

Sea Breeze Climatology and Nearshore Processes along the Perth Metropolitan coastline, Western Australia

G. Masselink¹ and C.B. Pattiaratchi²

Abstract

The Perth metropolitan coastline is characterised by one of the strongest and most consistent sea breeze systems in the world. In contrast to the 'classic' sea breeze system, characterised by sea breezes blowing in the onshore direction, the sea breeze in Perth blows in a predominantly alongshore direction. Each year, around 200 sea breezes are experienced with an average wind speed of 5.7 m/s. Sea breezes in summer are stronger and more persistent than in winter. The importance of the sea breeze is clearly indicated by wind spectra showing significant spectral peaks at the diurnal frequency. The sea breeze system directly forces the incident wave field and 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; and (4) an increase in suspended sediment levels and suspended sediment transport. In addition, the seasonal variation in sea breeze activity, with frequent and strong sea breezes in summer and infrequent and weaker sea breezes in winter, is responsible for a seasonal change in the littoral drift direction. In summer, longshore sediment transport is towards the north and causes beaches located south of structures or headlands to widen considerably. In winter, when littoral drift is towards the south due to northwesterly storms, beaches located north of structures or headlands will become wider. It is further demonstrated that strong sea breeze activity is common along the entire Western Australian coastline, implying that the results obtained for the Perth metropolitan coastline can be applied to some extent to the entire state.

¹ Research Fellow, Department of Environmental Engineering, Centre for Water Research, University of Western Australia, Nedlands, WA 6907, Australia.

² Head, Department of Environmental Engineering, Centre for Water Research, University of Western Australia, Nedlands, WA 6907, Australia.

Introduction

The Perth Metropolitan coastline experiences mixed, microtidal tides with a mean spring tidal range of 0.9 m (Department of Defence, 1996). Because of the relatively low range of the tide, it is frequently over-ridden by barometric pressure effects on sea level (storm surge and shelf waves), wind/wave set-up and seiche (Eliot and Clarke, 1986). The offshore wave climate is dominated by a low to moderate energy, deep water wave regime characterised by persistent south to southwest swell and an average significant wave height of 1.5–2.5 m (Lemm, 1996; Fig. 1). Closer to shore, the swell is refracted and diffracted by several offshore reef systems and greatly attenuated by shoaling across the inner continental shelf. As a result, the inshore wave height is about 40% of that outside the reef system (Steedman, 1993). A highly variable wind wave climate is superimposed on the swell regime, dominated by northwesterly to westerly storm waves during winter and by the wave field associated with strong south to southwesterly summer sea breezes.

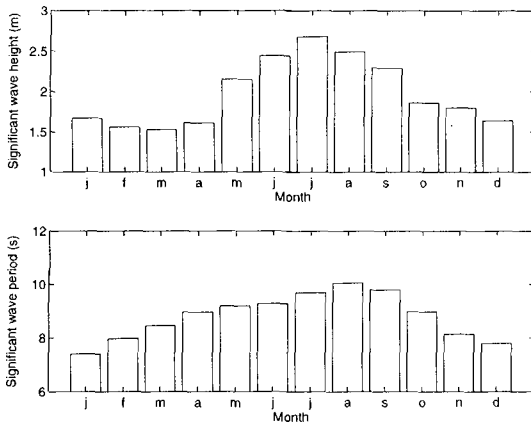


Fig. 1 - Offshore wave climate of Perth (data from Lemm, 1996).

The coastline of Perth is subject to one of the most energetic and consistent sea breeze systems in the world. A typical sea breeze cycle is characterised by offshore winds from an easterly direction ($80\text{--}100^\circ$) in the morning, switching to shore-parallel southerly ($180\text{--}200^\circ$) winds in the afternoon (Fig. 2). A significant feature of the sea breeze system along the Perth coast is that it blows parallel to the shoreline, in contrast to the "classic" onshore sea breeze. The shore-parallel sea breeze system in Perth, and in fact along most of Western Australian coastline, is attributed to the interaction between the sea breeze system and synoptic weather patterns (Pattiaratchi et al., 1997).

