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Regional Variations in Rip Density

Andrew D. Short† and Robert W. Brander‡

†Coastal Studies Unit
School of Geosciences F09
University of Sydney
Sydney, NSW 2006, Australia
A.Short@csu.usyd.edu.au

‡School of Earth Sciences
Victoria University of Wellington
P.O. Box 600
Wellington, New Zealand
rob.brander@vuw.ac.nz

ABSTRACT

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An extensive dataset combining information obtained from aerial photographs of selected Australian beaches and studies in the literature from a wide variety of sites in Europe, the United States, Japan, South Africa and New Zealand is used to investigate the relationship between rip current spacing on intermediate beaches and regional wave climate. A new parameter termed rip density (*RD*) is introduced which defines the number of rips per kilometre of beach and is defined as the relationship y_r/L_r where y_r is rip spacing and L_r is a nominal length of beach. The variation in rip density was examined for five different regional wave environments termed west coast swell (WCS), east coast swell (ECS), fetch-limited wind wave with strong (SWS) and moderate (MWS) winds, and fetch-limited bays (SWB). Patterns of rip density were extremely consistent between the grouped wave climate environments with WCS beaches characterised by the lowest *RD* of 2 rips/km and SWB and MWS beaches having the highest *RD* with values ranging from 11–13 rips/km. ECS beaches have a *RD* of 5 with SWS lying in between the range for WCS and ECS beaches at approximately 3 rips/km.

The variation in rip density between environments exhibits distinct scaling relationships with *RD* on SWB and MWS beaches being approximately 5 times greater than on WCS beaches and twice as great than on ECS beaches. ECS beaches also have 2.5 times the number of rips on WCS beaches. Based on measurements and estimates of rip channel and surf zone width, there is evidence to suggest that these scaling factors may also be applied to the variation in two-dimensional planform morphology between the environments. The results of this study also indicate that rip density decreases with increasing wave height, wave period, surf zone width, wave energy, and wave power, thus providing quantitative links between observed rip density and regional wave climate.

ADDITIONAL INDEX WORDS: *Rip currents, rip spacing, wave climate, intermediate beaches.*

INTRODUCTION

One of the most interesting features of rip currents, the strong and narrow currents which flow seaward across the surf zone, is their relatively regular spacing in the longshore direction. This commonly observed characteristic was described by the early studies of SHEPARD *et al.* (1941), SHEPARD and INMAN (1951), INMAN and QUINN (1952) and MCKENZIE (1958) who generally found that the size and number of rips on a beach is strongly and positively related to the wave energy level. With large waves, only a few large rips are produced, whereas when the waves are smaller the rips are smaller in size and spacing and subsequently more numerous. Existing theoretical investigations of rip spacing have been incorporated into the various mechanisms proposed for rip current generation, such as edge waves (BOWEN, 1969; BOWEN and INMAN, 1969), instability theory (HINO, 1974; 1976), intersecting wave trains (DALRYMPLE, 1975), and wave-current interactions (LEBLOND and TANG, 1974; DALRYMPLE and LOZANO, 1978). HINO (1974) suggested that rip spacing is equal to four times the surf zone width (x_s), but other workers have shown that this value can range from 1.5 to 8 (BOWEN and INMAN, 1969; SASAKI and HORIKAWA, 1975; SHORT, 1985) and rip spacing can range from 50–800 m (SHORT, 1985). In reality, most of the theoretical approaches still lack rigorous verification in the field and no approach has proven completely successful in predicting rip spacings on natural beaches.

Using an extensive dataset based on both qualitative and quantitative observations obtained from Narrabeen Beach, NSW, Australia, SHORT (1985) demonstrated that rip spacing (y_r) was directly related to the dimensionless fall velocity parameter $\Omega = H/w_sT$ (GOURLAY, 1968) where H is the breaker wave height, T the incident wave period and w_s the sediment fall velocity (DEAN, 1973). The dependence of y_r on Ω was reexamined by HUNTLEY and SHORT (1992) since it seemed counter-intuitive that shorter-period waves would produce larger rip spacings. They demonstrated quantitatively that rip spacing depends primarily upon breaker height and sediment fall velocity, and increases with increasing wave height and surf zone width and decreasing sediment size, and found a weak trend towards increased spacing with increasing wave period.

At present, however, there is still no adequate explanation for the variation in rip spacing between different beaches and this is largely due to an overall lack of field observations cov-

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ering a wide-range of wave environments. It is reasonable to assume that no single theory can adequately account for the spacing of rip currents and that it is a combination of driving mechanisms and physical boundary conditions which produce the observed rip current patterns on natural beaches. Rip currents and their associated rhythmic beach topography are now recognised as an integral component of intermediate beach types (WRIGHT and SHORT, 1984). Intermediate beaches however, occur almost worldwide and exist under a wide range of environmental conditions (SHORT, 1986). As the scale of beach systems varies, so too does the associated size and spacing of rip currents. Since the application of various theoretical models towards explaining and, indeed, predicting, rip spacing has proven difficult, it is possible that a detailed examination of rip spacing on a range of beaches exposed to different wave climates and sediment regimes may prove valuable in providing greater insight into the range and possible controls of rip current spacing.

Rip spacing is important because rip currents are a major component of the cellular surf zone circulation which characterises intermediate beaches (WRIGHT and SHORT, 1984). They are usually the dominant mechanism for offshore transport of water and sediment within these systems (BRANDER, 1997). As such, their dimensions and spacings are both a prominent indicator of overall surf zone circulation and sediment transport, as well as indicative of the prevailing environmental parameters that influence their spacing. Furthermore, rip spacing is also a major factor in assessing the recreational hazard potential of particular beaches, as rips account for the vast majority of surf rescues in Australia (SHORT and HOGAN, 1994), the United States (GOULD, 1997), Columbia (ZAUCHER, 1997) and Brazil (HOEFEL and KLEIN, 1998).

The aim of this study is to provide a preliminary description of the variation in rip spacing, and hence rip density, on intermediate beaches found under a range of regional wave environments. Data are primarily derived from aerial photographs of selected Australian beaches in contrasting wave environments and is supplemented by suitable datasets contained in the literature from a variety of sites in Europe, the United States, Japan, South Africa and New Zealand. The dataset is restricted to inner bar rip spacings on mostly transverse bar and rip beaches (WRIGHT and SHORT, 1984) which are of sufficient length not to be influenced by headland and embayment controls (MARTENS et al., in press). An additional aim is to suggest possible large-scale environmental controls of rip density for these beaches.

