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Sea breeze activity and its effect on coastal processes near Perth, Western Australia

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Abstract

The Perth Metropolitan coastline is exposed to one of the most energetic sea breeze systems in the world, with wind velocities frequently exceeding 10 m s^{-1}. The sea breeze induces a diurnal cycle of nearshore change by causing; (1) an increase in wave height, (2) a decrease in wave period, (3) an intensification of the nearshore currents, (4) an increase in suspended sediment levels and suspended sediment transport, and (5) a modification of the nearshore morphology. The role of sea breeze activity is particularly important along the Perth Metropolitan coastline, because here the sea breeze blows predominantly in a shore-parallel rather than a shore-normal direction. As a consequence, the wind waves induced by the sea breeze are larger, persist longer and approach the coast under a large angle with the shoreline. The alongshore component of the sea breeze and the obliquely-incident wind waves generate strong longshore currents and a northward littoral drift. The sea breeze therefore plays a dominant role in the sediment budget of the Perth Metropolitan coastline.

Introduction

The Perth Metropolitan coastline (Fig 1) is located within the Cape Bouvard to Trigg Island Sector of the Rottnest Shelf Coast (Searle & Semeniuk 1985). This sector is characterized by a complex nearshore bathymetry, and extensive but discrete cells of Holocene deposition in the form of prograded beach ridges and aeolian sand plains. The nearshore geomorphology and bathymetry is dominated by a series of more or less shore-parallel oriented submarine to emergent aeolinate ridges that provide extensive sheltering of the mainland coast (Hegge *et al.* 1996).

The mixed tides of the coast are microtidal with a mean spring tidal range of 0.4 m (Department of Defence 1990). Because of the relatively low range of the tide, it is frequently over-ridden by barometric pressure effects on sea level (Clarke & Eliot 1983). The wave climate is dominated by a low to moderate energy, deep water wave regime characterized by persistent south to southwest swell (Davies 1980) and an average offshore significant wave height of 1.5 m (Riedel & Trajer 1978). Closer to shore, the swell is refracted and diffracted by offshore reef systems and greatly attenuated by shoaling across the inner continental shelf. As a result, the inshore wave height is about half of that outside the reef system (Steedman 1977). A highly variable wind wave climate is superimposed on the swell regime, dominated by northwesterly to westerly storm waves during the winter and by the wave field associated with strong south to southwesterly summer sea breezes. Waves in the winter are more energetic than in the summer, inducing a seasonal cycle of beach change with barred, narrow beaches in the winter and wide beaches with a high berm in the summer (Eliot *et al.* 1983).

The coastline of Perth is exposed to one of the most energetic sea breeze systems in the world (Gentilli 1972). Commonly known as the "Fremantle Doctor", the summer sea breeze blows for approximately 60% of the summer days with wind velocities frequently exceeding 10 m s^{-1} (Hounam 1945). The impact of sea breeze activity on the coastal environment is often obscured by the presence of high wave energy levels or large tidal ranges. According to Sonu *et al.* (1973), there has been the tendency to discount its effects on coastal processes. However, along the low wave energy and microtidal Perth Metropolitan coastline, the sea breeze is expected to have a significant impact on the coastal processes in general and on the littoral drift in particular.

Studies by Kempin (1953) and Silvester (1961) indicate the presence of an oscillatory north-south motion of sand along the Perth Metropolitan coastline during the year with a resultant northerly bias. Sand is moving south during the winter as a result of southward-flowing currents generated by northwesterly storms, whereas during the summer the southerly sea breezes induce a northward sediment transport. Such a seasonal pattern of littoral drift is characteristic of the entire Rottnest Shelf region (Searle & Semeniuk 1985).

I report here the results of two field studies carried out at City Beach in Perth to investigate the impact of sea breeze activity on the coastal environment. The temporal scale of my study is considerably shorter than those of previous studies (cited above) as the focus is on the hydrodynamic and morphological changes that take place over the time scale of the sea breeze cycle (one day). I show that sea breeze activity significantly affects nearshore processes along the Perth Metropolitan coastline.

Methods

City Beach is characterized by a steep beachface gradient (7°) and medium-sized sediments (0.3–0.5 mm). Pro-