The impact of sea breeze activity on surf zone processes and morphology along the Perth metropolitan coastline has been extensively discussed by Masselink (1996), Pattiaratchi et al. (1997) and Masselink and Pattiaratchi (1998a, b). These studies indicate that the energy levels in the surf zone increase dramatically during the sea breeze, and suggest that the effect of a strong sea breeze on nearshore processes is similar to that of a small storm. The objective of this paper is put these previous

morphodynamic investigations in a wider perspective by characterising the Perth sea breeze climate using more than 50 years of wind data collected at Perth airport. The wind analysis is extended to nine other Western Australian coastal locations to demonstrate that strong sea breeze activity is common along the entire Western Australian coastline, implying that the results obtained for the Perth metropolitan coastline can be applied to some extent to the entire state.

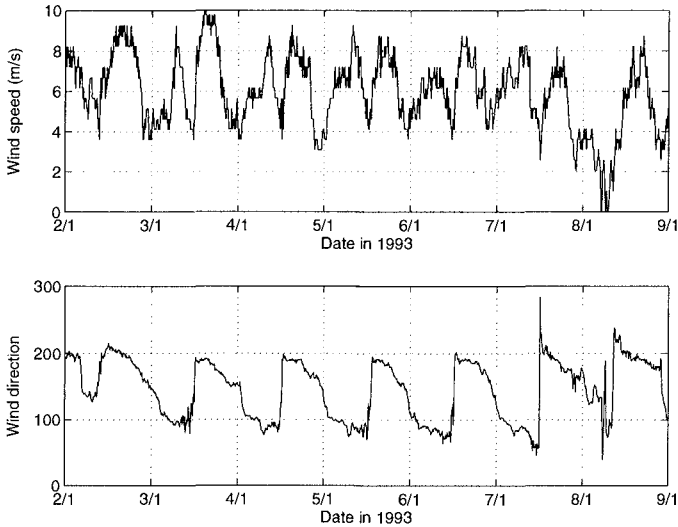


Fig. 2 - A typical 1-week time series of wind speed and direction collected at Ocean Reef, 2–9 January, 1993 (data from Pattiaratchi et al., 1997).

Time-Domain Analysis of Sea Breezes in Perth

Three-hourly wind data collected at Perth Airport from 1948–1997 were used to determine the sea breeze climate of Perth. The data were subjected to an algorithm that selected the days during which sea breezes occurred. A day was considered a “sea breeze day” if: (1) the wind direction in the afternoon (15:00 hrs) was from the sea breeze direction (190° – 300°), but the wind in the morning (09:00 hrs) was not from that direction; or (2) The wind direction in the morning and afternoon were both from the sea breeze direction, but the afternoon wind speed was larger than during the morning. Using these selection criteria the number of sea breezes per month and the mean sea breeze speed and direction were determined.

A strong seasonal variation in sea breeze activity is apparent (Fig. 3). In the summer months, more than 20 sea breezes are experienced per month with speeds (at 15:00 hrs) of 6–7 m/s. In the winter, only 10–15 sea breezes occur per month with speeds of around 5 m/s. On average, each year 197 sea breezes are experienced with a mean wind speed of 5.7 m/s. The direction of the sea breeze is consistently from the WSW throughout the year. However, the summer sea breeze blows from a slightly more southerly direction (240°) than the winter sea breeze (250°).

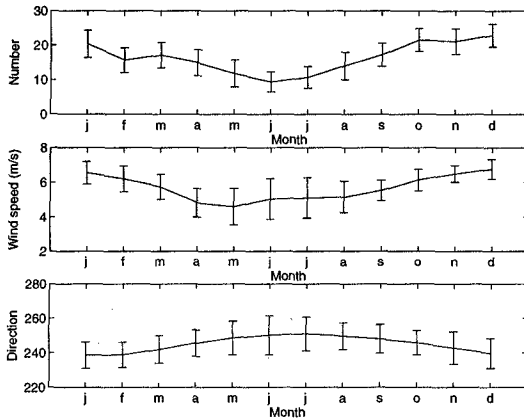


Fig. 3 - Seasonal variation in the number of sea breezes (upper panel) and the wind speed (middle panel) and direction during the sea breeze (lower panel) from three-hourly data collected at Perth Airport from 1948–1997. The vertical lines indicate the standard deviations associated with the averages.