DATABASE AND METHODS

Data for this study are restricted to intermediate beaches, particularly those exhibiting transverse bar and rip morphology, and consist of information on beach system morphology, extending from the subaerial beach seaward through the surf zone to the offshore extent of the inner bar, as well as variables that contribute to surf zone morphology such as wave climate and sediments. The primary beach and rip morphometric variables consist of rip spacing (y_r), surf zone width (x_s), beach type according to the model of WRIGHT and SHORT (1984), and a new dimensionless variable termed rip density (RD) defined as:

$$RD = L_b/y_r \quad (1)$$

where L_b is beach length, and may encompass an entire beach or a particular stretch of beach. In this study, L_b was set to 1000 m so that RD values are equivalent to the number of rips per km of beach. Additional variables included mean grain size (D) and nearshore gradient (tanβ). Wave climate variables consist of either significant (H_s) or deepwater wave height (H_o), depending on availability of information, and mean incident wave period (T).

Both the spatial and temporal sampling procedures adopted by this study were largely pre-determined by the nature and availability of data, which varied considerably, and it was not always possible to obtain information on all of the aforementioned variables. Data were obtained from three sources: i) existing data within the literature; ii) direct measurements made in the field; and primarily iii) analysis of aerial photographs (Table 1). Existing information was obtained from a variety of locations, including California (SHEPARD and INMAN, 1950), South Africa (HARRIS, 1967), Florida (SONU, 1972), Japan (SASAKI, 1977), Northern Ireland

Table 1. *Sources and locations of data used in the study. Acronyms for various locations are given in parentheses.*

Source	Location
1) Published Data	
Shepard and Inman (1950)	Scripps Beach, California
Shepard and Inman (1951)	Torrey Pines Beach, California
Sasaki (1977)	Ajigaura Beach, Japan
Sasaki (1977)	Kashiwazaki Beach, Japan
Sasaki (1977)	Kashima Beach, Japan
Sasaki (1977)	Kujuukuri Beach, Japan
Sasaki (1977)	Shoonan Beach, Japan
Shaw (1985)	Renkerry Strand, N. Ireland
Sonu (1972)	Seagrove Beach, Florida
Harris (1967)	Virginia Beach, South Africa
Short (1985)	Narrabeen Beach, NSW, Australia
Short (1991; 1992)	Central Netherlands Coast
Brander and Short (in prep.)	Muriwai Beach, New Zealand
2) Aerial Photographs	
Beach Protection Authority, QLD.	Ramsay Bay, QLD., Australia (RAMSAY)
Beach Protection Authority, QLD.	Wide Bay, QLD., Australia (WIDE)
Coastal Management Group, Department of Land and Water Conservation, N.S.W.	Broadwater Beach, NSW, Australia (BROAD)
Coastal Management Group, Department of Land and Water Conservation, N.S.W.	Stockton Beach, NSW, Australia (STOCK)
Royal Australian Survey Corps	90 Mile Beach, VIC., Australia (90MILE)
Royal Australian Survey Corps	Discovery Bay, VIC., Australia (DISBAY)
Port of Melbourne Authority	Seaford, VIC., Australia (SEA)
Dept. of Lands, S.A.	Gunyah Beach, S.A. (GUNYAH)

Table 2. *Aerial photograph information for Australian dataset. B/W = black and white; C = colour. Acronyms are used as defined in Table 1.*

Location by State	Date	Scale	Colour	Coverage (km)	# RIPS
QUEENSLAND:					
RAMSAY	20/7/87	1:12000	C	7	77
WIDE1	31/5/62	1:86200	B/W	19	40
WIDE2	6/7/67	1:86240	B/W	90	100
N.S.W.:					
BROAD1	21/5/67	1:10000	B/W	4	23
BROAD2	23/6/87	1:10000	C	27	116
BROAD3	12/5/94	1:10000	C	27	140
BROAD4	30/6/96	1:10000	C	30	80
STOCK1	26/10/51	1:28600	B/W	10	47
STOCK2	21/5/76	1:24000	C	29	48
STOCK3	17/11/76	1:8000	C	30	36
STOCK4	18/3/81	1:20000	C	24	26
STOCK5	27/11/81	1:20000	C	32	66
STOCK6	18/1/84	1:20000	C	24	53
STOCK7	22/5/86	1:16000	C	30	71
STOCK8	10/8/91	1:16000	C	29	24
STOCK9	19/6/94	1:16000	C	29	67
STOCK10	1/12/96	1:16000	C	29	113
VICTORIA:					
90MILE1	7/2/65	1:86200	B/W	37	11
90MILE2	3/5/67	1:86200	B/W	18	23
DISBAY1	8/2/66	1:86365	B/W	18	34
SEA1	7/1/60	1:7920	B/W	2	18
SEA2	30/7/60	1:7920	B/W	3	9
SEA3	29/12/68	1:7990	C	3	26
SEA4	14/1/72	1:10000	B/W	5	43
SEA5	18/1/74	1:10525	B/W	3	26
SEA6	7/7/76	1:5000	C	3	23
SEA7	22/12/76	1:10000	C	4	14
SEA8	16/4/77	1:10000	B/W	3	21
SEA9	13/12/77	1:10575	B/W	5	34
SEA10	9/12/80	1:10400	B/W	3	24
SEA11	4/5/81	1:10400	B/W	2	18
SEA12	12/11/82	1:10400	B/W	9	34
South Australia:					
GUNYAH1	8/2/73	1:40000	B/W	20	32
GUNYAH2	20/2/79	1:40000	C	14	26

(SHAW, 1985), the central Netherlands (SHORT, 1991; 1992) and New Zealand (BRANDER and SHORT, in prep.)

