Bedform Migration and Sediment Dynamics in the Nearshore of a Low-energy Sandy Beach in Southwestern Australia

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ABSTRACT


This paper relates nearshore ripple behaviour to cyclic changes in hydrodynamic conditions due to a sea breeze. Simultaneous time series measurements of waves, currents, sediment suspension and ripple crest positions were obtained from the nearshore of a micro-tidal low energy beach in southwestern Australia during two diurnal sea breeze cycles. Large parallel ripples with wavelengths of 0.3–1.2 m and heights of 0.05–0.15 m were present in coarse sand for the duration of observations. Mean ripple wavelengths and migration rates were measured at half hour intervals. During the sea breeze, wave height increased and wave period decreased with the addition of locally generated, short period wind waves on the incident swell waves. As a result, mean offshore flow (undertow) increased and nearshore cross-shore asymmetry decreased. ripple wavelength increased during the sea breeze in proportion to the nearshore orbital diameter. Ripple wavelength remained relatively constant, except for a slight decreasing trend, with respect to the varying near-bed orbital diameter during the swell-dominated periods before and after the sea breeze suggesting the presence of suborbital ripples. Ripples migrated onshore during the swell-dominated period and offshore during the sea breeze. It is proposed that the ripple migration direction is a function of the balance between onshore cross-shore velocity asymmetry and offshore mean flow. Increased sediment suspension concentration during the sea breeze resulted in an increase in the amount of sand available for transport by the larger mean offshore flow providing a mechanism for the offshore migration of ripples.

ADDITIONAL INDEX WORDS: Ripple migration, sediment resuspension, cross-shore flow, ripple wavelength.

INTRODUCTION

The ocean exposed low-energy sandy beaches of southwestern Australia provide ideal sites for the study of nearshore bedform dynamics due to the relatively calm conditions, the excellent underwater visibility and consistent sea breeze cycles. Here, the term low-energy refers to modal significant wave heights of less than 1.0 m over at least twelve months of observation. This study exploits these conditions to provide observations of bedform movement, hydrodynamics and sediment suspension in the nearshore of a sandy beach through a range of sea states. The observations were made under predominantly oscillatory motion conditions over a summer sea breeze cycle. Few studies have examined bedform migration under mainly oscillatory motion in the nearshore environment (Dingler and Inman, 1976; Osborne and Vincent, 1993; Vincent and Osborne, 1993). More frequently, studies of bedform migration under oscillatory motion have been in environments with super-imposed mean currents, such as rips (Shepherd et al., 1993) or strong tidal currents (Sternberg, 1967; Kachel and Sternberg, 1971; Langhorne, 1981, 1982; Yang, 1986). Other bedform migration studies have been in deeper shoreface environments (Li et al., 1997; Boyd et al., 1988; Amos et al., 1999; Traykovski et al., 1999). The lack of bedform migration studies in the nearshore is due to the difficulty in measuring bedform migration in the higher energy nearshore environments where conditions are hazardous for both researchers and equipment, water clarity interferes with bed observation and, until recently, there has been a lack of technology for bed observations.

The sea breeze cycle is important to the coastal processes along the central and southwest coast of Western Australia. It is the dominant wind during 60% of the summer afternoons (Hounam, 1945). The sea breeze in southwestern Australia has modal speeds of over 8 m/s (Gentilli, 1971). Few other places on earth experience sea breezes of this magnitude (Gentilli, 1972). The processes associated with them are similar to those of medium sized storms (Masselink and Pattiaratchi, 1998c) in which wind speeds commonly reach 12 m/s. While there have been several studies on the hydrodynamics, sediment resuspension and large scale changes in beach morphology associated with a sea breeze cycle on beaches of southwestern Australia (Masselink, 1996; Pattiaratchi et al., 1997; Masselink and Pattiaratchi, 1998a, 1998b, 1998c), there have been no studies of the response of small scale bed morphology.

Bedform wavelengths, migration rates and associated hy-
dynamics and sediment suspension were recorded during two sea breeze cycles in the nearshore of a low-energy micro-tidal sandy beach. The objectives of the study were to monitor cross-shore changes in bedform pattern and size; as well as to relate ripple wavelength, migration rate, and migration direction to sea breeze induced changes in hydrodynamic conditions and suspended sediment motion.

**STUDY AREA**

The field site was located 35 km southwest of Perth, Western Australia on the southwest corner of Garden Island (Figure 1). Measurements were made from Feb. 17, 99 to Feb. 19, 99 on a low-wave energy, micro-tidal beach, unofficially known as Quarry Road Beach. The beach faced WSW on an open ocean coast with a virtually unlimited fetch (EBLEN and RADO, 1977), but was sheltered by limestone reefs parallel to the coast and located approximately 150 m offshore. The beach was oriented toward the direction of the prevailing SW winds. The spring tidal range is less than 1.0 m and tidal regime is mixed, mainly diurnal (DEPARTMENT OF DEFENCE, 2000). The environment is micro-tidal, following the nomenclature of DAVIES (1964). During the neap tides occurring during the survey, the tidal range was 0.4 m on the major peak and 0.16 m on the secondary semi-diurnal peak. The beach-
face was steep (5°–8°) and consisted of coarse sand (D = 0.66 mm–0.74 mm). Sediment size decreased to fine to medium sand (D = 0.20 mm–0.25 mm) approximately 10 m from shore.

