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Characteristics of the Sea Breeze System in Perth, Western Australia, and its Effect on the Nearshore Wave Climate

G. Masselink† and C.B. Pattiaratchi‡

†Geography Department
Loughborough University
Loughborough LE11 3TU
United Kingdom
email:
G.Masselink@lboro.ac.uk

‡Centre for Water Research
University of Western Australia
Nedlands WA 6907 Australia
email:
pattiara@cwr.uwa.edu.au

ABSTRACT

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The coastline of Perth, Western Australia, is subjected to one of the strongest and most consistent sea breeze systems in the world. Using forty-nine years of wind data collected at Perth airport (about 20 km inland) it was found that almost 200 sea breezes are experienced per year with an average wind speed at mid-afternoon (15:00 hrs) of 5.7 m/s. At the coastline, sea breeze velocities are 1.4 times greater than 20 km inland and in the summer months, when the sea breeze system is best developed, sea breeze velocities frequently exceed 10 m/s. A significant feature of the sea breeze is that it blows obliquely-onshore, rather than onshore. The importance of the sea breeze is clearly indicated in spectra of the wind speed showing a significant spectral peak at the diurnal frequency. Spectral analysis of hourly inshore wave data also revealed a diurnal spectral peak, suggesting a forcing of the wave conditions by the sea breeze. It is concluded that the diurnal sea breeze system can have a major impact on the incident wave climate, and hence nearshore processes, of sheltered coastal environments in tropical and subtropical regions.

ADDITIONAL INDEX WORDS: *Sea breeze, wind, wave climate.*

INTRODUCTION

The Perth Metropolitan coastline (Figure 1) experiences mixed, microtidal tides with a mean spring tidal range of 0.6 m (DEPARTMENT OF DEFENCE, 1996). The offshore wave climate is dominated by a low to moderate energy wave regime characterized by prevailing south to southwest swell (DAVIES, 1980) and a mean summer significant wave height of 1.5 m and a mean winter significant wave height of 2.5 m (LEMM *et al.,* 1999). Closer to shore, the swell is refracted and diffracted by several offshore reef systems and islands, and is greatly attenuated as it propagates across the inner continental shelf. As a result, the inshore wave height is about 30–70% of that outside the reef system (WNI, 1998), depending on the inshore location and the incident wave period and direction. Swell height at the shoreline is generally less than 1 m (STEEDMAN, 1993). A highly variable wind wave climate is superimposed on the swell regime, dominated by northwesterly to westerly storm waves in winter and by the wave field associated with strong south to southwesterly sea breezes in summer.

The coastline of Perth is subjected to one of the most energetic and consistent sea breeze systems in the world (PATTIARATCHI *et al.,* 1997). Along the north-south trending coastline of Perth, a typical sea breeze cycle is characterized by offshore winds from an easterly direction (80–100°) in the morning, switching to obliquely-onshore winds from a south-southwesterly direction (180–220°) in the afternoon (Figure 2). The onset of the sea breeze is often well defined and indicated by an abrupt increase in wind speed and shift in wind direction (at 14:00 hrs in Figure 2). The cessation of the sea breeze is less clear because during the evening wind conditions gradually return to pre-breeze conditions. In the early hours of the morning, land breezes may prevail. Because of the sheltered nature of the coastline of Perth, locally-generated wind waves, particularly those generated by strong sea breeze activity, are a dominant mechanism controlling nearshore processes and morphology (MASSELINK *et al.,* 1997; PATTIARATCHI *et al.,* 1997; MASSELINK and PATTIARATCHI, 1998a, b).

Together with the land breeze, the sea breeze is part of a diurnal atmospheric circulation system that arises from the contrasting thermal responses of the land and the water surface (HSU, 1988; ABBS and PHYSICK, 1992). Descriptions of sea breezes date to the period of Greek philosophers (NEUMAN, 1984) continuing with writings of Dampier in the 17th Century (JEHN, 1973) to one of the first scientific accounts of DAVIS *et al.* (1890) and extending to the present (SIMPSON, 1994). Sea breeze occurrence is dependent on latitude (WEXLER, 1946) and consistent, diurnal sea breeze activity occurs along about two-thirds of the earth coastline, especially in the