Australian beaches were used as the prime source of information for two reasons: i) they exhibit most, if not all, of the ranges of beach scales and wave environments described in this study; and ii) they have satisfactory aerial photograph coverage of the entire coast, from which the beaches were selected (Table 2). The use of aerial photographs provides a relatively quick and inexpensive means to obtaining a data set that would otherwise be logistically difficult, if not impossible, but there are also drawbacks to this approach. While the Australian coast has 100% spatial coverage, temporal coverage varies considerably between states, with New South Wales having the best coverage (up to 20 flights, Table 2), while some states have as few as three repetitive flights. The representativeness of the photographs is therefore compromised by the extent of temporal coverage.

In addition, other factors eliminated some photographs or parts of photographs from the study. These included glare or cloud cover, which obscured the surf zone, small scale of photograph which did not permit sufficiently accurate measurements, and prevailing surf conditions. The latter did not always reveal rips because they were either not present, or high waves and more dissipative surf zones made them difficult to observe and measure. As a consequence, an exhaustive examination of aerial photographs from the New South Wales coast found that only about a third of all existing photographs were suitable for taking measurements of rip spacing and beach morphology. Therefore, the photo series listed in Table 2 represent the best data available from those particular sites.

Rip location was recorded for all rips visible on the aerial photographs and estimated error ranged from ± 10 m at photograph scales of approximately 1:10 000 and ± 50 m at scales of up to 1:80 000. To account for spatial variation, the beach/rip type (LBT = longshore bar and trough; RBB = rhythmic bar and beach; TBR = transverse bar and rip; LTT = low tide terrace) was determined from the bar and beach morphology at a sampling interval of 1 km. Surf zone width was measured seaward from the visible high tide mark. Where possible, the longshore length of individual rip systems (L_r) and the width of the rip channel (w_r) were also recorded. A mean value of rip spacing and rip density was computed for each beach series, but it was not uncommon for the beach type and rip spacing to vary along the beach. Similarly, rip spacing and beach type can vary over time, and in order to obtain gross representative values, x_s, y_r and RD for a given site were averaged when multiple photographic series were available. Wave and sediment characteristics for the beaches, where available, were obtained from a variety of sources which are referred to in Table 3.

RIP DENSITY AND REGIONAL WAVE ENVIRONMENTS

The locations of the various beach sites used in this study are shown in Figure 1. All of these sites are intermediate beaches and all are characterised by the presence of rip currents. In order to describe the variation of rip density on a global scale, the coastal morphogenic approach described by DAVIES (1964; 1980) was used as a conceptual basis to describe four wave regimes: (i) west coast swell; (ii) east coast swell; (iii) trade wind; and (iv) storm wave dominated environments (Figure 1). All of the data obtained from the literature fall within these categories and the representative Australian sites used for aerial photographic analysis were chosen based on this classification. The beach sites correlate well with the classification by DAVIES (1980), but their global distribution is restricted by the availability of data and it is emphasised that the results of this study are therefore based on representative sites and case examples. The database used for this study is given in Table 3 and is summarised in Table 4. The latter contains mean values of variables wherever possible in order to simplify comparisons between the four global wave environments. It was often difficult to find comparable and consistent wave climate variables for H and T, and in some case estimates were used. The wave characteristics and

Table 3. *Database of wave climate and rip density variables for field sites.* H = *mean breaking wave height;* T = *mean wave period; tanβ = nearshore gradient; BT = beach type (LTT = 2; TBR = 3; RBB = 4; LBT = 5);* x_s = *surf zone width;* y_r = *rip spacing;* σ = *standard deviation;* RD = *rip density. Asterisks denote wave height and wave period values based on in-situ measurements. n/a = not available.*

Site	Type	H (m)	T (s)	tanβ	BT	x_s (m)	y_r (m)	σ (m)	RD
Scripps Beach, California*	WCS	2.1	10.3	0.016	n/a	160	790	n/a	1.3
	WCS	2.6	7.6	0.016	n/a	200	250	n/a	4.0
	WCS	2.6	7.6	0.016	n/a	200	750	n/a	1.3
	WCS	2.2	7.3	0.016	n/a	170	510	n/a	2.0
	WCS	4.1	8	0.016	n/a	310	400	n/a	2.5
	WCS	4.1	8	0.016	n/a	310	800	n/a	1.3
Torrey Pines Beach, California*	WCS	1.5	12	n/a	n/a	n/a	553	58	1.8
Virginia Beach, S. Africa*	WCS	1.5	8	0.031	n/a	140	560	n/a	1.8
Muriwai Beach, N.Z. (1)	WCS	2.5	15	0.021	5	300	741	389	1.4
	WCS	2.5	15	0.021	3	300	357	123	2.8
Gunyah Beach, S.A. (2)	WCS	2	12	n/a	3	100	524	157	1.9
	WCS	2	13	n/a	3	106	505	153	1.9
Discovery Bay, Vic. (3)	WCS	2	13	n/a	3	143	512	186	2.0
Ajigaura Beach, Japan*	ECS	1.1	10	0.018	n/a	90	413	n/a	2.4
	ECS	0.8	7	0.018	n/a	50	375	n/a	2.7
	ECS	0.6	7.5	0.018	n/a	70	200	n/a	5.0
	ECS	2.4	10.6	0.018	n/a	130	433	n/a	2.3
Kashiwazaki Beach, Japan*	ECS	1.3	7	0.018	n/a	60	190	n/a	5.3
	ECS	0.8	8.5	0.018	n/a	60	270	n/a	3.7
Kashima Beach, Japan*	ECS	0.9	9.7	0.03	n/a	70	300	n/a	3.3
	ECS	1.4	8.5	0.025	n/a	43	230	n/a	4.3
	ECS	1.4	7	0.029	n/a	150	430	n/a	2.3
Kujuukuri Beach, Japan*	ECS	0.9	6.3	0.013	n/a	84	150	n/a	6.7
	ECS	0.9	9.6	0.012	n/a	65	260	n/a	3.8
	ECS	0.8	6	0.014	n/a	40	128	n/a	7.8
	ECS	0.8	6	0.014	n/a	50	164	n/a	6.1
	ECS	1.9	6.5	0.014	n/a	90	193	n/a	5.2
Katsuura Beach, Japan*	ECS	n/a	n/a	0.015	n/a	130	410	n/a	2.4
	ECS	n/a	n/a	0.015	n/a	30	130	n/a	7.7
	ECS	n/a	n/a	0.015	n/a	70	290	n/a	3.4
Narrabeen Beach, NSW (4,5)	ECS	1.5	10	0.03	3	80	188	100	5.3
Stockton Beach, NSW (5,6)	ECS	1.5	10	0.021	4.2	130	186	69	4.8
	ECS	1.5	10	0.021	3.1	91	291	1148	3.7
	ECS	1.5	10	0.021	2.9	106	239	102	3.8
	ECS	1.5	10	0.021	3	63	177	114	4.9
	ECS	1.5	10	0.021	3	90	202	104	4.9
	ECS	1.5	10	0.021	2.7	82	200	61	5.0
	ECS	1.5	10	0.021	3.1	87	216	52	3.6
	ECS	1.5	10	0.021	3	95	294	64	3.6
	ECS	1.5	10	0.021	2.8	61	142	110	7.0
	ECS	1.5	10	0.021	3	71	163	82	6.0
Broadwater Beach, NSW (5)	ECS	1.5	10	n/a	3	157	177	71	5.7
	ECS	1.5	10	n/a	2.9	128	204	90	4.4
	ECS	1.5	10	n/a	3	148	190	107	5.3
	ECS	1.5	10	n/a	3.5	182	225	87	4.4
Wide Bay, QLD. (2)	ECS	1.4	10	n/a	3	56	229	122	4.3
	ECS	1.4	10	n/a	3.5	81	304	109	3.3
Renkerry Strand, N. Ireland	ECS	1	9	0.021	3	75	174	42	5.7
Central Netherlands Coast	SWS	1	5	0.013	2.5	80	500	308	2.0
90 Mile Beach, Vic. (3,7)	SWS	1.6	8.5	0.002	3	82	351	150	3.2
Seagrove Beach, Florida	MWS	0.4	5	0.029	n/a	20	60	n/a	16.7
Ramsay Bay, QLD. (2)	MWS	0.5	4	n/a	3	60	82	15	9.7
Seaford, Vic. (3)	SWB	0.5	5	0.01	3	52	75	36	12.7
	SWB	0.5	5	0.01	3	61	108	28	9.3
	SWB	0.5	5	0.01	2.7	43	62	23	14.7
	SWB	0.5	5	0.01	3.2	42	78	36	11.9
	SWB	0.5	5	0.01	3.3	53	94	36	9.0
	SWB	0.5	5	0.01	3	30	67	26	14.8
	SWB	0.5	5	0.01	3.3	53	111	32	9.0
	SWB	0.5	5	0.01	3	57	91	26	10.6
	SWB	0.5	5	0.01	3.2	53	84	26	11.6
	SWB	0.5	5	0.01	3.7	59	93	93	10.7
	SWB	0.5	5	0.01	3	57	102	40	8.1
	SWB	0.5	5	0.01	3.1	47	115	47	7.1

