drifters would continue south until they reached the next transverse bar / rip feature where they performed a similar motion as previously described: e.g. moving out against the north end of the bar; ‘lifted’ onto the shallow sand bar and; pushed shoreward by waves (Figure 4.4). This circulation pattern resulted in 100% of retention of drifters entering a rip current.

On Julian Day 1478 (Table 4.2) an erosional TBR morphology had formed on the inner bar (cf. Appendix B.1) with wave breaking across a wide offshore linear bar restricting the surf zone circulation flow to a shore-adjacent trough (Figure 4.5). Weak rip circulation was observed as the ebb tide approached mid-low, but wave breaking on the linear eTBR restricted drifter exits offshore (Figure 4.5).

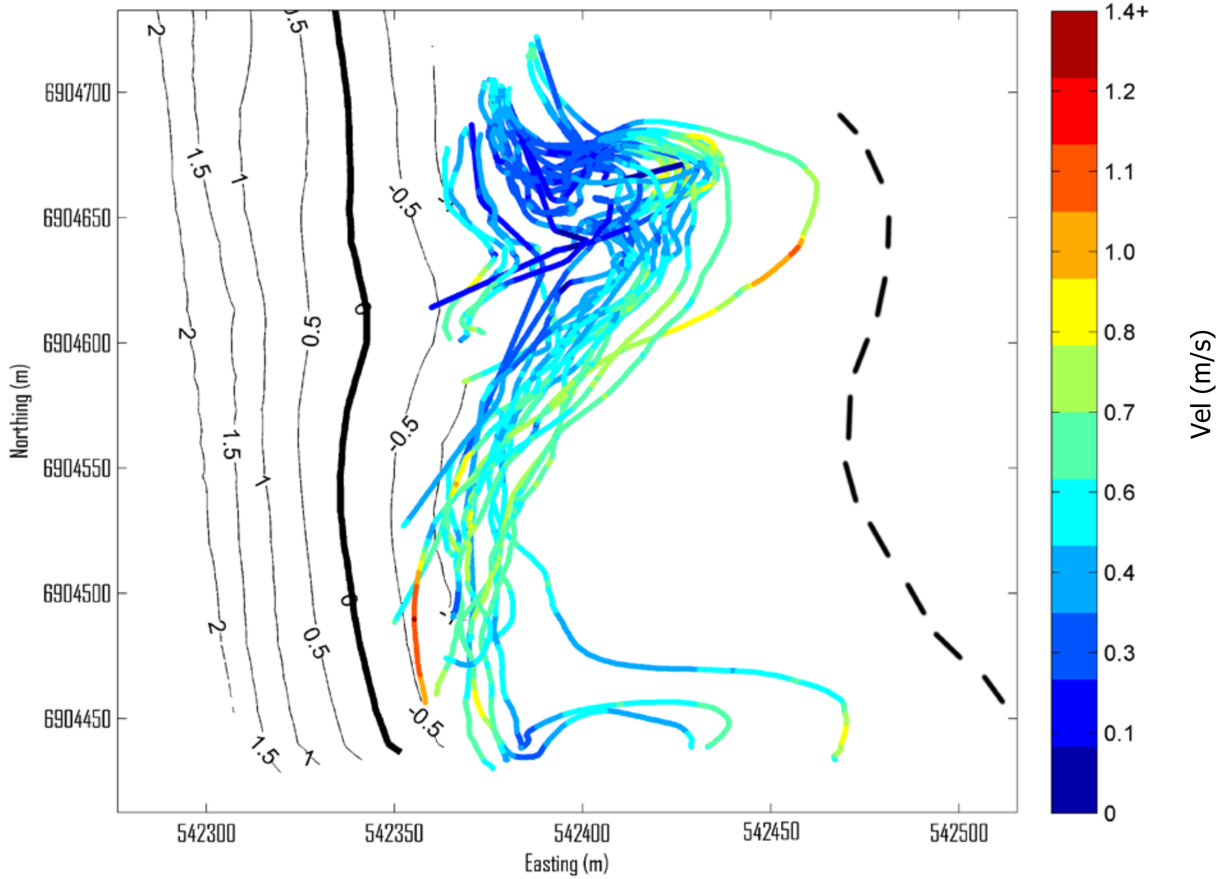


Figure 4.4: Drifter position and speed tracks for drifter deployments on Julian Day 239 at Main Beach – Narrowneck study site. Bathymetric contours are plotted in the background in gray (solid black 0 m AHD contour; dashed line approximate edge of inner bar). The colour bar represents drifter speed (m. s^{-1}). *Note: rectified timex image unavailable (study site outside camera field of view)*

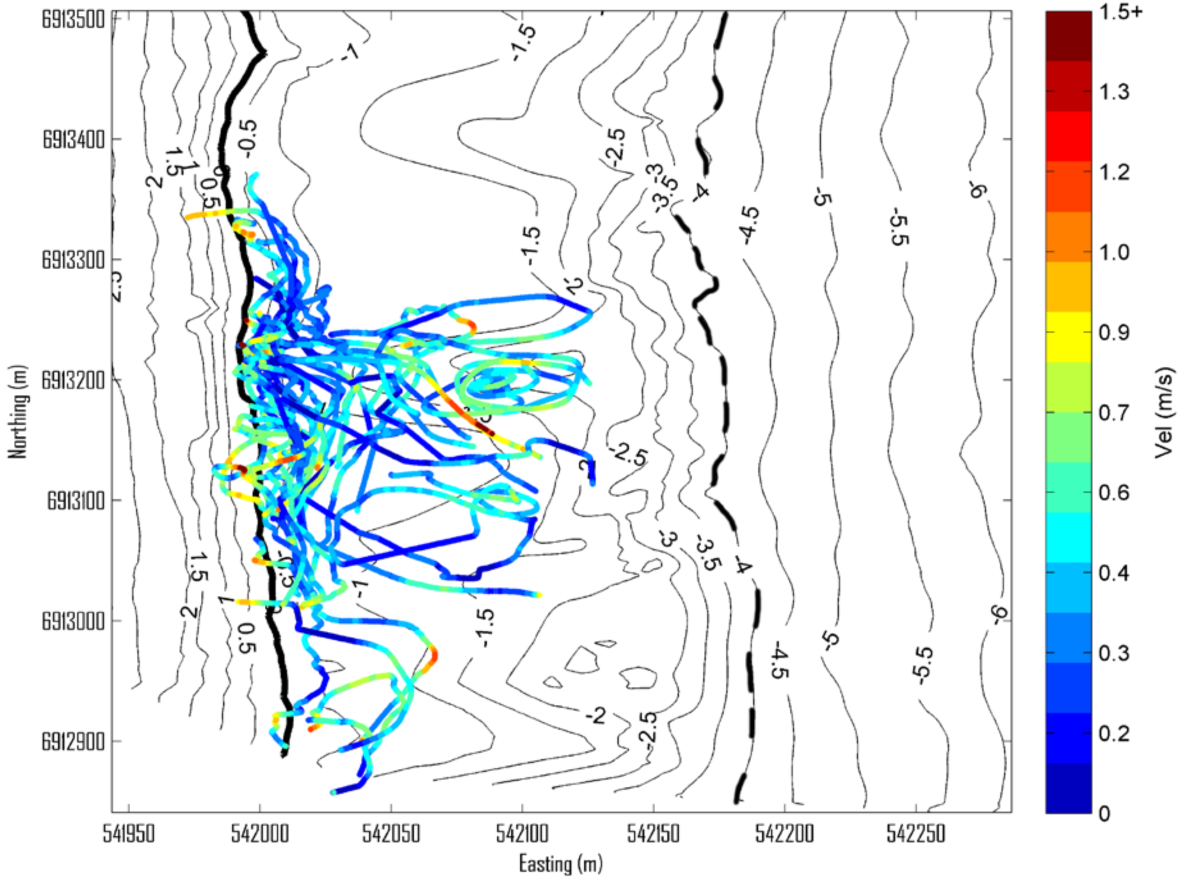


Figure 4.5: Drifter position and speed tracks for drifter deployments on Julian Day 1478 at Currigee Beach (South Stradbroke Island). Bathymetric contours are plotted in the background in gray (solid black 0 m AHD contour; dashed line approximate edge of inner bar). The colour bar represents drifter speed ($m.s^{-1}$). *Note: rectified timex image unavailable (study site outside camera field of view)*

4.4.5. **Influence of wind on surf zone circulation**

Changes in the wind conditions on any day of sampling were also observed to have an effect on nearshore circulation patterns through the daily sampling period (cf. Appendix B.1). As the alongshore winds strengthen in the afternoon(s) the circulation patterns often switched from *rip current dominant* to *alongshore current dominant*, with the strengthening longshore current dominating any cross-shore movement (cf. Appendix B.1; e.g. Figure 4.6).

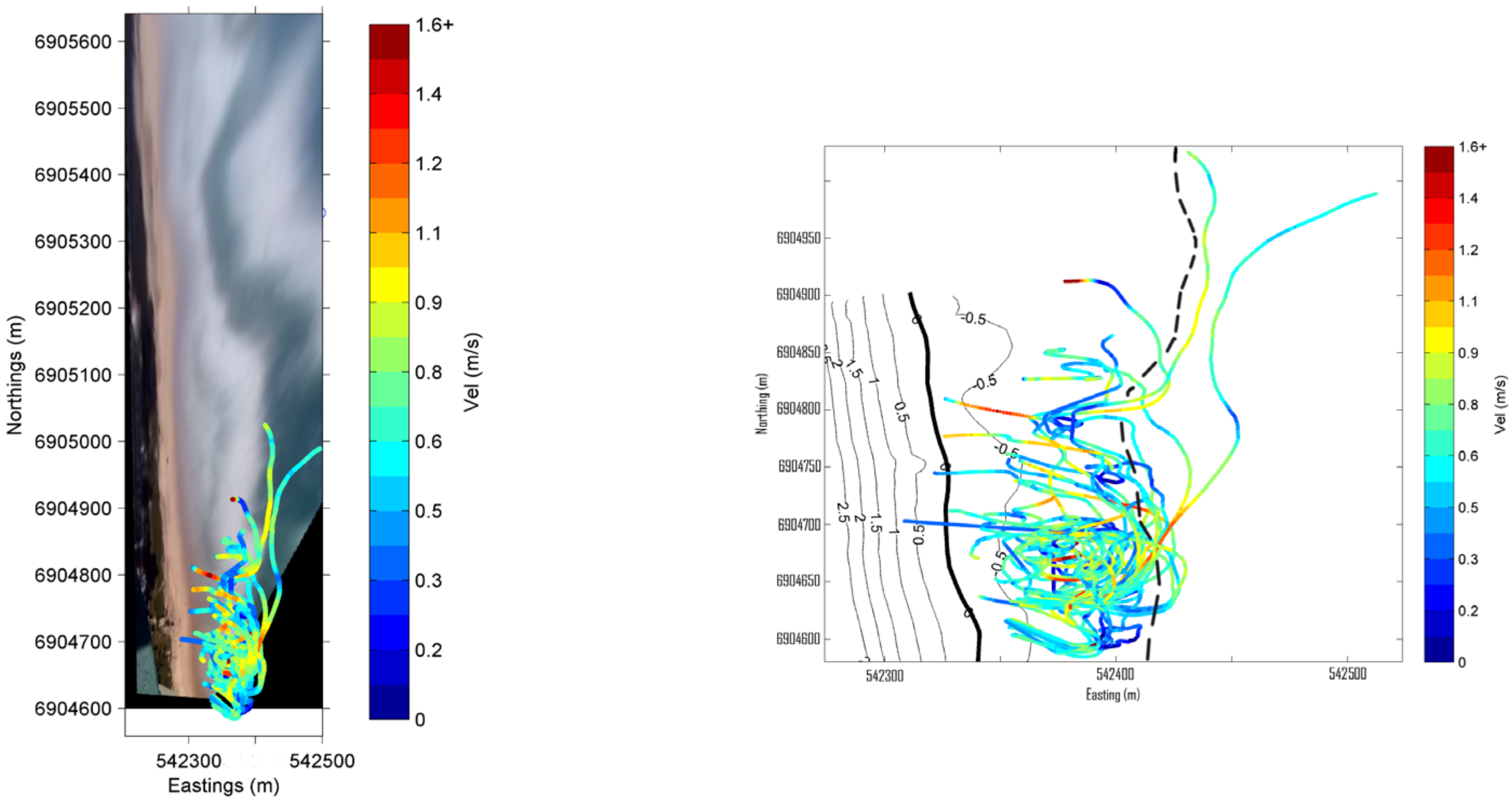


Figure 4.6: Drifter position and speed tracks for drifter deployments on Julian Day 210 at Main Beach – Narrowneck study site. (a) Overlayed on rectified timex image of the study site; (b) Corresponding contour plot. Bathymetric contours are plotted in the background in gray (solid black 0 m AHD contour; dashed line approximate edge of inner bar). The colour bar represents drifter speed ($m.s^{-1}$)

4.4.6. **Summary**

Drifter tracks highlight how complex the circulation patterns on an open coastline beach can be. The present drifter data are consistent with the simple models of classifying circulation patterns into: *alongshore current dominant, rip current dominant, meandering* and *terrace beach / inner bar* conditions to be beneficial for describing certain conditions on any particular day of sampling. *Rip current dominant* circulation patterns were observed to be characterised by large scale, semi-enclosed, surf zone eddies on the order of surf zone dimensions, which is consistent with previous Lagrangian drifter studies (cf. Section 4.4.2). Drifter pathways in the present study also responded in a similar manner under *alongshore current dominant* circulation patterns as to those described previously in the literature (cf. Section 4.4.1).

It is evident from observations presented in this chapter that a combination of circulation patterns may exist and that tide, wind, waves and morphology will all play a role in controlling cross and longshore movement of water, sediment and floatsam. The wave angle approach appears to have a significant control on surf zone circulation on the Gold Coast open beaches. An oblique angle of wave approach was observed to promote *alongshore current dominant* circulation, whilst a shore-normal wave approach favoured *rip current dominant* circulation patterns. Strong afternoon seabreezes were observed to alter circulation patterns through a day of sampling with strengthening shore oblique winds influencing a change in *rip current dominant* circulation to *alongshore current dominant* circulation. The complex beach and bar morphology (i.e. highly variable inner and outer bar combinations and skewed bar and rip morphology) in combination with the variable wave climate (e.g. often bimodal and bidirectional: Jackson et al., 1997; Short, 2000; Strauss et al., 2006) was also shown to produce surf zone circulation patterns that do not fit into the typical simplified models described in Section 4.2.1 (cf. Section 4.4.4).

Finally by comparing the exit rates of drifters across different morphodynamic, tidal and wave climates it is shown that retention of floatsam is not necessarily high or low but will vary based on a range of morphological and hydrodynamic controls.

4.5. **Controls on Surf Zone Retention and Exits of Lagrangian Drifters**

4.5.1. **Morphodynamic coupling**

From observations made in this thesis (cf. Section 4.4) and the literature it is argued that morphodynamic coupling of the large scale surf zone eddies to the underlying morphology will play a major role in determining surf zone retention rates and influence the cross-shore exchange of water, sediment and floatsam (i.e. drifters). The MacMahan et al. (2010a) model suggests that a morphodynamic threshold may exist for cross-shore exchange by rip currents where larger waves (breaking further offshore) induce coherent vortices (i.e. surf zone eddies) on the scale of surf zone dimensions and which retain material within the surf zone, thus reducing surf zone 'exits' (Scott et al., 2014). As a result it is argued that for lower wave heights, decreased morphodynamic coupling occurs which in turn encourages cross and alongshore exchange, resulting in an increase in surf zone 'exits' until the flow field becomes much less energetic and weak alongshore currents dominate (MacMahan et al., 2010a; Scott et al., 2014).

It is proposed that the moderate cross-shore exchange of drifters observed on the Gold Coast open beaches under *rip current, meandering* and *terrace beach* conditions (cf. Section 4.4) is due to a reduced coupling of the surf zone circulation patterns to the underlying surf zone morphology. The existence of the strong, almost always present longshore current, due to the dominant oblique angle of wave approach and obliquely skewed and complex rip channel morphology is the likely reason for this observation. A lack of bathymetric non-uniformities under terrace beach state conditions also does not allow for the rip current circulation to couple to the underlying sand bar morphology, leading to higher levels of offshore exchange of drifters (cf. Section 4.4.3).

Scott et al. (2014) also support this model explaining high drifter exit rates under reduced rates of morphodynamic coupling by introducing the non-directional parameter, *wave factor* (W_f).

$$(W_f \;=\; H_s\,T_p \;/\; \overline{H_s\,T_p}) \qquad 4.2$$

where the overbar represents the long term average. The W_f parameter describes the ratio between the associated H_sT_p and the long term average. Scott et al. (2014) found a strong correlation with W_f and drifter exit percentages. Their study showed exit percentages decreased with increasing W_f until $W_f = 1$, after which all exit values were < 10%, indicating that exit percentages increase once the wave factor drops below the long-term mean (Scott et al., 2014). Scott et al. (2014) suggest that the response of measured exit percentages as a function of W_f would support a hypothesis similar to that of MacMahan et al. (2010a) for single-barred beaches; that with decreasing wave energy, wave breaking on the outer bar and rip head is reduced and the rip circulation becomes decoupled from the full morphological template leading to increased rip current exits. McCarroll et al. (2014b) calculated a W_f value of 0.7 on their day of sampling, which was consistent with their high rate of exits observed, suggesting that the wave factor parameter may be useful in assessing exit rates on certain beaches and datasets.

The wave factor parameter W_f as described in Scott et al. (2014) and explored in McCarroll et al. (2014b) does not appear to show a strong relationship with surf zone retention on the Gold Coast open beaches (Table 4.4). This is most likely due to the highly oblique incident wave angle and presence of a strong longshore current on the Gold Coast, as well as the mixture of circulation patterns that exist on the open ocean Gold Coast beaches. It has been show in other studies (Strauss et al., 2006; Garnier et al., 2009; Strauss and Tomlinson, 2009; Price and Ruessink, 2011) that wave direction plays a major role in shaping the sandy bar morphology of the open beaches and surf zones, which would have flow on effects for surf zone circulation. The oblique wave angle has been shown in this study to create *alongshore current dominant* conditions irrespective of surf zone morphology; over-riding the rip cell circulation and possibly decoupling the rip cell circulation from the morphology (cf. Section 4.4.1). As such the W_f is not considered relevant for the present study as it does not incorporate a directional component.

Table 4.4: Comparing Wave parameter ($W_f = H_s T_p / \overline{H_s T_p}$) for each day of sampling and percentage exits of drifters entering a rip current. Note that the overbar represents the long term average (27 year average).