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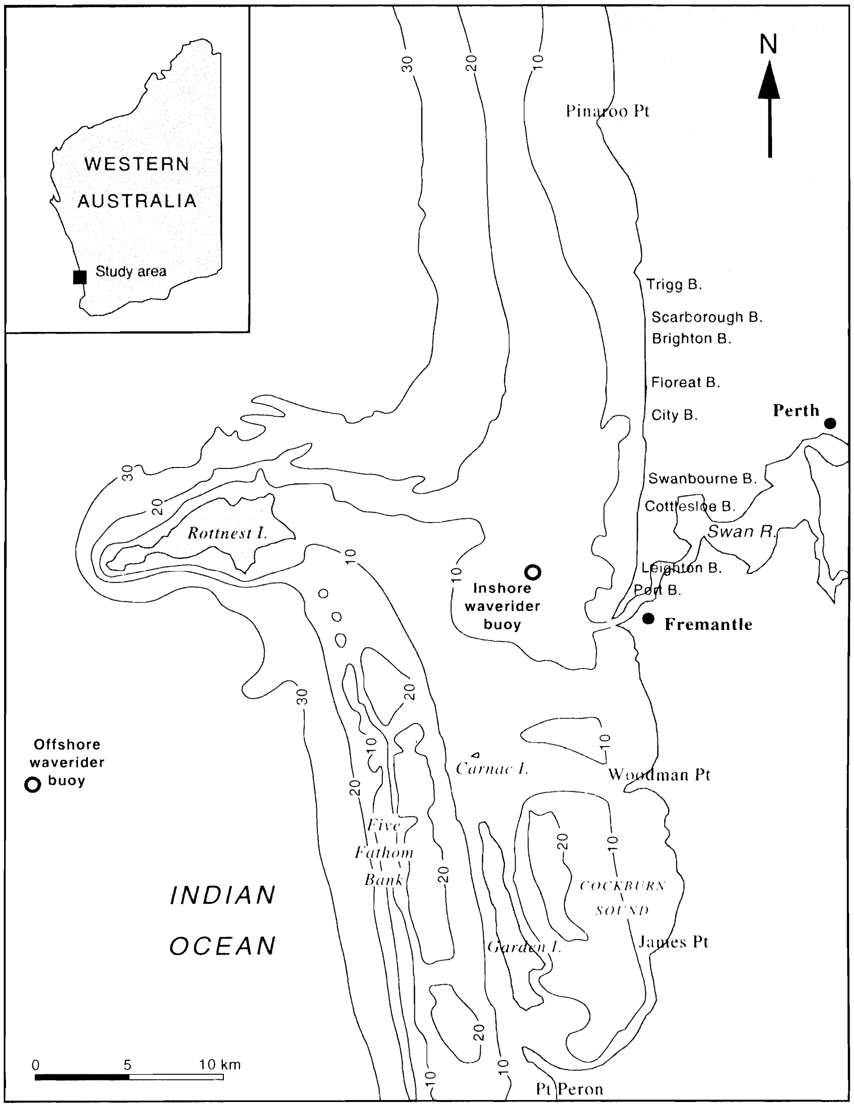
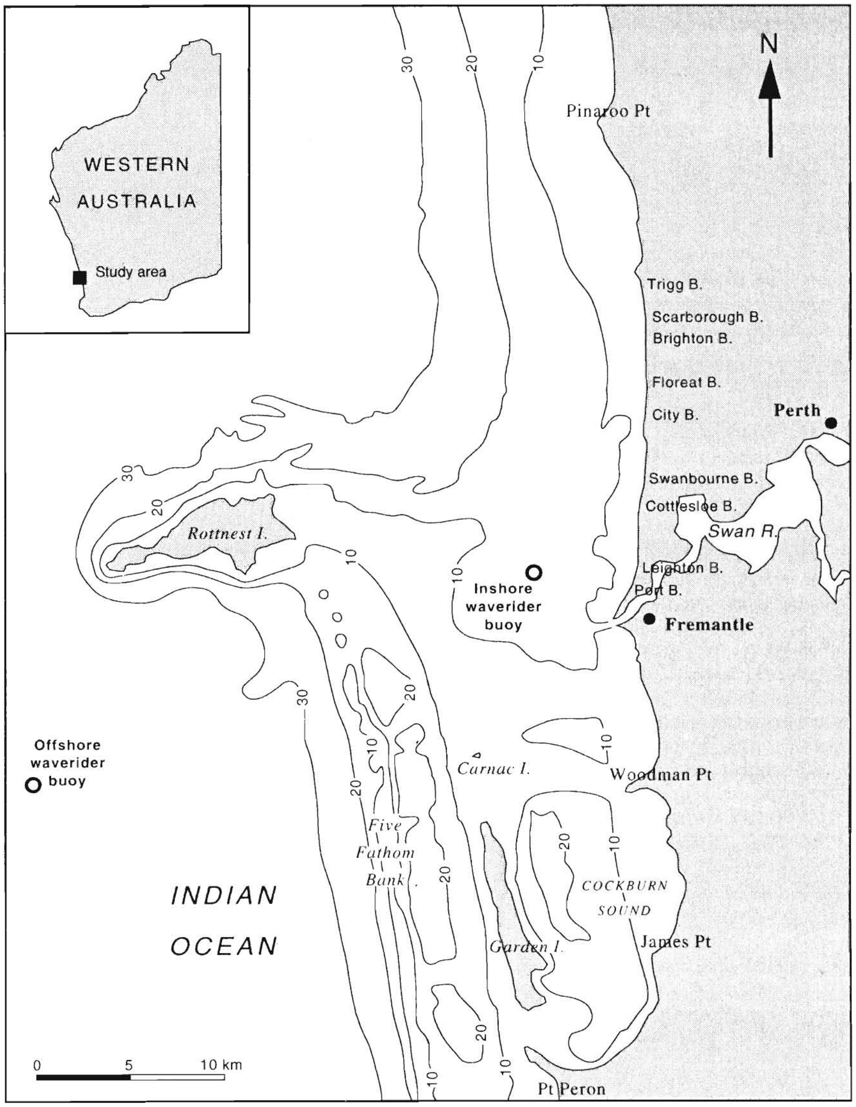