(1) Brander and Short (in press); (2) Short, field data; (3) Short (1996); (4) Short (1985); (5) Short (1993); (6) Roy and Crawford (1980); (7) Wright et al. (1982)

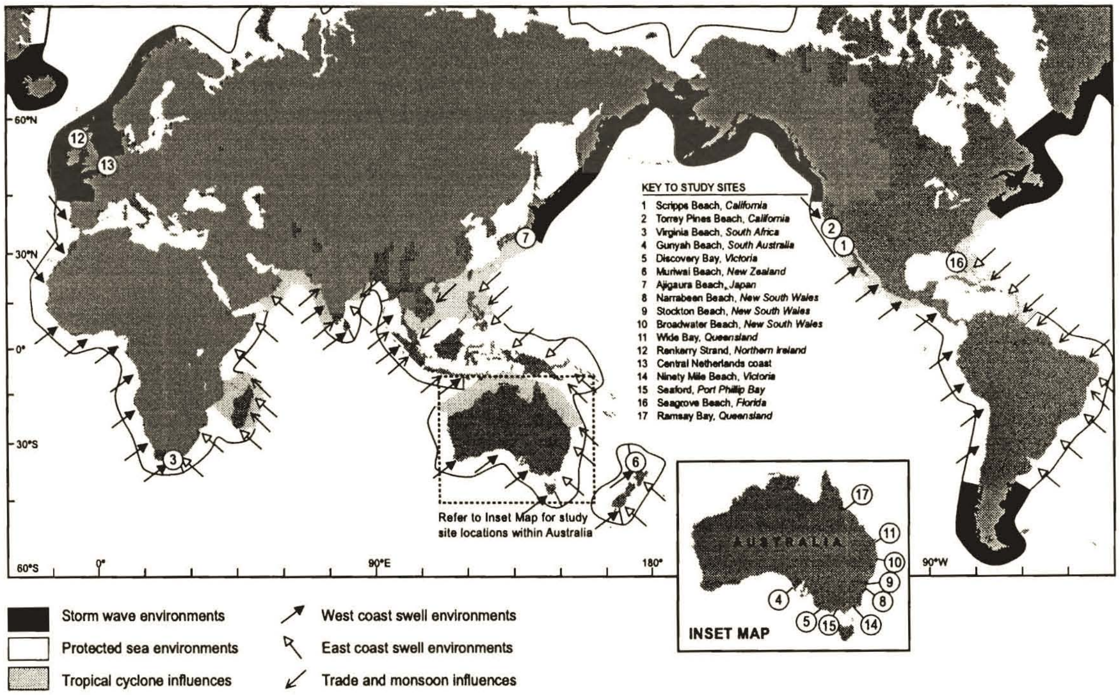

Figure 1. Location of database beach locations and the distribution of major world wave environments based on the classification of DAVIES (1980).

patterns of rip density in each of these environments are now described in detail.

WEST COAST SWELL (WCS)

The west and/or south coasts of the Americas, Africa, Australia and New Zealand all receive north/south westerly swell which originates in the northern/southern belt of mid-latitude cyclones, which occur seasonally in the northern hemisphere, and year round in the southern hemisphere (DAVIES, 1980). Typical west coast swell waves are long and moderate to high energy. They are relatively consistent in occurrence and direction (north-west or south-west) and span vast areas of the ocean and impact most on mid to low-latitude west to polar facing coasts. They are considered the most homogenous global wave environment, although towards the tropics they can be affected seasonally by trade and monsoonal winds and tropical cyclones (hurricanes) (DAVIES, 1980). As shown in Figure 1, beaches characterised by west coast swell in this study include sites from southern coastal Australia (Gunyah Beach, S.A. and Discovery Bay, Vic.), Southern California (Scripps Beach and Torrey Pines Beach), the southern Natal coast in South Africa (Virginia Beach) and the west coast of the north island in New Zealand (Muriwai Beach).