Date	W_f	Exits S_{exit} / R_{in} (%)
30/09/2011	0.9	46
02/11/2011	1.2	0
29/11/2011	0.4	56
22/02/2012	0.7	6
26/04/2012	1.2	33
24/05/2012	0.4	0
18/07/2012	1.8	29
01/09/2015	0.9	55
16/10/2015	1.1	0

Castelle et al. (2013) further argued that decoupling of rip cell circulation by increased rip spacing would be anticipated to increase drifter exit rates. As such they developed the rip spacing parameter:

$$\frac{X_s}{\lambda} \qquad 4.3$$

where X_s = rip spacing and λ = surf zone width, to describe cross-shore exchange and surf zone flushing. Recent studies of surf zone retention (Castelle et al., 2013; Castelle et al., 2014b; McCarroll et al., 2014b) have used the Castelle et al. (2013) rip spacing parameter to assess cross-shore exchange of drifters. With the presence of a strong alongshore current on the Gold Coast open beaches and the irregular nature of the bathymetry and surf zone circulation patterns, the rip spacing parameter was not utilised in this thesis for analysis of rip spacing control on retention of drifters. It is worthwhile noting however, that an increase in rip spacing or an absence of obvious rip channel morphology, as seen on terrace beach days, reduces the ability of rip current circulation to couple to the morphology (MacMahan et al., 2010a; Scott et al., 2014) leading to an increase in offshore exchange of drifters (Table 4.2 & Table 4.3). In agreement with statements made by Castelle and Coco (2012) and McCarroll et al. (2014b) it is suggested that the rip spacing parameter may be more relevant to embayed beaches which display cellular circulation ($9 \leq \delta'$) and intermediate circulation ($9 < \delta' \leq 16$).

4.5.2. **Low frequency pulsing of surf zone circulations**

In the present Gold Coast study, the ejection of drifters beyond the inner bar surf zone was found to be episodic, characterised by several drifters exiting the inner bar surf zone at the same time (cf. Appendix B.1). This result supports the hypothesis that drifter exits are influenced by low frequency pulsing of the rip current and the rip current temporally extending beyond the surf zone.

Recent studies have argued that the primary exit mechanism of floating material in rip current circulation is associated with infragravity frequency or very low frequency (VLF) dynamics (cf. Section 2.8.7.2) and the resulting eddies that detach from the main rip current (Reniers et al., 2010; Castelle et al., 2013). Reniers et al. (2010) argued that these VLF motions are associated with Lagrangian Coherent Structures (LCS's) (Shadden et al., 2005) (Figure 4.7) hidden in the pulsating rip-current surface velocity field (Castelle et al., 2013). Reniers et al. (2010) argues that the presence of VLF motions changes the rip current orientation over time occasionally creating conditions that promote the rip current to extend beyond the surf zone.

Once exited the inner bar surf zone drifters tended to flow shore-parallel with the dominant alongshore drift (e.g. Figure 4.1 - Figure 4.6). It was observed on days of weak or negligible longshore current that drifters would continue on the same pathway as that which they exited the rip current (e.g. Figure 4.3; Appendix B.1). This result may hold support for the LCS model presented by Reniers et al. (2010) with vortical motions ceasing as the LCS's extend beyond the surf zone, with drifters limited to travelling shore parallel in 'streaks.' An example of an LCS formed in a rip current is displayed in Figure 4.7.

Figure 4.7: Example of an LCS formed in a rip current, with green arrows indicating narrow streaks of surface floating material. Source: Reniers et al. (2010)

4.5.3. **Rip Head Bar**

Castelle et al. (2013) and McCarroll et al. (2014b) argue that the presence of a rip head bar may lead to increased drifter exit rates. The mechanism behind this is explained as wave breaking over the rip head bar generates an outer surf zone eddy that is counter-rotational to the main rip cell, therefore propagating drifters offshore (Castelle et al., 2013; McCarroll et al., 2014b) (Figure 4.8). In the present study a rip head bar was observed on Julian Days: 1, 34, 146, 210 and 293 (cf. Appendix B.1). Whilst the incident wave angle appears to play a fundamental role in controlling the circulation patterns on the Gold Coast (cf. Sections 4.4 & 4.5.1), the presence of a rip head bar may also help to explain the slightly higher exit rates of drifters observed on the Gold Coast beaches on Julian Days 1, 210 and 293 (Table 4.2) when compared with those of Reniers et al. (2009) and MacMahan et al. (2010a). The eTBR outer bar formation on Julian Day1478 is not indicative of a rip head bar as the system is eroding back toward a linear longshore bar state.

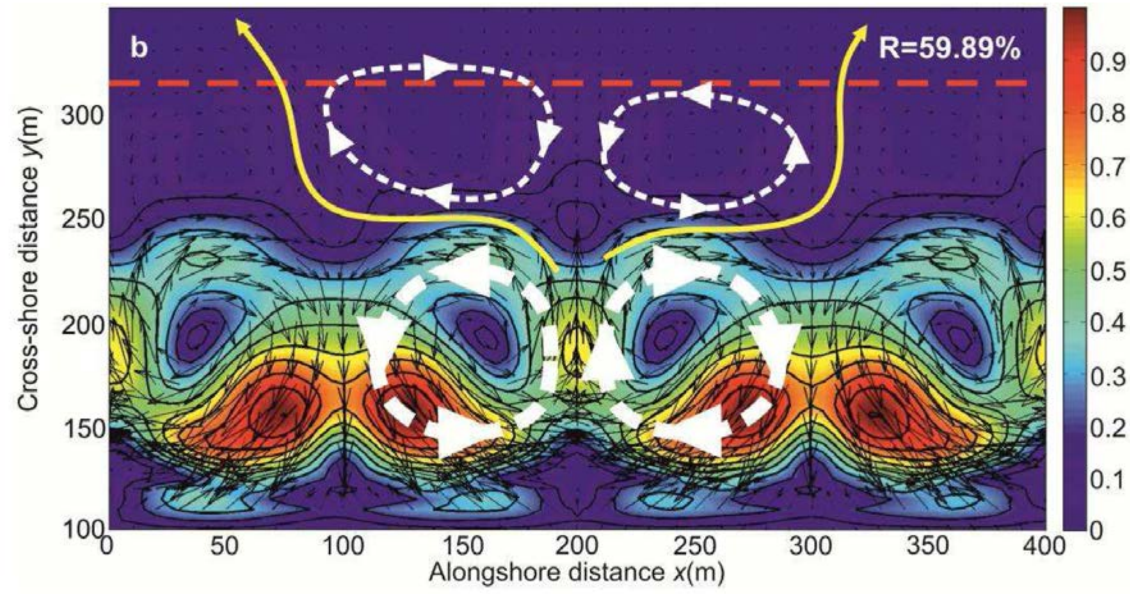


Figure 4.8: Numerical model of surf zone circulation in the presence of a rip head bar. The dotted white circles and yellow arrows indicate qualitatively the surf zone eddies and the preferred pathways of drifter exits. Source: Castelle et al. (2013)

Castelle et al. (2014b) also suggest that alongshore variations in the offshore bathymetry are important for cross-shore exchange of water, sediment and floatsam. Patterns in the wave field enforced by wave refraction and potentially wave breaking across offshore bathymetric anomalies, such as an outer bar, can provide a conduit for transporting floating material out of the surf zone (Castelle et al., 2014b). They argue that this has major implications for surf zone flushing by inner bar rips on multiple-barred beaches.

4.5.4. Drifter transfer between adjacent rip current systems

Under *alongshore current dominant* conditions, 100% of the drifters were observed to pass through several rip channels (when present), with a large amount of water interchanged between adjacent rip current systems. As mentioned previously the longshore current over-rides the rip cell circulation allowing for the drifters to 'escape' one rip current to move onwards to the next and so on. Under conditions where the rip current circulation is the dominant hydrodynamic process, only a small number of drifters (on average 15%) pass from one rip current system to another (e.g. Figure 4.2). This suggests a rather small interchange of water between the nearby rip current systems when the rips are stronger than the longshore current, which is consistent with drifter behaviour on rip-channeled beaches exposed to more shore-normal waves (e.g.

Castelle et al., 2011; Castelle et al., 2013). Under these conditions we also see an increase in drifter exits (Table 4.3).

4.6. Drifter Speeds

4.6.1. Longshore and cross-shore drifter speeds

An analysis of different components of the surf zone circulation (i.e. cross-shore in the form of waves and currents and longshore in the form of a longshore current and obliquely angled waves) provides an improved understanding of how water, sediment and floatsam are behaving in and beyond the inner bar surf zone. In accordance with previous Lagrangian drifter studies (Table 4.1) the highest peak drifter velocities are attributed to waves and rip current pulsing in the cross-shore and obliquely incident waves and pulsing of the longshore current in the longshore direction (e.g. Figure 4.1 - Figure 4.6; Appendix B.1).

The average cross-shore and longshore drifter speeds range from 0.1 – 0.3 m.s^{-1} and 0.1 – 0.5 m.s^{-1} respectively (Table 4.5). These results are comparable to the more detailed studies of MacMahan et al. (2010a) on meso-macrotidal, open coast beaches and McCarroll et al. (2014b) on a microtidal, embayed beach. Peak current velocities recorded in the present study (Table 4.5; Appendix B.1) are also on the same order as these previous Lagrangian drifter studies. The present Gold Coast study observed higher longshore drifter velocities than observed in previous microtidal, embayed beach drifter studies (McCarroll et al., 2014b) (i.e. < 0.2 m.s^{-1}) as would be expected of a long open coastline beach, with a modal obliquely incident wave angle and no headland control on circulation. The highest average longshore current speeds were recorded on days corresponding to *alongshore current dominant* circulation patterns (Table 4.3 & Table 4.5).

The time-averaged peak cross-shore current speeds calculated on Julian Day 61 (Table 4.5) are comparable to those observed by Castelle et al. (2014a) (0.2 – 0.8 m.s^{-1}) on a wave dominated and microtidal, Low Tide Terrace beach in West Africa; and on the same order as the rip growth rate calculated using video-imaging techniques in thesis (cf. Section 5.4.4, Appendix B.2).

Consistent with MacMahan et al. (2010a) drifter velocities reach a maximum in the middle of the surf zone and tend to decay to the outer edge of the surf zone (e.g. Figure 4.1 - Figure 4.6; Appendix B.1).

Table 4.5: Average and peak cross-shore and longshore drifter speed statistics on each day of sampling (data recorded at 1 Hz. A 30 second moving average filter applied to the raw data)

Date	Longshore drifter speeds (*v*)		Cross-shore drifter speeds (*u*)	
(Julian Day)	Average Mean Drifter Speed ($m.s^{-1}$)	Range of Peak Drifter Speeds ($m.s^{-1}$)	Average Mean Drifter Speed ($m.s^{-1}$)	Range of Peak Drifter Speeds ($m.s^{-1}$)
30/09/2011 *(1)*	0.2	0.1 – 0.6	0.2	0.3 – 0.9
02/11/2011 *(34)*	0.4	0.6 – 0.9	0.2	0.3 - 0.8
29/11/2011 *(61)*	0.1	0.2 – 0.7	0.1	0.2 – 0.8
22/02/2012 *(146)*	0.5	0.2 – 1.0	0.2	0.1 – 0.9
26/04/2012 *(210)*	0.3	0.5 – 1.3	0.3	0.6 – 1.3
24/05/2012 *(239)*	0.3	0.2 – 1.3	0.1	0.2 – 0.8
18/07/2012 *(293)*	0.2	0.4 – 1.2	0.3	0.7 – 1.3
01/09/2015 *(1433)*	0.3	0.2 – 1.8	0.2	0.1 – 1.5
16/10/2015 *(1478)*	0.3	0.2 – 1.1	0.2	0.2 – 1.0

4.6.2. **Surf zone exit speeds**

Drifter surf zone exit speeds in the present Gold Coast study (Table 4.6) were generally higher than those measured in the MacMahan et al. (2010a) study (0.2 $m.s^{-1}$). McCarroll et al. (2013b) found large numbers of drifter exits under fairly low to moderate mean current speeds (0.4 – 0.6 $m.s^{-1}$). In the present Gold Coast study transient rip current and mini rip current speeds are also relatively lower than their more 'semi-permanent' topographically controlled beach rip counterparts (cf. Section 4.4; Appendix B.1). Again mini rip and transient rip current exit velocities (Table 4.6) are comparable to those observed in Castelle et al. (2014a) (i.e. 0.2 – 0.8 $m.s^{-1}$). There is no obvious relationship between drifter exit speed and surf zone retention (cf. Section 4.4; Appendix B.1 & Table 4.6). This was also found to be the case in the physical model results of Castelle et al. (2011).

Generally after drifters exited the inner bar surf zone they decreased in speed to around 0.1 – 0.6 $m.s^{-1}$ (Table 4.6) with those drifters staying closer to the surf zone still influenced by the inner bar surf zone eddies and longshore current and therefore exhibiting higher velocities (Table 4.6; cf. Section 4.4; Appendix B.1). This decrease in drifter velocity after exiting the surf zone is generally consistent with all of the relevant Lagrangian drifter studies on surf zone circulation (Table 4.1).

Table 4.6: Summary of drifter exit speeds and drifter speeds seaward of the surf zone (data recorded at 1 Hz. A 30 second moving average filter applied to the raw data)

Date *(Julian Day)*	Number of 'semi-permanent' rips present at study site	Approximate range of time averaged (30 seconds) drifter exit speed ($m.s^{-1}$)	Approximate drifter speed after exiting the surf zone ($m.s^{-1}$)
30/09/2011 *(1)*	5	0.3 – 0.7	0.1 – 0.6
02/11/2011 *(34)*	2	NA	NA
29/11/2011 *(61)*	1 (mini rip) (*2 drifters in transient rip*)	0.2 – 0.5 *transient rips 0.2 – 0.5*	0.1 – 0.3 *0.1 – 0.3*
22/02/2012 *(146)*	4	0.3 – 0.7	0.1 – 0.6
26/04/2012 *(210)*	3	0.4 – 1.2	0.3 – 0.9
24/05/2012 *(239)*	2	NA	NA
18/07/2012 *(293)*	3	0.5– 1.8	0.1 – 0.4
01/09/2015 *(1433)*	4	0.4 – 0.8	0.1 – 0.6
16/10/2015 *(1478)*	4	NA	NA

On three out of the nine days of sampling wave breaking on the secondary outer bar was observed when the offshore significant wave height exceeded one metre (Table 4.2; cf. Section 4.4; Appendix B.1). A higher number of drifters were observed to exit then re-enter the inner bar surf zone under these conditions due to high wave energy beyond the inner bar that will 'push' the drifters back to shore. No drifters exited beyond the outer bar on these days.

Drifters exiting the surf zone at a shore-normal angle were observed to travel further offshore than those exiting on an oblique pathway (e.g. Figure 4.1 - Figure 4.3; Appendix B.1). Those exiting on an oblique pathway were more likely to be returned to the inner bar surf zone under the onshore forcing mechanisms of the semi-enclosed surf zone vortices (MacMahan et al., 2010a). The observed relationship between rip alignment and surf zone re-entrance is consistent with MacMahan et al. (2010a) who showed that the chance of re-entrance decreased with increasing distance offshore which is achieved for more shore-normal rip alignment.

4.7. Implications for Beach Safety

As mentioned previously any study concerned with surf zone currents and in particular rip currents will have inherent implications for beach safety and hazard management. The following section will discuss the observations made on the Gold Coast open beaches in terms of hazards to bathers and compare these results / ideas with the more detailed literature of McMahan et al. (2010), Miloshis and Stephenson (2011), McCarroll et al. (2014a) and Scott et al. (2014).

4.7.1. Alongshore Current Dominant Circulation

Whilst *alongshore current dominant* conditions have been shown to have high rates of surf zone retention (> 90%) both in the present study and in the literature (cf. Section 4.4.1) current velocities can be quite strong (cf. Section 4.4.1; Table 4.5), thereby moving swimmers from shallow bars into deeper troughs / rip channels rapidly. In saying this drifter studies (e.g. Scott et al. (2014) and the present Gold Coast study) have shown that bathers will travel shore-parallel with the meandering current and for

the most part end up on the beach / and or a shallow sand bar downdrift. The 'escape' strategies a swimmer may employ in such situations is to 'relax and float' with the prevailing longshore current until beaching on a shallow sand bar or the beach. When strong *alongshore current dominant* conditions are present, the lifesavers will often place the flags updrift of a sand bar, so if bathers are to be swept along with the current they will be 'pushed' on to the sand bar instead of into a deep trough or rip channel. Occasionally cross-shore flows will move bathers offshore (cf. Section 4.4.1), which conflicts with the 'relax and float with the current' technique.
Alternatively these conditions should provide reasonable circumstances for experienced bathers to swim toward the shore, in the direction of the longshore current. Swimming against the longshore current is difficult under the best circumstances and would 'tire' out a swimmer until they could no longer keep afloat. This 'swim back to the shore' strategy contradicts the traditional educational advice for rip currents and the average person, regardless of swimming ability, may not be equipped to determine if conditions are suitable to adopt this strategy. This sentiment has most recently been published in Leeuwen et al. (2015).

4.7.2. **Rip Current Dominant and Meandering Circulation**

The present study has observed moderate rates (~ 59%) of drifter retention in the surf zone under *rip current dominant* and *meandering current dominant* circulation patterns (cf. Section 4.4.2). The moderate number of drifter exits works as a proxy to show that these conditions can be extremely hazardous to bathers, moving floatsam beyond the inner bar zone, into deep water.

Most of the debate in the literature around surf zone circulation and hazards has focused on *rip current dominant* and *meandering current dominant* conditions. MacMahan et al. (2010a) argued that only 10 - 20% of the time bathers will exit the surf zone under these circulation conditions, with bathers / drifters on average completing a revolution of the rip circulation and returning to the beach or shallow bar in less than 10 minutes. Their study argued that the best strategy for bathers was to 'relax and float' with the current and wait until they return to the shallow nearshore, where they can stand. They argued against the 'swim parallel to the shoreline' escape strategy as they believe half the time swimmers will swim the 'wrong' way against the strong feeder current, which is difficult and tiring. Miloshis and Stephenson (2011) used human drifters to assess escape strategies of swimmers from rip currents. In agreement with MacMahan et al. (2010a), Miloshis and Stephenson (2011) found that 75% of the time the 'relax and float' strategy was the successful strategy to employ when caught in a rip current, as swimmers would eventually end up on a nearby shoal or on the beach.

McCarroll et al. (2013a; 2014a) went further by testing several 'escape strategies' under *rip current circulation* patterns. These studies deployed 'human' drifters in rip currents and mapped their movements with GPS units. Escape strategies employed by the human drifters included: floating with the current, or swim parallel to the beach (perpendicular to the rip current) in both the northerly and southerly direction. Results were quantified as either a positive (i.e. high chance of escaping rip current to safe location) or negative (i.e. greater potential for hazard). It was concluded that under beach rip circulation patterns, neither the 'relax and float' nor 'swim parallel' strategies were more likely to result in a positive outcome than the other. Floating was found to be a longer duration, more variable escape strategy (mean duration = 3.8 min, standard deviation = 2.4 min), than swimming parallel (mean duration = 2.2 min, standard deviation = 1.0 min) (McCarroll et al., 2014a). The study did agree with MacMahan et al. (2010a) finding that swimming parallel may be risky due to potential for bathers to swim against the longshore current. This was described as a failed attempt to employ the 'swim parallel' strategy. It did acknowledge however that the 'floating' technique is not a superior escape strategy under all conditions due to surf zone exits (McCarroll et al., 2013a; McCarroll et al., 2014a).

From the literature and the results of the Gold Coast drifter study it is difficult to determine a superior escape strategy for *rip current* and *meandering current* circulation patterns on the Gold Coast open beaches.