Frequency-Domain Analysis of Sea Breezes in Perth

The Perth wind data was also subjected to spectral analysis. For each year, spectra were computed for the periods December–February (summer), March–May (autumn), June–August (winter) and September–November (spring). Subsequently, an average spectra was determined for each of the seasons (Fig. 4). All spectra show three main characteristics. Firstly, a large amount of energy is present at the low-frequency end of the spectrum (periods longer than 1.5 days). This corresponds to the time scale of synoptic weather patterns, such as storms. Secondly, a pronounced peak can be found at the diurnal frequency (period of one day). This peak represent sea breeze activity. Thirdly, complementary peaks occur at the first and second harmonics of the diurnal frequency (periods of 12 and 6 hours, respectively). These are primarily due to the non-linear (non-sinusoidal) nature of the sea breeze signal. However, the occurrence of strong land breezes during night may also have contributed to the first harmonic frequency (refer Fig. 2). The diurnal peak is present in all the seasonal spectra, but is widest in the summer spectrum and narrowest in the winter spectrum.

Using the same data set, monthly wind spectra were computed and an average spectra was determined for each month. The total spectral energy was then partitioned into a low-frequency band (period larger than 1.5 days; ‘synoptic band’) and a high-frequency band (period smaller than 1.5 days; ‘sea breeze band’) to allow investigation of the seasonal variation in the importance of these components (Fig. 5). The spectral energy of the synoptic band and the sea breeze band show an anti-phase relationship; the synoptic band reaches its maximum energy levels in June/July when storm activity is prevalent, whereas the sea breeze band dominates from November–January when sea breeze are at their strongest and most abundant. In the summer months, the sea breeze band accounts for 60–70% of the total variance in the wind record.

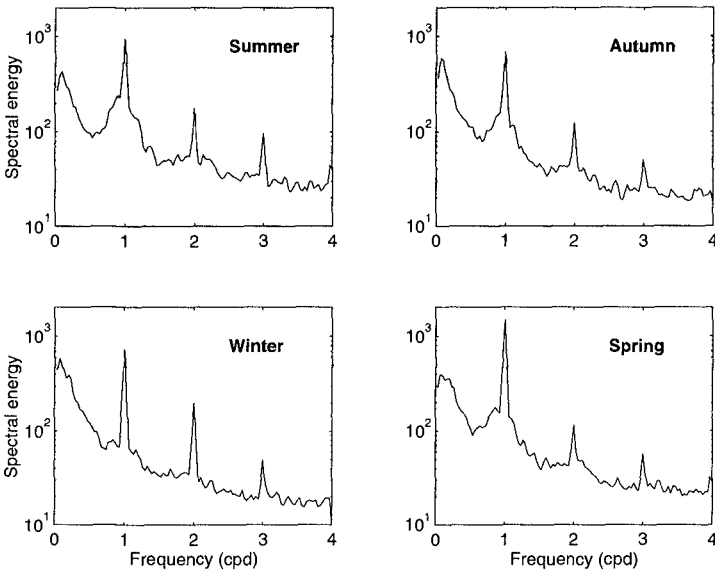


Fig. 4 - Average wind spectra for summer, autumn, winter and spring from three-hourly data collected at Perth Airport from 1948–1997.

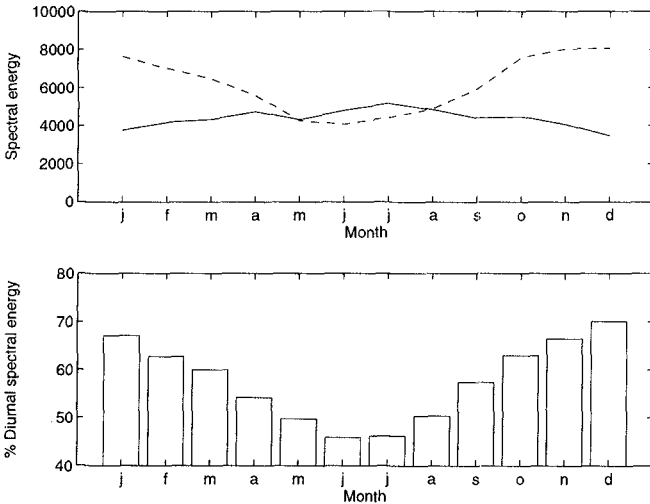


Fig. 5 - Monthly variation in spectral energy in the synoptic (solid line) and sea breeze (dashed line) frequency band (upper panel) and relative contribution of the sea breeze band to the total wind variance (lower panel). Based on three-hourly data collected at Perth Airport from 1948–1997.