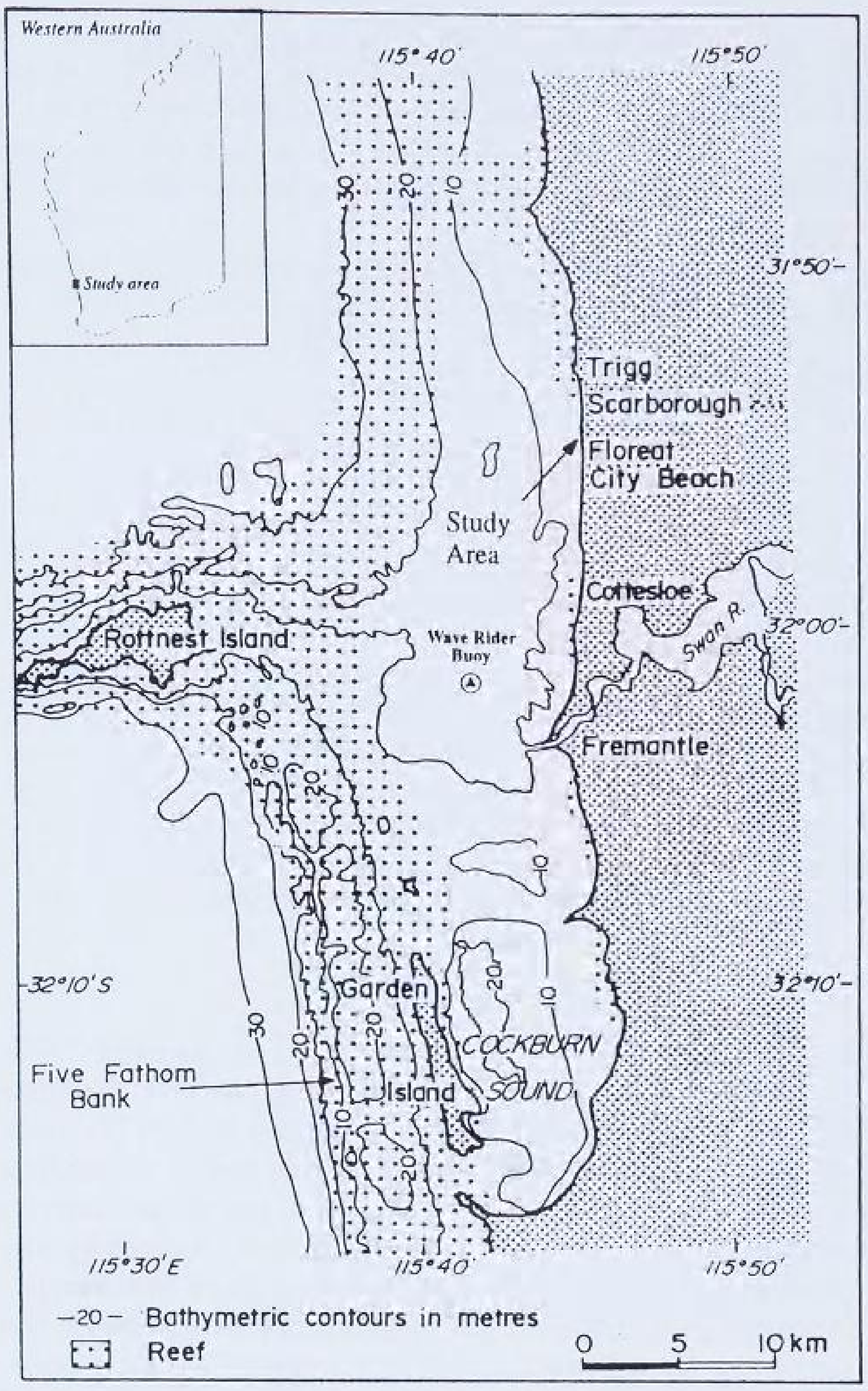

Figure 1. Location map of the Perth Metropolitan coastline and the study site.

nounced beach cusp morphology is typically present with a longshore cusp spacing of around 30 m. During the field surveys, measurements were conducted of; (1) wind speed and direction, (2) nearshore water levels, cross-shore and longshore current velocities and suspended sediment concentrations, and (3) beach morphology. Wind data were collected every five minutes using a standard weather station deployed on the beach berm at a height of 5 m. Hydrodynamic data were sampled continuously at 2 or 5 Hz using an instrument station equipped with a pressure sensor to measure water levels, an acoustic bi-directional current meter and three optical backscatter sensors to monitor suspended sediment concentrations at three different elevations above the sea bed ($z = 0.025$, 0.125 and 0.275 m). The instrument station was deployed in about 1.5 m water depth. The hydrodynamic data were subdivided into sections of 17 minutes and summary statistics were computed. Morphological measurements were made using an extensive array of mild steel pegs (length 1 m and diameter 10 mm) installed on the beachface. The elevations of the tops of the pegs were surveyed every day using a dumpy level. The distance of the top of the pegs to the sand surface was measured hourly using a ruler. The vertical resolution of the morphological measurements was 1 cm.

The first field survey was conducted in January 1992 and lasted half a day; the energetic surf zone conditions generated by the strong sea breeze (wind velocities > 10 m s^{-1}) caused frequent toppling of the instrument station and it was not possible to proceed with the measurements during the height of the sea breeze. The hydrodynamic measurements were made in the surf zone under the influence of breaking waves. The second field survey was carried out over six days in March 1995 and included three moderately-strong sea breezes (wind velocities 5–7 m s^{-1}). Hydrodynamic data were collected under shoaling waves just prior to breaking.