Large parallel crested ripples (wavelength, λ = 0.3–1.2 m, height, η = 0.05–0.15 m) were found at this site during several visits made at different times of the year. The ripples were parallel to shore and began either immediately seaward of the step or, if no step was present, ripples were present in the swash at the base of the beachface. The large ripples extended to the offshore limit of the medium size sand beyond which very low amplitude (η < 0.02 m) indistinct non-parallel bedforms were present.

**METHODS**

Currents, waves, suspended sediment concentrations and ripple crest positions were recorded for 46 hrs on Quarry Beach at Garden Island, Western Australia (Figure 1). The hydrodynamics and suspended sediment concentrations were recorded by an instrument pod deployed approximately 2 m from the foot of the beachface. The pod consisted of one Marsh McBirney 512 electromagnetic current meter mounted at 0.20 m above ripple crests oriented to measure cross shore and longshore currents; two D & A Instrument Company optical backscatter suspended solids sensors (OBS sensors) mounted at 0.05 m and 0.13 m above ripple crests; and one pressure sensor mounted at 0.05 m above the ripple crests. The stainless steel pod was designed to provide minimal disturbance to the flow and bed morphology around the instruments. The instruments were mounted on vertical arms that extended down from a cross bar supported by two triangular frames 2 m apart. Within this large space between the triangular supports, all instruments and frame components were at least 0.05 m above the ripple crests and there was no noticeable impact on the bed morphology. All instruments were logged at 4 Hz and hard-wired to shore for data collection on a notebook computer utilising Labtech software. Some breaks occurred in the time series due to equipment failure. The instrument pod was deployed just beyond the breaking waves, which were approximately 2 m from the foot of the beachface on this highly reflective beach (Figure 2).

Ripple crest position measurements were recorded along two lines perpendicular to shore and 9 m apart on either side of the instrument pod for the duration of the study. Along each line, a measuring tape was secured to the bed by steel pegs from mid swash to 10 m offshore. This offshore limit was chosen since it was generally the offshore limit of the large coarse grained ripples. The distance offshore of each ripple crest was recorded from the measuring tape at approximately half hour intervals by divers with mask and snorkel for a 46 hr period.

**RESULTS**

Wind

Wind speed and direction were obtained from the Bureau of Meteorology for the coastal weather station at Swanbourne approximately 35 km north of the field site (Figure 1). The data (Figure 3) were recorded by an anemometer at the standard weather station height of 10 m.

The sea breeze began approximately 1 hr after the commencement of observations and reached a peak speed of 8.5 m/s at 15:00 h Feb. 17, 99 (Figure 3). The sea breeze quickly subsided after the peak and ceased after 20:00 h Feb. 17, 99. Wind shifted southeast to east until the start of the second sea breeze at 12:00 h Feb. 18, 99. This southeast to east wind between the sea breeze events is referred to here as the land breeze. Note the abrupt commencement of the sea breeze with a rapid shift in wind direction and speed in the time series (Figure 3). The second sea breeze event had a mean maximum wind speed of 8 m/s, slightly less than the first sea breeze. The sea breeze decreased by 23:00 h Feb. 18, 99 although onshore winds of up to 3 m/s occurred between 3:00 h and 6:00 h Feb. 19, 99, ending before the start of the next sea breeze on the morning of the end of the observations. This pattern was typical of summer sea breeze cycles in southwestern Australia (Gentilli, 1972).

Hydrodynamics

A number of variables were calculated to quantify the differences in the hydrodynamic conditions that occurred during the sea breeze and land breeze. Wave data was divided into infragravity, swell and wind wave components. The groupiness factor was calculated to aid in characterising the different wave fields that occurred during the sea breeze and the land breeze. Local wave angles were determined to assess their possible effect on near-bed currents. The onshore and offshore migration of ripples suggests an imbalance in the cross-shore flow. Mean cross-shore current and cross-shore velocity asymmetry were calculated to quantify near-bed flow conditions that may effect ripple migration direction.

Waves

Wave heights and periods were calculated for every 8192 records or approximately 34 minute segments. Wave height and period were also calculated for three main frequency bands: infragravity-wave (f = 0.005–< 0.05 Hz); swell-wave (f = 0.05–< 0.15 Hz); and wind-wave (f = 0.15–< 0.5 Hz) as defined by Masselink and Pattiaratchi (1998a). For each frequency band, the significant wave height was estimated as $H_{sig} = 4\sqrt{\sigma}$, and mean wave period was estimated as $T = m_{\mu}$, where $m_{\mu}$ is the nth moment of spectral density.