Effect of Sea Breeze Activity on Nearshore Processes

Offshore wave conditions are significantly affected by the sea breeze and this is clearly illustrated by seasonal offshore wave spectra (Fig. 6). All spectra show a peak around the diurnal frequency, similar to that of the wind spectra (refer Fig. 4). However, in contrast to the wind spectra, the synoptic band in the wave spectra is of greater importance than the sea breeze band. This simply indicates that the variability in wave conditions due to storm activity is greater than that generated by sea breezes.

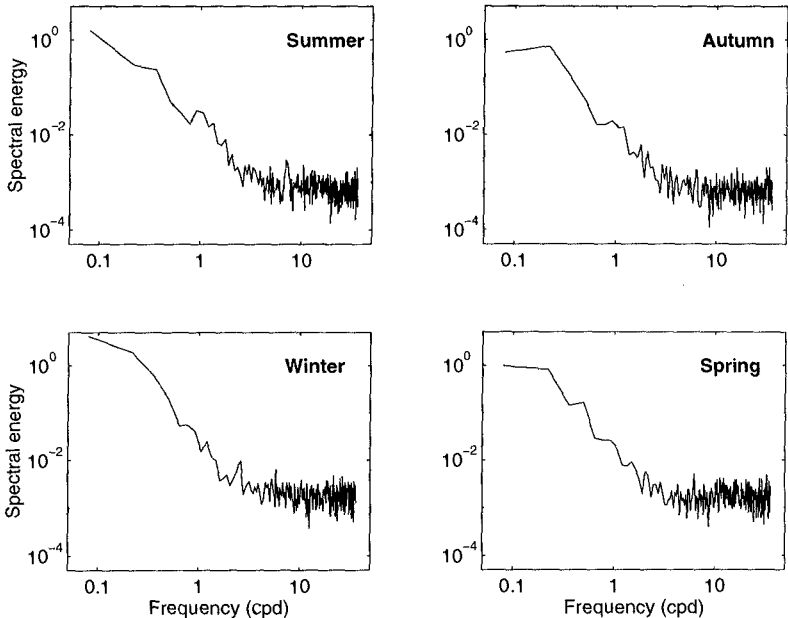


Fig. 6 - Wave spectra for summer (Jan–Feb 1995), autumn (Mar–Apr 1995), winter (Jun–Jul 1995) and spring (Sep–Oct 1995) from data collected off the coast of Perth in 48 m water depth. The spectra were computed from 20-min wave summary statistics.

Sea breeze activity has a pronounced effect on coastal processes. Pattiaratchi et al. (1997) and Masselink and Pattiaratchi (1998a) report on the results of a field experiment conducted on City Beach in Perth that monitored the effect of a strong sea breeze on the nearshore environment (Fig. 7). Prior to the onset of the sea breeze, offshore winds with speeds less than 5 m/s prevailed. During the sea breeze, alongshore winds with speeds higher than 10 m/s were experienced. The sea breeze induced pronounced changes to the nearshore morphodynamics which were similar to that of a storm event: (1) root mean square wave height increased from 0.3 to 0.5 m; (2) zero-upcrossing wave period decreased from 8 to 4 s; (3) mean cross-shore flows reached velocities of 0.2 m/s directed offshore; and (4) the longshore current increased in strength from 0.05 to 1.0 m/s. As a result of the increase in longshore current velocity and suspended sediment concentration during the sea breeze, the suspended

sediment flux increased by two order of magnitude. In addition, pronounced beach cusp morphology that was present on the beachface prior to the sea breeze, was completely destroyed during the sea breeze.