Results

First field survey

Time series of wind speed and direction measured during the first field survey are typical of a sea breeze cycle characterized by weak offshore winds in the morning and early afternoon, and a strong sea breeze starting in the afternoon and continuing into the evening (Fig 2). Wind velocities associated with the land breeze were less than 5 m s^{-1}, whereas they frequently exceeded 10 m s^{-1} during the sea breeze. Such wind speeds are above average, but commonly occur in the summer months on the Perth Metropolitan coastline. The sea breeze started at 14:45 hrs and the change in wind speed and direction was almost instantaneous. The direction of the sea breeze was consistently from the south (180°) and hence the sea breeze was blowing parallel to the shoreline.

The change in the wind climate is reflected in the incident wave field, nearshore currents and suspended sediment concentrations (Fig 2). Prior to the sea breeze, small-amplitude swell with significant wave heights of 0.4 m and zero-upcrossing periods of 7–8 s prevailed. Mean cross-shore currents were negligible (< 0.05 m s^{-1}) and mean longshore currents flowed in the northward direction with velocities less than 0.1 m s^{-1}. The mean suspended sediment concentration at a distance of 0.275 m above the bed was about 1 g L^{-1} and sediment was only suspended during the passage of large waves in wave groups. The onset of the sea breeze induced almost immediate changes in the nearshore hydrodynamics. The wave height increased, reaching 0.7 m at the end of the field survey. The wave period decreased and assumed a constant value of 4 s within one hour of the start of the sea breeze. Offshore-directed cross-shore currents in the surf zone rapidly increased in strength to 0.16 m s^{-1} and then fluctuated around 0.12 m s^{-1}. The northerly longshore current progressively increased in strength up to 1 m s^{-1} and was still increasing when the survey was abandoned. Sediment was continuously suspended by the waves and the amount of suspended sediment in the water column increased seven-fold to 7 g L^{-1}.

A crude estimate of the longshore suspended sediment transport rate was obtained by multiplying the longshore current velocity by the suspended sediment concentration and integrating the product over the water column and across the surf zone. Before the start of the sea breeze, the northward transport rate was approxi-