4.7.3. **Terrace beach / inner bar**

Terrace beach state conditions and associated transient rip currents and mini rip currents have previously not been studied in the scientific literature in terms of beach safety. The *terrace beach / inner bar* conditions were found to have the highest rate of surf zone drifter exits per rip entry (i.e. 56%). Whilst there is a greater chance for bathers to be taken offshore into deep water when caught in a rip under these conditions, the currents are limited in their longshore and offshore extents (Figure 4.3) and in terms of transient rips are temporary (lasting on the order of minutes) (cf. Chapter 5). As a result bathers should not be taken too far offshore before the current dissipates and experienced swimmers should be able to return to the surf zone once the current has terminated. This supports the 'relax and float' escape strategy for experienced swimmers under these conditions. Again unfortunately inexperienced swimmers are likely to 'panic' if they are taken offshore and expel excessive amounts of energy trying to re-enter the surf zone.

Whilst rip currents under these conditions were shown to remain inshore of the outer bar they are hazardous to bathers as they can move swimmers from shallow to deep water rapidly.

4.7.4. **Summary**

From the observations made in the present Gold Coast study and the literature it is obvious that the rip current hazard is complex and highly variable. As a result it is argued that a single escape strategy safety message for all conditions is inappropriate (McCarroll et al., 2014a). Instead, a combined approach and scenario-specific safety advice should be considered by beach safety practitioners to promote to the public (McCarroll et al., 2014a).

From an analysis of the results of the Lagrangian drifter study in this thesis and reviewing of the literature, *rip current dominant conditions* and *meandering current conditions* appear to provide a more hazardous beach environment, than *alongshore current dominant*, as bathers are more likely to be taken offshore beyond the edge of the surf zone under these conditions. *Terrace beach conditions* are hazardous as short-lived rip pulsations may move bathers unexpectedly from shallow to deeper water rapidly. During these conditions mini rips are hard to identify and transient rip formation is typically random, and thus it is difficult to mitigate the risk to swimmers.

McCarroll et al. (2014a) note that the presence of the longshore current and how it interacts with the rip cell circulation is important for beach safety. This idea is supported in the present Gold Coast study. Both the present study and McCarroll et al. (2014a) suggest that it is important for experienced swimmers to know how to recognise which direction the longshore current is flowing.

Under different conditions, different escape strategies are available to bathers. These escape strategies however are limited to experienced or 'strong' swimmers, with inexperienced bathers more than likely to get into dangerous situations regardless. For inexperienced bathers it is highly recommended to stay in shallow waist deep water and swim at patrolled beaches in the 'flagged areas' during patrol hours.

Alternatively from a management point of view, McCarroll et al. (2014a) argues that due to the complex and highly variable nature of surf zone circulation patterns, public education campaigns should focus on the strategy that works in favour of the swimmer in all situations. The majority of rip current studies concerned with beach safety (MacMahan et al., 2010a; Miloshis and Stephenson, 2011; McCarroll et al., 2014a) support the 'do nothing' or 'relax and float' escape strategy. This strategy conserves the most energy and more importantly does not hinder survival in an environment where decisions can be critical, such as, when a longshore current is operating (McCarroll et al., 2014a).

4.8. **Conclusions**

This chapter presents GPS drifter observations on a microtidal, wave dominated, double bar, open coast beach with no bounding headland morphology.

The surf zone circulation patterns on the Gold Coast open beaches were initially described in the context of the simplified open beach circulation classification model presented by MacMahan et al. (2010a) (cf. Sections 2.5 & 4.1). As with previous Lagrangian drifter studies *rip current dominant* circulation patterns were found to be characterised by large scale, semi-enclosed, surf zone eddies on the order of surf zone dimensions (~150 – 200 m) and *alongshore current dominant* patterns were characterised by sinuous shore-parallel flowing drifter pathways. Also in agreement with previous drifter studies, low alongshore exchange of drifters was found between adjacent rip current systems under *rip current dominant* circulation, whilst large alongshore exchange of drifters was found under *alongshore current dominant* conditions. *Terrace beach* conditions did not display semi-enclosed surf zone eddies with offshore directed currents (generally obliquely angled) taking the form of mini rips and transient rip currents.

In contrast to previous drifter studies, which displayed circulation patterns that fit well within the MacMahan et al. (2010a) model, drifter pathways in the present study highlight the complex nature of surf zone hydrodynamics and circulation on the Gold Coast open beaches. Surf zone circulation patterns were observed to be highly variable due to a range of tidal, wave, wind and morphological conditions and could be seen to vary as conditions changed through a day of sampling. The main driving mechanism for the variable circulation patterns observed on the Gold Coast open beaches are proposed to be the dynamic wave climate (e.g. often bimodal and bidirectional: Jackson et al., 1997; Short, 2000; Strauss et al., 2006), dominant oblique angle of wave approach, skewed bar and rip morphology and wide variety of double bar beach state combinations.

An interesting result from the study is that *rip current dominant* circulation (including surf zone eddy formation) and *alongshore current dominant* circulation patterns appear to be predominantly controlled by peak wave direction (i.e. angle of incoming wave approach) as opposed to wave height and period. This has been studied and observed on the Gold Coast open beaches in terms of morphology (Garnier et al., 2009, Strauss and Tomlinson, 2009, Price and Ruessink, 2011) and is presented here to explain surf zone current circulation patterns. Oblique wave approach will lead to a longshore current, which when strong enough was found to over-ride the cross-shore (offshore) rip current forcing, even in the presence of strong rip channel morphology. *Rip dominant* circulation was also observed to occur when wave approach angle was relatively shore-normal. Bathymetry and beach state also appear to control circulation patterns and morphodynamic coupling of the large-scale surf zone eddies.

Alongshore current dominant conditions were found to have 97% drifter retention for drifters entering a rip current (i.e. a 3% exit rate), which is consistent with the results of MacMahan et al. (2010a) on an open coast, meso-macrotidal beach (e.g. > 90% retention). As drifters may act as a proxy for bathers it is expected that bathers will rarely be carried offshore of the inner bar surf zone under these conditions (i.e. < 10%

of the time). One drifter was found to exit the inner bar surf zone on an oblique pathway, resulting in a higher possibility of surf zone 're-entry' due to wave breaking on the edge of the inner bar.

Drifter exit rates *under rip current dominant* and *meandering dominant* surf zone circulation conditions (41%) were found to be higher than those recorded in MacMahan et al. (2010a) on three open coast beaches in a meso-macrotidal environment (e.g. 10 – 20%). These higher rates of surf zone exits are in contrast with these previous field studies, which suggest that a floater will return to the shallow sand bar or beach 80-90% of the time (MacMahan et al., 2010a). In saying this, the percentage of drifters exiting the surf zone after entering a rip current in the present Gold Coast study was less than 50% for these conditions, suggesting that surf zone retention is still dominant. In comparison to the present Gold Coast study, higher drifter exit rates have been recorded on both a microtidal, embayed beach (McCarroll et al., 2014b - e.g. up to 80% in a headland rip) and a macrotidal open coast beach (Scott et al., 2014- e.g. up to 73%).

Terrace beach / inner bar conditions with minimal topographic non-uniformity alongshore, lead to a state where mini rip currents and transient rip currents are present in the surf zone. Exit rates of drifters under *terrace beach / inner bar* conditions (56%) were similar to the higher end of *rip current dominant* (55%) exit rates.

A comparison of cross-shore exchange of Lagrangian drifters between the present Gold Coast study and the literature (cf. Table 4.1) reinforces the sentiment that surf zone retention is not necessarily high or low due to rip current circulation but will vary due to a variety of wave, tide, wind and morphological parameters. This thesis supports this conclusion by observing a significant amount of variability in cross-shore exchange of floatsam (i.e. drifters) under different beach states and circulation patterns.

In accordance with McCarroll et al. (2014b) it is suggested that the non geological bathymetric controls that may influence the observed moderate exit rates of drifters on particular days (Table 4.2) may include:

- Reduced morphodynamic coupling; due to a range of factors including (but not limited to):

- Lower than average wave heights (and reduced wave breaking beyond the rip channels)
- Planar beach / bar morphology
- Narrow surf zone
- Characteristic strong longshore current and skewed rip channel morphology due to a dominant shore oblique wave climate

• Presence of rip head bars

The influence of the highly variable wave climate (i.e. bimodal, bidirectional and oblique) and lack of headland control on rip current circulation (cf. Section 4.1; Table 4.1) are proposed to be the major driver of reduced morphodynamic coupling and therefore higher rates of drifter exits than those observed in the MacMahan et al. (2010) study. As drifter exits were often characterised by a cluster of drifters exiting offshore at the same time it is also suggested that low frequency pulsing of the wave-driven currents, may lead to temporary ejections of water, sediment and floatsam.

The drifter data also highlights the cross-shore and longshore components of velocity in the surf zone. In accordance with previous Lagrangian drifter studies (Table 4.1) the highest peak drifter velocities are attributed to waves and rip current pulsing in the cross-shore and obliquely incident waves and pulsing of the longshore current in the longshore direction. Consistent with MacMahan et al. (2010a) drifter velocities reach a maximum in the middle of the surf zone and then tend to decay to the outer edge of the surf zone and further once drifters have exited beyond the edge of the inner bar.

Chapter 5. Transient rip currents: a remote video-imaging study

5.1. **Introduction**

Transient rip currents are known to vary in location and occurrence making them hard to predict and monitor. As the features are short-lived it is difficult to quantify their formation, location, persistence, geometry, rip growth rate, flow direction and termination using traditional field methodology including Lagrangian drifter techniques (cf. Section 3.5.1). Brander and MacMahan (2011) state that whilst there is a solid basic understanding of rip-flow behaviour in semi-permanent rip systems, more Lagrangian and Eulerian research is needed to study different types of rip systems such as transient rips under differing wave energy and tidal regimes.

Very little research has previously dealt with the transient rip current phenomena on an open coast beach (cf. Section 2.8.1). To date the only studies attempting to quantify transient rip geometry and current velocities have involved GPS-enabled Lagrangian drifter methodologies (e.g. Johnson and Pattiaratchi, 2004b; Castelle et al., 2014a) and numerical modelling (e.g. Murray et al., 2003; Johnson and Pattiaratchi, 2006). Whilst conventional Eulerian measurements can be used to capture relatively fixed surf zone currents (e.g. alongshore current, semi-permanent rips), they are essentially ineffective in capturing transient rip currents as they rely on a transient rip occurring within the field of a fixed array of current meters. Lagrangian studies of transient rip currents tend to be ‘opportunistic’ as a drifter has to be in the right place when a rip begins to form, or be deployed directly into the rip at the first sign of the current forming. This chapter aims to build on the database of transient rip currents by using remote video imagery to quantify transient rip current characteristics due to the strong visual clues such as turbulent broken water and suspended sediment (cf. Section 3.5.3).

Remote sensing techniques, such as the use of video data, are becoming more common in the study of surf zone hydrodynamics. The key advantage of using remote-video monitoring techniques is that they allow for the collection of large amounts of data relatively easily, and data can be obtained from a large temporal and spatial domain (Power et al., 2011). To date only a handful of studies have utilised remote sensing techniques to observe and quantify rip current geometry and dynamics (Lippmann and Holman, 1989; Lippmann and Holman, 1990; Ranasinghe et al., 2004; Holman et al., 2006; Turner et al., 2007; Slattery et al., 2011; Haller et al., 2013; Castelle et al., 2014a) and as such remote sensing of rip currents remains an evolving science. Slattery et al. (2011) and Castelle et al. (2014a) are the only studies to have used video imagery to characterise transient rip currents but their analyses were limited to qualitative descriptions of events, frequency of occurrence and duration.

5.1.1. **Aims**

This chapter aims to contribute to the knowledge base on a poorly understood surf zone phenomena. The chapter also aims to test new statistical and video techniques for measuring and analysing transient rip currents. The specific objectives of the chapter are:

(1) Quantify transient rip activity, duration and occurrence, via remote video techniques;
(2) Statistically test for transient rip occurrence against a range of environmental parameters in order to determine if there are any environmental conditions under which transient rip occurrence may favour;
(3) Quantify the location, spacing, mobility, rip growth rate, and geometry of transient rip currents, via remote video techniques.
(4) Qualitatively assess the impact of the video-imaging experiment findings to beach safety on wave dominated, double bar, open coast beaches.

Whilst there is very limited field data and observations on transient rip currents in the literature, it is believed that their formation and behaviour are driven by localised hydrodynamic forcing at gravity wave to wave group frequencies. It is therefore hypothesised that transient rip behaviour on wave dominated, double bar, open coast beaches (e.g. present study) will be comparable to previous studies on single bar beaches (e.g. Johnson and Pattiaratchi, 2004b; Slattery, 2010; Castelle et al., 2014b). It should be noted however that few quantitative measurements of transient rip currents have been undertaken in the past and therefore the rip geometry measured using video-image techniques in this thesis are a first in the field.

5.1.2. **Outline**

The Chapter is structured as follows. Initially the approach undertaken for the remote-video assessment of transient rip characteristics is described and the study site for the experiment reintroduced. Secondly transient rip current activity, duration and temporal spacing are quantified via remote-video observations. The influence of several key hydrodynamic and morphodynamic parameters: i.e. *beach state, averaged wave and wind parameters, breaker type, 'sea state', outer bar activity and tidal stage*, on transient rip occurrence are then discussed in detail. The physical characteristics of transient rip currents: i.e. *rip geometry, rip migration, rip location and spacing, and rip growth rate* are then quantified from the remote-video dataset. After which the influence of transient rip currents on the bathymetry of the Gold Coast open beaches is explored. Finally the implications of the remote-video analysis of transient rip currents on the Gold Coast open beaches in assessed in terms of bather safety.

5.2. **Approach**

5.2.1. **Overview**

This chapter extends the use of video imagery to measure transient rip characteristics. Initially the chapter seeks to explore transient rip formation, activity and duration under a variety of beach state, wind, wave and tidal conditions. In this chapter both simple parametric and more complex multivariate statistical tests are used to assess likely conditions which may favour transient rip development. Whilst this study focuses on possible conditions under which transient formation may increase, some inferences are made into possible forcing mechanisms of the rip currents, based on the theoretical frameworks outlined in Chapter 2 and other field observations in the literature. Through the use of rectified and geo-referenced images transient rip geometry, rip growth rate, migration, spacing and location of occurrence can be quantified. The details of the methods used in this chapter have previously been presented in Section 3.5.

The results of the video-imaging analysis on transient rip currents will be compared with a long-term video-imaging study conducted by Turner et al. (2007) on semi-permanent beach rip currents at the same study site. This is done in order to assess the role of transient rip currents in the context of overall rip current dynamics observed on the Gold Coast open beaches. The study of transient rip currents has implications for sediment transport, surf zone flushing and beach safety. As such implications for beach safety will also be addressed at the end of this chapter.

5.2.2. **Study site**

The Main Beach – Narrowneck study site was utilised for the remote-video study of transient rip currents (cf. Section 3.2.2).

5.3. **Transient Rip Activity and Occurrence**

5.3.1. **Rip Activity**

A transient rip signal was present for 4.17 hours out of the total 799 hours of video analysed for transient rip activity (Table 5.1). Transient rip currents were observed to occur for 0.5% of the video-dataset (Table 5.1). Approximately 2 rips were observed per kilometre per day, with low levels of transient rip activity (RA) for the duration of the study period (Table 5.1). Rip activity (RA) is defined as the sum of rip current duration (hr) per length of shoreline (km) divided by the total time of observation (hr).

Table 5.1: Transient rip activity statistics

Observations	Measurement
Video observed for Rip Activity (hr)	799
No. Individual Transient Rip Events	193
Frequency (%) of Transient Rip Signal Evident in Video	0.5
Rips / km / day	2.2
Rip Activity (n = 233) (km^{-1})	0.0047

Low rip current activity and rip occurrence (Table 5.1) is consistent with results of Slattery (2010), who measured rip activities (RA) of 0.00144 (km^{-1}) and 0.465 (km^{-1}) at two study sites on Long Island New York. Slattery (2010) observed over 1000 hours of remote-video to identify and characterise the appearance and activity of transient rip currents on a large stretch of coast on Long Island, New York. Long Island is a 190 km stretch of mostly continuous coastline cut by seven inlets (Slattery, 2010; Slattery et al., 2011). As with the Gold Coast the Long Island beaches are microtidal and present a similar wave climate with average wave conditions around 1 m with peak wave periods of around 7 s (Slattery, 2010; Slattery et al., 2011). Maximum wave heights of around 3.5 m with periods of 12 – 14 s occur during storm conditions (Slattery, 2010; Slattery et al., 2011).

Slattery (2010) also found transient rip currents persisting for less than 1% of the time in their video dataset, at both locations, which is consistent with the present Gold Coast study (Table 5.1). One of the sites on Long Island observed two rips per kilometre per day occurring, which is consistent with this study, whilst the other site observed 13 rips per kilometre per day. The larger RA and rips per kilometre at one of the sites in Slattery's study, coincided with a slight preference of location of the rip currents. Slattery (2010) suggested that some sort of bathymetric control was most likely playing a controlling influence on transient rip activity and location at that particular study site.

Two previous studies of transient rip currents on alongshore planar, open coast beaches (e.g. Murray et al., 2003; Slattery, 2010) found RA to decrease with increasing beach slope approaching zero, when beach slope is greater than 0.3. Beach slope used in the present Gold Coast study was evaluated using the beach and surf zone profile between 3 m and - 3 m AHD. The beach slope at the Gold Coast study site was calculated from the average profile taken from 37 surveys at a permanent survey line located at Narrowneck (cf. Figure 3.2), between 1987 and 2010. Average beach slope over this time was calculated to be approximately 0.03 and corresponding transient rip current activity was very low (Table 5.1). The results of RA for the Gold Coast study therefore fit in with the theoretical predictions made by Murray et al. (2003) and field experiments conducted by Slattery (2010). Murray et al. (2003) argue that the mechanism driving this low transient rip current activity is that a narrow surf zone would create weaker rip currents that form less readily and are more easily terminated.

Slattery (2010) argues that low RA supports the edge-wave driven system as the forcing mechanism for modulating the incoming wave field and thus along-crest variability in wave breaking. Slattery (2010) used a seismometer to measure infragravity wave energy in the nearshore zone. Wave spectra were analysed for the time periods during which transient rip currents were observed. A range of spectral peaks were captured by the seismometer, generally falling between 0.33 Hz (3 seconds) and 0.067 Hz (15 seconds) and less than 0.05 Hz (20 seconds) (Slattery, 2010). Spectral peaks at frequencies of long wave energy (<0.05 Hz) were common but not ubiquitous at one of the two sights (Slattery, 2010). Whilst these infragravity waves were detected seismically, an association with rip current occurrence was inconclusive (Slattery, 2010). Slattery (2010) argues that due to incident wave parameters not having a significant and explainable effect on transient rip generation and low levels of RA captured, along with the presence of infragravity peaks in the seismic record; that this evidence possibly supports a relationship between edge waves and breaking nearshore wave conditions in the generation of transient rip currents. The Gold Coast study found low RA but did not investigate *in situ* spectral wave data with the dataset. It is proposed that further investigation into low frequency wave motions and the interaction between long waves and the incident wave field should be explored to assess the fundamental driving mechanisms of transient rip currents.

