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# Beach morphodynamics in a strong-wind bay: a low-energy environment?

B.W. Goodfellow*, W.J. Stephenson[1]

*Department of Geography, University of Melbourne, Victoria 3010, Australia*

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**Abstract**

The morphodynamic behaviour of a multibarred beach in a fetch-limited, strong-wind bay (Seaford Beach, SE Australia) was examined during both high- and low-energy conditions, and considered in the context of a definition of low-energy provided in the literature. Measurements of nearshore waves, currents, and morphology revealed a bimodal behaviour. Under initial low-energy conditions, the beach exhibited a "low-tide terrace" state, and waves and currents were of very low magnitude. During subsequent high-energy conditions, the beach demonstrated dynamic behaviour through the formation of a transitional "transverse bar and rip-rhythmic bar and beach," and migration of the middle bar, with the morphology remaining in an arrested high-energy state during intervening low-energy periods. Although broadly conforming to the morphodynamic model, the beach did exhibit some distinct characteristics attributable to its fetch-limited location; limited progression through the morphodynamic model; and the importance of wind direction and magnitude in governing morphodynamic behaviour. Furthermore, rip currents were not significant in driving beach change through intermediate states. The presence of infragravity energy in the storm wave spectra; a dissipative, multibarred surf zone; dynamic inner and middle bars; and the attainment of a "transitional transverse bar and rip-rhythmic bar and beach" state during rising wave conditions, underline Seaford Beach as "bimodal", exhibiting process and morphologic features of both higher- and lower-energy beaches. As an example of a beach in a strong-wind bay, Seaford, illustrates that not all fetch-limited beaches are low-energy. Furthermore, the presence of infragravity energy in a highly fetch-limited environment indicates that infragravity energy may occur commonly in fetch-limited environments that are subject to periodic strong winds; a process that has remained largely unrecognised.


*Keywords:* Seaford Beach; beach morphology; coastal morphodynamics; fetch-limited environment; wave climate; infragravity

## 1. Introduction

This paper reports an investigation of the morphodynamics of a supposedly "low-energy" beach in a fetch-limited embayment. Previous studies (Bauer and Greenwood, 1990; Ekwurzel, 1990; Jackson and

* Corresponding author. Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden. Fax: +46 8 164 818.

*E-mail addresses:* brad.goodfellow@natgeo.su.se (B.W. Goodfellow), wjs@unimelb.edu.au (W.J. Stephenson).

[1] Fax: +61 3 8344 4972.

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Nordstrom, 1992; Barusseau et al., 1994; Guillen and Palanques, 1996; Hegge et al., 1996; Masselink and Pattiaratchi, 1998) indicate that low-energy beaches exhibit variable behaviour and do not necessarily conform to Wright and Short's (1984) morphodynamic model (Hegge et al., 1996; Masselink and Pattiaratchi, 1998; Jackson et al., 2002). Consequently, further studies of a range of low-energy beaches are important for determining a global model of morphodynamics (Stephenson and Brander, 2003), and for clarifying the term "low-energy", which remains poorly defined in the literature.

According to Jackson et al. (2002), low-energy beaches occur where non-storm wave heights are very small (e.g. less than 0.25 m), and significant wave heights during strong onshore winds are low (e.g. less than 0.50 m). Additionally, beachface widths are narrow (e.g. less than 20 m in microtidal environments), and morphological features are inherited from higher-energy events. Jackson et al. (2002) also stated that there is little cross-shore sediment exchange on low-energy beaches.

Low-energy beaches are located in sheltered and/or fetch-limited environments. Sheltered environments occur in the lee of islands, reefs, or submarine ridges (Hegge et al., 1996), so are protected to varying degrees from higher-energy waves generated in larger adjacent bodies of water. Conversely, fetch-limited environments occur in lakes (Bauer and Greenwood, 1990, Allan and Kirk, 2000), bays (Ekwurzel, 1990), estuaries (Jackson and Nordstrom, 1992), and lagoons (Jackson et al., 2002), where limited fetch produces small waves that are, however, steep and erosive due to short periods (Battjes, 1974; Jackson et al., 2002). These wind waves are also less affected by wave refraction, so can approach the shoreline at large angles, generating strong longshore currents (Jackson et al., 2002). Furthermore, the dependence of wave generation on local winds means that fetch-limited beaches experience a highly variable wave climate, with periods of high waves interspersed with periods of calm (Jackson et al., 2002), while the absence of low-steepness, long-period swell waves from fetch-limited environments restricts the shoreward return of sediment (Dean, 1973, Wright and Short, 1984).

One type of fetch-limited environment is a strong-wind bay (Short and Brander, 1999). A strong-wind bay, such as Port Phillip Bay, Australia (Fig. 1), which receives minimal ocean swell and is dependent on local winds for wave development, is a typical fetch-limited environment. However, beaches such as Seaford (Fig. 1), located at exposed locations in Port Phillip Bay, have an unusual morphology, including multiple offshore bars and rip channels, for what is commonly considered a low-energy environment. Although multibarred beaches exist in fetch-limited locations (Dolan and Dean, 1985; Bocar-Karakiewicz and Davidson-Arnott, 1987), they are generally a feature of dissipative, high-energy surf zones (Wright and Short, 1984). Rip channels, on the other hand, are a feature of intermediate beach states occurring in moderate to high-energy environments, where they have an important role in driving beach change (Wright and Short, 1984; Brander, 1999; Brander and Short, 2000). Apart from studies in Georgian Bay, Lake Huron (Greenwood and Sherman, 1984; Davidson-Arnott and McDonald, 1989; Bauer and Greenwood, 1990), and a cursory review by Short and Brander (1999), beach morphodynamics in strong-wind bays remains poorly studied.

The aim of this study is, firstly, to examine the morphodynamic behaviour at Seaford, as an example of a strong-wind bay beach and, secondly, to determine whether Seaford Beach can be considered low-energy according to the criteria outlined by Jackson et al. (2002).

## 2. Study site

Seaford Beach is located on the east coast of Port Phillip Bay, Victoria, Australia (Fig. 1). Port Phillip Bay is a large, circular, and nearly enclosed body of water. It has a mean depth of 12.8 m, a spring tidal range of approximately 1 m, and receives virtually no ocean swell (Black and Rosenberg, 1992; Short, 1996). Strong winds associated with the passage of mid-latitude low pressure systems in the Southern Ocean, blow predominately from the west and southwest during the summer and from the north and northwest during the winter (Bird, 1990). At Seaford, fetch distances range from 35.5 to 40.5 km (Fig. 1); however despite this, waves up to 3 m are possible

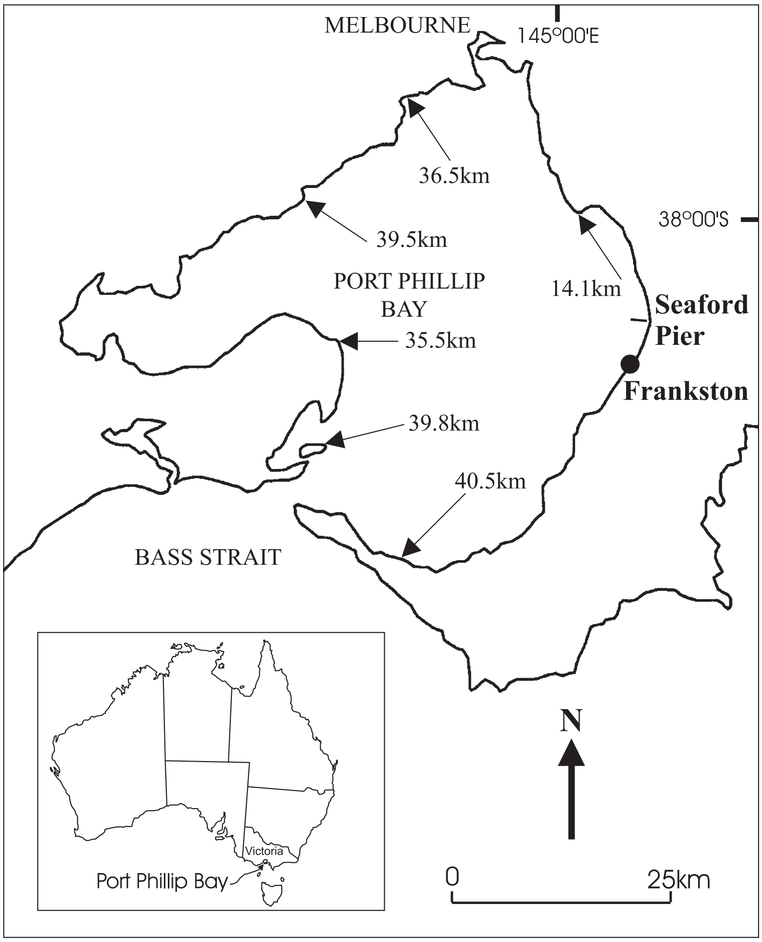



Fig. 1. Map of Port Phillip Bay, showing the location of Seaford. Arrows indicate fetch distances from Seaford.