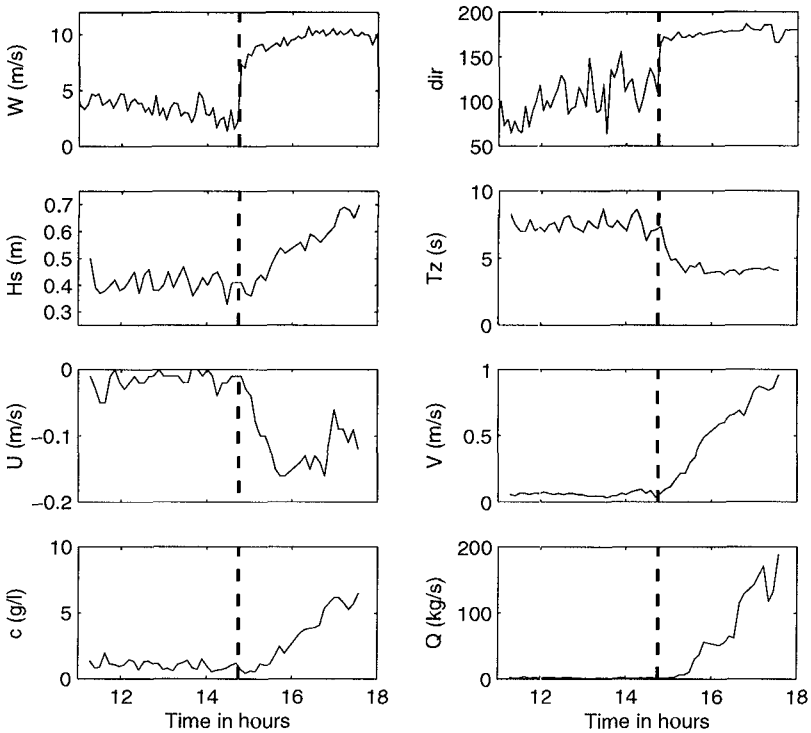


Fig. 7 - Wind speed (W), wind direction (dir), significant wave height (H_s), zero-crossing wave period (T_z), cross-shore current velocity (U), longshore current velocity (V), suspended sediment concentration measured 0.275 m above the bed (c) and longshore suspended sediment transport averaged across the surf zone (Q). The start of the sea breeze is indicated by the dotted line. The data were collected on City Beach, Perth on the 23rd of January 1992.

Masselink and Pattiaratchi (1998b) discuss the effect of weak sea breeze activity on nearshore processes. They demonstrate that even weak sea breezes with wind speeds of around 6 m/s induce pronounced changes to the surf zone hydrodynamics. A three-day time series of wind speed, direction, offshore wave height and nearshore current spectra illustrates clearly that the impact of sea breeze activity extends significantly longer than the duration of the sea breeze (Fig. 8). Over the three-day period, the narrow-banded swell peak remained at a constant frequency of around 0.085 Hz. Wind-wave energy starts appearing immediately after the onset of the sea breeze and remained present long after the cessation of the sea breeze. The presence of wind wave energy long after the sea breeze had ceased to blow is attributed to the alongshore component of the sea breeze (Masselink and Pattiaratchi (1998b).

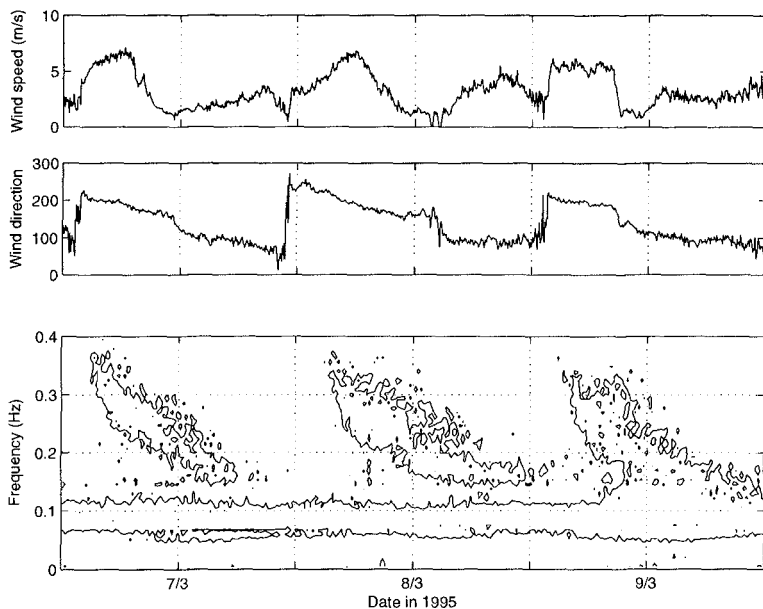


Fig. 8 - Three-day time series of wind speed (upper panel), wind direction (middle panel) and spectral shape of cross-shore current velocity data collected just outside the surf zone (lower panel). The contour lines represents an energy level of $0.25 \text{ m}^2/\text{s}$. All three sea breezes started at 14:45 hrs. The data were collected on City Beach (Perth) during three successive sea breeze cycles from the 6th to the 9th of March 1995.