The low levels of transient rip activity are in contrast to the presence of semi-permanent beach rip currents at the Gold Coast study site, which were observed 68% of the time in the daily remote-video database (~543 hours out of 799 hours). A three year daily video-observation study conducted by Turner et al. (2007) at the same site found semi-permanent beach rip currents to be present on 684 of their 947 day sampling period (i.e. 72%). These results highlight the fact that semi-permanent beach rip currents are the most common type of rip current observed on the Gold Coast open beaches and dominate the rip current forcing over transient rip currents.

5.3.2. **Rip Duration**

An average rip duration of 83 s was recorded with a large standard deviation of the mean (Table 5.2). Modal duration was 60 s and no rips lasted longer than 236 s (Table 5.2). 56% of transient rip currents identified lasted between 60 – 90 s with only 3% lasting between 180 to 240 s (Figure 5.1). Slattery (2010) measured similar average (47 and 76 s), maximum (150 and 180 s) and minimum (20 and 30 s) rip durations at their two study sites. Castelle et al. (2014a) also recorded transient rip durations of between 2 – 5 minutes, on an open wave dominated and microtidal beach, which is consistent with the results of the present Gold Coast study (Table 5.2). Transient rip currents were observed to pulse both once or multiple times during their evolution. By finding these repeatable results throughout the limited literature it has been shown that transient rip currents are temporary features that have a life-span on the order of tens of seconds to minutes before dissipation and termination. This is in contrast to semi-permanent rip current durations observed at the Gold Coast study site in Turner et al. (2007). Their study observed the majority of semi-permanent rip currents to persist for five or fewer days, but with a strongly skewed distribution resulting in an average of eight days and standard deviation of nine days.

Table 5.2: Transient rip duration statistics

Observations	Measurement
Video Observed (hr)	1029
Individual Transient Rip Events	233
Average Rip Duration (s)	83
Modal Rip Duration (s)	60
Minimum Duration (s)	30
Maximum Duration (s)	236
Standard Deviation (s)	33

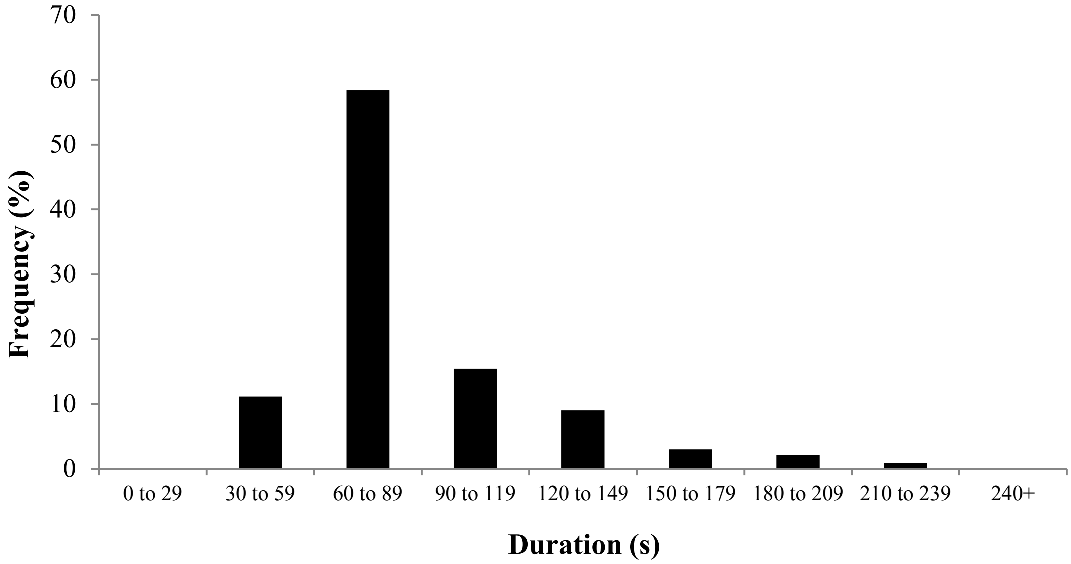


Figure 5.1: Frequency distribution (%) of transient rip duration (n = 233)

5.3.3. Temporal occurrence of transient rip currents

There was significant variability in temporal occurrence of the transient rip currents with consecutive rips observed to form between 20 seconds and 7.5 hours apart (Table 5.3). Approximately 20% of the time, multiple rips were observed to form simultaneously (Table 5.3) and generally exhibited similar durations. Slattery (2010) very rarely observed multiple rip currents to occur simultaneously at their study sites on Long Island, New York. The low frequency average temporal rip spacing reinforces the low levels of rip activity observed in the video (cf. Section 5.3.1). 80% of transient rip currents observed occurred as an individual event (Table 5.3).

Table 5.3: Daily statistics of temporal spacing of transient rips (n = 193)

Observations	Measurement
Maximum time between rips (daily) (hr)	7:28:30
Minimum time between rips (daily) (hr)	0:00:00
Minimum time between rips (> 0) (daily) (hr)	0:00:20
Average time between rips (daily) (hr)	0:35:10
Standard deviation of time between rips (daily) (hr)	1:02:52
Rips occurring simultaneously (% of total)	20%

5.3.4. **Influence of beach state**

Transient rip currents were identified forming off the shore-attached bar, with the offshore bar(s) ignored as it is too difficult to resolve small scale topographic non-uniformities on the offshore bar(s). If the inner bar was not shore-attached i.e. in a Rhythmic Bar Beach (RBB) state, the shore-attached bar or beach was always in a terrace state (even when displaying slight rhythmic morphology) and transient rips were identified off the beach terrace. During periods of transitional TBR/RBB morphology transient rips were identified in areas where the inner bar was shore-detached (i.e. in a more RBB state). Once again the transient rips were observed occurring off the beach terrace.

Transient rip currents were observed to favour and become more dominant under Low Tide Terrace conditions, occurring 68% of the time during these beach state conditions (Figure 5.2). As the influence of topographically controlled rip channels increases (under Rhythmic Bar and Beach and Transverse Bar and Rip beach states) transient rip occurrence tended to decrease (Figure 5.2).

Whilst transient rip currents are present, they are clearly not the dominant offshore directed current occurring on the Gold Coast open beaches, with ‘fixed’ (or semi-permanent) rip currents (channels) providing the main driving mechanism for moving water, sediment and floatsam cross-shore (cf. Section 5.3.1). Transient rip currents and topographically controlled semi-permanent rip currents were observed to coexist (Figure 5.2, Appendix C.2), with the topographically controlled currents dominating the rip current pulsing. Co-existence has also been observed to occur on a wave dominated and microtidal embayed beach (McCarroll et al., 2014b). It is important to note that the lowest number of transient rip currents occurred when the inner bar and rip morphology was shore-attached and no transient rip currents were observed under strongly formed Transverse Bar and Rip (TBR) conditions (Figure 5.2). TBR inner bar morphology was observed on 20% of the days analysed in the remote-video dataset.

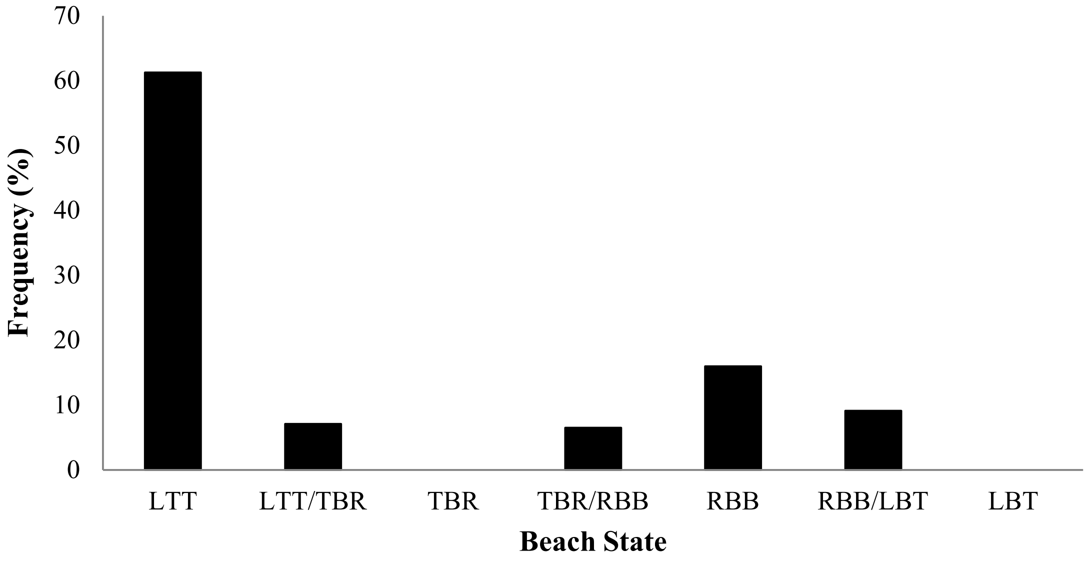


Figure 5.2: Weighted transient rip occurrence (%) vs. beach state (n = 193). The frequency of rip occurrence is weighted for the percentage of beach state occurrence.

108 hours (9 days) of video during Low Tide Terrace conditions were analysed during a 10 day period between the 20^{th} – 29th November 2011 (data for the 24/11/2011 absent). 124 individual transient rip events were identified during this period, which is 64% of the total number of rips identified during the daily video experiment (cf. Table 3.4). During this period offshore significant wave heights did not exceed 1.07 m and wave direction varied between NE-SE, with a modal ENE direction. At the same time the inner bar morphology was mostly alongshore planar. The maximum transient rip occurrence was on the 25^{th} November 2011 with 43 individual transient rips identified in the video in 12 hours of daily video recording. During this time period transient rip currents were observed to be the dominant rip current type along with mini rip channels occasionally present in the Low Tide Terrace bar/beach.

5.3.5. **Influence of averaged wave and wind parameters**

Table 5.4 displays the limits of half hourly wave recorded statistics for the study period and corresponding wave condition limits under which transient rip currents were observed to form. A comparison of simplified beach morphology: (i) bar-trough morphology and; (ii) terrace inner bar / beach morphology was also conducted. Transient rip currents forming under terrace beach conditions occurred under slightly lower incoming wave energy than under bar-trough conditions (Table 5.4). This is expected as lower wave energy conditions lead to infilling of rip channels and the more linear terrace beach states. This result is therefore more likely an indication of the wave energy conditions required to form the two different types of beach state conditions (bar-trough or terrace beach), rather than limits in forcing transient rip occurrence.

Transient rip currents were generated under peak wave directions from the NNE - SE swell conditions under bar-trough beach state conditions, whereas they formed under peak wave directions from the ENE – SE under terrace beach state conditions (Table 5.4). This is observation does appear to support other field observations explaining finite breaking crest-lengths in the surf zone (cf. Section 2.8.5.2) and wave induced vorticity. The shorter period N to NE swells do not appear to generate strong enough longshore currents to create shear instabilities under terrace conditions (cf. Section 2.8.5.1). Castelle et al. (2014a) argue that transient rip formation in the absence of a strong longshore current most likely indicates that the currents are driven by vorticity generated by along-crest variability in wave breaking as opposed to shear instabilities in the longshore current (cf. Section 2.8.5).

Table 5.4: Maximum and minimum half hourly wave buoy statistics (16 m water depth) and corresponding wave condition limits under which transient rip currents were observed to form. Recorded during the daily video study period (799 hours)

Wave statistics Limits					
	H_{max} (m)	H_{sig} (m)	Peak wave direction (º from N)	Peak wave period (T_p) (s)	Average Wave period (T_z) (s)
Upper limit	4.42	2.32	144	20	9.5
Lower limit	0.59	0.37	34	3.3	3.4
Corresponding Transient Rip Occurrence Wave Condition Limits					
	H_{max} (m)	H_{sig} (m)	Peak wave direction (º from N)	Peak wave period (T_p) (s)	Average Wave period (T_z) (s)
Upper limit	2.71	1.52	124	15.4	8.7
Lower limit	0.76	0.48	36	4.8	3.7
Corresponding Transient Rip Occurrence Wave Condition Limits for Terrace Beach State					
	H_{max} (m)	H_{sig} (m)	Peak wave direction (º from N)	Peak wave period (T_p) (s)	Average Wave period (T_z) (s)
Upper limit	2.04	1.15	121	13.3	7.3
Lower limit	0.82	0.53	62	6.3	3.7
Corresponding Transient Rip Occurrence Wave Condition Limits for Bar-Trough Beach State					
	H_{max} (m)	H_{sig} (m)	Peak wave direction (º from N)	Peak wave period (T_p) (s)	Average Wave period (T_z) (s)
Upper limit	2.71	1.52	121	15.4	8.7
Lower limit	0.76	0.48	36	4.8	3.8

No strong correlations were found to occur between transient rip occurrence and any of the half hour averaged wave or wind parameters (Table 5.5). This was also found to be true when analysing terrace (LTT and LTT/TBR); and bar-trough (TBR/RBB, RBB and RBB/LBT) beach states separately, with individual wind and wave parameters showing no significant correlation with transient rip occurrence (Table 5.5). As such, a Generalised Additive Model (Wood, 2006) was applied to further investigate relationships between environmental parameters and transient rip occurrence (cf. Section 5.3.10).

Additionally there were no strong correlations between wave power and Iribarren number (breaker type) and transient rip occurrence (Table 5.5). Again this was also found to be true when analysing terrace (LTT and LTT/TBR); and bar-trough

(TBR/RBB, RBB and RBB/LBT) beach states separately (Table 5.5). As the equations for wave power and Iribarren number are fundamentally driven by wave parameters and in the case of the Iribarren number beach slope, they are ignored for the GAM analysis. Given that there is no correlation between transient rip occurrence and any of the parameters, the r^2 values for the Log10 transformed data (only) are summarised in (Table 5.5). All the linear regression data is presented in Appendix C.1.

When analysing topographically controlled beach rip occurrence at the same study site Turner et al. (2007) also found no correlation between rip occurrence and H_{sig}, T_p and wave power.

The wind and wave data used had been averaged over 30 minute intervals, whereas the transient rip currents measured had a life time scale of the order of tens of seconds to minutes. This highlights the fact that transient rip events are more likely to be induced by short-lived spatial and temporal variations in the surf zone hydrodynamics and do not tend to favour any particular averaged wave or wind conditions. To date Slattery (2010) has conducted the only other comparison of averaged wave parameters and transient rip occurrence. Using offshore directional wave buoy data and SWAN modelling data, Slattery (2010) also did not observe any particular wave parameters to significantly favour the generation of transient rip currents.

Table 5.5: Summary of linear regression results (r^2 values) for transient rip occurrence vs. environmental parameters (Log10 transformed data). ξ = Iribarren number (representative of breaker type)

R^2 values	H_{max} (m)	H_{sig} (m)	T_p (s)	T_z (s)	Wave steepness (proxy for sea state) (H_{sig}/T_p)	Peak wave dir (º)	Wind dir (º)	Wind Speed (Kts)	Wind gust (Kts)	Wave power (kW/m)	ξ
All data (n= 193)	0.02	0.02	< 0.01	<0.01	0.02	0.03	0.12	0.01	0.04	< 0.01	0.02
Terrace Beach State data (n = 127)	0.06	0.04	0.03	0.06	<0.01	0.11	0.06	0.04	0.06	0.06	< 0.01
Bar-Trough Beach State (n= 66)	< 0.01	0.01	< 0.01	0.01	< 0.01	0.01	< 0.01	0.03	0.05	< 0.01	0.01

5.3.6. **Influence of breaker type**

All of the transient rip currents observed occurred under spilling or plunging wave conditions, with the weighted percentage of rips forming under spilling and plunging conditions approximately 50% respectively (Table 5.6). The same result was observed when analysing terrace beach states and bar-trough beach states separately (Table 5.6). These results contradict other qualitative field observations of transient rip occurrence (e.g. Vos, 1976; Castelle et al., 2014a), which suggest that transient rip formation favours plunging (or at least "more intense") wave breaker types due to the energy required to generate seaward currents and the sucking and erosive effects of such breaker types to reinforce the embryonic rip current (cf. Section 2.8.2). The power of these results however is quite low and requires further data collection for investigation. As expected the Iribarren number calculations did not return any conditions of surging or collapsing waves (n = 0) (Table 5.6). Surging and collapsing waves do not generally occur on the Gold Coast open beaches.

Table 5.6: Summary of the weighted (%) of transient rip occurrence for each breaker type (Iribarren number)

Wave breaker type	Terrace Beach Conditions (n = 127)	Bar-Trough Conditions (n =66)	All Beach States (combined data) (n = 193)
Spilling	51	51	53
Plunging	49	49	47
Surging or Collapsing	0	0	0

5.3.7. **Influence of 'sea state'**

As described in Section 3.5.5.2 model results from the nearest WaveWatch3 (NWW3) model node was used to describe the sea state during the study period in terms of the number of wave energy sources in the wave field. There was a clear negative correlation in the NWW3 data, with transient rip occurrence decreasing with an increase in the number of swell / sea sources in the water for the six hourly period of transient rip formation (Figure 5.3). 69% of transient rips occurred under swell dominant conditions (Figure 5.4). 27% of transient rips formed under wind wave dominant conditions, with only 4% of rips occurring when there was an equal influence of wind waves and longer period swell (Figure 5.4).

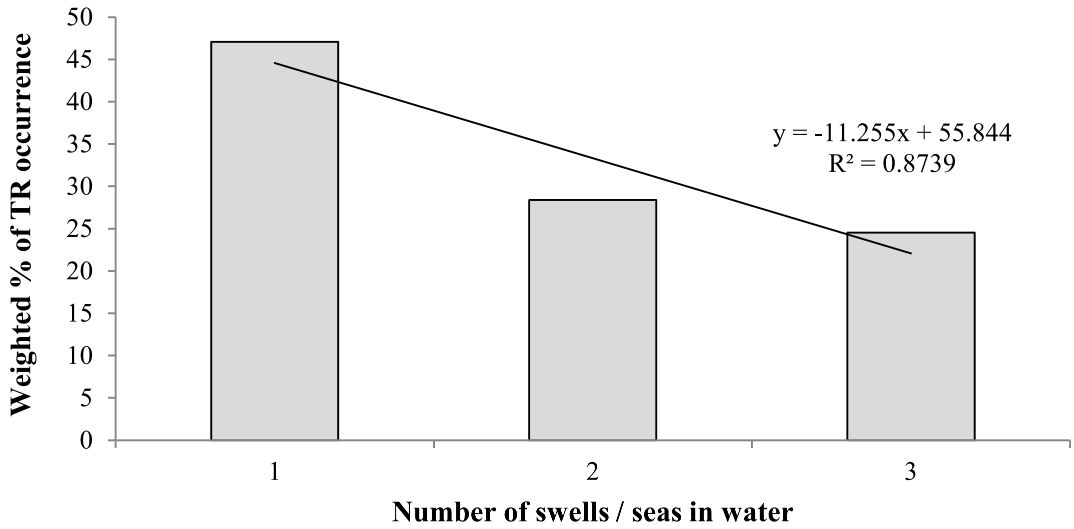


Figure 5.3: Weighted transient rip occurrence (%) vs. number of wave sources in the water (n = 193). The frequency of rip occurrence is weighted for the percentage occurrence of number of wave sources.