The summary results in Table 4 clearly illustrate that of all the global wave environments, west coast swell beaches are characterised by the largest and longest waves, the widest surf zones, the greatest rip spacings, and the smallest rip densities. Representative WCS beaches were characterised by wave heights ranging from 1.5–3 m with $\bar{H}$ = 2.1 m and incident wave periods ranging from 8–13 s with $\bar{T}$=11 s. Although the variance in spacing within sites was on the order of 100–200 m, rip spacing was extremely consistent between sites (σ = 25 m) with $\bar{y}_r$= 545 m (Table 4). Rip density was thus equally invariant, ranging from 1.8–2.1 with an average *RD* of value of 2. The data for Muriwai Beach (Table 3) reflect spacing conditions recorded at both the beginning and end of an accretion sequence, but long-term video observations suggest that the mean rip spacing on this beach is more commonly on the order of 600–800 m (P. OSBORNE, *pers. comm.*)

EAST COAST SWELL (ECS)

The source of swell in east coast environments is more variable than west coast swell regimes, and mean energy levels are relatively moderate in comparison even though many of these coastlines are prone to tropical and extra-tropical cyclones (DAVIES, 1980; SHORT and TRENAMAN, 1992). Although east coast swell environments include the east coasts of Africa, South-East Asia, South America, the United States and the Caribbean, this study examines representative beaches from the east coast of Japan, just north of Tokyo, and the east coast of Australia (Narrabeen Beach, Stockton Beach, Broadwater Beach, and Wide Bay, Fraser Island). Although the entire Irish coastline is classified as a storm wave environment (Figure 1) by DAVIES (1980), Renkerry Strand in Northern Ireland is included here as an ECS environment since it faces north-west and receives refracted Atlantic swell (SHAW, 1985).

The results summarised in Table 4 reflect the more moderate energy conditions of east coast swell beaches in comparison with west coast swell beaches in all respects. Wave

Table 4. *Summary of wave climate and rip density data.* H = *mean breaking wave height;* T = *mean wave period; tanβ = nearshore gradient; BT = beach type (LTT = 2; TBR = 3; RBB = 4; LBT = 5),* x_s = *surf zone width;* y_r = *rip spacing,* σ = *standard deviation;* RD = *rip density. Asterisks denote wave height and wave periods based on in-situ measurements. Note that* σ *in the main body of the table refers to within variation whereas in the summary of mean values it represents between sites variation. n/a = not available.*

Site	Type	H (m)	T (s)	tanβ	BT	x_s (m)	y_r (m)	σ (m)	RD
Scripps Beach, California*	WCS	3	8.1	0.016	n/a	225	583	211	2.1
Torrey Pines Beach, California*	WCS	1.5	12	n/a	n/a	n/a	553	58	1.8
Virginia Beach, S. Africa*	WCS	1.7	8	0.021	n/a	143	558	137	1.8
Gunyah Beach, S.A.	WCS	2	12	n/a	3	103	515	155	1.9
Discovery Bay, VIC.	WCS	2	13	n/a	3	143	512	186	2.0
Muriwai Beach, N.Z.	WCS	2.5	13	0.01	4	300	549	201	2.1
Ajigaura Beach, Japan*	ECS	1.1	7.9	0.018	n/a	75	269	105	4.4
Narrabeen Beach, NSW	ECS	1.5	10	0.03	3	80	188	100	5.3
Stockton Beach, NSW	ECS	1.6	10	0.021	3.1	88	211	91	4.7
Broadwater Beach, NSW	ECS	1.6	10	n/a	3.1	84	199	89	5.0
Wide Bay, QLD.	ECS	1.4	10	n/a	3.2	81	227	101	4.8
Renkerry Strand, N. Ireland	ECS	1	9	0.021	3	75	174	42	5.7
Central Netherlands Coast	SWS	1	5	0.013	2.5	80	500	308	2.0
90 Mile Beach, VIC	SWS	1.6	8.5	0.02	3	82	351	150	3.2
Seaford, Port Philip Bay	SWB	0.5	5	0.01	3.1	51	90	37	10.8
Seagrove Beach, Florida	MWS	0.4	5	0.029	n/a	20	60	n/a	16.7
Ramsay Bay, QLD	MWS	0.5	4	n/a	3	60	82	15	9.7
MEAN	WCS	2.1	11.0	0.016	3.3	183	545	25	2.0
MEAN	ECS	1.4	9.5	0.023	3.1	81	211	31	5.0
MEAN	SWS	1.3	6.8	0.017	2.8	81	426	75	2.6
MEAN	SWB	0.5	5.0	0.010	3.1	51	90	37	10.8
MEAN	MWS	0.5	4.5	0.029	3.0	40	71	15	13.2

heights were much lower, ranging from 1–1.6 m with $\bar{H}$=1.4 m, and wave periods were shorter, ranging from 8–11 s with $\bar{T}$= 9.5 s. Surf zone width was also much narrower with $\bar{x}_s$= 92 m compared to 154 m for WCS beaches. The variance in rip spacing within sites was much less than on WCS beaches, ranging from 40–100 m. Rip spacing was considerably less on ECS beaches, but was equally consistent between sites (σ = 31 m), with $\bar{y}_r$= 211 m. The increased number of rips on ECS beaches is evident by the higher rip density value of $\bar{RD}$= 5 that characterises these beaches.

WIND WAVE ENVIRONMENTS (WW)

Wind wave environments are characterised by locally generated wind waves, with little or no swell. The wind waves are short in period and, depending on the dominant wind and fetch, can range in height to several meters, and in frequency from periodic to seasonal. A distinction in made in this study between wind wave environments exposed to periodic high velocity winds associated with mid-latitude cyclones, and those exposed to moderate velocity trade winds. Finally, whereas seas may receive limited swell, bays receive no swell and are therefore treated separately.