Figure 1. Location map of the Perth metropolitan and coastal regions. Bathymetry is in meters.

tropics and sub-tropics (SONU *et al.,* 1973). The sea breeze system is directly driven by the atmospheric pressure gradient that results from the temperature difference between the air over land and over water. At night and in the morning, the air temperature over land is cooler than over the sea, and the land breeze prevails. From late morning to late afternoon, the land is warmer than the surrounding waters, and the sea breeze prevails. Generally, the sea breeze system begins some distance (*c.* 10 km) offshore and expands in the offshore and onshore direction (LAUGHLAN, 1997). The sea breeze system moves inland as a front, very much like a density current (SIMPSON, 1994), as long as a temperature difference between land and water is maintained. The inland advance can be characterized by a series of pulses (WALLINGTON, 1960). The inland penetration speed is initially relatively rapid (1–3 m/s), but slows down as a result of friction (LAUGHLAN, 1997). In mid-latitude regions, the sea breeze can be detected up to 100 km inland, whereas at low latitudes inland penetration can be in excess of 200 km (CLARKE, 1955; WALLINGTON, 1961; GARRATT and PHYSICK, 1985). The seaward extent of the sea breeze is not very well demarcated and has not received much investigation (FINDLATER, 1963; HSU, 1970; BANTA *et al.,* 1993). The available measurements seem to indicate that the seaward extent is comparable to the landward extent (SIMPSON, 1994). The seaward extent of the sea breeze is important with respect to the generation of wind waves by the sea breeze because it directly determines the fetch length; the greater the seaward extent of the sea breeze, the larger the fetch length and the higher the waves generated by the sea breeze.

In addition to the temperature difference between the air above land and water (*i.e.,* the driving force), the occurrence



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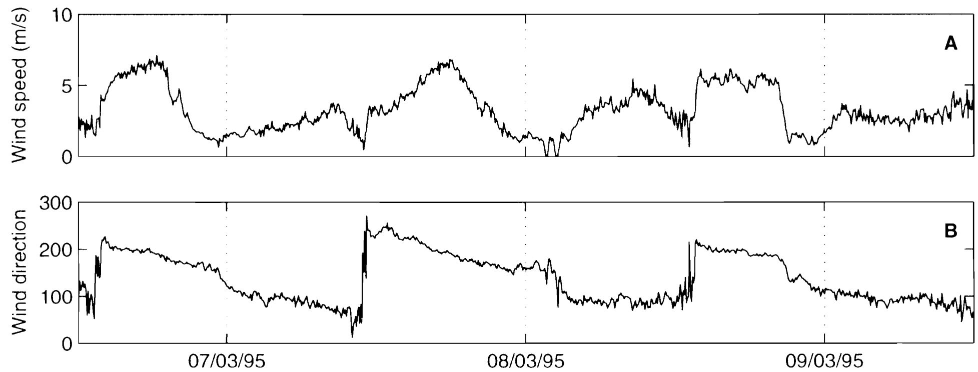