(Bird, 1990; Short, 1996). Seaford Beach may have two or three shore-parallel bars, and is modally "transverse bar and rip" (Short and Brander, 1999).

## 3. Methods

The study was conducted over a 3-month period (1 April–7 July 2002), focussing on higher-energy conditions during June 2002. Wind data were obtained from the Victorian Bureau of Meteorology's Frankston weather station (Fig. 1), while ADV current and wave meters were deployed in the surf zone. Instruments were deployed in water depths between 0.4 and 1.5 m, and were programmed to record 60-s current samples at 10-min intervals. The ADV probe was fixed in a position 0.22 m above the surf zone bed, similar to previous studies (Aagaard et al., 1997; Brander, 1999; Brander and Short, 2000).

Due to an emphasis on recording currents, placement of the ADVs was dictated by the flow of Rhodamine dye released in the surf zone. Consequently, the positions of the ADVs were different on each deployment. Accordingly, one current meter was deployed on each occasion in a longshore trough located in the inner surf zone, while the second current meter was deployed further offshore in what was considered to be a shallow rip neck. Deployment times varied, between 2 and 12 h, as the instruments required constant supervision due to Seaford being a well-used public beach.

Waves recorded by the ADVs are also used in our analysis. To record waves, the ADVs were programmed to record 1024 wave samples per burst at the rate of two samples per second. Each successive burst began 10 min after the start time of the previous one, with samples collected in the form of PUV data. Initial processing of data was completed with the manufacturer's software. In total, surf zone current data were collected on 18 occasions spanning 30 April–7 July, while wave data were collected on 16 occasions spanning 24 May–7 July.

To assess changes in beach morphology, 10 cross-shore transects, centred on Seaford Pier and extending to the seaward slope of the middle bar, were established at an average interval of 54 m (due to water depth, the outer bar was not included in this study). The actual distance between each transect varied according to the beach morphology at the beginning of the study, with transects being established on alternate rip embayments and horns. The profiles were surveyed 11 times during the study period using a total station.

## 4. Results

### 4.1. Wind and waves

Wind data indicate general low-energy conditions up to 6 June, broken by two brief higher-energy events on 26 April and 16–21 May (Fig. 2). From 7 June, high-energy conditions predominate.

Wave data from the outer ADV indicate a direction of incidence from the southwest to west (Fig. 3). As the ADV was located differently on each deployment, and never in the outer surf zone, the recorded wave height provides only an indication of the true significant height of breaking waves. In general, waves were small with 50% below 0.22 m. Wave steepness, ($H/L$), increases from about 0.01 for small waves up to approximately 0.04 for large waves (Fig. 4).

### 4.2. Currents

The outer ADV was used primarily to determine, if present, the velocity of rip currents (Fig. 5). Currents were highly variable, with onshore currents related to incident waves ranging from southwest to north–northwest. However, offshore currents ranging from northeast through to southeast also occur, and it is these latter currents that represent rips flowing obliquely offshore of an embayment horn. Although rip currents from the southeast attained the highest velocities, currents were generally weak, with 60% below 0.04 ms$^{-1}$ (Fig 5). In contrast, inner ADV data (Fig 6) highlight the presence of a dominant north to south longshore current. These currents were higher in magnitude

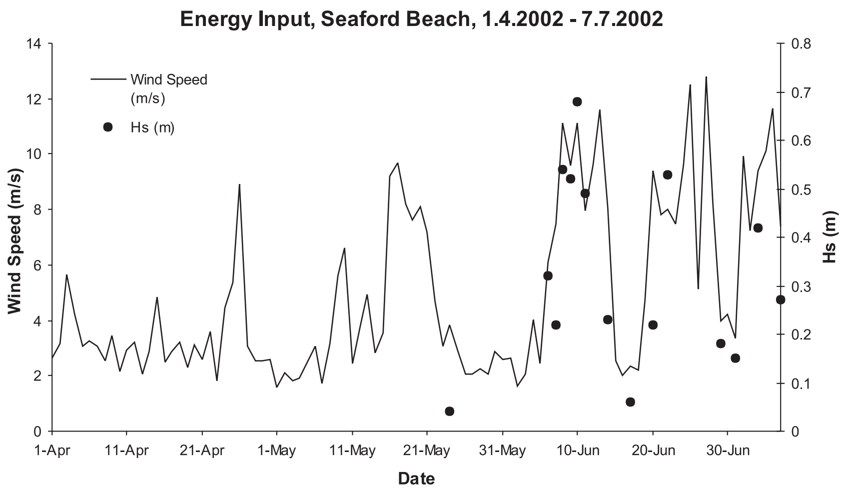



Fig. 2. Wind speed and significant wave height, Seaford Beach, 1 April–7 July 2002.

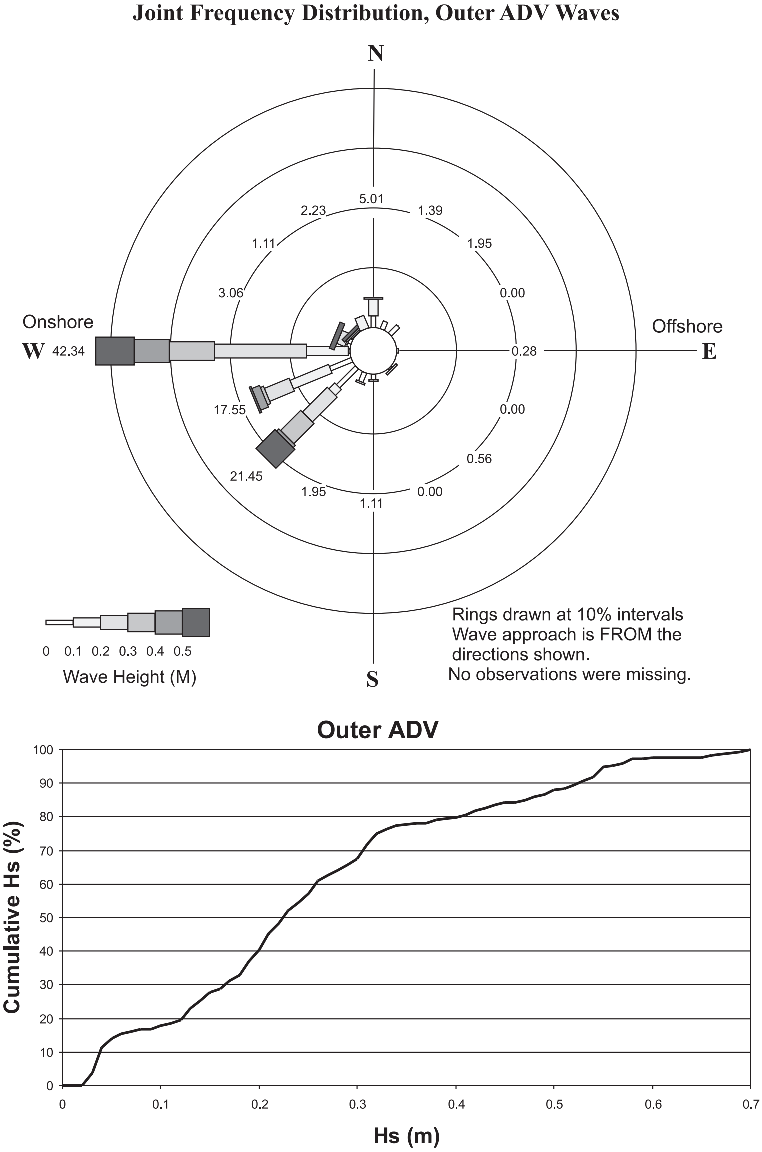



Fig. 3. Summary rose of breaking incident waves, and cumulative frequency plot of significant breaking wave height, 24 May–7 July 2002. Note the predominance of low wave heights, with 50% below 0.22 m. Wave data is from the outer ADV (RoseWorks software courtesy of UAI International).

than those recorded by the outer ADV, with 60% exceeding 0.04 $ms^{-1}$ (Fig. 6).