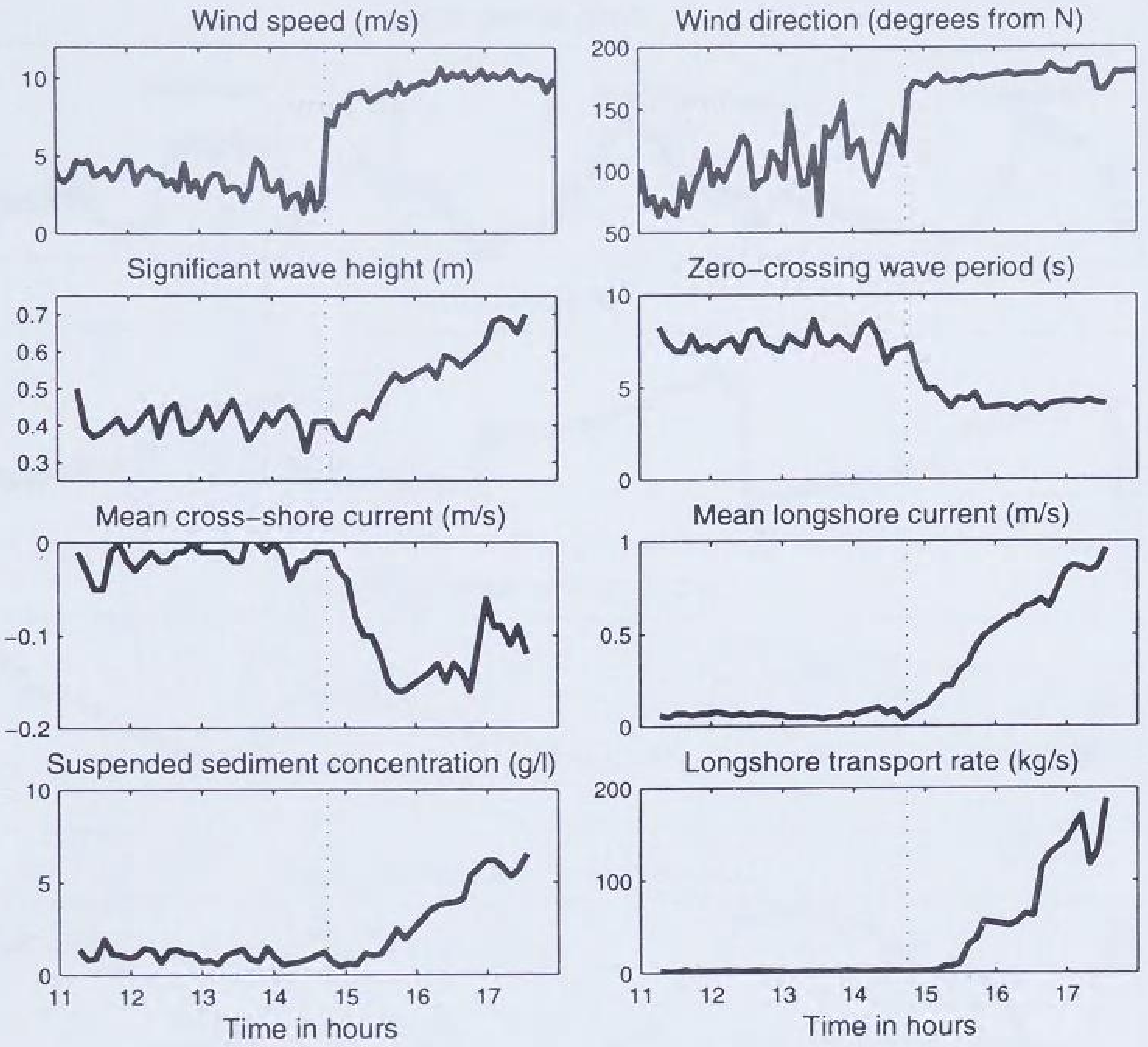

Figure 2. Wind speed, wind direction, significant wave height, zero-crossing wave period, cross-shore current velocity, longshore current velocity, suspended sediment concentration measured 0.275 m above the bed and longshore suspended sediment transport averaged across the surf zone measured on City Beach (23/01/92). The start of the sea breeze is indicated by the dotted line. The sea breeze induces almost instantaneous changes in the nearshore hydrodynamic conditions

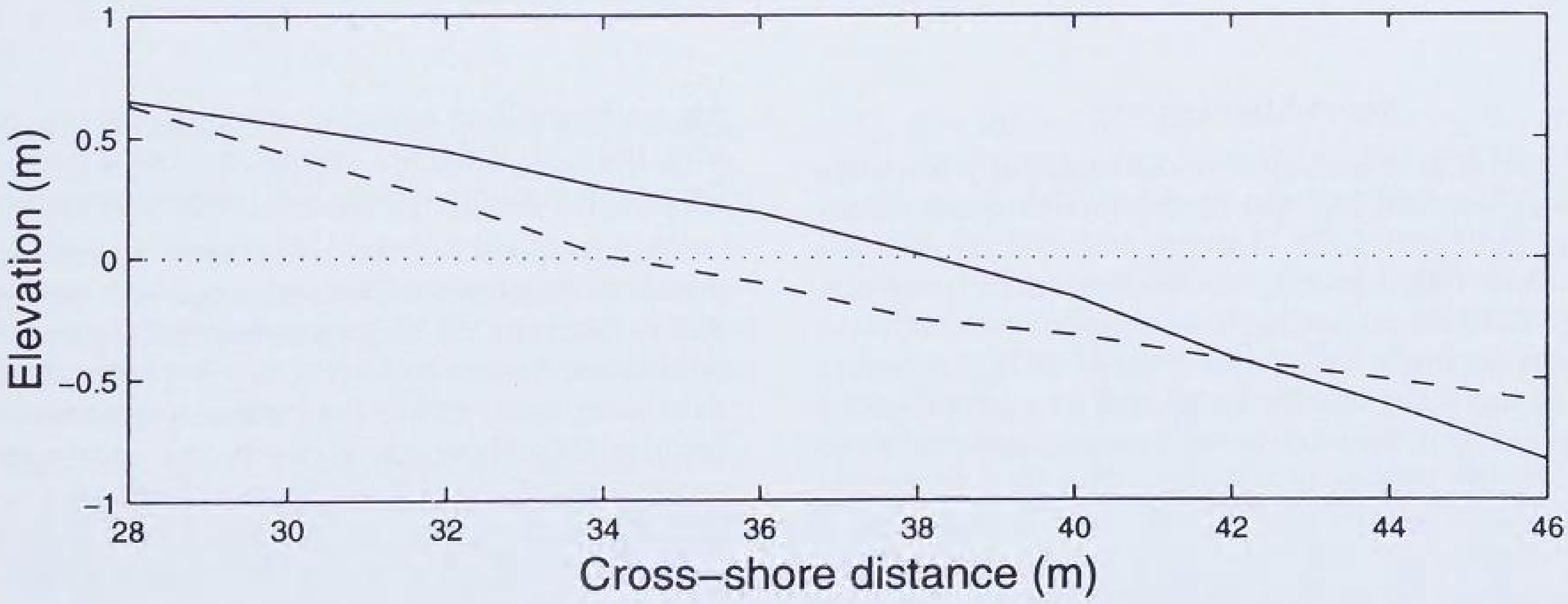

Figure 3. Beachface profile of City Beach (23/01/92) before (solid line; 14:00 hrs) and at the height of the sea breeze (dashed line; 19:00 hrs). During the sea breeze, erosion takes place on the upper part of the beach, whereas accretion occurs low on the beach. The elevation is measured relative to approximately 1 m above mean sea level.

mately 1 kg s^{-1}, but it increased during the sea breeze by two orders of magnitude to 100–200 kg s^{-1} (Fig 2).