Seasonal Variation in Beach Morphology

A number of Perth metropolitan beaches have been monitored weekly to two-weekly since November 1995. All display a strong seasonal variation in beach width (Fig. 9). Three of the beaches display a widening trend during summer (City, Brighton and Triggs Beaches), one becomes narrower over summer (Floreat Park) and one displays a hybrid behavior (Port Beach). These dissimilar trends are somewhat at odds with the strong seasonal variation in the incident wave conditions (refer Fig. 1) on the basis of which one would expect all beaches to behave in a similar manner. In addition, the amplitude of the beach width cycle varies substantially between the different beaches.

To explain the observed trends in beach width one needs to take into consideration the seasonal change in the direction of littoral drift. In the summer, when the southerly sea breeze prevails, longshore transport is towards the north. As a result, beaches that are located south of coastal structures (City Beach) or headlands (Triggs Beach) become wider during summer due to the accumulation of sediment against the structure/headland. These beaches will erode in winter when the longshore sediment transport is towards the south due to northwesterly storm waves. In contrast, beaches located to the north of coastal structures (Floreat Park) or headlands will become narrower during summer and wider during winter. Beaches located at

relatively “straight” coasts (Brighton Beach) will conform to the wave-induced seasonal cycle of beach change by widening during summer and narrowing during winter. The amplitude of the straight beach cycle, however, will be smaller than those beaches affected by the seasonal reversal in the littoral drift direction.

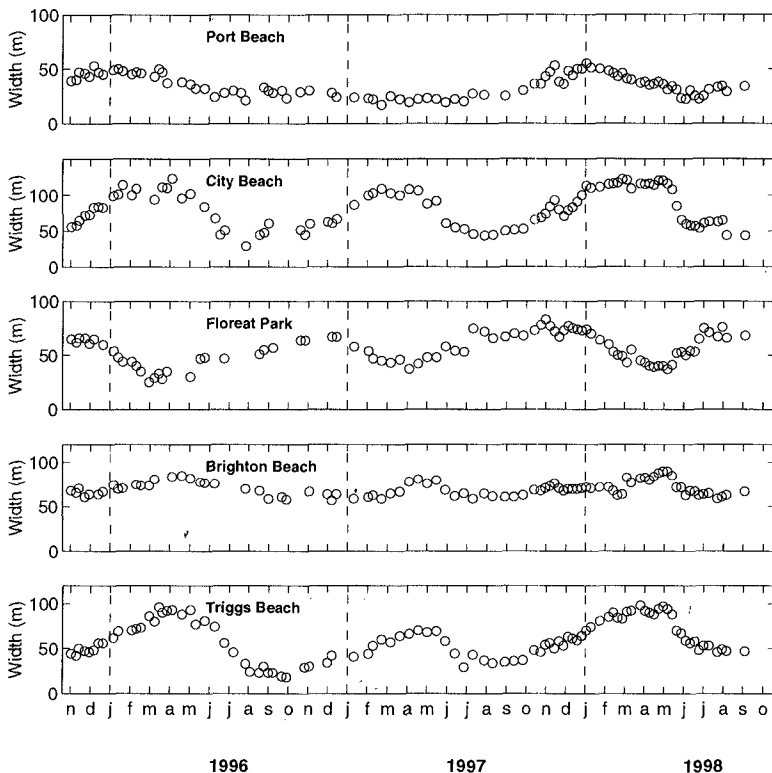


Fig. 9 - Temporal variation in beach width for five Perth metropolitan beaches for the period November 1995 to September 1998. The data were collected weekly or two-weekly.