Wave spectra for the two days of observation are shown in Figure 4. The time series were divided into approximately 34 minute segments consisting of 8192 data points and Hanning tapered. The data were divided into 16 segments with an overlap of 256 data points between segments. This resulted in 32 degrees of freedom and a frequency-bin width of 0.0078 Hz, which reduced the variability of the spectral estimates. Wind waves begin to form with the start of the sea breeze one hour after the commencement of observations (Figure 4). The wind waves were initially evident in the spectra at 2.5 s (0.4 Hz) and grew to 6 s (0.17 Hz). They subsided after the cessation of the sea breeze at 20:00 h Feb. 17, 99. Wind waves began again with the resumption of the sea breeze at 12:00 h Feb. 18, 99. The initial wind wave periods were again cen-
tered around 2.5 s. The final wind wave period before the cessation of the sea breeze at 23:00 h Feb. 18, 99 was not measured due to equipment failure. Visual observations suggested that wind waves did not grow as large as the first day of observations due to lighter winds. Swell wave period remained fairly constant at 10–12 s for the duration of observations with higher values recorded during the sea breezes. The peaks in swell wave period and height also corresponded to the peak in water level at 22:00 h Feb. 17, 99. The higher water level allowed larger waves to pass over the offshore reef without breaking. Since the larger swell waves also corresponded to the peak in the sea breeze, it was possible that there was some energy transfer from the wind waves to the swell (SONU et al., 1973). Infragravity wave periods increased slowly throughout the study from approximately 36 s to 55 s at the end of the study.

The contribution of each of the wave components to the total water surface elevation variance changed significantly due to the sea breeze (Figure 5a). The sea breeze began soon after the start of the observations and the portion of the variance due to wind waves quickly increased to approximately 50%, surpassing that due to swell waves (~37%). As the sea breeze ended, the wind wave contribution to variance quickly decreased to 15% and the swell proportion of the water surface variance increased up to 70%. The pattern repeated over the second sea breeze, but due to the slightly weaker sea breeze the wind waves did not quite surpass the swell in their contribution to the total variance. The changes after the sea breeze ended were not fully captured. The infragravity wave contribution to the total variance varied from 14% to 32% with the highest values occurring during the land breezes.

Significant heights for each wave component are given in Figure 5b. Wave heights were very small and significant wave height ranged between 0.13 m and 0.23 m. Heights for each of the components followed similar trends but the swell and the infragravity waves reached peaks later than the wind
waves. Mean water level at the instrument pod varied between 0.62 m and 1.02 m with two peaks each day, one large (~1 m depth) and one smaller (~0.78 m depth) peak. Thus tidal ranges were very small, with a range of 0.4 m leading to the larger peak and 0.16 m on the smaller. Although the mean water level changed, the normalised significant wave height ($H_{sw}/h$) did not change a great deal since the larger waves occurred when the water levels were high.

The groupiness factor was used to quantify some of the differences in the wave fields that existed during the distinct sea and land breeze events (Figure 6b). Since the groupiness of ocean waves is thought to have a role in long wave generation in the nearshore (Symonds et al., 1982), it is possible that groupiness may be related to the migration of nearshore bedforms. The wave groupiness factor was calculated using the technique proposed by List (1991). The surface elevation data ($\eta(t)$) was first demeaned and then high pass filtered (cutoff = 0.04 Hz). Then the absolute value of $\eta(t)$ was low pass filtered (cutoff = 0.02 Hz) and multiplied by $\pi/2$ to create the envelope function $A(t)$. Lastly, the groupiness factor was defined by:

$$GF = \frac{\sqrt{2}\sigma_A}{A(t)}$$

where $\sigma_A$ is the standard deviation of $A(t)$ and $\bar{A}(t)$ is the mean of $A(t)$. The groupiness factor slowly increased from 0.45 to a peak of 0.8 at 4:00 h Feb. 18, 99 and then returned to 0.45 by 13:00 h Feb. 18, 99. The groupiness factor increased during the land breeze when swell waves dominated the spectrum.

The local wave angle was determined using the technique

\[\text{Figure 3. Time series of (A) wind speed; and (B) direction at Swanbourne.}\]

\[\text{Figure 4. Wave spectra over time.}\]
described by SHERMAN and GREENWOOD (1986). Wave angles were always very small due to the orientation of the beach being nearly perpendicular to the sea breeze. Overall wave angle was always between 2–3° and could be divided into swell wave angle (1–3°) and wind wave angle (4–5°). It was assumed that these small local wave angles did not significantly influence the near-bed flow since longshore mean currents were always below 0.03 m/s and assumed to be negligible.