Table 1 illustrates the bimodal nature of processes at Seaford Beach. Higher-magnitude waves and currents accompany the passage of high-energy weather events, with very low-magnitude waves and currents otherwise occurring.

### 4.3. Storm wave spectra

Fig. 7 illustrates a wave spectral sample obtained during storm conditions on 8 June. In addition to the incident wave peak at 0.23 Hz, there is a distinct peak at 0.04 Hz indicating a significant amount of energy within the infragravity band. Similar records, also

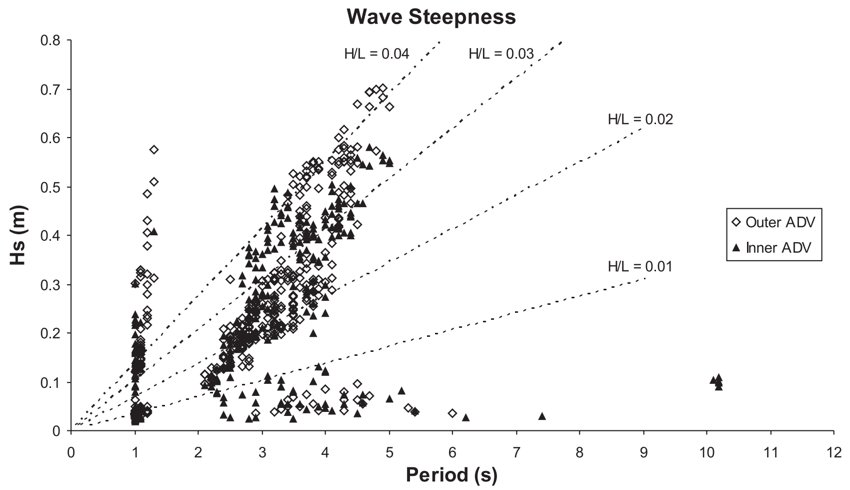



Fig. 4. Significant wave height and period from both instruments plotted against wave steepness isolines. Note the increase in wave steepness with increasing wave height.

indicating a peak in infragravity energy, were obtained on 6, 7, and 10 June.

### 4.4. Sediment size, beach slope, and beach parameters, $\Omega$ and $\xi_b$

There are differences in sediment size and sorting between the beachface, inner trough, and inner bar (Table 2). Beach slope was determined using linear regression fitted by the least squares method (Huntley, 1976). The difference in gradient between the beachface and surf zone necessitated the separate calculation of slope for each (Wright et al., 1979), while an inshore slope that included the beachface and surf zone was also calculated. Table 3 displays these slopes averaged for all transects. Profiles before 6 June were excluded due to the lack of morphological change. Note in Table 3 the very low surf zone gradient and only moderate beachface gradient. There was little change in beach gradients during the study.

To assist in determining beach state, and the relative degree of dissipation and reflection, the dimensionless parameter ($\Omega$) and the Iribarren number ($\xi_b$) were calculated (Table 4) for the beachface and surf zone (Wright et al., 1979; Sallenger et al., 1985). $\Omega$ provides a prediction for beach state based on the sediment size and wave steepness (Wright and Short, 1984), and is expressed as:

$$\Omega = H_b/(w_s T) \qquad (1)$$

where $H_b$=breaking wave height (m), $w_s$=sediment fall velocity (ms$^{-1}$), and $T$=wave period (s).

Based on Dean (1973), sediment fall velocities of 0.06 and 0.03 ms$^{-1}$ were determined for the beachface and surf zone, respectively, using grain sizes of 0.42 mm for the beachface and 0.29 mm (average of inner bar and trough) for the surf zone (Table 2). Seaford Beach existed primarily in the intermediate range of $\Omega$. Reflective conditions occurred only with very small waves (Table 4).

The Iribarren number is used to predict beach state and breaker type according to the ratio between beach slope and wave steepness (Battjes, 1974). This ratio is expressed as:

$$\xi_b = S/(H_b/L_\infty)^{1/2} \qquad (2)$$

where $\xi_b$=the inshore form of the Iribarren number, $S$=beach slope (tan$\beta$), $H_b$=breaking wave height (m), and $L_\infty$=deepwater wavelength (m). Results highlight the dissipative nature of the surf zone. Based on $\xi_b$, waves break by spilling in the surf zone and by plunging at the beachface, matching observations.

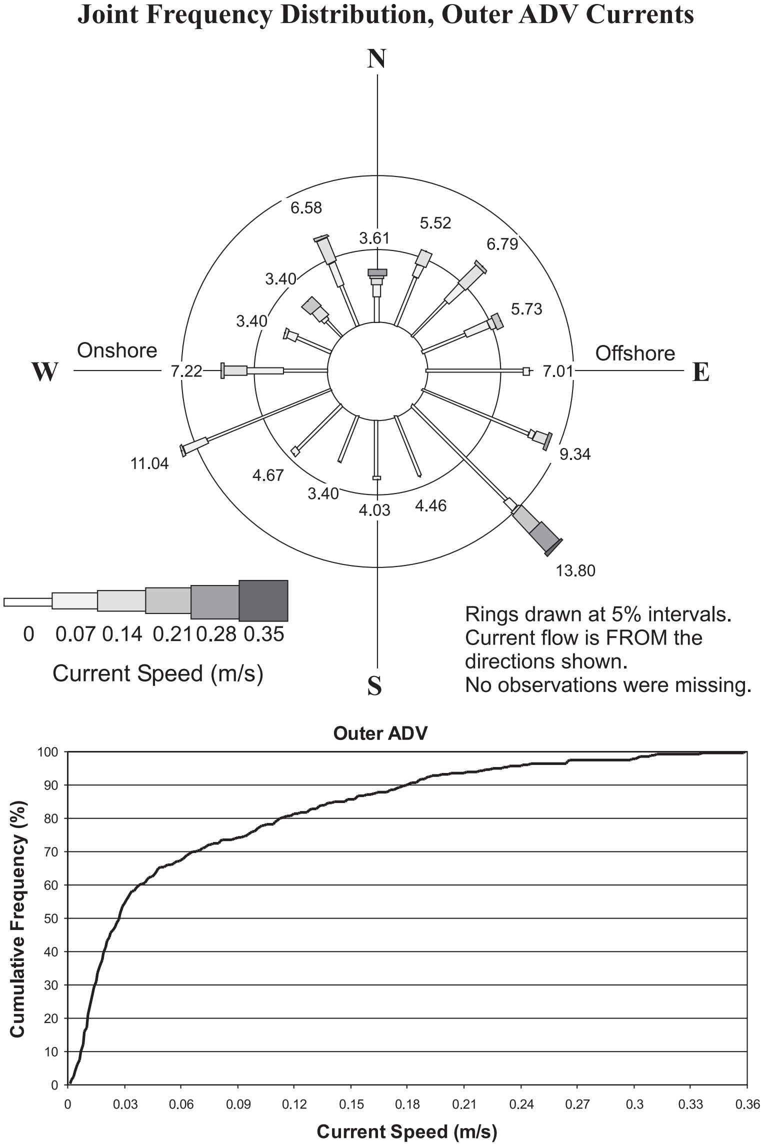



Fig. 5. Summary current rose and cumulative frequency plot of current speeds from the outer ADV, 30 April–7 July 2002. Note the wide dispersion of currents and the predominance of very low current speeds, with 60% below 0.04 $ms^{-1}$. The strong current flowing offshore from the southeast represents a rip current. (RoseWorks software courtesy of UAI International, Inc.).