The changes in the hydrodynamic conditions caused by the sea breeze induced an adjustment of the beach morphology; up to 0.4 m of erosion occurred on the upper part of the beach, whereas deposition took place on the lower part (Fig 3). The cusp morphology that was present on the beach prior to the sea breeze was completely eradicated. Field observations indicated that the beach cusps reformed overnight, after the sea breeze had subsided.

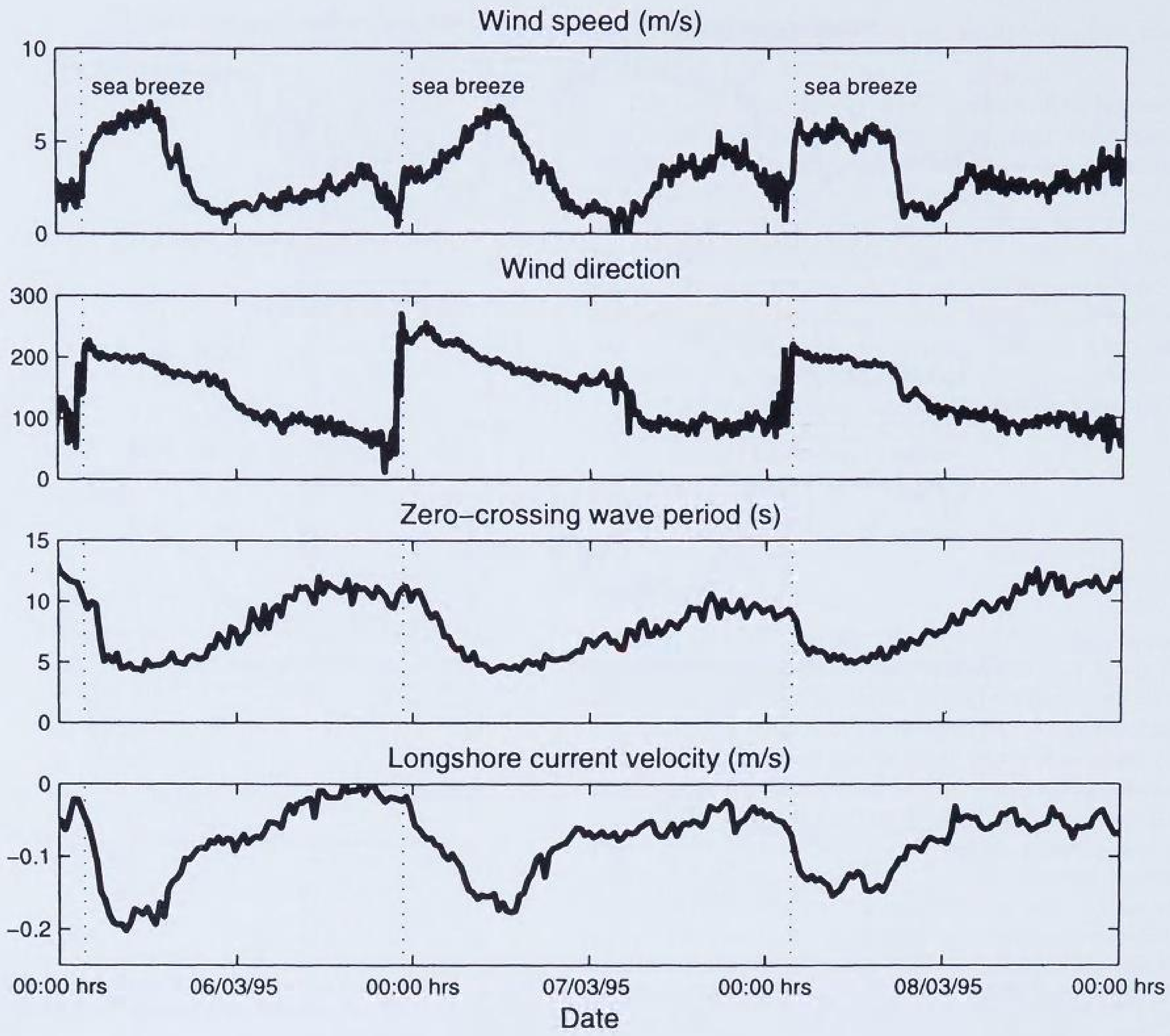

Figure 4. Wind speed, wind direction, zero-crossing wave period and longshore current velocity measured on City Beach (from 12:00 hrs on 06/03/95 to 12:00 hrs on 09/03/95). The start of the sea breezes is indicated by the dotted lines. The effect of the sea breeze on the nearshore hydrodynamic conditions extend a considerable duration after the cessation of the sea breeze.