Currents

Mean cross-shore currents, calculated hourly as the mean of the cross-shore current record, fluctuated between 0.04 m/s and 0.09 m/s offshore, reaching the minimum during the swell-dominated periods between the sea breezes (Figure 6c). Some doubt has been expressed in the past as to the accuracy of low mean flow measurements with the Marsh-McBirney electromagnetic current meters (AUBREY and TROWBRIDGE, 1985, 1988). It is now accepted that the instruments are capable of measuring mean flows greater than −0.04 m/s in an oscillatory flow field with a gain error of less than 10% (GUZA et al., 1988). Therefore the mean currents recorded here are all within the generally accepted range of measurements of the electromagnetic current meter.

Cross-shore velocity asymmetry has been defined by CLIFTON (1976):

\[ u_{sym} = u_{on} + u_{off} \]

where \( u_{on} \) and \( u_{off} \) are the maximum onshore and offshore velocities for each zero up-crossing of the cross-shore velocity record. Velocity asymmetry was calculated for each wave and averaged in 34 minute intervals (Figure 6d). Cross-shore velocity asymmetry was nearly always onshore (positive) and with some offshore (negative) values at the beginning of the sea breezes. Maximum values occurred during the swell-dominated period.

Ripple Wavelength

Ripple crest positions over time are shown in Figure 7a and 7b. Each point is the position of a ripple crest on the cross-shore profile measured half hourly and hourly in circumstances when more frequent measurements were not possible. Distance offshore is defined as distance from mean sea level intersection with the beachface calculated for the duration of the study. The parallel ripples were present immediately seaward of the step (eg. between 11:00–17:00 h Feb. 17, 99) or, when no step was present (eg. at time 8:00–24:00 h Feb. 17, 99), ripples occurred at the base of the swash zone. The step was approximately 0.4 m high at the foot of the steep beachface and its presence is denoted on Figure 7a and 7b. The profiles (Figure 2) were similar to a stepped beach morphotype as defined in the low energy beachface classification of HEGGE et al. (1996). The transition from step to swash ripples occurred in less than one hour as the step divided into a number of ripple crests and ripple crests appeared above the step at the foot of the beachface. The beachface became flatter when the step was not present (Figure 2) and corresponded with HEGGE et al.’s (1996) steep beach morphotype. The evolution of the stepped profile to a non-stepped profile occurred as mean water level rose. The stepped profile coincided with low tide and the non-stepped profile coincided with high tide (Figure 6a).

Individual ripple crests could be traced for the duration of the study but several bifurcations occurred and these are apparent on Figure 7a and 7b. Bifurcations consisted of new ripple crests emerging near an existing crest. The crests then
Figure 6. Time series of (A) water level, (B) Groupiness Factor, (C) mean cross-shore velocity, (D) cross-shore velocity asymmetry, (E) mean ripple wavelength. The shaded areas denote the sea breeze.

move apart, equalising the ripple spacing. The bifurcation that began at 15:00 h Feb. 17, 99 at approximately 5 m offshore is a good example. The new ripple crest emerged closer to the shoreward crest as this crest moved shoreward to adjust to the new ripple spacing. Most of the bifurcations occurred within 5.5 m of shore. This was possibly due to rapid adjustment to maintain ripple wavelength with increasing or decreasing space for ripples depending on whether or not the step was present. The foot of the beachface was further seaward when the step was present, possibly ‘squeezing’ the ripples offshore. When the step was not present the ripples closest to shore had space to migrate onshore as water level rose. Further detailed measurements of cross-shore profiles and ripple positions over longer time periods are required to determine the exact relationship between the step and the nearshore bedforms.

Mean ripple wavelength along both lines followed an increasing trend through the study (Figure 6e). At the beginning of the study, mean ripple wavelengths along line 1 were ~0.5 m. They increased up to ~1 m by 4:00 h Feb. 19, 99, then decreased to ~0.85 m by the end of the study. Line 2 had slightly smaller mean ripple wavelengths of ~0.4 m at the start of observations and increased to ~0.7 m by the end of the observations.

Maximum orbital velocity (\(u_{w,max}\)), Shields parameter (\(\theta\)) and near-bed orbital diameter (\(d_0\)) were used to describe the near-bed hydrodynamic conditions. The parameters were calculated for every 8192 records or approximately 34 minute segments. Only cross-shore oscillatory currents were used in determining the Shields parameters since both longshore and cross-shore mean flows were less than 0.08 m/s. Maximum orbital velocity has been estimated as \(u_{max} = 2\sigma_o\) where \(\sigma_o\) is the standard deviation of the cross-shore current (MASELINK and PATTIARATCHI, 2000). The skin friction Shields parameter
was used here to represent the shear stress at the bed in the form of a dimensionless number defined by:

\[
\theta = \frac{1}{2} f_w \frac{u_{*}^2}{\nu}
\]

where \( f_w \) is the wave friction factor proposed by Jonsson (1966) and estimated by Swart (1974) as:

\[
f_w = \exp\left[5.213 \left(\frac{k_s}{a_s}\right)^{0.194} - 5.977\right]
\]

and \( a_s \) is the near-bed orbital semi-excursion which is half of the near-bed orbital diameter \( d_s \) and \( k_s \) is the bed roughness height approximated by 2.5 \( D \) for smooth beds. In other words, only the skin friction was considered here to give a consistent method of calculating the Shields parameter.
throughout the period of observation. The near-bed orbital diameter was calculated using linear theory using:

$$d_o = \frac{H}{\sinh(kh)}$$

where $H$ is the significant wave height and $k$ is the wavenumber $(2\pi/L)$.