### *4.5. Beach profiles*

Low spatial and temporal variability was exhibited by all profiles (Fig. 8), with the spatial variability a consequence of longshore rhythmicity. Using Fig. 8A as an example, morphological features common to all profiles include: (a) a steep beachface, (b) a low-tide terrace extending approximately 60m from the shoreline, (c) a small bar at the seaward edge of the terrace, (d) then a trough, (e) followed by another bar. The outer bar on the profiles is the middle bar on Seaford Beach. The middle bar is located approximately 110 m from the base of the beachface and marks the outer limit of the surf zone.

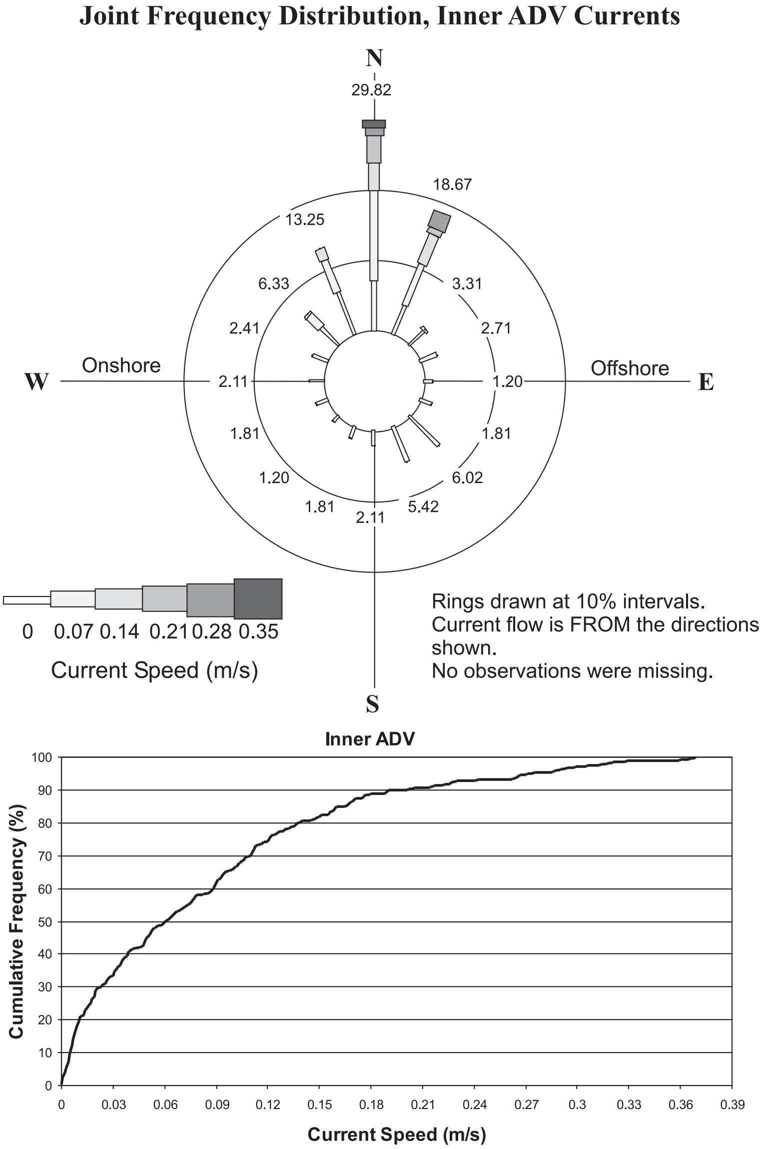



Fig. 6. Summary current rose and cumulative frequency plot of current speeds from the inner ADV, 30 April–7 July 2002. Note the striking dominance of a north to south longshore current, which attains a maximum speed of 0.37 $ms^{-1}$ (RoseWorks software courtesy of UAI International).

Due to the prevalence of low-energy conditions up to 6 June (Fig. 2), there were only minor profile changes to this date. A high-energy event on 25 April was too brief to cause any significant change. However, a second storm event spanning 6 days from 16 May caused minor onshore movement of the inner and middle bars (Fig. 8F). The onshore movement of the middle bar continued during a subsequent high-energy event occurring 7 June–13 June (Fig. 8B, G, H, and J). It was only under the highest energy conditions during the study (20–28 June) that the middle bar moved offshore, and reduced in height (Fig. 8E, F, and H).

Apart from movement of the middle bar, a number of other morphological adjustments occurred during

Table 1
Summary of daily mean wind, wave, and current processes recorded at Seaford Beach, 30 April–7 July 2002[a]

| Date | Wind | | Waves (O) | | | Waves (I) | | | Currents (O) | | Currents (I) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed ($ms^{-1}$) | Dir$^n$ (deg) | $H_s$ (m) | $T_s$ (s) | Dir$^n$ (deg) | $H_s$ (m) | $T_s$ (s) | Dir$^n$ (deg) | Speed ($ms^{-1}$) | Dir$^n$ (deg) | Speed ($ms^{-1}$) | Dir$^n$ (deg) |
| 30 April | 2.6 | 135 | – | – | – | – | – | – | 0.05 | 215 | – | – |
| 10 May | 6.6 | 225 | – | – | – | – | – | – | 0.10 | 132 | – | – |
| 24 May | 3.8 | 135 | 0.04 | 1.8 | 225 | 0.04 | 2.0 | 238 | 0.01 | 233 | 0.01 | 152 |
| 6 June | 6.1 | 45 | 0.32 | 3.2 | 271 | – | – | – | 0.07 | 272 | – | – |
| 7 June | 7.5 | 0 | 0.22 | 2.9 | 263 | 0.24 | 2.9 | 0 | 0.02 | 89 | 0.10 | 347 |
| 8 June | 11.1 | 315 | 0.54 | 4.0 | 354 | 0.44 | 4.2 | 354 | 0.16 | 333 | 0.15 | 16 |
| 9 June | 9.6 | 315 | 0.52 | 3.6 | 305 | 0.41 | 3.7 | 1 | 0.02 | var* | 0.22 | 0 |
| 10 June | 11.1 | 315 | 0.68 | 4.8 | 228 | 0.56 | 4.8 | 15 | 0.20 | 55 | 0.15 | 8 |
| 11 June | 8.0 | 315 | 0.49 | 3.5 | 263 | 0.40 | 3.6 | 353 | 0.04 | 81 | 0.09 | 17 |
| 14 June | 8.1 | 315 | 0.23 | 3.5 | 281 | 0.10 | 5.5 | 262 | 0.05 | 125 | 0.08 | 325 |
| 16 June | 2.0 | 225 | – | – | – | 0.08 | 2.8 | 272 | – | – | 0.01 | 75 |
| 17 June | 2.3 | 135 | 0.06 | 3.0 | 217 | 0.04 | 2.8 | 274 | 0.01 | 236 | 0.01 | 151 |
| 20 June | 9.4 | 0 | 0.22 | 3.3 | 244 | – | – | – | 0.05 | 0 | – | – |
| 22 June | 8.0 | 315 | 0.53 | 3.8 | 231 | 0.38 | 3.6 | 274 | 0.14 | 41 | 0.10 | 13 |
| 29 June | 3.2 | 225 | 0.18 | 1.1 | 249 | 0.16 | 1.5 | 229 | 0.05 | 239 | 0.03 | 222 |
| 1 July | 3.3 | 315 | 0.15 | 2.4 | 311 | 0.13 | 2.3 | 289 | 0.02 | 358 | 0.02 | 233 |
| 4 July | 9.4 | 315 | 0.42 | 3.6 | 240 | 0.37 | 3.7 | 185 | 0.17 | 58 | 0.30 | 0 |
| 7 July | 7.4 | 315 | 0.27 | 3.2 | 224 | 0.40 | 3.2 | 195 | 0.04 | 103 | 0.19 | 4 |

[a] (O) and (I) refer to the outer and inner ADVs, respectively, while Dir$^n$ refers to the direction from which wind, waves, and currents are flowing. $T_s$ is the significant wave period. Var* refers to a variable direction.

the higher-energy conditions that prevailed after 6 June (Fig. 2). Surveys from 17 June and 1 July show: parallel retreat of the beachface, resulting in a widening of the inshore terrace (Fig. 8D and F); concurrent development of a shallow trough at the base of the beachface (Fig. 8B and C); and inner bar development on the low-tide terrace (Fig. 8B, C, G, and I). Also apparent in all cross-shore transects is the accentuation of bar morphology during moderate to high-energy conditions, through the formation of a steep slope on the shoreward side of the inner and middle bars.