The profile behavior of Port Beach is complicated and shows only two beach cycles in the 3-year monitoring period. During the first part of the time series, the beach width decreased in summer as well as in winter. From mid-1996 to mid-1997, the width of the beach remained constant. During the last part of the time series, Port Beach has been widening from mid-winter to early summer 1997, narrowing from mid-summer to early winter 1998 and widening again from mid-winter 1998. The complex behavior of Port Beach is attributed to anthropogenic influences (Masselink and Pattiaratchi, 1997). Prior to 1996, Port Beach was located about 500 m north of a small groyne. The beach behaved like a straight beach, attaining its maximum width just prior to the start of the winter storm season (cf., Brighton Beach). At the end of 1995, however, the groyne was significantly extended to accommodate for a marina development. As a result, Port Beach is now acting like a beach located north of a coastal structure, attaining its maximum width early-summer (cf., Floreat Park).

Analysis of Coastal Stations along Western Australian Coastline

The analysis of the wind data was extended to include nine additional coastal meteorological stations spread out along the coast of Western Australia (Fig. 10). Most of these stations were located some distance inland of the coastline at local airports, except for Ocean Reef and Cape Leeuwin which were directly located on the coast and Abrolhos, which was located on an island. One year of data (1995) were analyzed. Prior to analysis, all data were converted to hourly data for reasons of consistency.



Fig. 10 - Map of Western Australia with ten coastal meteorological stations.

Table 1 summarises the time and frequency domain analysis of the ten Western Australian coastal weather stations. In the northern region (Derby, Broome, Karratha, Learmonth), the sea breeze mainly blows from an offshore and northwesterly direction. In the central region (Carnarvon, Abrolhos, Ocean Reef, Perth), alongshore and southeasterly sea breezes prevail. In the southern region (Cape Leeuwin and Esperance), the sea breeze blows from a predominantly onshore and southeasterly direction. The data were subjected to the same analysis as the long-term Perth wind data and the number of sea breezes and the mean sea breeze wind speed were determined. Excepting Cape Leeuwin, the mean annual wind speed for all coastal stations is significantly less than the wind speed associated with the sea.

breeze. This indicates that at all locations, the sea breeze represents a condition that is more energetic than normal. The number of sea breezes that occurred in 1995 ranges from 137 (Cape Leeuwin) to 304 (Karratha).

Table 1 - Summary of time and frequency domain analysis of 1995 wind data collected at ten coastal meteorological station in Western Australia. W = mean annual wind speed; N = number of sea breezes; W_{sb} = mean wind speed during sea breeze at 15:00 hrs.

	Dominant sea breeze direction	W	N	W_{sb}	% of variance in the sea breeze band (period smaller than 1.5 days)				
					Sum.	Aut.	Win.	Spr.	Ann.
Derby	250-340°	4.3	191	5.8	72	73	61	71	69
Broome	230-330°	2.8	179	4.3	63	69	51	71	63
Karratha	260-90°	5.6	304	7.0	40	72	64	46	55
Learmonth	250-60°	5.4	164	6.0	40	63	53	47	51
Carnarvon	180-290°	6.1	266	7.3	48	61	55	41	51
Abrolhos	170-220°	7.1	174	7.1	31	34	22	23	28
Ocean Reef	170-230°	5.7	193	6.7	66	54	28	50	50
Perth	190-300°	4.5	190	5.6	63	59	40	61	56
Cape Leeuwin	120-210°	8.6	137	7.2	20	18	15	21	19
Esperance	120-260°	5.3	193	6.7	67	49	31	55	50

The importance of sea breeze activity is somewhat underestimated in Table 1 because most meteorological stations are located some distance landward of the coastline. A comparison between the characteristics of the sea breeze measured at Ocean Reef (on the coast) and Perth (about 20 km inland) indicates a reduction in the wind speed by about 20%. In addition, the direction of the sea breeze becomes more onshore with distance from the coastline. The number of sea breezes at Ocean Reef and Perth, however, are very similar.

Wind spectra were computed for all coastal stations and except Cape Leeuwin, all exhibit a pronounced diurnal peak with associated harmonics (Fig.11). Partitioning the total spectral energy into the low-frequency synoptic band and the high-frequency sea breeze band (period smaller than 1.5 days; 'sea breeze band') further demonstrated the dominance of the sea breeze for most of the coastal stations. In general, more than 50% of the total variability in the wind record can be attributed to the sea breeze band. The only exceptions are Cape Leeuwin and the Abrolhos Islands. The former is one of the stormiest locations on the Western Australian coastline and winds at this site are expected to be dominated by storm activity. At the latter site, strong southerly winds prevail throughout the year, with the sea breeze only inducing a modest increase in the wind speed and a slight change in the direction.