Figure 2. A typical three-day time series of: (A) wind speed; and (B) wind direction. The data were collected at 5 m height on City Beach in March 1995 (data from Masselink and Pattiaratchi, 1998a).

and development of the sea breeze is strongly dependent on the speed and direction of geostrophic winds associated with synoptic weather patterns (LAUGHLIN, 1997). Unless winds speeds are small (< 2 m/s), onshore geostrophic winds inhibit the formation of a sea breeze, because such conditions do not allow the build-up of a significant temperature difference, and hence surface pressure difference, between land and water. Strong offshore geostrophic winds (> 5 m/s) also hinder the development of a sea breeze circulation because the onshore pressure gradient due to differential heating may not be sufficient to overcome the offshore geostrophic winds. Optimal conditions for sea breeze development are therefore light to moderate offshore winds (2–5 m/s) or alongshore winds induced by the synoptic system.

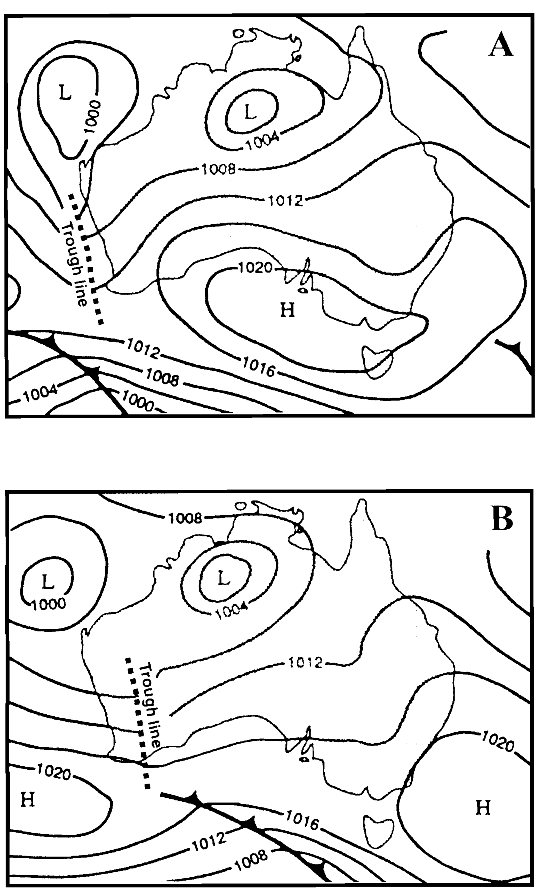

Figure 3. Pressure distribution over Australia in summer: (A) West Coast trough lying offshore; and (B) West Coast trough moving onshore (after Tapper and Hurry, 1993).

The occurrence and intensity of the sea breeze in Perth is strongly related to the presence and position of the West Coast trough (TAPPER and HURRY, 1993). In summer, the Australian continent is generally under the influence of easterly airflow and as a result of intense heating of the air across the continent, a low-pressure trough is formed in a north-south direction (KEPERT and SMITH, 1992). This pressure trough is generally located inland of the coast, but its position is subject to day-to-day variations (WATSON, 1980). When the trough lies offshore (Figure 3a), the gradient winds across the coast are strong east to northeasterly bringing hot, dry continental air from central Australia. Under these conditions, especially with a large anticyclone to the south of Australia, coastal sea breezes are delayed or non-existent. However, when the trough moves onshore (Figure 3b), usually with an approaching front, the easterly flow weakens and becomes more northeasterly. These conditions favor the development of strong and early sea breezes.