In summary, Seaford is a low-gradient beach with a slightly steeper beachface and rhythmic longshore variation. Although there was little change in mor-

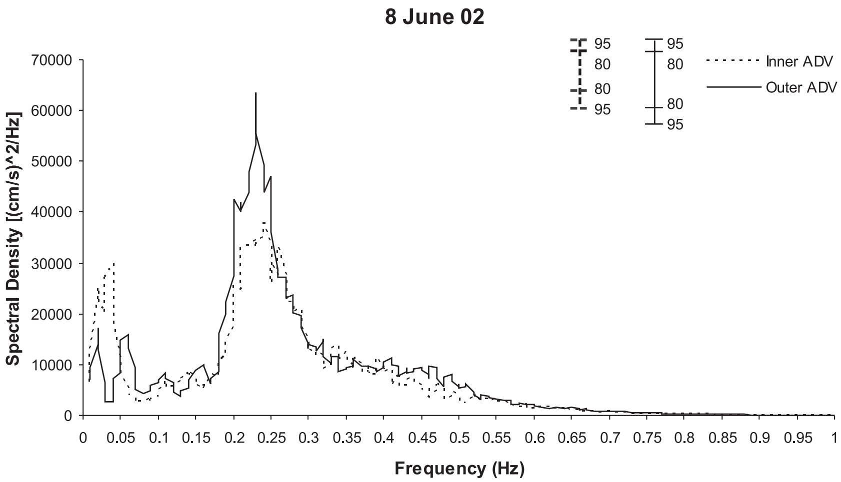



Fig. 7. Mean wave spectra, 13:30–18:30, 8 June 2002. Note the growth in infragravity energy under high wave energy conditions, with a distinct peak at 0.04 Hz on the inner ADV spectral record, and peaks at 0.06 Hz and 0.02 Hz on the outer ADV record.

Table 2
Sediment analysis based on the methods of Folk and Ward (1957)[a]

| Site | Sediment size (mm) | Sediment sorting (s.d.) |
|---|---|---|
| Beachface | 0.42-medium sand | 0.90-moderately sorted |
| Inner trough | 0.18-fine sand | 0.45-well sorted |
| Inner bar | 0.29-medium sand | 1.43-poorly sorted |
| Mean | 0.30-medium sand | 0.93-moderately sorted |

[a] Sediment size is recorded in mm for the later calculation of fall velocity, while sorting is a function of the standard deviation (s.d.) of the sediment sample.

Table 3
Mean beach slope (tan$\beta$) for transects 1–10[a]

| Date | Inshore | Beachface | Surf zone |
|---|---|---|---|
| 6 June 2002 | 0.015 | 0.125 | 0.010 |
| 17 June 2002 | 0.018 | 0.129 | 0.015 |
| 1 July 2002 | 0.018 | 0.115 | 0.011 |
| Mean | 0.017 | 0.123 | 0.012 |

[a] Dates before 6 June 2002 were excluded due to a lack of morphological change.

phology under low-energy conditions, the beach was found to be dynamic during higher-energy conditions. Important processes that occurred during such events include: the formation of steep plunging and spilling breakers, a strong longshore current, and infragravity energy in the wave spectra. Rip currents were not prevalent during this study.

## 5. Discussion

### *5.1. The morphodynamics of a strong-wind bay beach*

Seaford Beach evolved from a "low-tide terrace" to a transitional "transverse bar and rip-rhythmic bar and beach" during fieldwork (Fig. 9). The progression towards a dissipative beach occurred primarily during the 7–13 June high-energy event (Fig. 2). The later, more significant, high-energy event (20 June–28 June (Fig. 2)) did not drive the beach further towards a dissipative state, but was responsible for significantly increasing the scale of the nearshore morphology, with both the shoreline embayment and inner bar of the study area extending alongshore (Fig. 9).

That Seaford Beach did not attain a true "rhythmic bar and beach" state under continued high-energy conditions is significant, and indicates an upper limit

Table 4
Beach parameters[a]

| Date | $H_s$ (m) | $\Omega$ (beachface) | $\Omega$ (surf zone) | $\xi_b$ (beachface) | $\xi_b$ (surf zone) |
|---|---|---|---|---|---|
| 24 May 2002 | 0.04 | ***0.33*** | ***0.77*** | 1.56 | *0.11* |
| 6 June 2002 | 0.32 | 1.67 | 3.33 | 0.89 | *0.07* |
| 7 June 2002 | 0.22 | 1.40 | 2.57 | 0.91 | *0.08* |
| 8 June 2002 | 0.54 | 1.75 | 4.50 | 0.98 | *0.07* |
| 9 June 2002 | 0.52 | 1.83 | 4.77 | 0.91 | *0.06* |
| 10 June 2002 | 0.68 | 1.93 | 4.77 | 1.00 | *0.07* |
| 11 June 2002 | 0.49 | 1.87 | 4.61 | 0.88 | *0.06* |
| 14 June 2002 | 0.23 | ***0.32*** | 2.26 | ***2.64*** | *0.09* |
| 16 June 2002 | 0.08 | ***0.46*** | ***0.92*** | 1.56 | *0.13* |
| 17 June 2002 | 0.06 | ***0.23*** | ***0.61*** | ***2.31*** | *0.24* |
| 20 June 2002 | 0.22 | 1.13 | 2.26 | 0.29 | *0.03* |
| 22 June 2002 | 0.53 | 1.80 | 4.65 | 0.92 | *0.10* |
| 29 June 2002 | 0.18 | 1.83 | 5.32 | 0.59 | *0.05* |
| 1 July 2002 | 0.15 | 2.12 | ***0.98*** | 0.89 | *0.09* |
| 4 July 2002 | 0.42 | 1.66 | 3.88 | 0.87 | *0.08* |
| 7 July 2002 | 0.27 | 2.12 | 2.82 | 0.71 | *0.09* |
| Mean | 0.31 | 1.40 | 3.06 | 1.12 | *0.09* |
| Breaker type | – | – | – | Plunging | Spilling |

$\Omega$>6 and $\xi_b$<0.3 indicate dissipative conditions and the formation of spilling breakers, while $\Omega \leq 1$ and $\xi_b$>2.0 represent reflective conditions and the formation of surging breakers. Intermediate values of $\xi_b$ indicate that waves will break by plunging (Battjes, 1974; Komar, 1998). *Italics* and ***bold italics*** denote dissipative and reflective conditions, respectively.

[a] $H_s$ is the significant wave height.

to the progression of this strong-wind bay beach through the morphodynamic model. Except for perhaps more extreme storms events than those observed during the study, it appears that a transitional "transverse bar and rip-rhythmic bar and beach" is the modal state during high-energy conditions. Although the limited fetch apparently prevents further progression through the morphodynamic model, energy levels are sufficient to increase the longshore scale of the beach morphology, as previously described by Short (1985). Therefore, we propose that Seaford Beach is bimodal, exhibiting the features of a "low-tide terrace" during low-energy conditions, and a transitional "transverse bar and rip-rhythmic bar and beach" during high-energy conditions.