Maximum orbital velocity fluctuated between 0.4 m/s and 0.8 m/s (Figure 8a). This was an order of magnitude greater than the mean cross-shore currents. The Shields parameter fluctuated between 0.095 and 0.36 (Figure 8b). The largest values of both the maximum orbital velocity and the Shields parameter occurred during the sea breeze events. Near-bed orbital diameter increased between the sea breezes during the swell dominated period and decreased at the beginning of each sea breeze as wind waves became more dominant (Figure 5).

During the sea breeze there is a linear relationship between mean ripple wavelength and near-bed orbital diameter where $\lambda = 1.04 d_o$ ($r^2 = 0.62$, Figure 9). This is much larger than the value for orbital ripples $\lambda = 0.65 d_o$ found by Miller and Komar (1980) under laboratory conditions and the similar relationship of $\lambda = 0.62 d_o$ found by Wiberg and Harris (1994) using data from field and laboratory studies. The swell-dominated conditions during the land breeze exhibited very little change, except for a slight decreasing trend, in mean ripple wavelength with increases in near-bed orbital diameter. This suggests a shift from orbital, where ripple wavelength is proportional to the near-bed orbital diameter, to suborbital ripples, where the ripple wavelength is inversely proportional to near-bed orbital diameter, as the sea breeze gives way to the land breeze. Clifton (1976) found that orbital ripples ($\lambda \propto d_o$) occur when $d_o/D < 1000$, suborbital ripples ($\lambda \propto 1/d_o$) occur between $1000 < d_o/D < 5000$ and anorbital ripples ($\lambda \propto D$) occur when $d_o/D > 5000$. Values of $d_o/D$ for this study fall between 538 and 1309 where $d_o/D$ was generally less than 1000 during the sea breeze and greater than 1000 during the land breeze. By Clifton's (1976) definition the
ripples were orbital ripples during the sea breeze and sub-orbital ripples during the swell-dominated period. The relationships in Figure 9 are consistent with CLIPTON's (1976) observations of ripple type.

Ripple Migration

Cross-shore ripple movement was monitored to determine its relationship to the near-bed hydrodynamics. Individual ripples on each cross-shore survey line that could be traced for the duration of the study are shown in Figures 10a and 10d. A general onshore trend in ripple migration was evident with some offshore movement during sea breeze events. Ripple migration rates were calculated for each ripple identified in Figures 10a and 10c. These ripple migration rates were then averaged together for each cross-shore survey line and shown in Figures 10b and 10d. Substantial variability was evident in the migration rates. This was due to rapid movement of the very peak of the ripple crest that could move onshore or offshore up to 5 cm, due to a single larger than average wave. Therefore, the actual position of the ripple would change depending on whether its position was observed immediately after the passage of a large wave crest or trough. Averaging the migration rates of several ripples together significantly reduced the variability and general trends could be identified. Also, the ripple migration rate was smoothed with a 3 point running mean to further eliminate the fluctuations due to measurements taken during different wave phases. Ripple migration tended to be offshore during the sea breeze and onshore during the swell-dominated period.

Ripple migration varied inversely with significant wave height \( r = -0.55 \). This correlation with wave height was mainly due to the correlation of ripple migration with wind wave height \( r = -0.71 \) since there was no significant correlation between swell wave height \( r = -0.16 \) and ripple migration direction. As wind wave height increased, ripple migration was directed offshore (negative). Ripple migration quickly shifted onshore again as wind wave height decreased.

Ripple migration rate was significantly negatively correlated with the maximum near-bed orbital velocity \( r = -0.31 \) and Shields parameter \( r = -0.46 \). Ripples moved offshore during the higher Shields values associated with the sea breeze and moved onshore during the 'calmer' swell-dominated period. A significant positive correlation \( r = 0.62 \) was found between ripple migration rate and near-bed orbital diameter. Ripples migrated onshore during the relatively longer near-bed orbital diameters of the swell dominated period. The decrease in near-bed orbital diameter at the start of the sea breeze events coincided with a change in the ripple migration direction from onshore to offshore. Since the groupiness factor increased during the 'cleaner', calmer wave conditions during the land breeze, it was positively correlated to ripple migration. Ripples were found to move onshore as wave groupiness increased.

Ripple migration was also directly correlated with mean cross-shore velocity and cross-shore velocity asymmetry with \( r \) values of 0.66, and 0.38 respectively. This means that ripple migration was directed offshore during the highest offshore (negative) mean cross-shore currents and onshore as offshore mean velocity decreased (Figure 6c). Ripple migration was directed onshore when higher onshore (positive) values of cross-shore velocity asymmetry occurred.