A significant feature of the sea breeze system along the West Coast of Australia is that it blows obliquely-onshore (*i.e.,* south-southwesterly). This is in contrast to the classic sea breeze, which blows perpendicular to the shoreline. In fact, so-called 'pure' sea breezes, *i.e.,* sea breezes that are not interfered with by geostrophic winds (*e.g.,* KOTINIS-ZAMBAKAS *et al.,* 1989), are virtually non-existent along the Perth coastline. The reason for the obliquely-onshore sea breeze system in Perth may be attributed to the interaction between the sea breeze and the geostrophic winds associated with the synoptic weather patterns. The Perth sea breeze system in *sensu stricto* is southwesterly due to a combination of pressure gradient flow (owing to differential heating) and the Coriolis force (KEPERT and SMITH, 1992). The Coriolis force has no influence on the wind direction at the start of the sea breeze, but may induce a small anti-clockwise shift in the wind direction of about 20° during the sea breeze (refer to Figure 2). When the West Coast trough is located inland, the synoptic pressure gradient acts in a northeasterly direction (refer to Figure 3b). The combination of the sea breeze system (strong southwesterly airflow) and the synoptic pressure (weak northeasterly airflow) results in a obliquely-onshore, south-southwesterly sea breezes. When the location of the trough is such that the synoptic pattern induces southerly winds, the sea breeze enhances the southerly winds, resulting in very strong sea breezes with wind speeds in excess of 10 m/s. The direction of land breeze is not much affected by geostrophic winds because both winds generally blow from the same quadrant (south to southwest).

Despite the dominant occurrence of the sea breeze along the Perth coastline in summer and its significant influence on coastal processes it has not attracted much scientific interest. To date, the most comprehensive investigation is by HOUNAM (1945), who analyzed several years of wind data collected at the Perth Observatory (6 km inland). At this location, the mean sea breeze direction is approximately 230°, but varies between 200° and 280°. In summer, the mean velocity of the sea breeze is 5.5 m/s and sea breezes occur more than 60% of the time. In winter, sea breezes are experienced up to 20% of the time with mean velocities of 3 m/s. The onset of the sea breeze is usually around 14:00 hrs, but can be anytime between 11:00 and 16:00 hrs. According to HOUNAM (1945), the sea breeze in Perth does not penetrate inland beyond 90 km due to the presence of the Darling Ranges, a north-south trending mountain range located 30–35 km inland. However, TAPPER and HURRY (1993) mention that the sea breeze may penetrate 150 km inland from Perth by about 22:00 hrs. Using balloon flights, HOUNAM (1945) established that the thickness of the sea breeze layer in Perth averages 600 m.

The objective of this paper is to characterize and quantify the sea breeze climate of Perth and indicate the impact of sea breeze activity on the nearshore wave conditions. A comprehensive analysis of forty-nine years of wind data collected at Perth airport (20 km inland) will be presented. One year of wind data measured at nine other Western Australian coastal locations will also be analyzed to demonstrate strong sea breeze activity to be a dominant feature along the entire Western Australian coastline. Finally, the effect of sea breeze activity on the nearshore wave conditions will be addressed using four years of offshore and inshore wave data.

DETAILS OF THE SEA BREEZE SYSTEM IN PERTH

Time-Domain Analysis of Perth Wind Data

Wind data collected every three hours at 10 m height at Perth airport (20 km inland) from 1949–1997 were used to determine the long-term sea breeze climate of Perth. The first part of the data set (1949–1964) does not include measurements at 21:00 hrs, but these data were obtained through linear interpolation using the 18:00 hrs and 00:00 hrs data. Linear interpolation to derive the 21:00 hrs wind speed data does not have any effect on the time-domain analysis and only an insignificant effect on the frequency-domain analysis of the wind data. Other occasionally missing data were also linearly interpolated.

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. It is acknowledged that the use of such a selection algorithm is somewhat subjective, but is preferred to tedious inspection of synoptic charts and plotted time series of wind speed and direction. Day-by-day analysis of sections of the wind data indicated that the sea breeze selection algorithm works extremely well for summer wind data, but is slightly less successful in identifying sea breezes during the winter.

Sea breeze activity is subject to strong seasonal variability (Figure 4). In summer (December–February; southern hemisphere summer), approximately 20 sea breezes are experienced per month with speeds (at 15:00 hrs) of 6–7 m/s. In winter (June–August; southern hemisphere winter), around 12 sea breezes occur per month with speeds of around 5 m/s. On average, 197 sea breezes are experienced each year with a mean wind speed of 5.7 m/s. The direction of the sea breeze is consistently from the southwest and does not exhibit much variability (standard deviations are less than 10°). However, the summer sea breeze blows from a slightly more southerly direction (240°) than the winter sea breeze (250°). The larger sea breeze direction in winter (and also the larger standard deviations of the sea breeze speed and direction) may indicate that occasionally westerly winds associated with the passage of mid-latitude depression have been misinterpreted as sea breezes. Hence, the number of identified sea breezes in the winter is probably over-estimated by *c.* 4 sea breezes per month.