Discussion and Conclusions

The diurnal sea breeze system in Perth, Western Australia, is a very important contributor to the overall wind climate. Around 200 sea breezes are experienced per year with an average wind velocity at 15:00 hrs of 5.7 m/s. In summer, more than 20 sea breezes occur on a monthly basis, whereas in winter between 10 and 15 sea breeze cycle are experienced each month. Throughout the year, more than half the variance in

the wind speed record can be attributed to the sea breeze frequency band (period less than 1.5 days). Analysis of wind data collected at nine other coastal meteorological stations in Western Australia indicated similar results, demonstrating that the sea breeze system is highly significant state-wide.

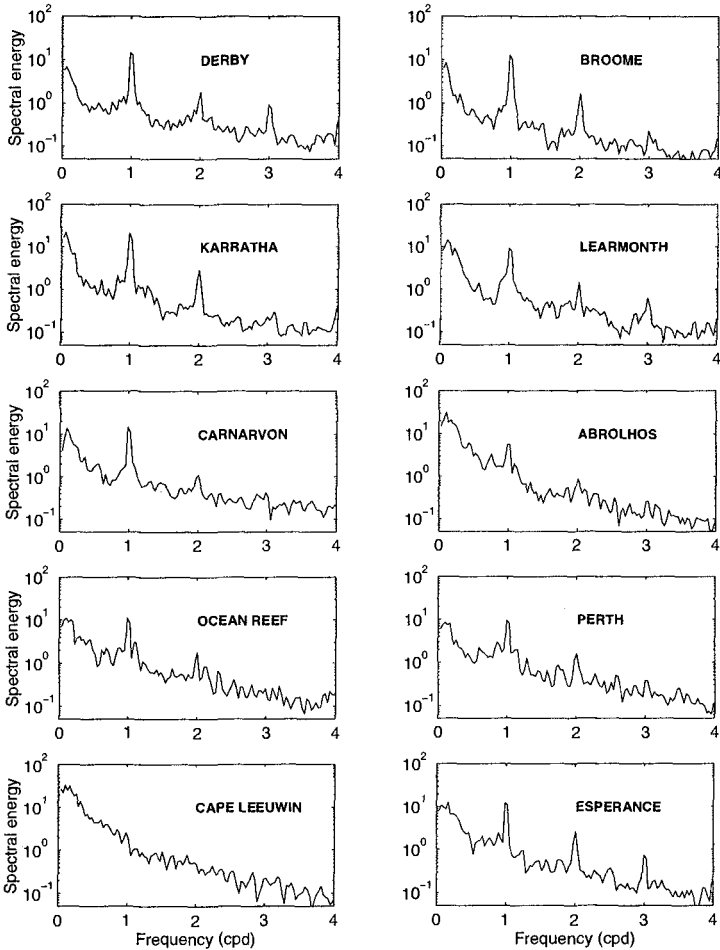


Fig. 11 - Wind spectra for ten Western Australian coastal stations. The data represent hourly data collected in 1995.

The strength and persistence of the sea breezes has important implications for the offshore wave climate and nearshore processes and morphology in the area. Spectral analysis of wave data collected off the coast of Perth revealed significant amounts of spectral energy present within the sea breeze band, in particular during summer when the sea breeze system is best developed. In the nearshore zone, the sea breeze generates energetic, obliquely-incident wind waves. In turn, these waves generate strong longshore currents and sediment transport.

The wind climate along the Perth metropolitan coastline displays a pronounced seasonality characterised by strong and persistent southerly sea breezes in the summer and infrequent northwesterlies associated with the passage of mid-latitude storms. As a consequence, the dominant direction of the littoral drift is towards the north in the summer and towards the south in winter. In the vicinity of coastal structures or natural headlands, the seasonal variation in littoral drift direction induces a seasonal cycle of beach change that is different from the classic transition from summer to winter profile. During summer, a beach located south of an obstacle becomes progressively wider due to the piling up of sediment against the obstacle. At the same time, the beach located north of the obstacle becomes narrower. The opposite will occur during winter.

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