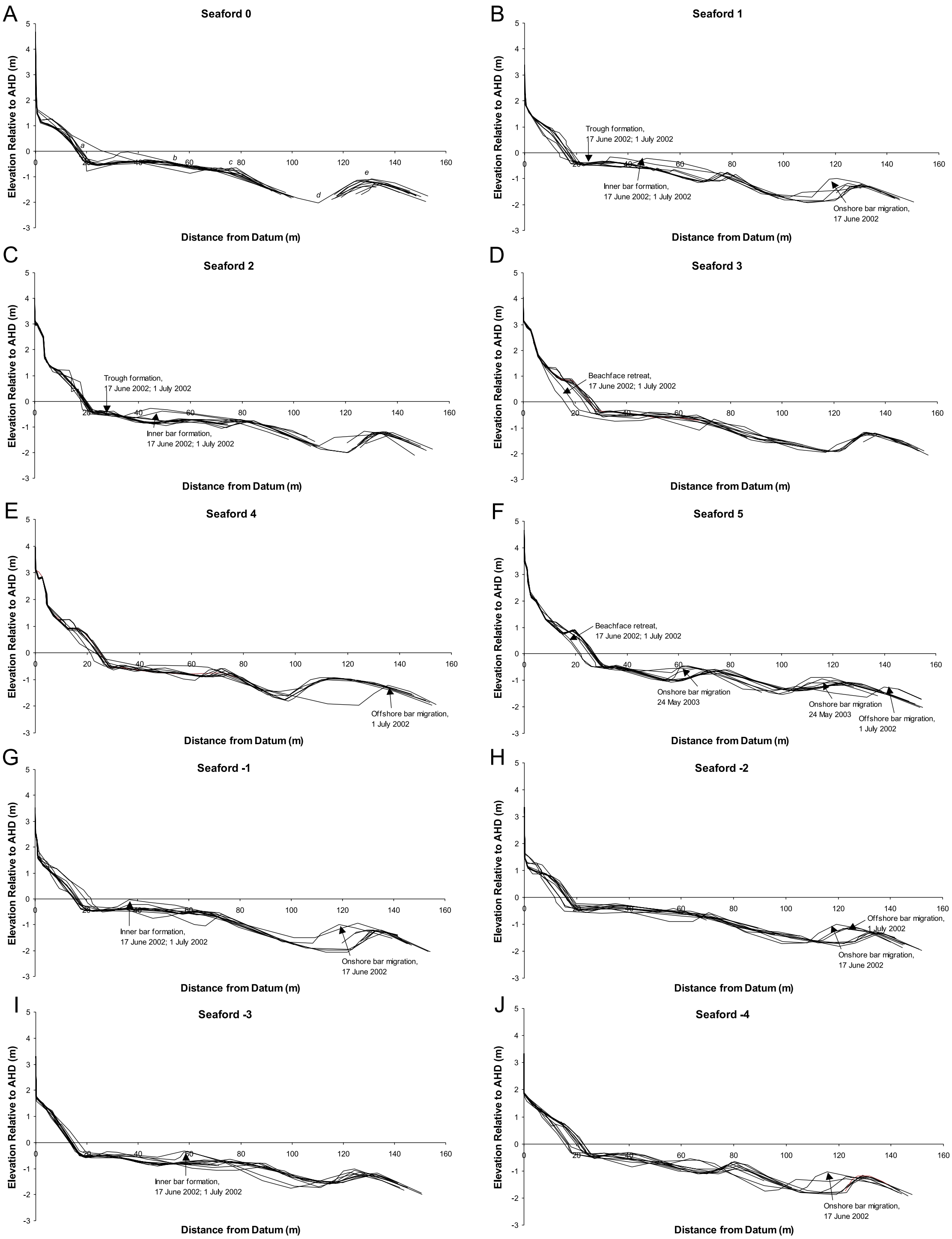
The multibarred surf zone has an important stabilising effect on this strong-wind bay beach and restricts the progression towards more dissipative states. The very low Iribarren numbers (Table 4) indicate that the surf zone is highly dissipative. Consequently, there is no requirement for the beach to progress through a number of states as wave energy increases. Despite a dissipative surf zone, the beachface is still stripped of sediment during high-energy events. Removal of beachface sediment results from the increase in steepness with larger waves; such waves plunge at the base of the beachface (Table 4 and Fig. 4), and are particularly effective at entraining sediment (Sallenger et al., 1985). Consequently, storm waves in a strong-wind bay are highly effective at mobilising sediment stored on the beachface.

The parallel retreat of the beachface during high-energy conditions (Fig. 8A–J) indicates the dominance of longshore, as opposed to cross-shore, sediment transport (Jackson and Nordstrom, 1992). In addition, the inner ADV recorded a persistent and strong north to south longshore current (Fig. 6). However, cross-shore currents (Fig. 5) and sediment transport are evident further out in the surf zone, with the cross-shore movement of the middle bar (Fig. 8A–J) and the formation of a distinct inner bar on the low-tide terrace (Fig. 8).

On the few occasions where rips were present, they were, with one exception, weak. The absence of rip currents at Seaford raises two important issues. Firstly, rip currents are regarded as a key process in driving beach change during both rising and falling wave conditions (Wright and Short, 1984; Short, 1985, Brander, 1999). It is the presence of rip currents that makes intermediate beaches more dynamic than their fully dissipative or reflective counterparts (Wright and Short, 1984). However, the lack of strong rip currents indicates that rips did not, in this instance, play a major role in driving beach morphology from a "low-tide terrace" to a transitional "transverse bar and rip-rhythmic bar and beach" state. Other processes, such as breaking waves and longshore currents, must therefore have controlled the movement towards a more dissipative beach state.

The second issue is the importance of wave direction (in addition to magnitude), to beach morphodynamics in strong-wind bays. Both the magnitude and direction of waves are highly variable; consequently, there is considerable variation across a range of spatial scales in the processes that are active at any one time. This is illustrated by the reversal of longshore currents with changes in wind direction (Table 1), and the erosion of beachface sediment from different sections of an embayment, as the direction of wave attack changes. While a beach may be broadly classified as existing in a particular morphodynamic state, significant changes in processes over very short temporal scales indicate that this strong-wind bay beach rarely attains equilibrium with the prevailing wave conditions. Even during periods of calm, the absence of swell means that the beach exists in an arrested state from higher-energy events (Aagaard, 1988; Hegge et al., 1996). The dependence of processes on an extremely variable wind and wave direction highlights an important difference between ocean beaches and fetch-limited beaches in general (Greenwood and Sherman, 1984; Davidson-Arnott and McDonald, 1989; Jackson and Nordstrom, 1992; Masselink and Pattiaratchi, 2001).

So far, the parallel bar system has been considered only in terms of its ability to dissipate incident wave energy; however, there are further issues. Aagaard (1991) observed that due to its small scale, and therefore susceptibility to lesser storm events, the inner bar is the most dynamic of the parallel bars; with a highly variable appearance attributable to wave breaking and current processes in the inner surf zone. The intermediate (i.e. $1 \leq \Omega < 6$) surf zone values of Dean's dimensionless parameter (Table 4) and beach profiles (Fig. 8A–J) show a highly dynamic inner bar at Seaford. The middle bar is more stable the energy


A
Seaford 0
a
b
c
d
e
B
Seaford 1
Trough formation,
17 June 2002; 1 July 2002
Inner bar formation,
17 June 2002; 1 July 2002
Onshore bar migration,
17 June 2002
C
Seaford 2
Trough formation,
17 June 2002; 1 July 2002
Inner bar formation,
17 June 2002; 1 July 2002
D
Seaford 3
Beachface retreat,
17 June 2002; 1 July 2002
E
Seaford 4
Offshore bar migration,
1 July 2002
F
Seaford 5
Beachface retreat,
17 June 2002; 1 July 2002
Onshore bar migration
24 May 2003
Onshore bar migration
24 May 2003
Offshore bar migration,
1 July 2002
G
Seaford -1
Inner bar formation,
17 June 2002; 1 July 2002
Onshore bar migration,
17 June 2002
H
Seaford -2
Offshore bar migration,
1 July 2002
Onshore bar migration,
17 June 2002
I
Seaford -3
Inner bar formation,
17 June 2002; 1 July 2002
J
Seaford -4
Onshore bar migration,
17 June 2002
Elevation Relative to AHD (m)
Distance from Datum (m)