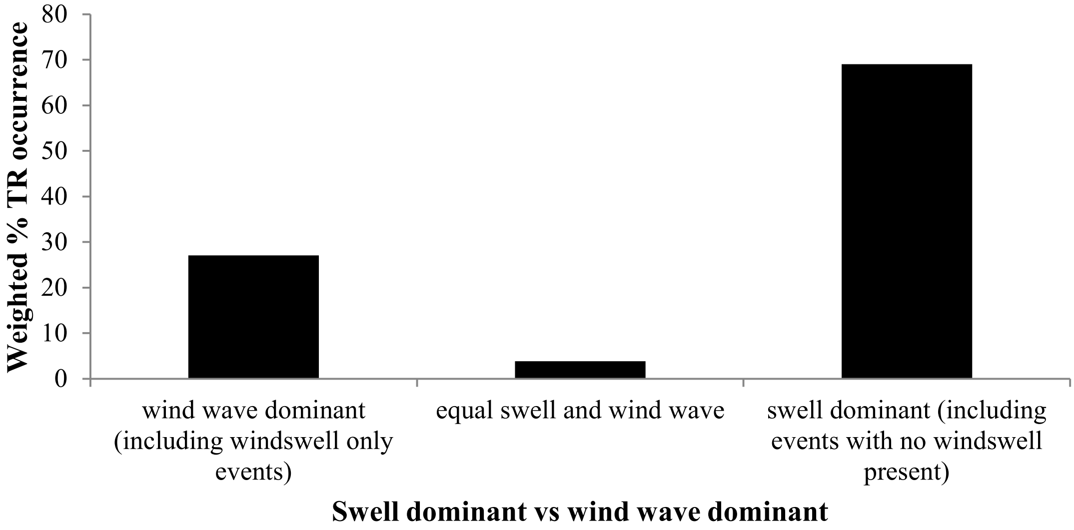


Figure 5.4: Weighted transient rip occurrence (%) vs. 'sea state' conditions (n = 193). The frequency of rip occurrence is weighted for the percentage occurrence of 'sea state' conditions.

The NWW3 data suggests that transient rip formation favours less stochastic 'sea state' conditions: occurring more often under swell dominant conditions, as opposed to wind wave dominant and wave conditions where fewer swell sources were present (Figure 5.3 & Figure 5.4). This contradicts the traditional belief that transient rip formation will tend to occur under 'confused sea states' or a highly directionally spread wave field.

Murray et al. (2003) modelled average rip current duration and rip activity on an open coast beach to decrease with increasing variation in incident wave heights. They argue that this result is due to the conditions that initiate the feedback that causes rip currents to cease, to occur more frequently. Field measurements of rip activity also confirmed their model results (Murray et al., 2003). This may aid in explaining the NWW3 observations in the present study, with rip occurrence decreasing with an increase in wave sources and thus incident wave height variability. In saying this the hypothesised drivers of transient rip currents outlined in Section 2.8.5 suggest that some sort of along-crest variability in wave breaking is necessary to induce surf zone vorticity, which can cascade up through the levels to produce a transient rip current.

As noted in Section 2.8.5.2 a number of surf zone interactions can lead to a locally directionally spread wave field and in turn along-crest variability in wave breaking. Field observations suggest that around 50% of the time transient rip occurrence on the Gold Coast open beaches is more likely driven by localised variations in the breaking waves, as opposed to multiple swell / wave sources. Wave modification by an offshore submerged sand bar; rhythms in the alongshore terrace bar/beach; wave-current interactions and; wave-long wave interactions may all contribute to along-crest variability in wave breaking under a single swell source (cf. Section 2.8.5.2). This may lead to wave breaking induced surf zone vorticity and transient rip generation (cf. Section 2.8.5.2). It is noted that ~50% of the time transient rip currents were observed under two or more swell sources, which represents a directionally spread wave field, which can drive the along-shore variability in wave breaking.

5.3.8. **Influence of outer bar activity**

To reiterate an independent (two-sample) t-test was conducted for outer bar activity (i.e. whether there was wave breaking or no wave breaking on the outer bar) to determine whether wave breaking or shoaling on the offshore bar had a significant influence on transient rip occurrence. For this statistical test, transient rip currents occurring under shore-attached terrace beach states (LTT and LTT/TBR transitional states) and bar-trough beach conditions (LBT, RBB and RBB/TBR transitional states) were also analysed separately to determine whether or not there was a difference in behaviour of occurrence under different beach state conditions.

The results of the independent t-test revealed a significant effect of outer bar activity for terrace beach states, $t(272.98) = 6.06$, $p < 0.001$ and bar-trough beach states $t(417.67) = 4.68$, $p < 0.001$, with a greater number of transient rip currents occurring when there was no wave breaking on the outer bar as opposed to when wave breaking was present.

As all transient rips recorded were measured off the shore-attached terrace / beach, this result is attributed to wave energy dissipation on the outer bar limiting transient rip formation inshore, due to a lack of significant wave energy (and wave breaking) inshore to create short-lived currents. Additionally, although there is no wave breaking on the outer bar the incoming wave field is still influenced by the bar through shoaling and refraction processes which may lead to a more variable inshore breaking wave field. This in turn would create spatial and temporal variations in wave breaking which has been proposed to drive small scale surf zone vorticity and transient currents (cf. Section 2.8.5.2). This hypothesis is supported by the finding that the majority of the transient rips forming under bar-trough inner bar surf zone morphology, occur around the high tide (cf. Section 5.3.9).

Murray and Reydellet (2001) argue that refraction over offshore bathymetry can create alongshore variations in wave height and therefore setup but at larger scales than those of topographic rip currents. They do note however that wave refraction can lead to the interaction of different wave trains to create alongshore variations in wave crest breaking, which may contribute to the forcing of transient rip currents. They do not distinguish whether offshore bathymetry is in the form of outer surf zone sand bars or other larger scale structures, such as holes, reefs, canyons etc. Price and Ruessink (2011) conducted a long term study of beach morphodynamics at Surfers Paradise and concluded that the outer bar will have a significant effect on governing the inner bar morphodynamics.

5.3.9. **Influence of tidal stage**

As with outer bar activity an independent (two-sample) t-test was conducted for tidal stage (ebb vs. flood) to determine whether there was a significant influence of the rising or falling tide on transient rip occurrence. For this statistical test, transient rip currents occurring under shore-attached terrace beach states (LTT and LTT/TBR transitional states) and bar-trough beach conditions (LBT, RBB and RBB/TBR transitional states) were also analysed separately to determine whether or not there was a difference in behaviour of occurrence under different beach state conditions.

A significant effect of tide stage was found for terrace beach states, $t(330.73) = 4.96$, $p < 0.001$, with a greater number of transient rip currents occurring on the ebb tide compared with the flood tide. Transient rip currents were found to occur throughout most of the tidal cycle under terrace beach conditions, favouring the ebb and low tide (Figure 5.5). These results are consistent with the understanding of topographically controlled rip currents. It is generally accepted in the literature that topographically controlled beach rip currents increase in velocity during falling to low water conditions due to nearshore bar morphology becoming increasingly shallow and offshore flows being confined to rip channels (Short, 2007). The tide level will also directly affect the water depths in the nearshore zone and the intensity of wave breaking, which supports the Nielsen et al. (2001) concept of rip currents responding to the efficiency of the wave pump.

As discussed in Section 2.8.7.4 a mild-sloped topographic depression in a mostly alongshore planar beach may induce significant alongshore variations in the breaking wave field (e.g. significant wave height, wave direction, directional spreading, infragravity waves, and very low frequency motions) (MacMahan et al., 2008). The results of the present Gold Coast study lend some observational support to the hypothesis that a small bathymetric perturbation on a planar terrace beach may lead to an increase in transient rip activity on the low tide. The proposed mechanism of action is: the generation of along-crest wave breaking variability due to wave-current and wave-long wave interactions, caused by the interaction of the mild-topographic depression (i.e. not a well-defined rip channel) and the incoming wave field, can lead to short-crested wave breaking vorticity and the generation of transient rip currents (cf. Section 2.8.5.2).

No significant difference was found in transient rip occurrence on the ebb or flood tide under bar-trough beach state conditions, $t(1141.98) = 0.42$, $p = 0.67$. This suggests that other surf zone hydrodynamics are more important for transient rip current forcing, when the beach morphology is in a bar and trough state. Transient rip currents during bar-trough inner bar conditions favoured the high tide and did not occur around the low tide (Figure 5.5). It is likely that the topographically controlled rip currents dominate the forcing over transient rip currents, particularly on the lower tide as the flows are more confined to the narrower channels and rip current velocities increase. This may explain the lack of transient rip currents observed under bar trough conditions around the low tide (Figure 5.5). The topographically controlled beach rip currents may be less active on the high tide, with transient rip current occurrence increasing. There is a fair amount of conjecture in these conclusions and future work on this is required to better understand the processes.

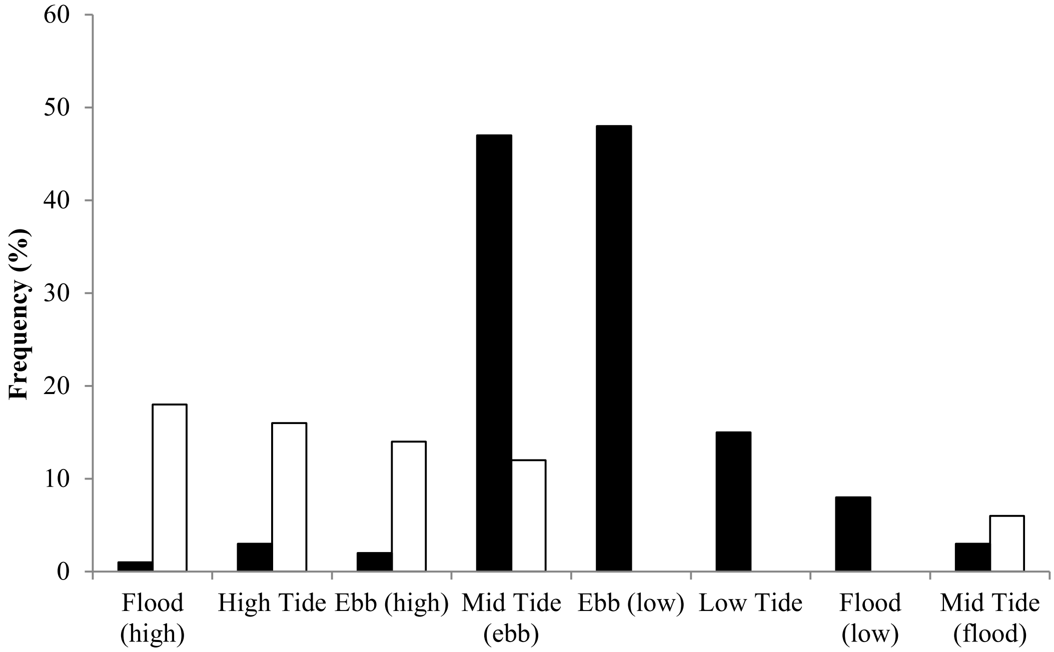


Figure 5.5: Frequency distribution (%) of transient rip occurrence for tidal stage. Terrace beach state (■) n = 127; Bar-trough beach state (□) n = 66.

5.3.10. **Generalised Additive Model (GAM) analysis for transient rip occurrence**

Surf zones are characterised by complex interactions of hydrodynamic and morphodynamic processes occurring and interacting on a variety of timescales. As simple univariate statistical models do not take into account the complex nature of surf zone hydrodynamic and morphodynamic interactions a multivariate Generalised Additive Model (GAM) analysis was conducted to further investigate relationships between transient rip occurrence and environmental parameters, such as wave, wind, tide and bar morphology.

This is first time that a GAM regression analysis has been used to analyse transient rip occurrence. This methodology provides a more robust statistical procedure to understanding the relationships between the transient rip occurrence and the suite of predictor variables tested. The flexibility (i.e. assumption of a non-normal distribution; specifying a relationship between the variance and mean of the response variable; fitting the data using thin plate regression splines) and nonparametric modelling approach of GAMs make them an appropriate method of uncovering potentially nonlinear trends in data, especially as environmental processes often generate complex data that are often multivariate in nature (Ferguson et al., 2008).

The model explained 44.1% of the deviance in the response variable with an adjusted $R^2 = 0.324$. The significant (p-value < 0.05) predictor variables were, *wind* (comprised of x and y vector components - Figure 5.6a) and *peak wave direction* (Figure 5.6b) and the parametric coefficients of *tide stage* (Figure 5.20c) and *outer bar activity* (Figure 5.6d). Of these significant variables, *tide stage* ($p = 2.7e^{-11}$) and *outer bar activity* ($p = 6.87e^{-08}$) appeared to be the most influential. Both the GAM analysis for tide stage and outer bar activity support the parametric t-tests in observing a significant increase in rip occurrence under ebb tide conditions and inactive outer bar conditions. The implications for these two significant results are previously described in Sections 5.3.9 and 5.3.8 respectively and therefore will not be discussed again here. The remaining predictor variables of *Tp* (Figure 5.6e) and *Hsig* (Figure 5.6f) were observed to not have a significant effect on the response variable. Only the significant results of *wind vectors* and *peak wave direction* will be discussed from here as the non significant results are briefly explained above in the Section 5.3.

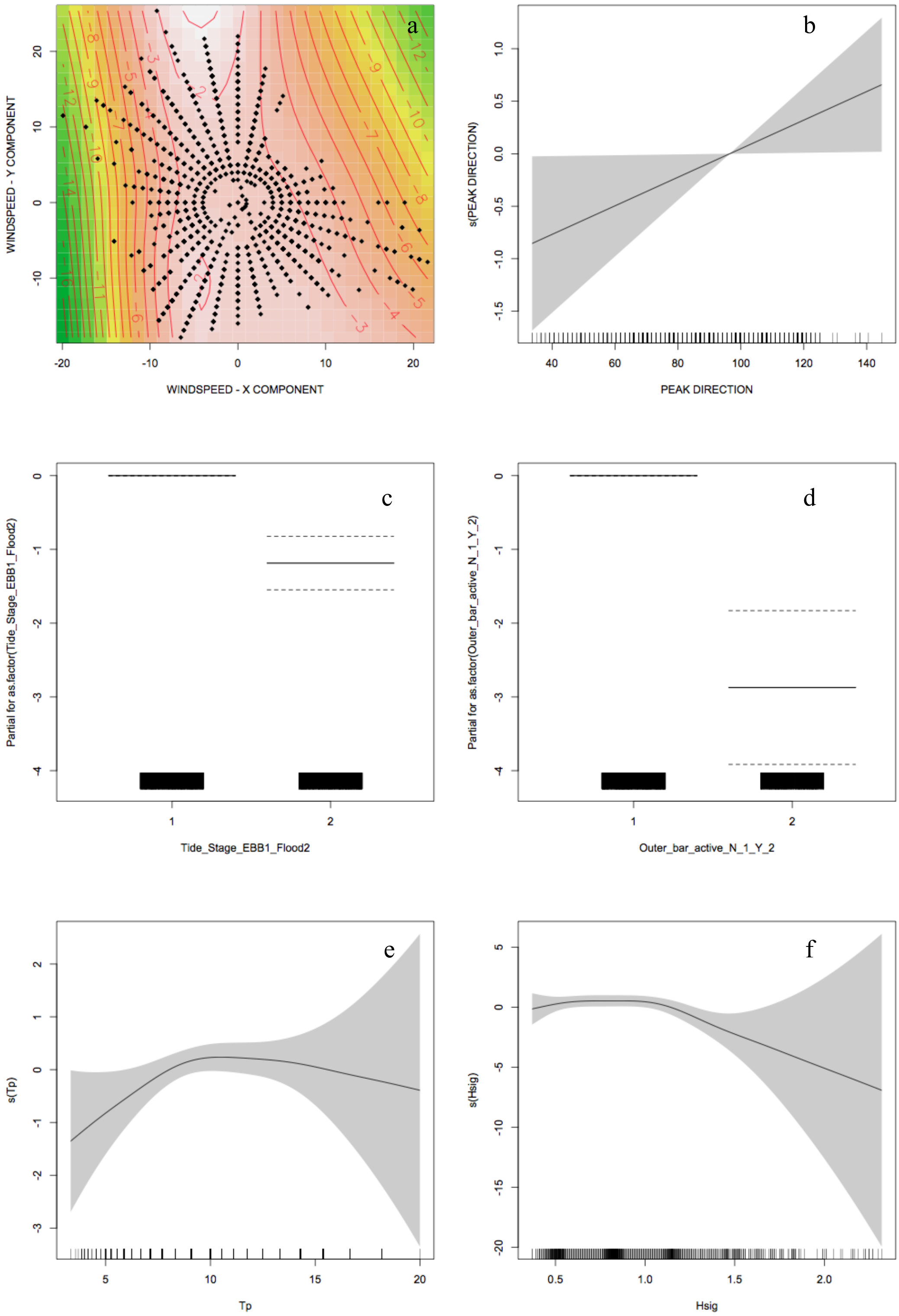


Figure 5.6: Non-parametric smoothes (a-b, e-f) and parametric coefficients (c, d) resulting from the generalised additive modelling. Note that figures a-d represent significant predictors (p-value < 0.05) while figures e-f are not significant (p-value > 0.05). 'Rug' marks on the x-axes represent data recordings.

Wind vectors

The GAM provides a slightly better statistical analysis of wind effects on transient rip occurrence than the parametric linear regression analysis. The limitation in the linear regression analysis is that wind speed and direction have to be analysed separately, whereas the GAM can combine the effects of both wind speed and direction together on the response variable (i.e. transient rip occurrence) providing a more realistic interpretation of the effects of wind on transient rip occurrence.

The GAM analysis suggests that transient rip occurrence significantly decreased as wind speeds increase along the x-vector (i.e. cross-shore) in both the east to west (i.e. onshore) and west to east (i.e. offshore) direction. There appears to be little influence from the *y-vector component* of the wind (i.e. longshore).

Moderate to strong onshore winds may promote the generation of sea swell or secondary period swell, which has been shown to decrease the likelihood of transient rip formation (cf. 'sea state' results outlined in Section 5.3.7). Strong offshore winds are also rare on the Gold Coast, which may account for the low numbers of transient rips observed during these conditions. Secondly light winds help to promote plunging breaker types in nature which have been qualitatively observed, but not quantified, to favour transient rip formation (Vos, 1976; Castelle et al., 2014a). The present Gold Coast study did not observed transient rip current formation to favour any 'breaker type' (cf. Section 5.3.6) but types of wave breaking were calculated statistically using the Iribarren number (equation 3.5) and not qualitatively tested for as the camera position (e.g. ~100 m above sea level) was too far away from the breaking waves to resolve this information accurately.

Peak wave direction

The GAM smoother for peak wave direction indicates that transient rip occurrence increases as wave direction increases (i.e. from N to S) (Figure 5.6b). Whilst it has been previously hypothesised that a stochastic sea state may lead to the increased transient rip occurrence (e.g. Dalrymple et al., 2011), studies performed on near planar, alongshore uniform beaches and boussinesq modelling of transient rip currents have found that transient rip activity is greatest in a swell type wave field with narrow directional spreading and longer peak wave period (Murray et al., 2003, Johnson and

Pattiaratchi, 2006). SE swells on the Gold Coast tend to be longer period with narrow directional spreading, whereas the NE to E swells tend to be shorter period, 'messier' seas. This result in some sense tends to act as a proxy for what is observed in the literature and backs up the NWW3 results with transient rip formation favouring less stochastic sea states (cf. Section 5.3.7). It is important to note the large variance in Figure 5.6b (indicated by the grey bands) and overall poor performance of the model.