Frequency-Domain Analysis of Perth Wind Data

For each year, spectra were computed of wind speed data measured every three hours for the periods December–February (summer), March–May (autumn), June–August (winter) and September–November (spring). Subsequently, an average spectrum was determined for each of the seasons (Figure 5). 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). These frequencies correspond to the time scale of synoptic weather patterns, such as the passage of mid-latitude depression (storms). Secondly, a pronounced spectral peak can be found at the diurnal frequency (period of one day), representing sea breeze activity (*cf.*, WISEMAN *et al.*, 1998). Thirdly, complementary spectral peaks occur at the first and second har-

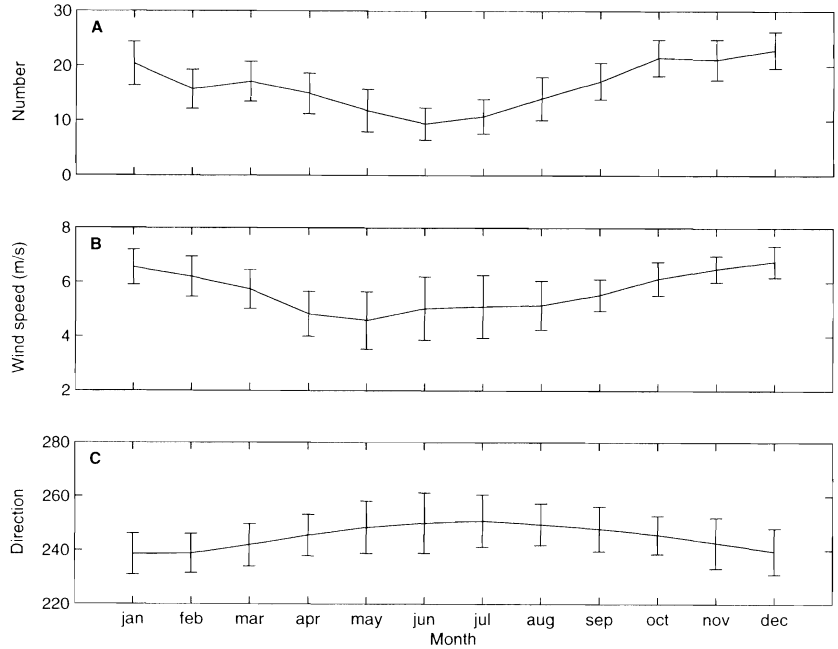

Figure 4. Seasonal variation in: (A) number of sea breezes; (B) sea breeze speed; and (C) sea breeze direction. The vertical lines indicate the standard deviations associated with the averages. Based on three-hourly wind speed data collected at Perth airport from 1949–1997.

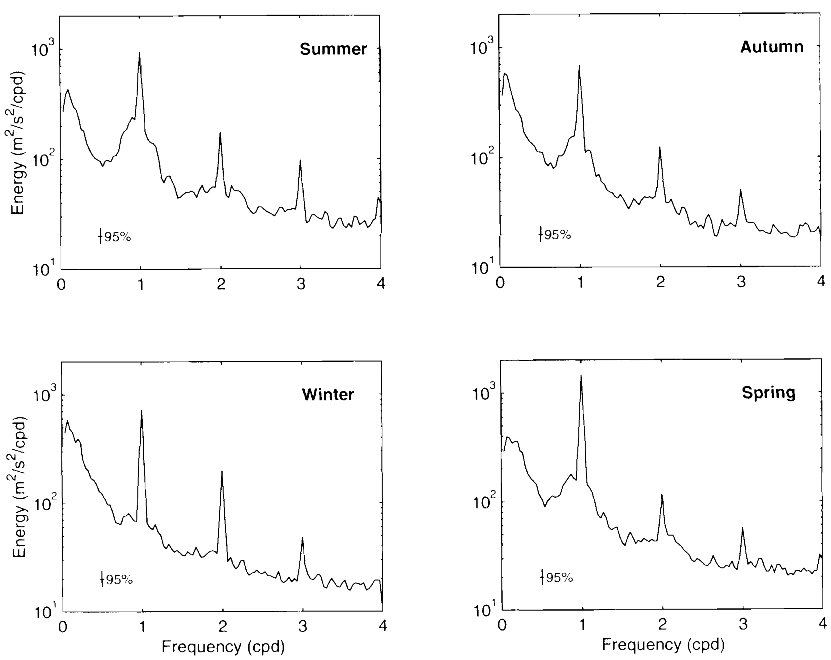

Figure 5. Average seasonal spectra of wind speed. The 95% confidence limits are indicated by the scale bar and were calculated using 294 degrees of freedom and "cpd" refers to cycles per day. Based on three-hourly wind speed data collected at Perth airport from 1949–1997.