Second field survey

The second field survey showed essentially the same features as the first, but due to the smaller wind velocities, the hydrodynamic changes induced by the sea breeze were less extreme. Around-the-clock measurements of three successive sea breeze cycles were collected and these enabled the investigation of the recovery period of the wave conditions after the cessation of the sea breeze (Fig 4). Prior to the sea breezes, offshore winds prevailed with speeds of 2–3 m s^{-1}. The start of the sea breezes is indicated by an abrupt change in the wind direction from east to south and an concomitant increase in the wind velocity. All three sea breezes persisted for approximately 7 hours and a relatively constant wind velocity of 5–7 m s^{-1} was maintained throughout. After the onset of the sea breeze, almost immediate changes occurred to the incoming wave field as indicated by a decrease in the wave period from 10 to 5 s and an increase in the longshore current velocity from insignificant to 0.15–0.2 m s^{-1}. Around 20:45 hrs, the sea breezes stopped. The wind direction gradually shifted back to the east and the wind velocities dropped below 4 m s^{-1}. The wave period started increasing and the longshore current velocity started decreasing as soon as the sea breeze had subsided. Around 6:00 hrs, nine hours after the end of the sea breeze, the wave period and the longshore current velocity had reached pre-breeze levels.

Energy spectra of the cross-shore current were computed to construct a three-dimensional time-frequency plot to illustrate the change in spectral signature over the second sea breeze cycle (Fig 5). The cross-shore current data were used, rather than the water surface elevation because they show more clearly the short-period wave energy caused by the sea breeze (frequency > 0.15 Hz). The long-period background swell was present in the time-frequency plot in the form of a linear ridge at frequency 0.07–0.1 Hz. The peak period associated with the swell energy was 12 s and remained relatively constant. After the onset of the sea breeze, wind wave energy started to emerge at the high-frequency end of the spectra, indicating peak wave periods of 2.5 s. During the sea breeze, the frequency associated with the wind waves decreased progressively, forming a curving ridge in the frequency-time plot. At the end of the sea breeze (21:00 hrs), the wind wave energy was concentrated around a frequency of 0.25 Hz, indicating a peak period of 4 s. After the sea breeze had subsided, the wind wave energy gradually decreased, but remained significant.