The directional spectrum of the incoming wave field is often bi-modal (i.e. swell from one direction and sea from another) and the peak wave direction recording is simply the swell or sea with the biggest peak in energy (even if there may be significant energy from another source). The sea state leading to transient rip formation may in fact be bimodal and this is not deduced from the waverider buoy for GAMs analysis. This was further explored by using Wave Watch III data as a proxy for sea state (Section 5.3.7), however it is proposed that a spectral analysis of *in situ* wave data and transient rip occurrence, will better explain this relationship.

The key characteristics of the significant predictor variables can therefore be summarised as follows:

- Wind (Figure 5.6a) - this interacting smoother, which is comprised of two predictor variables (i.e. the *x- and y-vector components*), indicates that transient rip occurrence decreases as wind speeds increase along the x-axes (i.e. cross-shore), regardless of whether the wind is from the east (*x-vector component* of wind > 0) or the west (*x-vector component* of wind < 0). There appears to be little influence from the *y-vector component* of the wind (i.e. longshore).
- Peak wave direction (Figure 5.6b) - characterised by a positive and linear effect on the response variable (i.e. transient rip occurrence increases as peak wave direction goes from N to S).
- Tide stage (Figure 5.6c) - this factor predictor variable indicates that there is significantly higher transient rip current occurrence during the ebb tide compared to the flood tide.
- Outer bar (Figure 5.6d) - factor predictor variable indicates that transient rips are significantly more likely to occur when wave breaking on the outer bar is absent.

5.4. Physical Characteristics of Transient Rip Currents

5.4.1. Transient rip geometry: length and width

Quantitative analysis of the spatial rip current length scales confirms qualitative descriptions of transient rip currents both in this present study (cf. Section 3.5.3) and the literature (cf. Section 2.8). Rip necks are the narrow, jet-like features which extend offshore and terminate in a rip head where sediment dispersal and settling occurs. 85% of the rip necks measured were between 5 to 15 m wide (Figure 5.7). Only one rip neck was recorded that was greater than 20 m wide, however this was the result of two individual transient rips merging together (Figure 5.7). Johnson and Pattiaratchi (2004b) also found the rip neck region to have short length scales (i.e. 20 – 30 m) during their drifter studies on a low energy, single bar, open ocean beach (cf. Table 4.1).

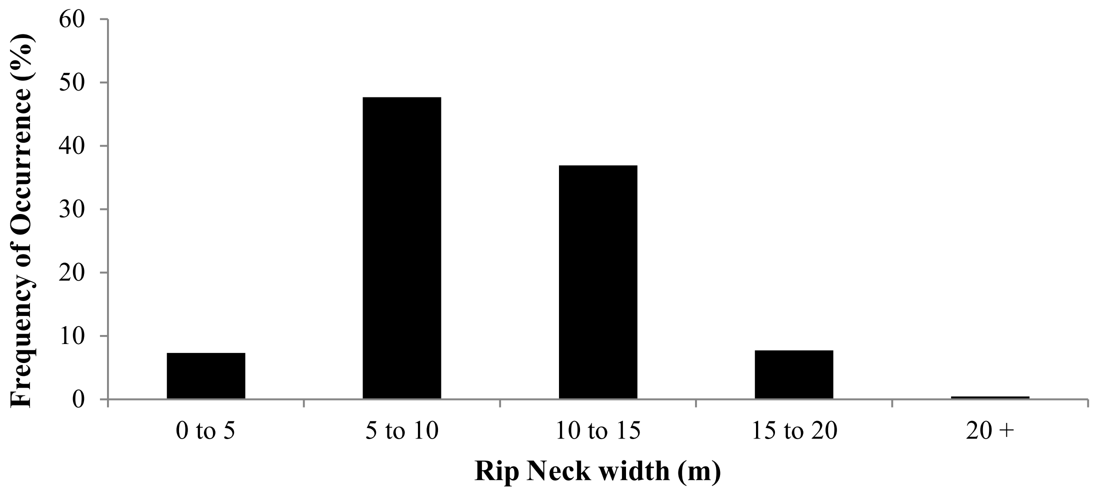


Figure 5.7: Frequency histogram of rip neck width (n =233).

Overall, the rip length and cross-shore extent of the transient rip currents measured were highly variable (Table 5.7). The longest rip was 87.4 m (Table 5.7). 21% of transient rips recorded extended less than 20 m in the cross-shore (x) direction (Figure 5.8). 76% of rips extended between 20 to 50 m in the cross-shore direction, whilst only 3% of measured rips extended further than 50 m offshore (Figure 5.8).

The maximum recorded cross-shore (offshore) extent of a transient rip current was 65.6 m (Table 5.7) which is shoreward of the outer surf zone bar (150 – 200 m offshore). As such the offshore limit of the transient rip currents appears to be constrained to the inner bar region. It is hypothesised that both transient rip length and duration are linked to the scale of the morphology: i.e. the rip forms in shallow water and moves quickly offshore to the trough where the water depth increases rapidly and therefore the current dissipates quickly. This result supports the previous research of Murray et al. (2003) and Slattery et al. (2011) who observed a decrease in rip activity and duration with an increase in bed slope (cf. Section 5.3). The conclusion drawn is that a steep gradient between shallow bed depths and the adjacent deeper water more readily induces rip current termination (Murray et al., 2003). Slattery et al. (2011) also observed (but did not quantitatively measure) transient rip currents remaining relatively close to shore.

Table 5.7: Rip Geometry: Length and Cross-shore Extent (n = 182)

	Approximate Rip Length (m)	Cross-shore Extent (m)
Average	32.5	27.3
Maximum	87.4	65.6
Minimum	9.8	6.9
Standard Deviation	12.8	9.9

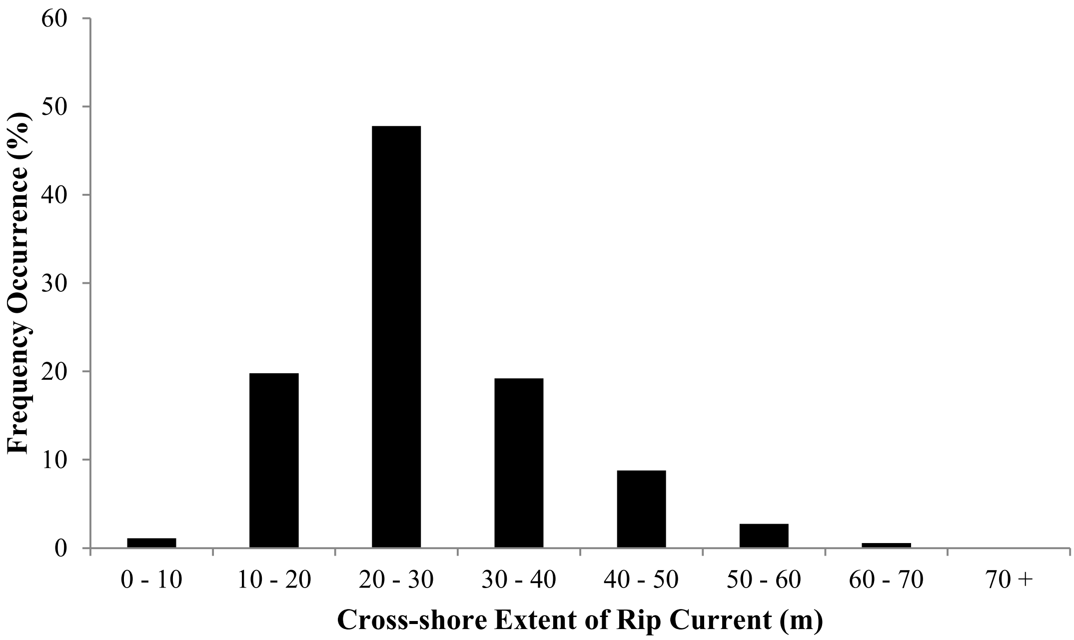


Figure 5.8: Frequency histogram of cross-shore (offshore) rip extent (n = 182).

5.4.2. Transient rip current migration

During conditions when an alongshore current was present, the rip currents were observed to migrate in the direction of the dominant alongshore water movement. 74% of transient rip currents identified for occurrence (cf. Table 3.4) were qualitatively observed to migrate, whilst 27% were relatively stationary (minimal alongshore movement of the current). Castelle et al. (2014a) also observed transient rip currents to migrate in the direction of the prevailing longshore current in a study on an open coast, wave dominated and microtidal beach in West Africa.

Approximately 50% of all transient rip currents observed displayed minimal (< 10 m) to no longshore movement, whilst 74% of all transient rip currents migrated less than 20 m alongshore (Figure 5.9). Only 2% of rips were observed to travel more than ± 50 m in the longshore (y) direction (Figure 5.9). Turner et al. (2007) observed the semi-permanent, topographically controlled rip currents on the Gold Coast open beaches to be stationary 33% of the time. Their study reported alongshore migration rates of semi-permanent topographic beach rip currents to be less than 5 m / day for 47% of the time, whilst the other 53% of the time rip currents migrated alongshore at up to 50 m per day. Generally, semi-permanent topographic rip currents were observed to migrate in the direction of the alongshore current, but a number of rip currents were observed to migrate south, opposing the predominant longshore current (Turner et al., 2007). This was attributed in part to NE sea breezes and locally generated windswells (Turner et al., 2007). It can be concluded that both transient rip currents and topographically controlled rip currents migrate alongshore primarily in the direction of the alongshore current, with the transient rip currents acting on more instantaneous or wave group scales on the order of seconds to minutes, whilst the more semi-permanent beach rip currents, migrate over similar distances on the order of days.

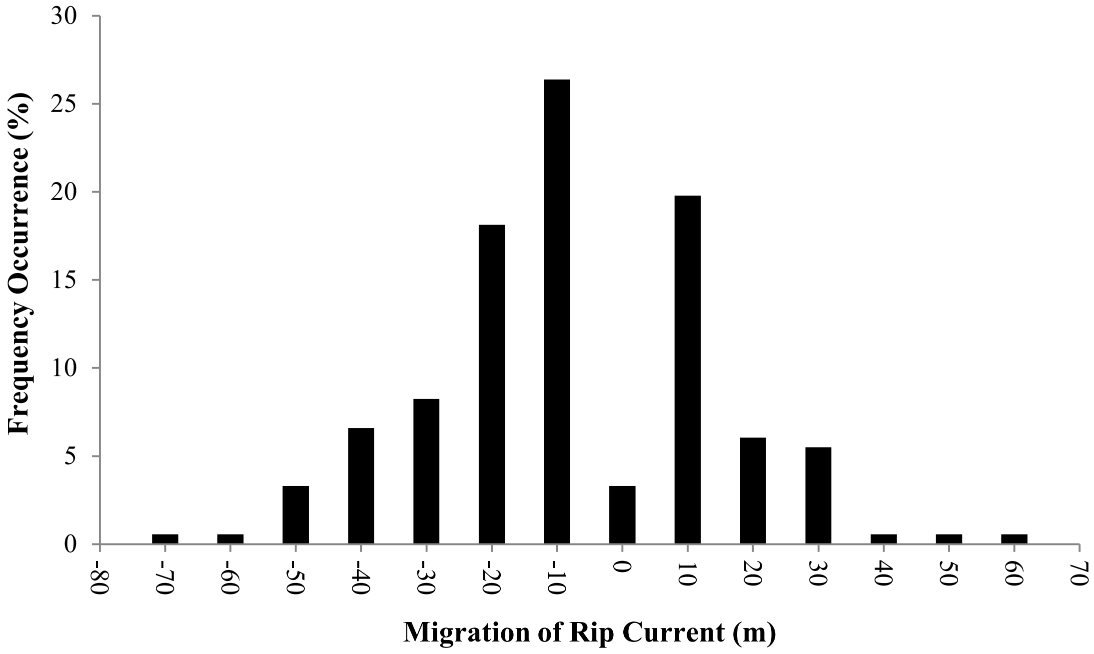


Figure 5.9: Frequency histogram (%) of longshore rip movement (n = 182). Negative values represent migration to the north, whilst positive values represent southward migration of the current.

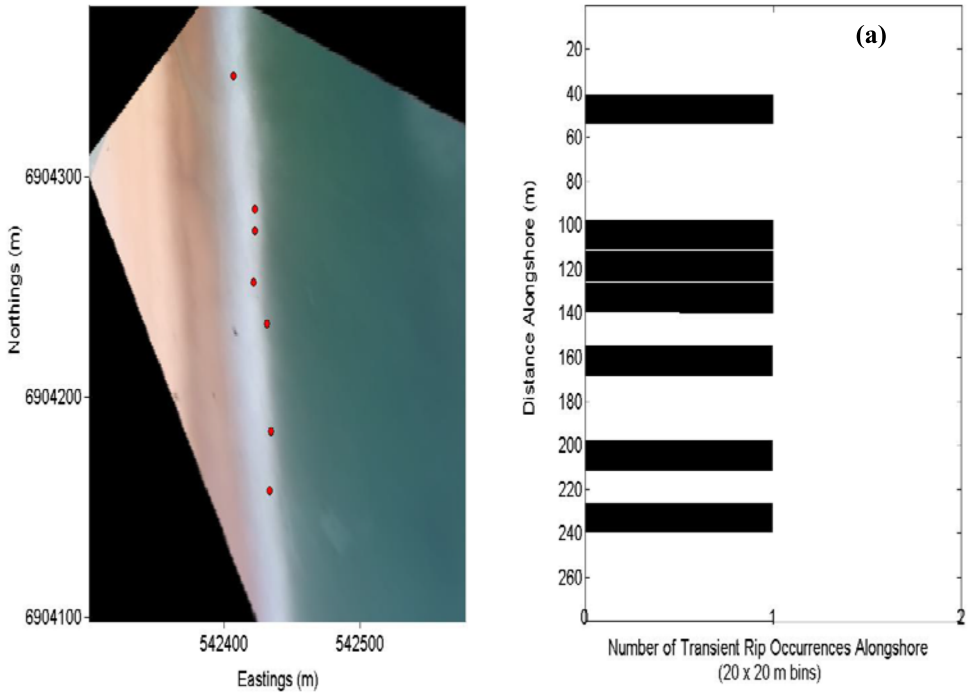
5.4.3. Rip location and spacing

After rectification of the images, 192 individual rips were identified for rip location and spacing (Table 5.8). Two examples of rip location and spacing are provided in Figure 5.10, with the full dataset presented in Appendix C.2. All of the transient rips observed in the present study developed over the seaward edge of the inner bar terrace or beach (e.g. Figure 5.10, Appendix C.2). The rip currents extended from the shallow bar into the deeper trough immediately offshore. There was high variability in rip spacing and alongshore rip location observed (Table 5.8; Figure 5.10) which supports the argument that these types of currents are predominately hydrodynamically driven rather than topographically controlled.

The location and spacing statistics presented here may also provide some support for the theorised forcing mechanisms of the following ephemeral features, as presented in the literature (e.g. Clark et al., 2012; Feddersen, 2014) (cf. Section 2.8). As shown in Figure 5.10, the transient rip currents have been shown to most likely occur over the edge of the inner bar as this is where the wave breaking is occurring and local changes in the water level are occurring (i.e. wave set up and set down) and small-scale surf zone vorticity is being generated (e.g. Figure 5.11; cf. Section 2.8.5). Alternatively, it is theoretically possible that temporary pressure gradients may be generated locally between the wave setup in the breaker zone (terrace bar / beach) and the region of wave setdown in the shoaling zone (trough). The resulting offshore flows would need to be reinforced however, by some sort of positive feedback mechanism to develop into ‘mature’ rip currents (Murray and Reydellet, 2001) (cf. Section 2.8.7.3).

Table 5.8: Rip spacing statistics for each camera view for the 799 hours of full day video analysis (n = 192)

Camera View	Mean Rip Spacing (m)	Maximum Rip Spacing (m)	Minimum Rip Spacing (m)	Standard Deviation (m)
Centre (n = 45)	55.1	182.8	4.0	43.2
Other (n =111)	68.4	233.7	1.4	53.7
Left (n = 36)	74.7	238.8	1.4	57.5



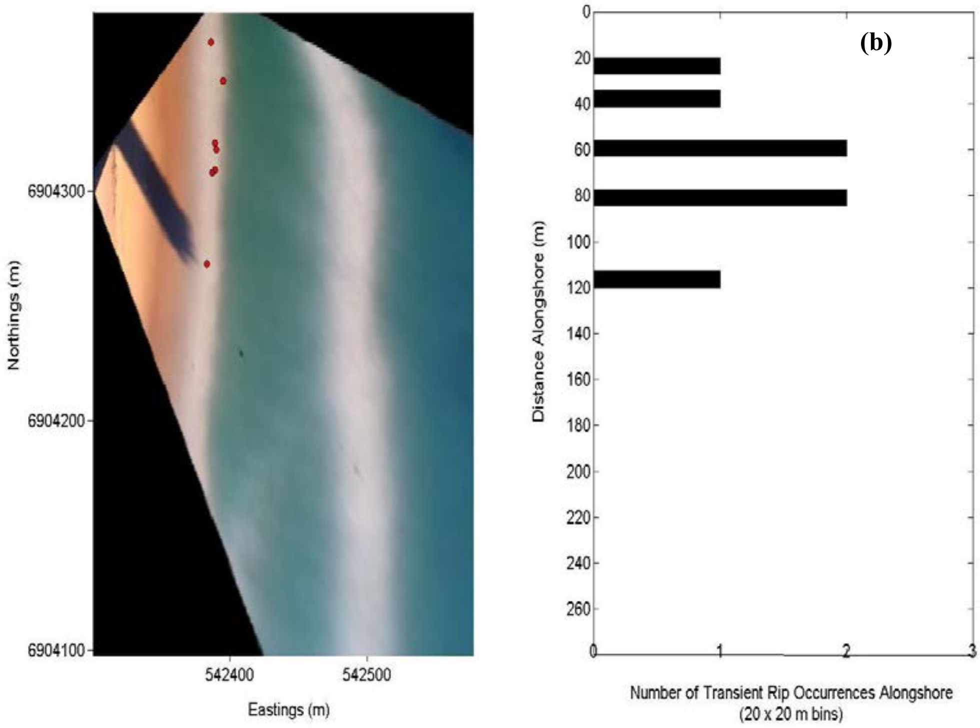


Figure 5.10: Examples of rip location overlayed on rectified timex image (left) and alongshore rip spacing (right): (a) 22/11/2011 (low tide terrace beach morphology); (b) 8/7/2012 (longshore bar and trough beach morphology)