Strong Wind Seas (SWS)

The two strong-wind-sea sites used in this study are exposed to periodic high velocity westerly winds associated with the passage of mid-latitude cyclones across the North Sea in the case of the central Netherlands coast (51°N), and across eastern Bass Strait in the case of Ninety Mile Beach, Vic. (38°S) (Figure 1). Both sites are characterised by inherently complex wave climates and this is reflected in the results shown in Table 4. With the absence of significant swell, it is not surprising that values of $\bar{H}$ and $\bar{T}$ are further reduced in SWS environments at 1.3 m and 6.8 s respectively. Similarly, surf zone widths are narrower with $\bar{x}_s$ = 81 m. The most distinctive characteristics of SWS beaches, however, is the surprisingly large rip spacing values ($\bar{y}_r$ = 426m) and the relatively large variability in y_r both within sites (σ = 150–300 m) and between sites (σ = 75 m). As a result, a mean value for rip density of 2.6 is more comparable to that of high-energy WCS beaches.

The variability of results for SWS beaches can be explained by examining the wave climates of the particular sites in closer detail. For example, the most unusual results are those from the central Netherlands coast (SHORT, 1991; 1992), where $\bar{y}_r$ = 500 m and RD = 2 (Table 4), which are almost exactly the same as the results for WCS beaches, despite the fact that $\bar{H}$ and $\bar{T}$ are completely different in this region at 1 m and 5 s respectively. As noted by SHORT (1992), however, the North Sea wave climate is extremely variable and it is not uncommon for waves to exceed 1.5 m some 30–40 times a year. Since beach change is driven by temporal variations in wave conditions, it is likely that the rip spacing observed in this environment is generated by the lower frequency, but higher storm waves, rather than modal energy conditions. This storminess factor is also characteristic of Ninety Mile Beach in Victoria, which has a complex wave climate strongly influenced by locally generated wind waves related to the passage of cyclones and gales, but with background low south easterly swell (SHORT, 1996). WRIGHT et al. (1982) report that the average interval separating the occurrence of deepwater waves of 2 m or more in height in this region is a little less than 3 days, so it is not surprising that values of $\bar{y}_r$ and $\bar{R}D$ (351 m and 3.2 respectively) are comparable to those found on WCS and ECS beaches.

Strong Wind Bays (SWB)

Bays receive no swell and rely entirely on local winds for wave generation. Port Phillip Bay, Victoria, Australia (38°S; Figure 1) receives no swell, has a maximum fetch of 60 km and along its eastern shore is exposed to periodic strong westerly winds associated with the passage of mid-latitude cyclones, the same that generate the bigger seas along Ninety Mile Beach, approximately 250 km to the west. Within the bay, wave period peaks at 5 s and heights at 3 m. Between the storm waves are longer periods of calms, and little activity in the surf, resulting in a modal wave height of only 0.5 m. The bar and rip systems are entirely generated by the less frequent wind waves. The Seaford site is characterised by a narrow inner bar surf zone width ($\bar{x}_s$= 51 m) and closely spaced rips with $\bar{y}_r$ = 90 m and a corresponding $\bar{R}D$ of approximately 11. Although none have been well-documented in the literature, rip spacing along suitable lacustrine coastlines would fall into this category.

Moderate Wind Seas (MWS)

Moderate wind seas exist in the mid- to low-latitudes, particularly in the trade wind belt, in sea areas protected from ocean swell by coral reefs and by physical location in large gulfs and seas. They differ from the foregoing fetch limited sites in that the winds rarely exceed 20 ms^{-1} and, consequently, waves rarely exceed 1.5 m, while wave periods remain short (2–5 s). Ramsey Bay on Queensland's Hinchinbrook Island (18°S; Figure 1) faces squarely into the prevailing, moderate velocity, south-east trade winds. The Great Barrier Reef eliminates most swell and limits fetch to between 50–100 km. Waves average only 0.5 m in height with maximums of approximately 1.5 m and wave periods are on the order of 4 seconds. These conditions produced the most regularly spaced rips (σ = 15 m) in the dataset with $\bar{y}_r$= 82 m. Seagrove Beach on the Florida Panhandle (30°N; Figure 1) is dominated by afternoon sea breeze conditions during summer with wave heights of 0.5–0.6 m and wave periods of 2–3 s (SONU et al., 1973). Under similar conditions, SONU (1972) recorded rip currents with an average spacing and rip density of 60 m and 16.6 respectively (Table 4). By combining the two datasets, this environment produces the most closely spaced rips $\bar{y}_r$= 71 m) and therefore, the greatest rip density ($\bar{R}D$= 13).

RIP DENSITY AND BEACH SCALE

While all of the rips analyzed can be classified as transverse bar and rip types (WRIGHT and SHORT, 1984), they vary in scale by over an order of magnitude, with the most closely spaced rips only 60 m apart (Seagrove Beach) compared to rips identical in type averaging almost 800 m apart (Muriwai Beach, Scripps Beach) (Table 3). Averaged rip densities in turn range from 17 down to 2 per kilometre of beach (Table 4). A number of other factors are also evident from these data. First is the remarkable consistency in rip densities between the grouped wave climate environments, with WCS rip density averaging 2, the ECS beaches 5, and the wind wave environments 2–3 for high-energy conditions (SWS) and up to 11 to 13 for the low- to moderate-energy beaches (SWB and MWS) (Table 4). In particular, the WCS and ECS grouped rip densities were almost identical despite the wide range of locations incorporated in each of the data sets (Table 3). Second is the potential scaling relationships of bar and rip morphology between sites since the mean values of rip density for the various environments shown in Table 4 indicate that *RD* on SWB and MWS beaches approximately 5 times greater than on WCS beaches and twice as great than on ECS beaches. Similarly, rip density on ECS beaches is 2.5 times greater than on WCS beaches.

To investigate whether these scaling factors were applicable to the entire beach and rip systems, the variation in *RD* and y_r, as well as the dimensions of the bars, rip channels, and surf zone width based on both aerial photograph and field data were plotted to scale in Figure 2. For WCS and ECS environments, mean values of *RD* and x_s were used (Table 4) with rip-neck width (w_r) representative of the Gunyah and Stockton Beach datasets respectively. For fetch limited wind wave environments, a composite between SWB and MWS data is presented. Muriwai Beach is included as an example of a WCS beach characterised by longshore bar, trough and rip morphology at a large spatial scale.