Ripple migration rates for each ripple identified in Figures 10a and 10c were plotted against the water depth at each ripple (Figure 11a). Since measurements of waves and currents were only obtained at one cross-shore location, it is not known exactly how the near-bed flow changed with depth cross-shore. To estimate changes with depth, mean cross-shore velocity and cross-shore velocity asymmetry were grouped according to the temporal changes in water depths. Mean cross-shore velocity and cross-shore velocity asymmetry were grouped by 0.05 m depth intervals for both the sea breeze and swell-dominated period. A depth interval of 0.05 m was chosen so data from several time intervals fell within each depth category and an average could be calculated to give a representative value for each depth interval (Figure 11b-c). For ripples in depths less than approximately 0.9 m, the ripple migration rate increased in the onshore direction as depth decreased towards the shore (Figure 11a). The increase in ripple migration rate toward the shore as depth decreased coincided with decreasing offshore mean flow (Figure 11b) and increasing onshore velocity asymmetry (Figure 11c). This relationship changed in depths over 0.9 m since the greatest depth coincided with the highest swell and wind waves at the end of the sea breeze and beginning of the land breeze. At depths between 0.9 m and 1.02 m, the cross-shore velocity asymmetry increased and the offshore mean velocity decreased. Therefore, near-bed flows were similar to those in
depths 0.62 m–0.80 m where higher onshore velocity asymmetry also coincided with onshore ripple migration at a different point in time. The distribution of mean cross-shore velocity and cross-shore velocity asymmetry with depth were similar for both the sea breeze (dotted line on Figure 11b and c) and swell dominated periods (solid line on Figure 11b and c). At all depths, ripple migration was generally directed onshore during the swell dominated period and offshore during the sea breeze events (Figure 11a), suggesting that changes in near-bed flow due to the sea breeze were more significant than water level fluctuations in causing changes in the ripple migration direction.

Cross-Shore Suspended Sediment Transport

Suspended sediment concentration measurements were only reliable for the first 25 hrs of observations due to suspended plant matter in the water column after this time. Mean sediment concentrations for each OBS sensor for the first day of observations show two large distinct peaks at the lower OBS (arrows on Figure 12). These peaks occurred when the OBS sensors were very close to a ripple crest. The data from the lower OBS sensor (elevation of 0.05 m) was not analysed further here since it was difficult to separate variation in suspended sediment concentration over time from varia-

Figure 10. Ripple crest positions over time for ripples that could be traced for the duration of the study on (A) line 1 and (C) line 2. Time series of averaged migration rate (B) and (D) for ripples identified in (A) and (B) respectively. The shaded areas denote the sea breeze.
Figure 11. (A) Ripple migration rate for individual ripples by depth. * occur during land breeze and + occur during sea breeze. Mean cross-shore velocity (B), and cross-shore velocity asymmetry (C) by depth for sea breeze (dotted line) and land breeze (solid line).

Discussion

Ripple Wavelength

The ripples appeared to behave as orbital ripples during the sea breeze and suborbital ripples during the swell-domi-
nated period. Marsh et al. (1999) suggest that under field conditions there is often a broad wave spectrum where no particular near-bed orbital diameter is dominant and therefore the bed is unable to reform at the same pace as the changing near-bed flow. The bed morphology would then be highly dependent on the past bed morphology and near-bed flow. Also, they propose that a considerable amount of sediment must be moved in order to change the wavelength of a ripple field by a small amount. It is possible that the bed was unable to adjust to the new near-bed orbital diameter under the less energetic conditions during the swell-dominated period but observations suggest this was not the case for two reasons. First, the maximum cross-correlation between near-bed orbital diameter and ripple wavelength was found at a zero lag, suggesting rapid adjustment to changing conditions. Second, maximum migration rates were recorded during the land breeze, meaning that the ripples were just as mobile as during the sea breeze. It is therefore assumed that the change from orbital to suborbital ripple behaviour was due to crossing of the breakoff point (Grant and Madsen, 1982) at the beginning of the land breeze when longer orbital diameters occurred due to the dominance of swell waves.

The strongest correlation occurred between ripple wavelength and infragravity wave period ($r = 0.60$). The reason for this correlation is that both variables had increasing trends throughout the study. It seems possible that the increasing infragravity wave period had an influence on the ripple wavelength. An increase in the period of the longer

Figure 12. Time series of mean suspended sediment concentration at the lower OBS (solid line) and upper OBS (dashed line). Arrows indicate peaks in concentration referred to in the text. The shaded area denotes the sea breeze.

Figure 13. Time series of local transport rate at upper OBS. Solid, dashed and dotted lines denote net, mean and oscillatory transport rates respectively.
waves would cause an increase in the average near-bed orbital diameter, which has been shown to determine the wavelength of orbital ripples (INMAN, 1957; CLIFTON, 1976; DINGLER and INMAN, 1976). However, this is a matter for further research.