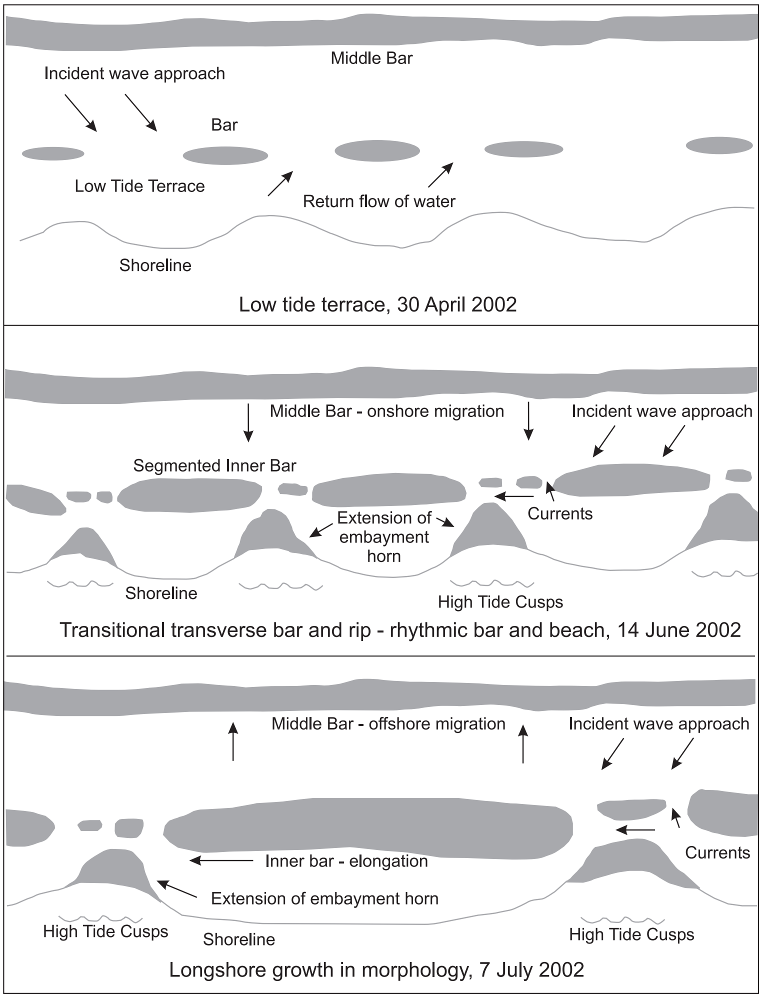



Fig. 9. Beach evolution from a low-tide terrace on 30 April 2002 to a transitional "transverse bar and rip-rhythmic bar and beach" on 7 July 2002. The change in beach state occurred during a high-energy event spanning 7 June–13 June 2002. Note the onshore movement of the middle bar. During a subsequent high-energy event (20–28 June 2002), there was an increase in the longshore scale of the beach morphology, but no further change in beach state. Note the offshore movement of the middle bar.

threshold of movement is greater than that for the inner bar (Aagaard, 1991). However, it is also susceptible to changes in position under large waves. The onshore movement of the Seaford middle bar during the June 7–14 storm event (Fig. 8A–J) is similar to observations in other fetch-limited environments (Greenwood and Sherman, 1984; Aagaard, 1990). However, during a second, higher-magnitude, storm event (June 20–28), the middle bar once more retreated seawards, while undergoing a reduction in height (Fig. 8A–J); an observation that differs from Greenwood and Sherman (1984) and Aagaard (1990).

Aagaard (1990) attributed the phenomenon of onshore bar migration to greater wave set-up during

Fig. 8. Transects -4 to 5. The outer bar on all transects is actually the middle bar on Seaford Beach. Letters a–e in Fig. 2A, and notations on various transects, highlight features discussed in the text. Note that low-energy conditions prevailed up to 6 June 2002, and with the exception of some minor adjustments that occurred during a low-magnitude storm event that spanned six days from 16 May 2002, there was minimal profile change. Significant profile changes occurred during higher-magnitude events that spanned seven days from 7 June 2002, and 9 days from 20 June 2002.

storms, with the bar moving shoreward to adjust to the elevated water level. However, the offshore retreat of the middle bar during the second storm event indicates that this conclusion is incorrect when applied to Seaford Beach. We therefore propose that the Seaford middle bar migrates to a position of equilibrium with prevailing wave conditions. The onshore movement of the middle bar occurred because its initial position was in equilibrium with the last major storm, which was presumably of higher magnitude than the 7–13 June storm event, and had positioned the bar further offshore. Consequently, the bar moved shoreward during the later, apparently more moderate, event to a position of equilibrium with the prevailing wave conditions. The low-energy waves of the intervening period had not been sufficient to alter the location of the bar. Under the higher magnitude June 20–28 storm event, the middle bar once more retreated seawards to attain a new equilibrium with the larger waves.

Finally, while the transition from a low-energy to high-energy beach state was observed, the return sequence to a "low-tide terrace" under low wave conditions was not. The formation of a "low-tide terrace" is of particular interest in a strong-wind bay, due to the absence of long-period swell, which on ocean beaches provides the mechanism for the return to a reflective beach state (Wright and Short, 1984). It is suspected that low waves occurring with onshore sea breezes during summer and autumn provide the mechanism for the shoreward return of sediment and the development of a "low-tide terrace." However, this remains to be confirmed.

### 5.2. Should a beach in a strong-wind bay be considered low energy?

As a type of fetch-limited environment, strong-wind bays are considered low-energy and for much of the first 2 months of this study, during which light easterly winds prevailed, Seaford behaved exactly as predicted by Jackson et al. (2002). Significant wave heights were very low (<0.1 m), the offshore bars were all extremely stable, and there was no evidence of cross-shore sediment exchange (Table 1 and Fig. 8A–J). Furthermore, significant wave heights and current speeds for the duration of the study were generally very low (Figs. 3, 5 and 6).

However, during high-energy events, Seaford Beach exhibited a number of characteristics that were not typical of a low-energy environment. In particular, the presence of significant infragravity energy in the storm wave spectra (Fig. 7) and a dissipative surf zone under all but the smallest waves (Table 4) are features of high-energy, rather than low-energy, environments. During high-energy events, breaking wave heights exceeded 0.5 m (Table 1) and currents velocities exceeded 0.15 ms$^{-1}$ (Table 1), while sediment was readily mobilised, with middle bar migration and evidence of cross-shore sediment exchange in the formation of the inner bar as the beachface eroded. Furthermore, Seaford Beach attained a transitional "transverse bar and rip-rhythmic bar and beach" state during an increase in wave energy (Fig. 9), while low-energy beaches typically vary around the "reflective" and "low-tide terrace" states (Wright and Short, 1984). From the above evidence, Seaford Beach cannot be considered a true low-energy beach and does not fit comfortably into any existing category. Again, we regard this strong-wind bay beach as "bimodal," exhibiting temporally segregated characteristics of both higher- and lower-energy environments.

The findings of this study have implications for beach morphodynamics in other fetch-limited environments. In proposing Seaford Beach as bimodal, it follows that not all fetch-limited beaches can be regarded as low-energy. A greater recognition of the frequency and intensity of storm events, rather than just modal wave conditions, is required in classifying beaches as low-energy. Due to low modal wave energies, fetch-limited beaches are generally regarded as exhibiting limited morphodynamic behaviour (Jackson et al., 2002). There has been little discussion of wave frequency in relation to the energetics and morphodynamics of beaches. However, the dynamic behaviour exhibited by Seaford Beach during storms indicates that wave frequency is important. Breaking waves at Seaford were never large (<0.7 m, Fig. 3), but the high frequency of waves, and consequently the steepness of those waves (periods <5.0 s, Table 1), resulted in a significant capacity for geomorphic work, and dynamic behaviour.