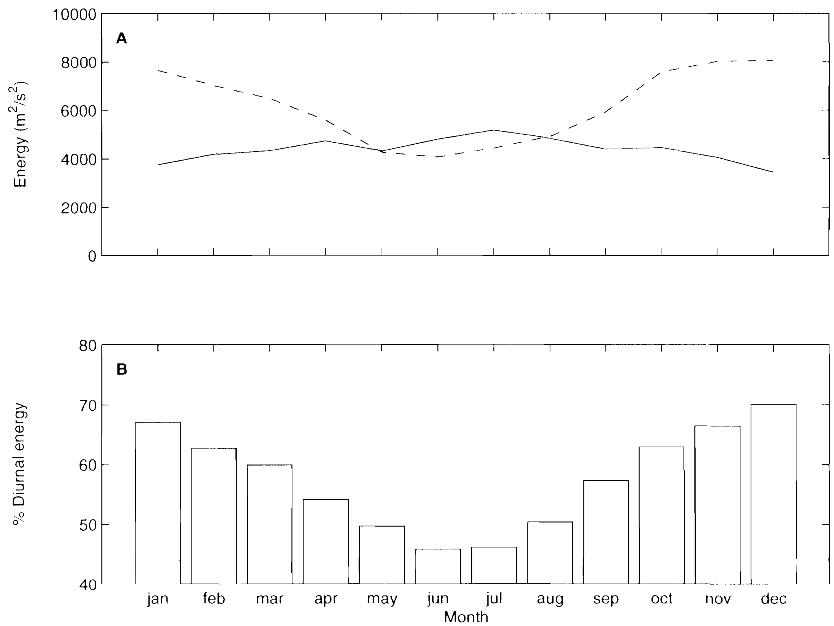

Figure 6. Monthly variation in: (A) spectral energy in the synoptic (solid line; periods larger than 1.5 days) and sea breeze (dashed line; periods smaller than 1.5 days) frequency band; and (B) relative contribution of the sea breeze band to the total variance in the wind speed record. Based on three-hourly wind speed data collected at Perth airport from 1949–1997.

monics of the diurnal frequency (periods of 12 and 6 hours, respectively). These are primarily due to the non-sinusoidal nature of the sea breeze signal. However, the occurrence of land breezes during the night and early morning may also have contributed to the first harmonic frequency (refer to Figure 2). The diurnal peak is highly significant and present in all seasonal spectra, but is widest in the summer spectrum and narrowest in the winter spectrum. With respect to the energy associated with the diurnal frequency, and hence its importance, it is noted that the area under the spectral peak is of greater relevance than the actual peak value.

Monthly spectra of the wind data were computed and an average spectrum was determined for each month. The total spectral energy was then partitioned into a low-frequency band (periods longer than 1.5 days referred to as the 'synoptic band') and a high-frequency band (periods shorter than 1.5 days referred to as the 'sea breeze band') to allow investigation of the seasonal variation in the importance of these components (Figure 6). 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 breezes are at their strongest and most abundant. The variance associated with the sea breeze band in summer is twice as large as in winter. In summer, the sea breeze band accounts for 60–70% of the total variance in the wind record, whereas in winter, less than 50% of the total variance can be ascribed to the sea breeze band.

Comparison of Perth Wind Data with Coastal Wind Data

The Perth airport wind data were collected approximately 20 km inland and may therefore not be representative for the sea breeze characteristics at the coastline. In particular, the strength of the sea breeze can be expected to decrease landward due to friction. In addition, frictional effects (and perhaps the Coriolis force) may alter the direction of the sea breeze. To investigate the characteristics of the sea breeze in the coastal region, wind data collected at the coastline (Swanbourne) and on Rottnest Island, located 20 km off the coast of Perth, were investigated (refer to Figure 1). These data were collected at 10-min intervals, but numerous gaps are present in the data, so attention is focused on one month of data collected in January 1994. Both inland (Perth airport) and coastal (Swanbourne and Rottnest Island) wind data were converted into hourly time series by means of linear interpolation and block-averaging, respectively, for reasons of consistency.