Ripple Migration and Cross-shore Sediment Transport

There are very few measured bedform migration rates in nearshore wave dominated environments with which to compare those measured at Garden Island. Migration rates reached a maximum of 0.2 cm/min and were closest to those measured by BOYD et al. (1988) (0.16 cm/min). Their rates were measured in a shoreface environment in a depth of 10 m and their mean flows were of similar magnitude (<0.1m/s) to those measured here. DINGLER and INMAN (1976) and OSBORNE and VINCENT (1993) found much greater nearshore migration rates of up to 5 cm/min although these were for small scale (<0.20m) bedforms and, in the case of the latter study, for a macro-tidal environment with measurable tidally induced flows. OSBORNE and VINCENT (1993) found lunate mega-ripples of comparable size, yet different shape to the ones observed here, migrating at rates up to 3 cm/min. Similar rates were observed by BRANDER (1991), but they were for much smaller ripples with average heights of 0.8 cm and wavelengths between 8 and 12 cm under higher cross-shore orbital velocities (maximum of 1.22 m/s) and much shorter wave periods (peak wave period of 8 s). Ripple migration rates in this study were much lower than those found in other nearshore studies, possibly due to the very low energy conditions (θ < 0.36) of Garden Island and the large size of the bedforms (λ = 0.3–1.2 m, η = 0.05–0.15 m). Migration of larger bedforms would require a greater amount of sediment movement.

VINCENT and OSBORNE (1993) found a positive relationship between the migration rate of small ripples (λ = 0.07–0.2 m, η = 0.005–0.02 m) and shear stress, but did not find a relationship between the migration rate of larger ripples (λ = 0.3–0.8 m, η = 0.03–0.08 m) and shear stress. The opposite was found in this study since bedform migration rate was found to have a significant negative correlation with the Shields parameter. These conflicting results could be due to the fact that the observations of VINCENT and OSBORNE (1993) were made in a higher energy environment (wave heights ≥ 0.3 m and often > 1 m) over smaller bedforms. VINCENT and OSBORNE’s (1993) observations were from a macro-tidal (spring tidal range of 5 m) environment with tidally induce currents and rapidly changing near-bed flows (OSBORNE and VINCENT, 1993). The results presented here are from a micro-tidal low-energy environment without significant tidal currents and subject to relatively slow changes in water level under neap tide conditions.

The question remains as to why the bedform migration rate actually decreased with an increase in bed shear stress. A physical explanation for this relationship has been proposed by AMOS et al. (1999). They found that bedform migration rate increased up to the threshold for saltation/suspension defined by:

\[ U_\text{w} + 3.0U^*_\text{w} = 0.13 \text{m/s} \]

The threshold was interpreted as the breakoff region described by GRANT and MADSEN (1982). Below the threshold, ripples are in the equilibrium range and bedform migration rate increases with flow, whereas above the threshold, in the breakoff range, bedform migration rate may increase or decrease, with increasing flow. The decrease in bedform migration rate with increasing flow was due to an increase in ripple by-passing by the saltating or suspended grains (AMOS et al., 1999). In other words, above the threshold the difference between bedform transport and bedload transport increases. Conditions during this study were above this threshold at all times due to the oscillatory current alone. The highest migration rates were directed onshore and occurred during lower-energy, longer-period, swell-dominated groupy conditions. It is possible that during the lower energy conditions (θ < 0.24), since less sand was moving in suspension (Figure 12), a greater portion of the sediment movement was as bedload which resulted in the increased bedform migration.

The direction of ripple migration apparently is dependent on a balance between the offshore mean velocity (bed return flow) and the onshore velocity asymmetry. The bedform migration could not be simply related to the mean flow as suggested by BAGNOLD (1963). Ripples in this study were observed to migrate both onshore and offshore under a mean flow that was directed offshore for the duration of the observations. DINGLER and INMAN (1976) and TRAYKOVSKI et al. (1999) both observed onshore migration of ripples. DINGLER and INMAN (1976) found that onshore ripple migration was positively correlated to a theoretical bottom wave-drift current whereas TRAYKOVSKI et al. (1999) found onshore ripple migration related to measurements of onshore wave asymmetry. During the swell-dominated period the onshore migration was proportional to the onshore velocity asymmetry.

During the sea breeze, the increase in offshore mean velocity and the decrease in onshore directed velocity asymmetry resulted in a change in the ripple migration direction. This can be seen in Figures 11a–d where the reversal of trend with depth for the velocity mean, and asymmetry at 0.9 m is mirrored by a change in trend in ripple migration rate. Changes in the near-bed flow due to the sea breeze appear to be more significant to ripple migration direction than changes in near-bed flow due to water level fluctuations since, at all depths, ripple migration was generally directed onshore during the swell dominated period and offshore during the sea breeze events. The change in water level over the period of observations altered the relative position of the EMCM in the water column which could have had an effect on the currents measured. This did not appear to be significant since there was no relationship between the water level and mean cross-shore currents or cross-shore velocity asymmetry.