Although Figure 2 clearly illustrates the marked difference in rip density and spacing between WCS, ECS, and WW environments, it can also be argued that the same scaling factors evident in values of *RD* can be applied to other aspects of the beach system. For example, typical values of w_r ranged from an average of 56 m on Stockton Beach (551 rips, σ= 21 m) up to an average of 120 m on Gunyah Beach (58 rips, σ = 28 m), which is only slightly less than the 2.5 scale factor between WCS and ECS beaches. Similarly, rip widths at Ramsey Bay and Seaford were on the order of 20–30 m, which supports the scaling factors between WCS, ECS and WW environments. In addition, the matrix shown in Table 5 illustrates the comparison between scale factors based on rip density and those based on mean surf zone width (Table 4). Despite poor correlation in the case of SWB environments and WCS and ECS environments, the results are remarkably similar. The discrepancies may be explained by the difficulty in estimating surf zone width of SWB beaches (in this case Seaford, Port Phillip Bay) during the formation, or existance of actively flowing rips, since almost all of the aerial photographs were taken during periods of calm, when wave breaking is virtually absent. In general however, since surf zone width is a good indicator of the offshore extent of nearshore bars, it can be argued that the planform dimensions of bar morphology between the global wave environments are characterised by the same scale factors that exists for rip density and spacing.

Of all the global wave environments, sea environments characterised by strong winds are the most difficult to account for since they are characterised by rip density variables comparable to those for WCS environments (Table 4), which

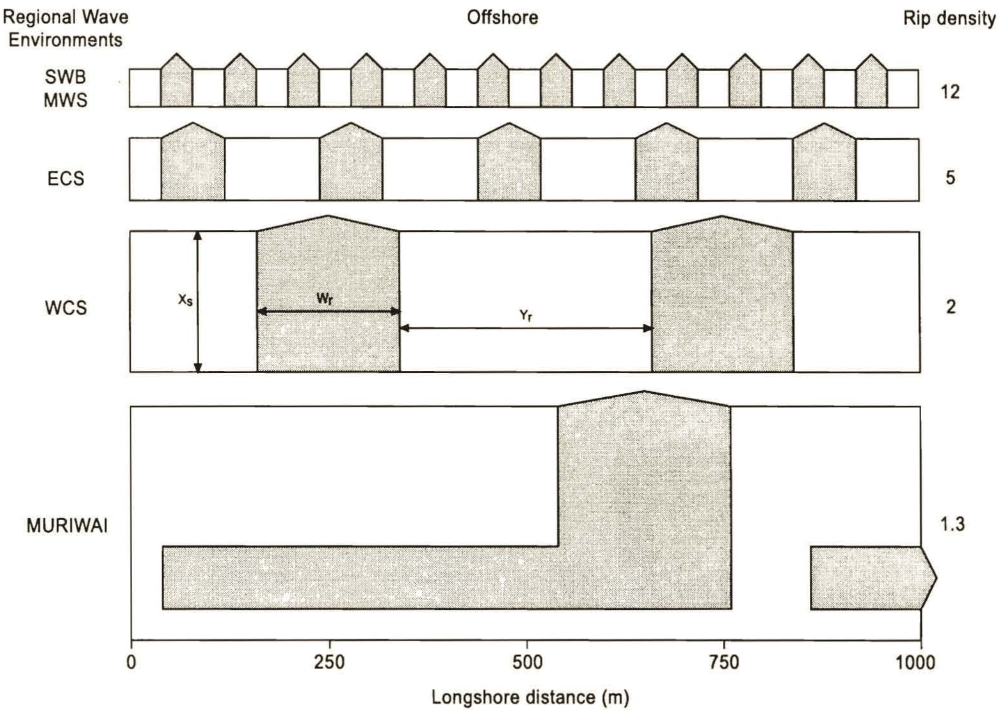

Figure 2. Variation in rip density by global wave environment where: SWB = strong wind bays; MWS = moderate wind seas; = ECS = east coast swell; and WCS = west coast swell. Shaded regions are rip currents where x_s = surf zone width; w_r = rip width; and y_r = rip spacing. Offshore distance is the same scale as the longshore distance.

seems incongruous. Both ECS and SWS environments can, however, exhibit rip densities typical of WCS environments under storm conditions, but given the almost constant presence of swell, ECS environments have a morphological configuration which is constantly changing, usually towards a greater rip density. SWS environments, on the other hand, are almost completely dependant upon antecedent bar morphology (SHORT, 1992), the scale of which is itself determined by the energy level of the storm. It is therefore not surprising that SWS environments have an average rip density value of 2.6. Similarly, given the variability in magnitude of storm events, it is not surprising that beaches in this environment were characterised by the highest variance in rip spacing measurements within sites with σ = 308 m for the Central Netherlands Coast (Table 3). Antecedent morphology is an equally important factor in SWB and MWS environments, but the variance in rip spacing is reduced by the more moderate and consistent wind regimes.

Table 5. *Matrix illustrating scaling relationships between global wave environments based on rip density (RD), shown in lighter shading, and surf zone width (x_s), shown in darker shading.*

	WCS	ECS	SWB	MWS
WCS	*1*	2.5	5	5
ECS		*1*	2	2
SWB			*1*	≦1
MWS				*1*

The amount of variance found in WCS environments can be explained by the fact that these systems, as illustrated by the Muriwai Beach example in Figure 2, exist at immense spatial scales and longshore variability is therefore inherently large. In the example shown, which represents conditions several weeks after a major storm event, the rip system consists of a 400 m longshore feeder channel with a width ranging from 50–100 m and a 150–200 m wide rip-neck channel extending approximately 300 m offshore (BRANDER and SHORT, in prep.). Although an extended period of 'calm' conditions (H_b < 2 m) enabled the system to evolve towards a transverse bar and rip state with correspondingly shorter rip spacing (Table 3), this latter scenario is extremely rare (P. OSBORNE, *pers. comm.*).