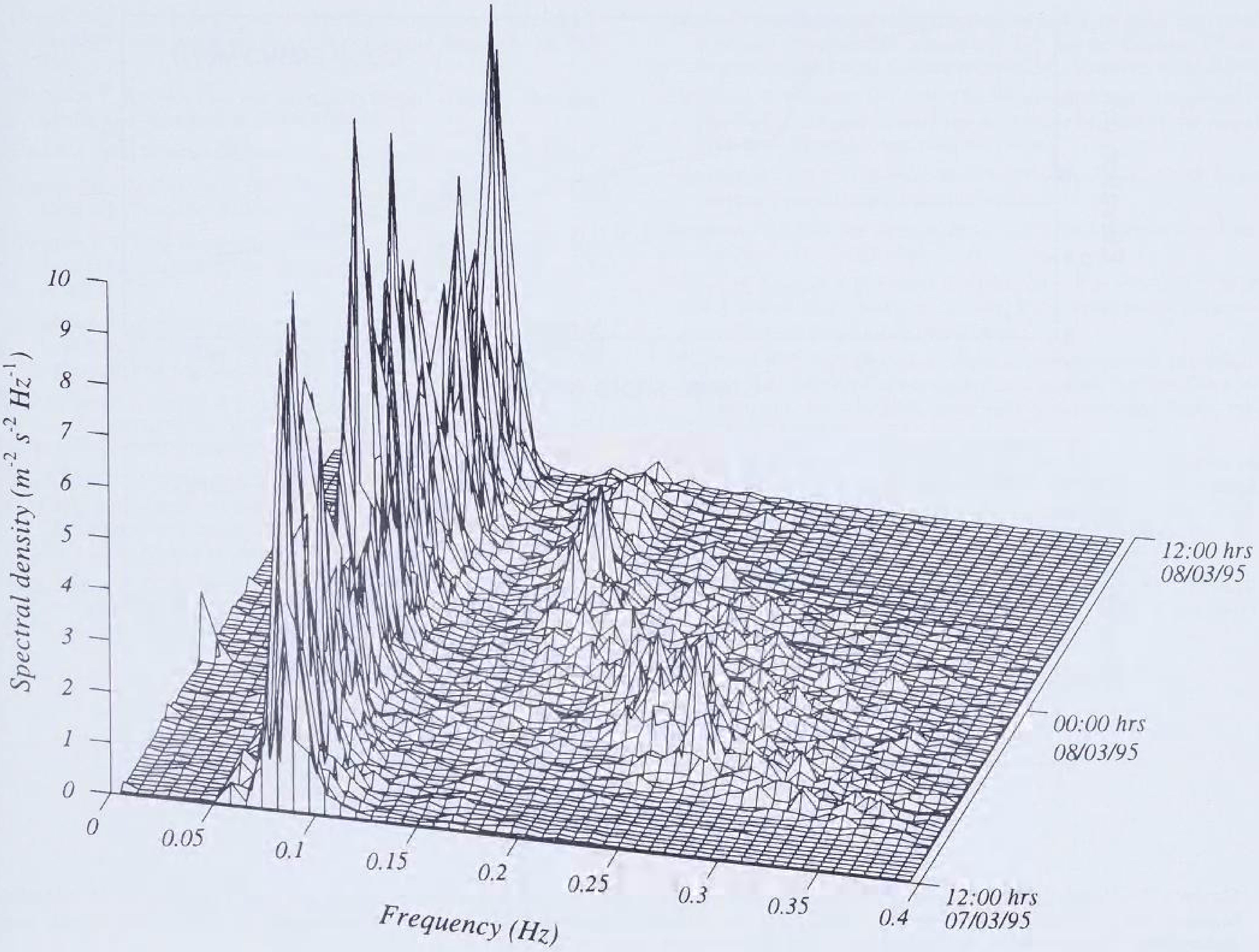

Figure 5. Frequency-time plot of spectra of the cross-shore current velocity measured on City Beach (from 12:00 hrs on 07/03/95 to 12:00 hrs on 08/03/95). The background swell is represented by the linear ridge around 0.08 Hz, whereas the wind waves are indicated by the curving ridge at 0.15–0.4 Hz.

The frequency associated with the wind wave energy decreased to 0.15 Hz, merging with the swell energy. Fifteen hours after the cessation of the sea breeze (12:00 hrs 08/03/93), there was still some wave energy present that was generated by the sea breeze in the nearshore zone. This implies that the effect of the sea breeze on the nearshore hydrodynamics may be continuous during the sea breeze season (summer).

The three sea breezes monitored during the second field survey induced changes to the beach morphology (Fig 6). Pronounced beach cusp morphology remained present on the beach, but during the sea breeze, erosion took place on the cusp horn and accretion occurred in the cusp embayment. Consequently, the beach cusp morphology became less pronounced. No sediment exchange was observed between the upper part of the beach and the nearshore zone, since morphological changes involved a shore-parallel redistribution of sediment over the beach cusp system.

Discussion

The findings of two field surveys, aimed at investigating the impact of sea breeze activity on nearshore processes, are similar to those of Sonu *et al.* (1973), the only other study into sea breeze effects. The sea breeze results in; (1) an increase of the wave height, (2) a decrease in the wave period, (3) an intensification of the nearshore currents, (4) an increase in suspended sediment levels and suspended sediment transport, and (5) a modification of the nearshore morphology. Due to the predominantly longshore component of the sea breeze, the nearshore hydrodynamics are affected long after the sea breeze has ceased to blow. Sonu *et al.* (1973) refer to this as the "afterglow effect". Both the strength and consistency of the sea breeze, and the afterglow effect contribute to the important role that the sea breeze plays on the nearshore processes along the Perth Metropolitan coastline.

The role of sea breeze activity in this region is particularly important because the sea breeze blows predominantly in a shore-parallel direction. The seaward extent of the sea breeze is usually 50–100 km (Hsu 1988; Simpson 1995) and consequently, the generation of wind waves by an shore-normal sea breeze is limited by the fetch length, restricting both the height of the wind waves and the duration over which the waves influence