In measurements of ripple migration rates on the shoreface, BOYD et al. (1988) did not find any consistent relationship between near-bed mean currents or near-bed velocity skewness and bedform migration. These opposing results were likely due to the fact that they observed smaller bedforms (wavelengths of 0.12 m) in finer sediment (mean size of 0.11 mm). The smaller bedforms and finer sediment would respond at different rates to the near-bed flows than the larg-
er coarser grained bedforms due to the different entrainment thresholds of the finer sediments and the different amounts of sediment involved in the movement of the smaller ripple crests.

The suspended sediment transport measurements indicate a possible mechanism for the reversal in migration direction with the onset of the sea breeze. During the sea breeze there was more sediment in suspension and therefore more sediment to be carried offshore by the increase in mean offshore velocity. This is one of the mechanisms observed by Russell (1993) for net offshore transport during storms. The increase in offshore mean transport rate was not balanced by a corresponding increase in onshore velocity asymmetry. Net localized suspended transport increased slightly offshore, which possibly led to the change in ripple migration direction, although Trykovski et al. (1999) found that an increase in offshore suspended sediment transport occurred concurrently with an increase in onshore ripple migration rate. However, they found that onshore wave asymmetry also increased concurrently with the onshore ripple migration rate and they suggest that bedload, in the direction of ripple migration, was much greater than suspended sediment transport.

Masselink and Pattiaratchi (1998c) found that the morphodynamic changes during a sea breeze cycle were similar to those that occur during a medium intensity storm event. Offshore transport resulted in the erosion of the beachface during the sea breeze, whereas onshore transport prevailed during the land breeze, causing beachface accretion. During this study the sea breeze was not as strong as that during the Masselink and Pattiaratchi (1998c) study and beachface changes were expected to be small. Therefore, the degree of beachface change was not monitored in detail here. Despite this, erosion and deposition on the beachface was evident by the change in the cross-shore profiles at the different water levels (Figure 2). The offshore migration of the ripples during the sea breeze and onshore migration during the land breeze, suggests some beachface erosion occurred during the sea breeze and accretion occurred during the land breeze. As conditions become more energetic, the ripples changed direction and moved offshore. The migrating ripples provide a possible mechanism by which sediment is moved on and offshore during the sea breeze cycle. Addition concurrent measurements of cross-shore profiles and ripple migration are required over longer time periods to determine whether or not this is the case.

CONCLUSIONS

The following conclusions can be made concerning large parallel ripples in the nearshore of the low-energy beach at Garden Island:

1. Different relationships existed between ripple wavelength and near-bed orbital diameter during the swell-dominated period and the sea breeze. The departure of the ripple wavelength from a linear relationship with near-bed orbital diameter during the land breeze suggested that the breakoff point between orbital and suborbital ripples was crossed with the increase in near-bed orbital diameter during the swell-dominated period.

2. It is proposed that ripple migration direction was a result of the balance between offshore mean flow and onshore wave asymmetry. Swell-dominated groupy conditions with relatively low offshore mean flow and relatively high onshore velocity asymmetry favoured onshore ripple migration. Wind wave dominated conditions with relatively high offshore mean flow and relatively low onshore velocity asymmetry favoured offshore ripple migration. A longer time series of ripple migration, waves and currents is needed to more thoroughly separate the effects of tidal changes from those of the sea breeze and to establish the effects of wind setup.

3. Masselink and Pattiaratchi (1998c) suggest that the sea breeze cycle along the central and southwestern coast regions of Western Australia produces morphodynamic changes which are similar to a medium intensity storm event. The onshore movement of ripples during the land breeze and offshore movement during the sea breeze suggest a switch from accreting to eroding conditions with the onset of the sea breeze. Increase in suspended sediment concentrations during the sea breeze resulted in additional sediment available for transport offshore by the increased mean offshore flow. This same process causes erosion during storms (Russell, 1993). The offshore movement of the ripples provides a possible mechanism for offshore movement of sediment during storm or other onshore wind events on this low energy beach. Additional concurrent measurements of ripple migration and detailed beachface morphology are needed to determine the exact nature of the relationship between the step and the nearshore bedforms.

ACKNOWLEDGEMENTS

The research was completed as part of my doctoral research supported by the University of Western Australia and NSERC Canada. The tireless efforts of the field assistants Paul Bradwell, Kirsten Dahl, Astrid Dahl, Lucy McNicol, Sarah Gardner, Emma Slarke, Brendan Ward and Clare Wood were much appreciated. Ian Eliot, Gerd Masselink, Paul Vil­lard, Chari Pattiarachi and two anonymous reviewers provided very helpful comments. I would also like to thank Dr. Boyd Wykes for arranging access to the field site.

LITERATURE CITED