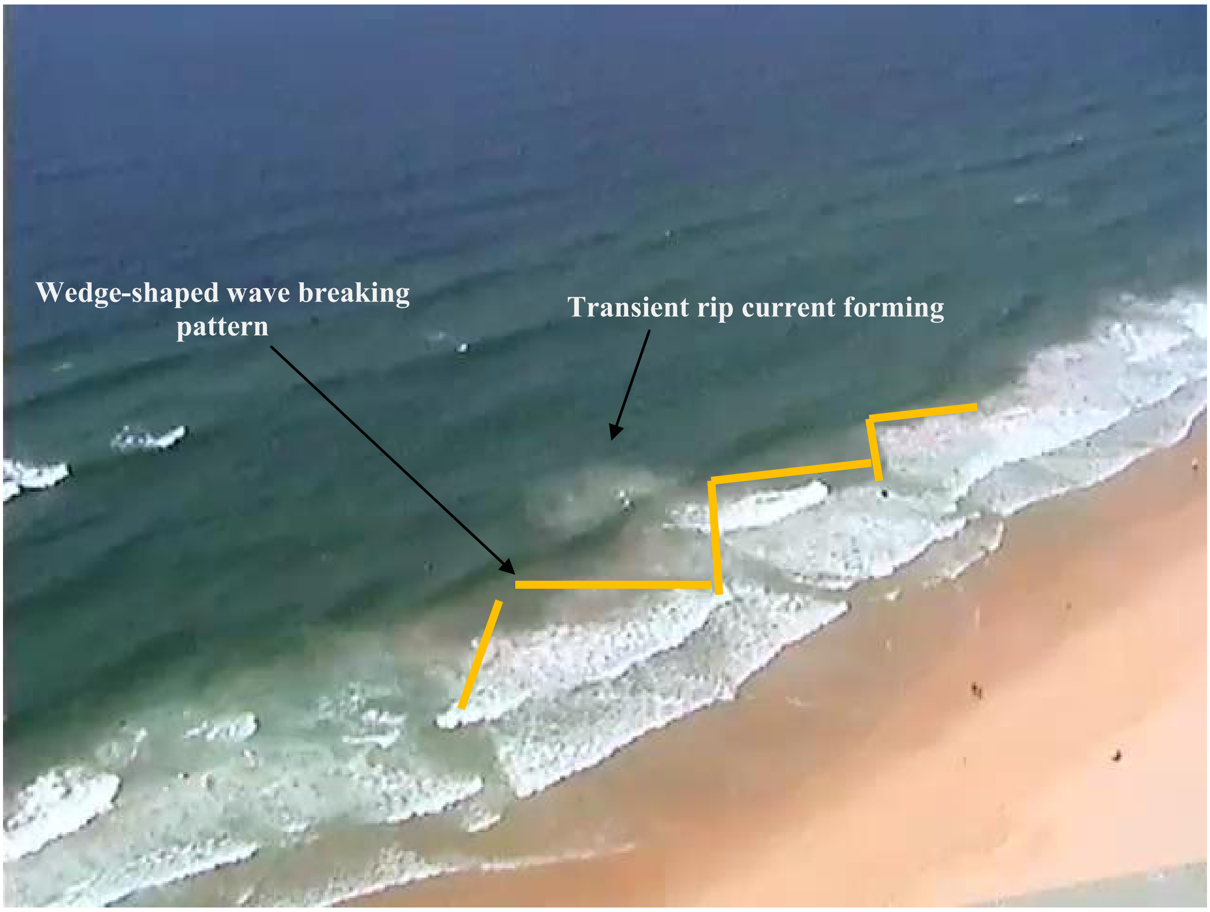


Figure 5.11: Initiation of a transient rip current off the edge of the inner bar terrace. Note along-crest variability in the wave crests and breaking.

It is difficult to quantitatively describe the processes driving transient rip currents, but the currents do appear to be influenced by cross-shore variability in topography, albeit these influences allow for the hydrodynamic forcing of the rip currents. Transient rip currents will appear irrespective of alongshore variability in topography. There is a degree of speculation in these conclusions, which are based upon previous field observations (Murray and Reydellet, 2001; Clark et al., 2012; Feddersen, 2013). Whilst capturing transient rip currents using Eulerian methodologies is extremely difficult in the field an experiment such as that conducted by Clark et al. (2012) (cf. Section 2.8.5.2) in conjunction with a coastal-imaging study may improve the overall understanding of transient rip current forcing mechanisms.

5.4.4. **Rip growth rate**

The rip growth rate (acting as a proxy for average rip current speed) of the transient rip currents observed over the lifetime of the rip was measured to range from 0.1 – 1.3 $m.s^{-1}$ (Table 5.9). The average observed cross-shore and longshore components of rip growth rate were 0.4 $m.s^{-1}$ and 0.2 $m.s^{-1}$ respectively (Table 5.9). 85% of rips had a growth rate of between 0.2 – 0.6 $m.s^{-1}$ (Figure 5.12). Approximately 1% of rips had a growth rate in excess of 1 $m.s^{-1}$ (Figure 5.12) which was mostly attributed to migration with the longshore current (Table 5.9). Rip neck speeds are expected to be slightly higher than the rip growth rate.

These results are however consistent with transient rip current speeds detailed in the literature (Johnson and Pattiaratchi, 2004b; MacMahan et al., 2010a; Brander and MacMahan, 2011; Castelle et al., 2014a) where average transient speeds are generally low when compared to their topographically controlled counterparts (Short, 2007; MacMahan et al., 2010a; Brander and MacMahan, 2011).

Table 5.9: Average rip growth rate statistics (n = 182)

	Rip Current Growth Rate ($m.s^{-1}$)	Cross-shore Growth Rate ($m.s^{-1}$) u	Longshore Growth Rate ($m.s^{-1}$) v
Average	0.4	0.4	0.2
Maximum	1.3	0.8	1.1
Minimum	0.1	0.1	0
Standard Deviation	0.2	0.2	0.2

**Note: negative values indicate northward current flow and positive values indicate southward flow.*

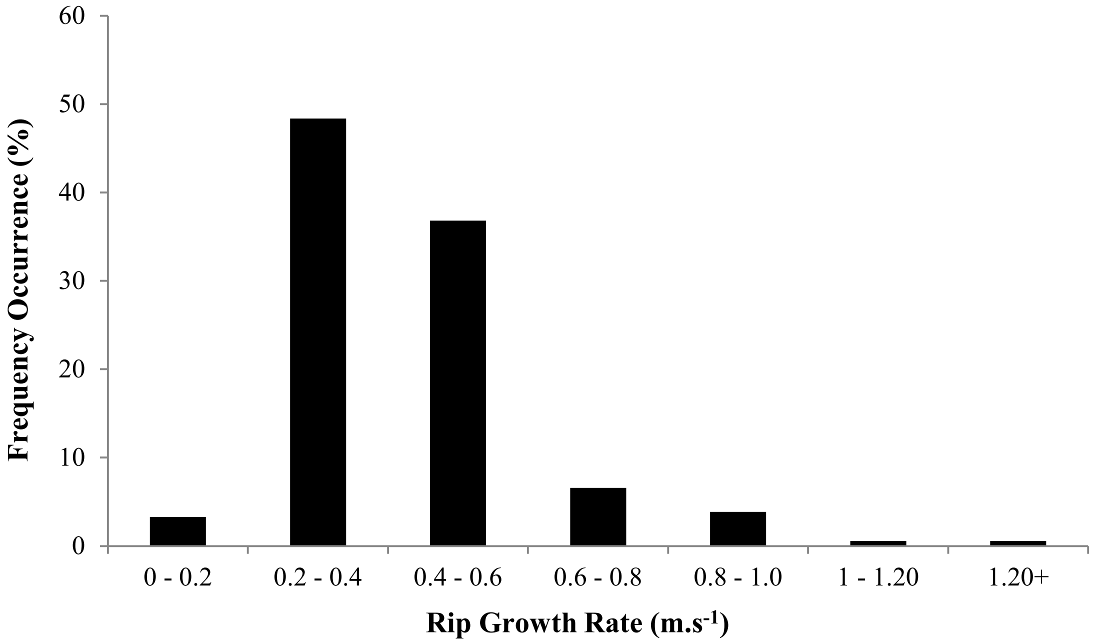


Figure 5.12: Frequency histogram (%) of transient rip current growth rate (proxy for average rip current speed) (n = 182)

5.5. Transient Rip Influence on Bathymetry

Slattery (2010) argues that as the transient rip currents tend to be confined close to shore they may generate semi-permanent topographic rip channels by scouring out the bar through positive feedback and / or modifications to ridge and runnel features on the Low Tide Terrace beach. The Gold Coast study presented very weak to no evidence of transient rip forcing leading to semi-permanent rip channels, with the currents not persisting for long enough in one place to modify the beach morphology. Rip formation and spacing was also highly variable in this present study, which leads the author to believe the currents are not prevalent enough or strong enough to scour out well-defined rip channels.

Whilst transient rips have been described as *erosional rip* types in the past (cf. Table 2.2), the rip speeds and velocities recorded in this study suggest they form under more beach *accretionary* conditions. This can also be seen in the wave record (cf. Table 5.4) and beach state analysis (Figure 5.2), with transient rip currents becoming more dominant under lower than average wave heights and lower energy beach state conditions. Under higher energy beach state and wave conditions, larger scale surf zone circulation appears to over-ride smaller scale transient rip forcing.

5.6. Implications for Beach Safety

Very limited information is available in the literature detailing the hazard transient rip currents present to beach goers. This section discusses the implications that the spatial and temporal results (detailed in Sections 5.3 & 5.4) infer in terms of the hazard transient rip currents present to bathers.

Whilst all rip currents present the hazard of moving bathers from shallow to deep water rapidly (offshore), transient rip currents present a hazard at a different spatial and temporal scale to topographically controlled beach rip currents. Topographically controlled beach rip currents have been shown to be the major type of rip current present on the Gold Coast, whilst transient rip currents are much less common (cf. Section 5.3). Topographically controlled beach rip currents are classified as 'semi-permanent' as they persist on the order of days and migrate slowly (cf. Sections 5.3 & 5.4). In this sense semi-permanent beach rip currents are easily identified by qualified experts and management strategies for swimmer safety can be modified accordingly. In contrast transient rip currents displayed no preference of location, were short-lived events and were observed to migrate up to 70 m alongshore in a matter of minutes (cf. Sections 5.3 & 5.4). The seemingly random occurrence and spacing as well as the high mobility of transient rip currents makes them almost impossible to manage in terms of restricting bather access to where they might occur. Transient rip currents have also been shown to occur over the edge of the sand shoal (i.e. bar-terrace), where the lifeguard 'red and yellow' flags are more likely to be aligned, transporting unsuspecting bathers into the deeper trough immediately adjacent.

Semi-permanent beach rip currents have much larger spatial and temporal scales than transient rip currents and are traditionally believed to have higher flow velocities than transient rip currents (Brander and MacMahan, 2011). Brander and MacMahan (2011) concluded from the literature that topographically controlled beach rips under low to moderate wave energy are tidally modulated, flowing faster around the low tide with mean velocities typically on the order of 0.3 – 0.8 $m.s^{-1}$. The present Gold Coast study and a similar study by Castelle et al. (2014a) found average transient rip currents to pulse at similar velocities, albeit on average rip growth rates were a the lower end of the velocity spectrum (i.e. on average 0.4 $m.s^{-1}$). It is therefore concluded that transient rip currents also have the capability to move bathers offshore from shallow to deep water rapidly, but over smaller spatial and temporal length scales.

Based on Brander and MacMahan's (2011) assumption that competent swimmers will be able to swim in excess of $1m.s^{-1}$, the growth rate of transient rips recorded in this experiment (cf. Section 5.4.4) indicate that they will not present too difficult a hazard to 'escape' by experienced swimmers. Again the hazard that transient rip currents present to bathers are more relevant to inexperienced swimmers or those with a poor understanding of surf zone waves and currents.

5.7. **Study Limitations**

The CoastalCOMS camera that produces the video for the study is set up on a pre-existing tour as it is primarily used for other coastal engineering purposes. The camera switches between the three views every 60 – 300 s as necessary for its other engineering purposes. All of the 5 minute video recordings were stationary on each view for the full 300 seconds. Whilst this limitation has implications for the accuracy of the frequency and duration data, the method is able to depict a solid approximation of transient rip occurrence and due to the short life span of the currents provide a general approximation of rip current duration in the study region statistically. Glare on the water surface, particularly in the winter months and afternoon shadows from the buildings also make it difficult to resolve the transient rip signal in the video at certain times of the day / year. At its worst 20 minutes of video footage a day for 55 days of the sample period (~2% of the total video) is affected by glare on the water surface, with low confidence on resolving transient rip activity. Wind conditions may also affect the transient rip signal in the video with a stormy sea state making the surf zone 'messier' and thus more difficult to identify transient rip occurrence.

5.8. Conclusions

Approximately 1029 hours of coastal video footage was used to describe transient rip current occurrence and behaviour on a wave dominated and microtidal open coastline beach. 233 individual transient rip currents were identified in the video-imagery. The novel remote-video methodology allowed for the collection of the largest sample data set used to capture and analyse transient rip currents to date. Via these novel video techniques it is possible to identify, measure and describe transient rip formation, location, persistence, geometry, rip growth rate, flow direction, migration and termination. The simple video-imaging techniques outlined in Section 3.5 allowed for a significant improvement in the overall understanding of transient rip characteristics and are easily repeatable in future studies.

The physical characteristics and behaviour of transient rip currents observed on the Gold Coast open beaches are consistent with other field measurements and numerical modelling of transient rip currents (Vos, 1976; Johnson and Pattiaratchi, 2004b; Johnson and Pattiaratchi, 2006; Slattery, 2010; Slattery et al., 2011; Castelle et al., 2014a). Transient rip currents were observed to manifest in the 'classic' mushroom cloud rip head and narrow trailing rip neck formation, as described previously in the literature (e.g. Vos, 1976; Johnson and Pattiaratchi, 2006; Slattery et al., 2011). Transient rip currents display similar flow characteristics to semi-permanent (i.e. topographically controlled) beach rip currents, however they act over much shorter spatial and temporal length scales.

Transient rip events are characterised by short life-spans (30 – 236 s) and low temporal frequency, but high temporal variance, occurring for only 0.5% of the time in the video. Meanwhile the present study and Turner et al. (2007) have shown topographically controlled beach rip currents to be present 68% and 72% of the time at the study site respectively. Transient rip current formation, intensification and pulsing, and finally termination occur on the order of tens of seconds to minutes, whilst semi-permanent beach rips have been shown to last on the order of days to weeks. Both types of rip currents generally migrate over small spatial scales (i.e. < 20 m) alongshore, however can migrate alongshore over 50 m. Transient rip currents tend to do this on the order of minutes, whilst semi-permanent beach rip currents take days to migrate.

By utilising the measurement of transient rip current growth rate as a proxy for the average speed of the rip current over its entire lifespan, it was observed that transient rip currents flow at similar velocities to those of topographically controlled rip currents, although the majority of the time at the lower velocities (i.e. on average 0.4 $m.s^{-1}$).

For the first time in any study of transient rip currents a combination of univariate and multivariate statistical analyses were utilised to test for transient rip occurrence against a range of environmental parameters in order to determine if there are any preferential environmental conditions for transient rip occurrence. The multivariate GAMs analysis generally supported the findings of the simple parametric, univariate statistical tests for transient rip occurrence. The GAMs however provides a more robust statistical procedure to understanding the relationships between the transient rip occurrence and the environmental parameters tested. Overall the statistical tests add weight to field observations and theoretical models of transient rip formation and occurrence.

Whilst there were no half-hour averaged wave or wind parameters under which transient rip formation appeared to favour, transient rip current occurrence and influence on beach morphodynamics, sediment transport and hazards is increased when the beach is in a low energy LTT state, with the bar and beach planar and mostly uniform. Around 68% of transient rip events occurred under LTT and LTT/TBR (down state transitional) beach states.

Transient rip occurrence was found to be significantly greater on the ebb tide as opposed to the flood tide under terrace beach conditions and when wave breaking was absent on the outer bar under both terrace and bar-trough beach conditions. Transient rip occurrence also appears to favour a swell type wave field with narrow directional spreading and longer peak wave period, which is consistent with other modelling studies (Murray et al., 2003; Johnson and Pattiaratchi, 2006)

The short spatial and temporal scales of transient rip currents; migration with the alongshore current; haphazard occurrence and spacing; and lack of clear bathymetric perturbations in the low tide timex-images suggests that these temporary events are driven by hydrodynamics rather than beach and surf zone morphology. The results of this study lend observational support for the "short-crested breaking wave vorticity forcing due to along-crest variation in wave dissipation" theory of transient rip formation (cf. Section 2.8.5.2). Whilst the conclusions are based on a fair amount of observational conjecture, they do support the theoretical framework (Chapter 2) and other field observations made about transient rip currents in the literature (Murray et al., 2003; Johnson and Pattiaratchi, 2004b; Johnson and Pattiaratchi, 2006; Slattery et al., 2010; Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014; Castelle et al., 2014a). It must also be noted that the forcing mechanisms of transient rip currents may vary from beach to beach, as well as through time (cf. Section 2.8.7). This view is supported by Slattery (2010).

Whilst transient rips were shown to remain inshore of the secondary outer bar they are hazardous to bathers as they can move swimmers from shallow to deep water rapidly. Whilst the hazard is short-lived their formation appears sporadic with no bathymetric clues as to where they will initiate. As a result transient rip hazard is more difficult to mitigate against, in terms of restricting bather interaction with the hazard, than the more visually obvious semi-permanent (topographically controlled) beach rip hazard.

Chapter 6. Conclusions and Recommendations

6.1. **Overview**

The thesis has presented field investigations into the surf zone circulation patterns on the open beaches of the Gold Coast, Australia with a focus on specific wave-driven currents namely: (i) semi-permanent rip currents, (ii) transient rip currents and (iii) alongshore currents. The surf zone circulation patterns and associated wave-driven currents have been investigated in detail for the first time on an open coast microtidal, wave dominated double bar beach with highly dynamic morphology and wave climate. Comparisons to previous studies on single bar embayed beaches and open coast beaches with stable bar morphology and unidirectional, shore-normal wave climate were undertaken to compare and contrast differences in circulation patterns between different beach types.

GPS drifters were used to first characterise the nature of the various surf zone circulation patterns and to then quantify surf zone retention rates under the different circulation regimes. Remote-video imagery analysis has also been used to quantify the characteristics of transient rip currents. Univariate and multivariate statistical analysis was applied to the transient rip current dataset to test transient rip occurrence against a range of environmental parameters. The specific conclusions associated with each of these aspects of the thesis are detailed in the sections below followed by a summary of the implications of the thesis findings in the context of beach safety. Lastly some recommendations for future work are presented.

6.2. **Surf Zone Circulation Patterns and Retention Rates**

Four general circulation patterns were observed to occur in the Lagrangian drifter study over nine unique days of deployment: (i) *alongshore current dominant*; (ii) *rip current dominant*; (iii) *meandering* (i.e. a combination of rip current and sinuous alongshore current); and (iv) *terrace beach / inner bar conditions*. Figure 6.1 presents the conceptual models associated with each of these circulation patterns. The first three of these circulation patterns adhere to the simplified MacMahan et al. (2010a) conceptual surf zone circulation model outlined in Section 2.5. As was observed in previous Lagrangian drifter studies, *rip current dominant* circulation patterns were characterised by large scale, semi-enclosed, surf zone eddies on the order of surf zone dimensions (~150 – 200 m). *Alongshore current dominant* conditions on the Gold Coast open beaches also displayed similar flow behaviour to those described in studies on single bar embayed beaches and open coast beaches in a meso-macrotidal environment.