POTENTIAL CONTROLS ON RIP DENSITY

As described in the introduction, previous findings in the literature suggest that rip density should decrease with increasing wave height, wave period and surf zone width (SHEPARD and INMAN, 1951; MCKENZIE, 1958; HINO, 1974; SHORT, 1985; HUNTLEY and SHORT, 1992) and decreasing sediment size (SHORT, 1985; HUNTLEY and SHORT, 1992). An

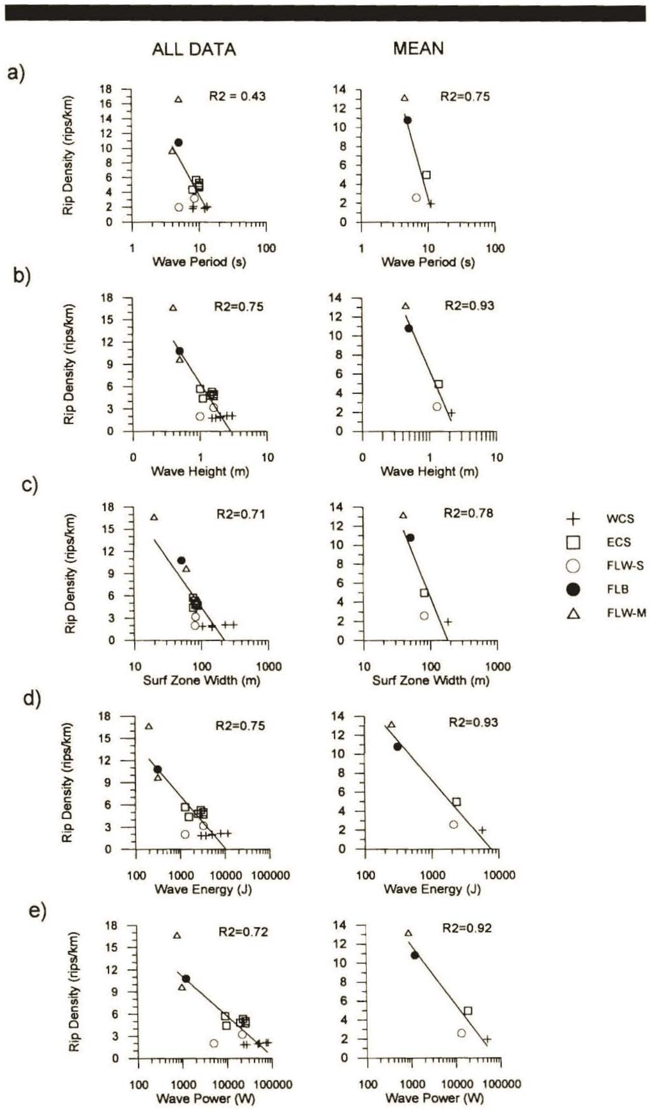

Figure 3. Relationships between RD and: a) wave height, H; b) wave period, T; c) surf zone width, x_s; d) wave energy, E ($= 0.125\rho g H^2$, where ρ is density of salt water); and e) wave power, P ($=0.25\rho g(H/2)^2(gT/2\pi)$), where g is gravity (CERC, 1984)). Plots in the left column show all of the data between sites whereas plots on the right column show mean values for each regional wave environment. Data is based on values shown in Table 4. Note the logarithmic x-axis and the R^2 value for the logarithmic function plotted on each graph.

advantage of this study is that these trends can be examined with data from a variety of sites having a wide range of H, T and RD as opposed to only a single location. Unfortunately, it is not possible to comment on the role of sediment size due to lack of information, but there does not appear to be any distinct trend between $\tan\beta$ and RD based on the results shown in Table 4. As shown in Figure 3, however, rip density does tend to decrease with increasing H, T, x_s, wave energy (E), and wave power (P).

Although it is not the intention of this study to provide predictive formulas for the variation in rip density, each case in Figure 3 is described well by a logarithmic function. These trends are all significant at the 0.01 confidence level, but are stronger in the plots displaying the mean values for each global wave environment rather than those showing data from all of the sites (Table 4). In both cases, most of the apparent scatter can largely be attributed to the dataset from the central Netherlands coast. This is not unexpected since, as explained previously, rip densities in SWS environments are quite inconsistent due to inherent climatic variability and antecedent morphology. It is particularly encouraging that a strong relationship exists between wave power and RD ($R^2 = 0.72$ and 0.92; Figure 3) since wave power incorporates both H and T and provides a quantitative link between global wave climate and rip density.

CONCLUSIONS

Rip currents are an integral part of all intermediate beach systems, and as such are a major feature of the world's sandy beaches. While a global classification of wave climates was developed by DAVIES (1964), and rip spacing has previously been related to surf zone width (HINO, 1974) and level of wave energy (SHORT, 1985), this study has identified a strong relationship between rip density and and levels of wave energy, which in turn is closely related to regional wave climate. Five distinct global wave climates were identified, with west coast swell (WCS) beaches having the lowest rip density of 2 rips/km and fetch-limited bays (SWB) and moderate wind environments (MWS) having the highest at 11–13 rips/km. East coast swell (ECS) beaches are characterised by rip densities on the order of 5 rips/km, with fetch-limited wind-wave environments with strong winds (SWS) falling somewhere in between the range for WCS and ECS beaches.

Distinct scaling relationships were evident between global wave environments, with the greatest rip densities on severely fetch limited bays and moderate wind seas (RD = 11–13), while the largest rips and smallest densities (RD = 2–3) occur in WCS and high-energy seas, with ECS rip densities being on the order of 5. There is also evidence to suggest that a similar range of scaling exists between the wave environments and the width of the surf zone and rip channel. The results of this study also indicate that rip density decreases with increasing wave height, wave period, surf zone width, wave energy and wave power, with each relationship being described best by a logarithmic relationship (Figure 3).

Clearly, the ability to predict the number and size of rips occurring on a beach is critical to our understanding of surf zone circulation, sediment transport and shoreline change, as well as the relative hazards of the beach to the bathing public. Similarly, the classification presented in this study is broad and simple by design, and more detailed measurements of rip spacings from a range of environments are necessary in order for the beach scaling factors and controls on rip density described in this study to be validated. Finally, one needs to ask to what degree are rip current flow velocities and dynamics influenced by rip size and density. Until these questions are answered, rips will continue to remain a highly visible, but still poorly understood component of intermediate surf zones.

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