Finally, infragravity energy has been recognised in only two other fetch-limited environments; Georgian Bay, Lake Huron, and along the north and east coasts of Denmark (Greenwood and Sherman, 1984;

Aagaard, 1990; Bauer, 1990). In both instances, maximum fetch distances are much greater (235 and 175 km, respectively) than at Seaford, with a maximum fetch of 41 km. Although predicted by the morphodynamic model, the finding of infragravity energy in a highly fetch-limited environment indicates that, rather than being a rare finding, infragravity energy may be more common in fetch-limited environments than previously recognised, and important for morphodynamics; it is just that to date, few attempts have been made to record it.

## 6. Conclusion

As an example of a beach in a strong-wind bay, the morphodynamic behaviour at Seaford was found to conform to Wright and Short's (1984) morphodynamic model, by progressing from a "low-tide terrace" to a transitional "transverse bar and rip-rhythmic bar and beach" during periods of increased wave energy. However, the beach did exhibit some distinct characteristics attributable to its fetch-limited location: there was evidence of limited progression through the morphodynamic model; wind direction and magnitude played a key role in governing the morphodynamic behaviour of the beach; the importance of previous high-energy events was seen in the middle bar migrating shoreward during an increase in wave energy; rip currents were not important in driving beach change; and the beach maintained an arrested state during periods of light winds.

As infragravity energy is predicted for intermediate beaches by the morphodynamic model, its presence during storm events further supports the application of the model to fetch-limited, strong-wind environments. It is also a potentially important process that has remained largely unrecognised in fetch-limited locations.

Although exhibiting the features of a low-energy beach during light winds; the presence of infragravity energy in the storm wave spectra; a dissipative, multibarred surf zone; dynamic inner and middle bars; and the attainment of a "transitional transverse bar and rip-rhythmic bar and beach" state during rising wave conditions, imply that Seaford Beach is not a low-energy beach as defined by Jackson et al. (2002). Rather, we propose that Seaford is "bimodal," as it exhibits process and morphologic features of both higher- and lower-energy beaches. Therefore, not all fetch-limited beaches are low-energy.

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## References

Aagaard, T., 1988. Nearshore bar morphology on the low energy coast of northern Zealand, Denmark. Geograf. Annal. 70A, 59–67.

Aagaard, T., 1990. Infragravity waves and nearshore bars in protected, storm-dominated coastal environments. Mar. Geol. 94, 181–203.

Aagaard, T., 1991. Multiple-bar morphodynamics and its relation to low frequency edge waves. J. Coast. Res. 7 (3), 801–813.

Aagaard, T., Greenwood, B., Nielsen, J., 1997. Mean currents and sediment transport in a rip channel. Mar. Geol. 140, 25–45.

Allan, J.C., Kirk, R.M., 2000. Wind wave characteristics at Lake Dunstan, South Island, New Zealand. N. Z. J. Mar. Freshwater Res. 34, 573–591.

Barusseau, J.P., Radulescu, M., Descamps, C., Akouango, E., Gerbe, A., 1994. Morphosedimentary multiyear changes on a barred coast (Gulf of Lions Mediterranean Sea, France). Mar. Geol. 122, 47–62.

Battjes, J.A., 1974. Surf similarity. Proceedings of the 14th Coastal Engineering Conference. American Society of Civil Engineering, pp. 466–479.

Bauer, B.O., 1990. Assessing the relative energetics of "infragravity" motions in lakes and bays. J. Coast. Res. 6 (4), 853–865.

Bauer, B.O., Greenwood, B., 1990. Modification of a linear bar-trough system by a standing edge wave. Mar. Geol. 92, 177–204.

Bird, E.C.F., 1990. Artificial beach nourishment on the shores of Port Phillip Bay, Australia. J. Coast. Res. 6, 55–68 (Special Issue).

Black, K.P., Rosenberg, M.A., 1992. Natural stability of beaches around a large bay. J. Coast. Res. 8 (2), 385–397.

Bocar-Karakiewicz, B., Davidson-Arnott, R.G.D., 1987. Nearshore bar formation by non-linear wave processes—a comparison of model results and field data. Mar. Geol. 77, 287–304.

Brander, R.W., 1999. Field observations on the morphodynamic evolution of a low-energy rip current system. Mar. Geol. 157, 199–217.

Brander, R.W., Short, A.D., 2000. Morphodynamics of a large-scale rip current system at Muriwai Beach, New Zealand. Mar. Geol. 165, 27–39.

Davidson-Arnott, R.G.D., McDonald, R.A., 1989. Nearshore water motion and mean flows in a multiple parallel bar system. Mar. Geol. 86, 321–338.

Dean, R.G., 1973. Heuristic models of sand transport in the surf zone. Proceedings of the 1st Australian Conference on Coastal Engineering, Engineering Dynamics in the Surf Zone. Sydney, Australia, pp. 208–214.

Dolan, T.J., Dean, R.G., 1985. Multiple longshore sand bars in the upper Chesapeake Bay. Estuar. Coast. Shelf Sci. 21, 727–743.

Ekwurzel, B., 1990. A complex bayside beach: Herring Cove beach, Cape Cod, Massachusetts, USA. J. Coast. Res. 6 (4), 879–891.

Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. J. Sediment. Petrol. 27 (1), 3–26.

Greenwood, B., Sherman, D.J., 1984. Waves, currents, sediment flux and morphological response in a barred nearshore system. Mar. Geol. 60, 31–61.

Guillen, J., Palanques, A., 1996. Short and medium term grain size changes in deltaic beaches (Elbro Delta, NW Mediterranean). Sediment. Geol. 101, 55–67.

Hegge, B., Eliot, I., Hsu, J., 1996. Sheltered sandy beaches of southwestern Australia. J. Coast. Res. 12, 748–760.

Huntley, D.A., 1976. Long-period waves on a natural beach. J. Geophys. Res. 81 (36), 6441–6449.

Jackson, N.L., Nordstrom, K.F., 1992. Site specific controls on wind and wave processes and beach mobility on estuarine beaches, New Jersey, USA. J. Coast. Res. 8 (1), 88–98.

Jackson, N.L., Nordstrom, K.F., Eliot, I., Masselink, G., 2002. Low energy sandy beaches in marine and estuarine environments: a review. Geomorphology 48, 147–162.

Komar, P., 1998. Beach Processes and Sedimentation, 2nd ed. Prentice Hall, New Jersey.

Masselink, G., Pattiaratchi, C.B., 1998. The effect of seabreeze on beach morphology, surf zone hydrodynamics and sediment resuspension. Mar. Geol. 146, 115–135.

Masselink, G., Pattiaratchi, C.B., 2001. Seasonal changes in beach morphology along the sheltered coastline of Perth, Western Australia. Mar. Geol. 172, 243–263.

Sallenger, A.H., Holman, R.A., Birkemeier, W.A., 1985. Storm-induced response of a nearshore-bar system. Mar. Geol. 64, 237–257.

Short, A.D., 1985. Rip-current spacing and persistence, Narrabeen Beach, Australia. Mar. Geol. 65, 47–71.

Short, A.D., 1996. Beaches of the Victorian Coast and Port Phillip Bay. Australian Beach Safety and Management Program, Sydney.

Short, A.D., Brander, R.W., 1999. Regional variations in rip density. J. Coast. Res. 15 (3), 813–822.

Stephenson, W.J., Brander, R.W., 2003. Coastal geomorphology into the twenty-first century. Progr. Phys. Geogr. 27 (4), 607–623.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93–118.

Wright, L.D., Chappell, J., Thom, B.G., Bradshaw, M.P., Cowell, P., 1979. Morphodynamics of reflective and dissipative beach and inshore systems: southeastern Australia. Mar. Geol. 32, 105–140.