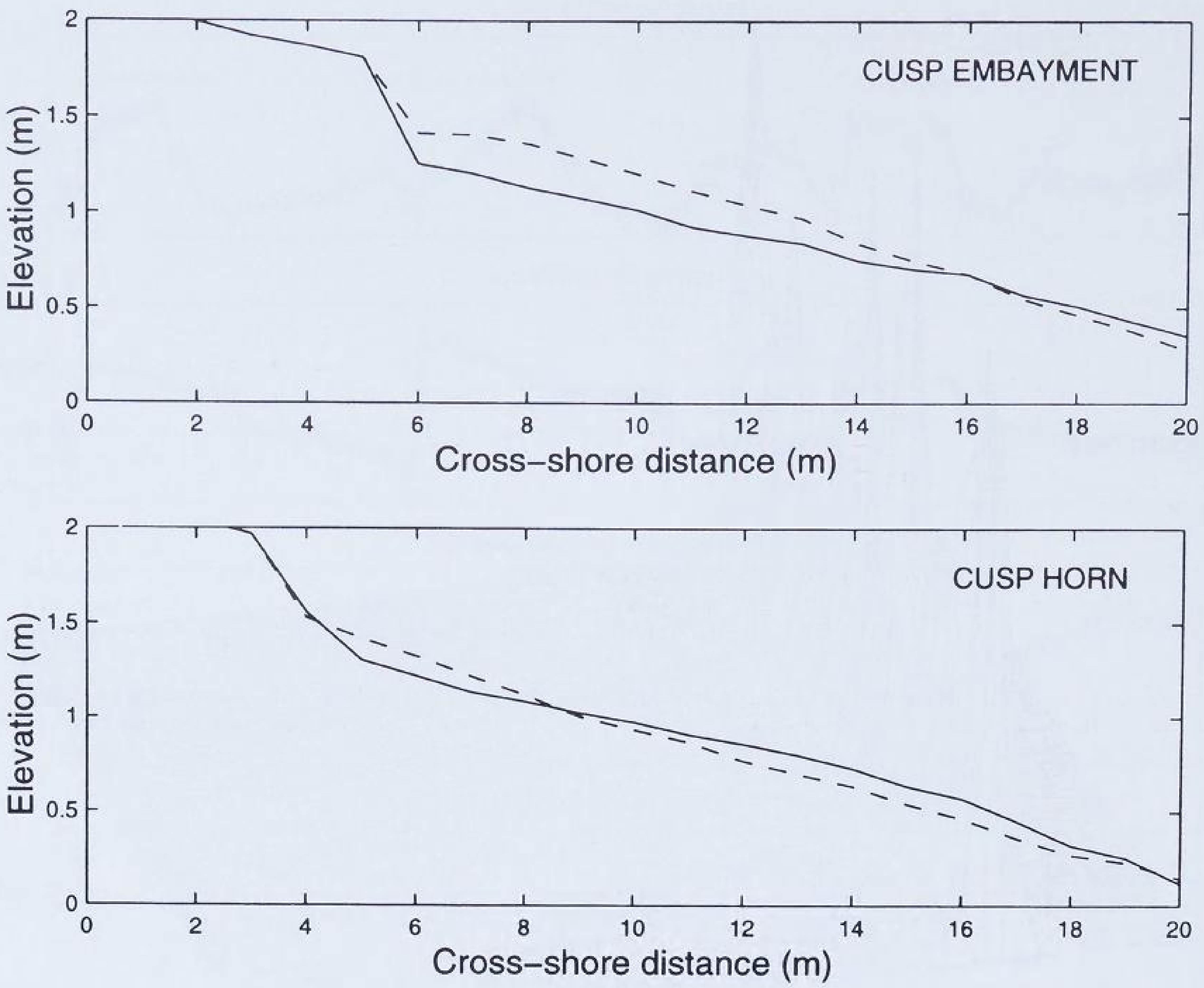

Figure 6. Beachface profile of the cusp embayment and the cusp horn on City Beach (08/03/95) before (solid line; 14:00 hrs) and after (dashed line; 21:00 hrs) the sea breeze. During the sea breeze, erosion of the cusp horn is accompanied by accretion in the cusp embayment. The elevation is measured relative to approximate mean sea level.

nearshore processes. For a shore-parallel blowing sea breeze, the fetch is virtually unlimited and given sufficient duration of the sea breeze, the wind wave field can attain its maximum energy level and develop into a "fully-developed" sea. In addition, wind waves may continue to arrive at the coastline long after the sea breeze has subsided. Finally, the obliquely-incident wind waves and the longshore wind stress may induce strong longshore currents that affect littoral transport.

The sea breeze induces a diurnal cycle of beach change by causing erosion of the upper part beach and/or planation of beach cusp morphology. These changes are reversible in that the beach is usually restored to its pre-breeze state after the cessation of the sea breeze. On the larger temporal and spatial scale, the dramatic increase in the longshore sediment transport caused by the sea breeze is important. Masselink & Pattiaratchi (in press) and Pattiaratchi *et al.* (in press) estimate that along the Perth Metropolitan coastline, the annual longshore transport driven by the sea breeze is approximately 100,000 m^3. This estimate corresponds to calculations of sediment accumulation at the southern side of Trigg Island (Perth) at the end of the summer. It is apparent that the sea breeze must play a dominant role in the sediment budget of the coastline around Perth. For example, a significant proportion of the sediment required for shoreline progradation of cuspate forelands such as Becher Point and Rockingham (Woods & Searle 1983), Whitfords Cusp (Semeniuk & Searle 1986), Jurien (Woods 1983), and other types of coastal landforms such as tombolas and salients (Sanderson & Eliot 1996) is probably contributed by the littoral drift induced by sea breeze activity.

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