For the first time a detailed description of surf zone circulation under *terrace beach / inner bar* conditions was presented. These conditions were observed on one of the nine days of sampling. The beach was in a low wave energy ($H_{sig} = 0.57$ *m;* $T_p = 8.0$ *s;* $D_p = 108°$ *i.e. ESE*) accretionary phase with a mostly alongshore planar shore-attached terrace cut by the occasional mini rip (e.g. Figure 6.1d). No surf zone eddies were observed under *terrace beach / inner bar* conditions. Mini rips or transient rips were present under these conditions and were characterised by narrow offshore directed flows at a shore-normal or shore-oblique angle.

In contrast to the majority of previous Lagrangian drifter studies, the present study examined circulation patterns under a variety of beach state and wave climate conditions. Surf zone circulation behaviour on the Gold Coast open beaches appears to be controlled by the interaction of the double bar beach state and the incoming wave climate. For example *rip current dominant* circulation patterns favoured a shore-normal angle of wave approach, with conditions showing little alongshore exchange of drifters (i.e. floatsam / water) between adjacent rip current channels. Alternatively, a*longshore current dominant* conditions occurred when the angle of wave approach was shore-oblique. A strong alongshore current was found to override rip current forcing on these days of sampling, with high exchange rate of drifters alongshore between adjacent rip current channels.

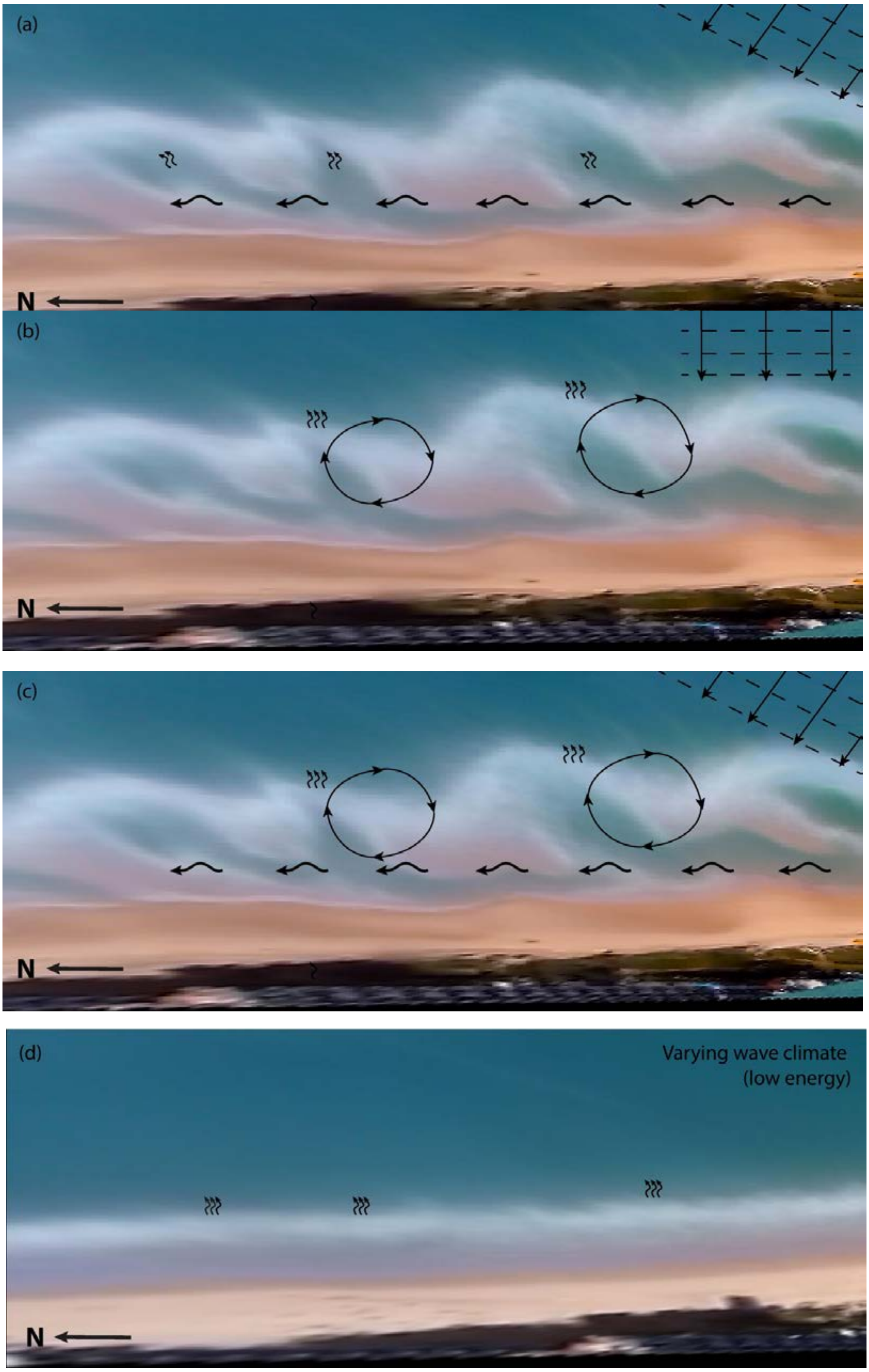


Figure 6.1: Conceptual model of the four major surf zone circulation patterns observed on the Gold Coast open beaches (a) alongshore current dominant; (b) rip current dominant; (c) meandering; (d) terrace beach / inner bar. Dashed lines with arrows represent modal swell direction for each condition. Clusters of offshore directed arrows represent episodic ejections of the currents offshore. In (d) the arrows are representative of transient rip currents

It should also be noted that in contrast to previous drifter studies, which displayed circulation patterns that fit well within the MacMahan et al. (2010a) model, drifter pathways in the present Gold Coast study also highlight the complex nature of surf zone hydrodynamics and circulation on double bar, microtidal and wave dominated open coast beaches. Two out of the nine days of sampling displayed a combination of the four characteristic surf zone circulation model patterns, with the interaction of the complex double bar morphology and incoming wave climate controlling circulation behaviour (cf. Section 4.4.4). Surf zone circulation patterns were also observed to vary through a day of sampling with changes in tide and in particular wind forcing changes in circulation through the day. For example strong cross-shore winds were qualitatively observed to drive sea swell and switch circulation conditions from *rip current (or meandering)* dominant to *alongshore dominant* (cf. Appendix B.1).

Surf zone exit rates of drifters entering a rip current were highly variable between different circulation patterns. *Alongshore current dominant* conditions (Figure 6.1a) had an exit rate of 3%; *rip current* (Figure 6.1b) and *meandering current* (Figure 6.1c) *dominant* conditions had an exit rate of 41% and *terrace beach / inner bar* conditions (Figure 6.1d) had an exit rate of 56%. By comparing the results of the Gold Coast study to the literature it is argued that surf zone retention of water, sediment and floatsam is not necessarily high or low due to rip current forcing but will vary due to a variety of wave, tide, wind and morphological parameters.

The drifter observations support the previous literature (e.g. McCarroll et al., 2014b) in suggesting potential non geological bathymetric controls that may influence the observed moderate exit rates of drifters observed on the Gold Coast open beaches. In summary these may include (but are not limited to):

- Reduced morphodynamic coupling; due to a range of factors including (but not limited to):
    - Lower than average wave heights (and reduced wave breaking beyond the rip channels)
    - Planar beach / bar morphology
    - Narrow surf zone
    - Characteristic strong longshore current and skewed rip channel morphology due to a dominant shore oblique wave climate

• Presence of rip head bars

The influence of the highly variable (e.g. often bimodal and bidirectional) and generally shore oblique incoming wave climate and lack of headland control on rip current "cellular" circulation (cf. Section 4.1; Table 4.1) are proposed to be the major driver of reduced morphodynamic coupling and therefore higher rates of drifter exits then those observed in the MacMahan et al., 2010 study. As drifter exits were often characterised by a cluster of drifters exiting offshore at the same time it is also suggested that low frequency pulsing of the wave-driven currents, may lead to temporary ejections of water, sediment and floatsam.

Whilst recent studies have shown that for open coast beaches with a dominant oblique angle of wave approach that wave direction will play a major role in shaping morphology (Garnier et al., 2009; Strauss and Tomlinson, 2009; Price and Ruessink, 2011) the angle of wave approach has not been previously explored in terms of surf zone circulation and retention of floatsam. The drifter pathways highlight the importance of the interaction between the wave climate and the bar morphology in controlling surf zone retention rates and exchange of water between nearby rip systems on an open coast, double bar, wave dominated and microtidal beach.

In accordance with previous Lagrangian drifter studies (Table 4.1) the highest peak drifter velocities (> 1.5 $m.s^{-1}$) are attributed to waves and rip current pulsing in the cross-shore and obliquely incident waves and pulsing of the longshore current in the longshore direction. Consistent with MacMahan et al. (2010a) drifter velocities reach a maximum in the middle of the surf zone, related to wave breaking and pulsations of the wave-driven currents and then tend to decay to the outer edge of the surf zone and further once drifters have exited beyond the edge of the inner bar.

6.3. **Transient Rip Currents**

Through remote-video techniques this thesis produced the largest ever dataset for measuring and analysing transient rip current characteristics in the field. For the first time rectified images were analysed to measure the activity, duration, location, spacing, mobility, rip growth rate, and geometry of transient rip currents.

The physical characteristics and behaviour of transient rip currents observed using video imagery on the Gold Coast open beaches are consistent with other field measurements and numerical modelling of transient rip currents (e.g. Vos, 1976; Murray et al., 2003; Johnson and Pattiaratchi, 2006; Slattery, 2010; Slattery et al., 2011; Castelle et al., 2014a). Transient rip currents were observed to manifest in the 'classic' mushroom cloud rip head and narrow trailing rip neck formation. Transient rip currents display similar flow behaviour to the topographically controlled semi-permanent beach rips, however they act over much shorter spatial and temporal length scales and occur in spatially variable locations. For example, both types of rip currents were observed to migrate alongshore between 0 – 50 metres, however transient rip currents tend to do this on the order of minutes, whilst semi-permanent beach rips take days to migrate.

Transient rip current duration was measured to be between approximately 30 – 236 seconds, which is consistent with other studies of transient rip currents on open coast beaches (e.g. Johnson and Pattiaratchi, 2004b; Johnson and Pattiaratchi, 2006; Castelle et al., 2014a). Rip current activity was observed to be low (i.e. transient rip signal evident for 0.5% of the remote-video dataset) when compared to semi-permanent beach rips, which were observed 68% of the time in the video (a total of 1029 hours of video were analysed). There was high variability in rip spacing and alongshore rip location observed, which supports the argument that these types of currents are predominately hydrodynamically driven rather than topographically controlled.

By utilising the measurement of transient rip current growth rate as a proxy for the average speed of the rip current over its entire lifespan, it was observed that transient rip currents flow at similar velocities to those of topographically controlled rip currents, although the majority of the time at the lower velocities (i.e. on average 0.4 $m.s^{-1}$).

A combination of univariate and multivariate statistical techniques were successfully employed in order to test for transient rip occurrence against a suite of environmental parameters. This was undertaken in order to determine if there are any environmental conditions under which transient rip occurrence may favour. Regression analysis found no correlation between transient rip occurrence and half-hourly averaged wave or wind parameters. Transient rip occurrence however was observed to increase when the inner bar was in a mostly alongshore planar terrace beach state. Both a univariate t-test analysis and multivariate GAM analysis showed transient rip occurrence to be significantly greater on the ebb tide as opposed to the flood tide under terrace beach conditions and when wave breaking was absent on the outer bar under both terrace and bar-trough beach conditions. Transient rip occurrence also appears to favour a swell type wave field with narrow directional spreading and longer peak wave period, which is consistent with previous modelling studies (Murray et al., 2003; Johnson and Pattiaratchi, 2006), but contradicts the previous hypothesis that transient rip formation favours a stochastic or ‘confused sea state’ (Johnson and Pattiaratchi, 2004b; Reniers et al., 2004; MacMahan et al., 2004b; Dalrymple et al., 2011; Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014).

Overall results of the study provide some observational support for the theory that transient rip currents are fundamentally driven by short-crested breaking wave vorticity forcing due to along-crest variation in wave dissipation (e.g. observed by Feddersen, 2014). This supports the hypothesis that transient rip currents observed on a wave dominated, double bar, open coast beaches (e.g. present study) display length and time scales comparable to previous studies on single bar beaches (e.g. Johnson and Pattiaratchi, 2004b; Slattery, 2010; Castelle et al., 2014b). The new finding that contradicts previous research is that transient rip current occurrence appears to favour a wave field with narrow directional spreading and longer peak wave period. Future work involving *in situ* wave and current measurements in conjunction with video-imaging of transient rips is required to further investigate this new finding (cf. Section 6.5).

6.4. **Implications of Results for Beach Safety**

The results of the Lagrangian drifter field study on surf zone circulation patterns and the video-imaging study of transient rip currents have been used to qualitatively assess the rip current hazard on a wave dominated and microtidal, double bar, open coast beach.

From the observations both from the present Gold Coast field study and the literature it is obvious that the rip current hazard is complex and highly variable. As a result it is argued that a single escape strategy safety message for all conditions is inappropriate (McCarroll et al., 2014a). Instead, a combined approach and scenario-specific safety advice should be considered by beach safety practitioners to promote to the public (McCarroll et al., 2014a).

Drifters acting as a proxy for bathers have been shown both in the present study and the literature (cf. Section 4.4) to exit the surf zone more often under *rip current dominant* and *meandering current* conditions than *alongshore current dominant conditions*. *Alongshore current dominant* conditions are characterised by drifters travelling shore-parallel to the beach and where present passing through several shoals and rip channels until beaching. The new scenario of *terrace beach / inner bar* conditions introduced in this thesis also observed generally moderate to high rates (56%) of drifters exiting the surf zone beyond the edge of the inner bar. Under these conditions however current velocities were low (i.e. drifter exit speed recorded in the 0.2 – 0.5 $m.s^{-1}$ range) and offshore drifter movement was limited (cf. Section 4.4.3). As such it may be relatively easy for bathers to swim back to shore after exiting the surf zone under these low energy conditions. Mini rip currents and transient rip currents are present under *terrace beach / inner bar* conditions, with transient rip currents producing a uniquely different hazard to bathers when compared to semi-permanent beach rips.

Very limited information was previously available in the literature detailing the hazard transient rip currents present to beach goers. The major difference in hazard between transient rips and semi-permanent beach rips is that there are no obvious visual clues as to where exactly a transient rip will form. Their occurrence was found to be random and they were measured to migrate up to 70 m alongshore in a matter of minutes. As a result it is extremely difficult for beach managers to restrict bather interaction with transient rip currents, without preventing swimmers from entering the water. Transient rip growth rates (acting as a proxy for average rip speed) were observed to be low (e.g. on average 0.4 $m.s^{-1}$) for the majority of the time. Based on Brander and MacMahan's (2011) assumption that competent swimmers will be able to swim in excess of 1$m.s^{-1}$, the growth rate of transient rips recorded in this experiment (cf. Section 3.5.6.4) indicate that they will not present too difficult a hazard to 'escape' by experienced swimmers.

6.5. Future Work

Higher energy wave and beach state conditions (e.g. storm conditions) were not assessed in the present Lagrangian drifter study, although this is common across GPS drifter studies worldwide (cf. Table 4.1). It is suggested that future work be undertaken under higher energy wave conditions both on open ocean beaches and embayed beaches under a variety of tidal regimes. On the other end of the energy scale only one day of low energy, Low Tide Terrace beach conditions were captured for Lagrangian drifter analysis (cf. Table 4.2). These conditions are particularly rare on the Gold Coast (Price and Ruessink, 2011) (cf. Chapter 5) and require weeks to months of uninterrupted low wave energy and beach accretion (Short, 2000). It is important to note that due to low levels of transient rip activity on the Gold Coast open beaches, days where transient rips are dominant are infrequent and as such are difficult to study with Lagrangian drifter deployments. This supports the use of video-imagery in researching these random and temporary currents.

The complexity of the morphodynamic and physical processes involved in transient rip formation suggest further investigation is required to provide a better understanding of conditions under which transient rip occurrence is favoured. The end goal is to be able to forecast transient rip events ahead of time or at least conditions where transient rip activity is more prevalent. The dataset needs to be increased to improve the accuracy of results as well as to further assess possible forcing mechanisms. In order to do this data collection should be automated in future studies.

There is scope for detection methods identifying rip plumes to be automated in future using HSV/RGB clustering methods and/or differencing imaging. Slattery (2010) attempted to utilise an automated computer recognition system to capture rip currents based on pixel colour. This attempt was unsuccessful as the signature of the rip currents depended too much on sun angle, cloudiness, the extent of white water and rippling of water surface due to wind (Slattery, 2010). The CoastalCOMS infrastructure already automates several processes, such as timex-imaging and time-stacking of video data (Lane et al., 2010; Lane et al., 2011) and by adding an automated rip detection tool, there is opportunity to expand on the sample set and improve on the results of this thesis. Timestack images and video-derived wave height analysis may aid in the analysis of incident wave statistics and their relationships with transient rip formation, evolution and termination. Timestack images may also produce further information on local bathymetry and rip neck speed.

As the hydrodynamic forcing mechanisms for transient rip formation remain elusive, future work utilising *in situ* wave and current data in the surf zone, is required to further investigate the triggers of these temporary hazards. It is also suggested that an increased insight into transient rip dynamics would involve the quantification of the alongshore variability of wave breaking over the outer and inner bars. Clark et al. (2012) set up a circular array of current meters in the surf zone to measure surf zone vorticity, which transient rip currents are thought to be a signal of (cf. Sections 2.7.4 & 2.8.5). This type of experiment is logistically very difficult to implement, but would provide detailed *in situ* wave measurements in conjunction with improved remote-video techniques.

Recent research by the Scripps Institution of Oceanography has used tracer dye to monitor cross-shore exchange of sediment, water, floatsam and marine organisms between the surf zone and inner shelf (Feddersen, 2013; Feddersen, 2014; Hally-Rosendahl et al., 2014). Dye tracers are also very useful as an educational tool. A similar experiment could be undertaken on the Gold Coast open beaches in future in conjunction with remote-video techniques to further assess transient rip current circulation and cross-shore exchange.

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Appendix Outline

(all appendices on attached CD)

Appendix A. Methodology (Chapter 3)

A.1 GPS Drifter Validation and Background on Lagrangian Surf Zone Studies

A.2 Matlab Rectification of Video Images

Appendix B. GPS Lagrangian Drifter Data (Chapter 4)

B.1 Qualitative description of beach morphodynamics and hydrodynamics on each day of sampling

B.2 Video-image derived rip speeds for November 29, 2011

Appendix C. Remote-video Analysis of Transient Rip Characteristics (Chapter 5)

C.1 Linear Regression Analysis TR Occurrence

C.2 Full Data Set of Rip Location and Spacing

Appendix D. Published Journal Article

MURRAY, T. P., CARTWRIGHT, N. & TOMLINSON, R. (2013) Video-imaging of transient rip currents on the Gold Coast open beaches. *Journal of Coastal Research,* SI65, 1809-1814.