The sea breeze selection algorithm was applied to the January 1994 data, whereby the direction of the sea breeze at Perth airport was considered 190–300° and the coastal sea breeze direction was taken as 170–230°. The number of recorded sea breezes at Perth airport, Swanbourne and Rottnest Island was 25, 28 and 29, respectively. The smaller number of identified sea breezes at Perth airport is ascribed to incorrect wind direction data at the end of the data record, probably a result of a malfunctioning wind vane, because sea breezes were clearly present in the wind speed data, whereas

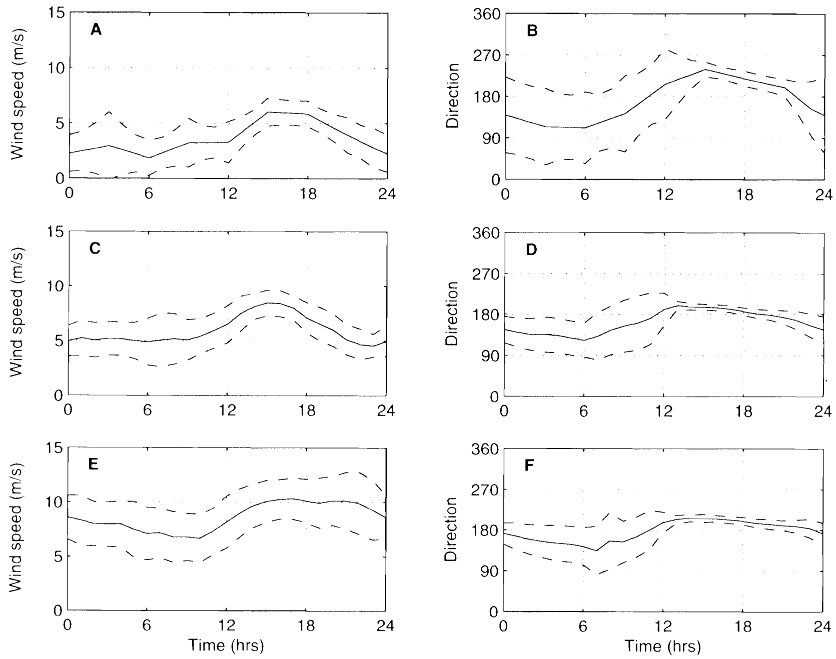

Figure 7. Ensemble-averaged daily time series of: (A) wind speed and (B) direction at Perth airport; (C) wind speed and (D) direction at Swanbourne; and (E) wind speed and (F) direction at Rottnest Island. The solid line represents the mean and the dashed line indicates the mean ± one standard deviation. The data were collected in January 1994 and only the days during which a sea breeze was present at all three locations (23 days) were included in the ensemble averaging.

the wind direction remained constant. The number of coastal sea breezes is therefore considered similar to that experienced at Perth airport. However, the associated velocities and direction are significantly different. The mean sea breeze speed (at 15:00 hrs) at Perth airport, Swanbourne and Rottnest Island was 6.1 m/s, 8.4 m/s and 10.2 m/s, respectively. In other words, the sea breeze at Swanbourne and Rottnest Island was 1.4 and 1.7 times stronger than at Perth airport, respectively. In addition, the mean sea breeze direction at Swanbourne and Rottnest Island is 200°, whereas at Perth airport the mean sea breeze direction is 240°.

For those days in the data record that a sea breeze was present at all three locations, ensemble-averaged daily time series of wind speed and direction were computed (Figure 7). In conjunction with cross-spectral and cross-correlation analysis (not shown) it appears that the time history of the sea breeze is similar for all three stations: (1) the onset of the sea breeze, as indicated by a shift in direction from easterly (offshore) to southwesterly (obliquely-onshore) and an increase in wind speed, occurs within one hour across all three measurement sites and generally occurs around 13:00 hrs; (2) the maximum speed of the sea breeze is generally attained around 17:00 hrs; and (3) the cessation of the sea breeze, indicated by a change in wind direction from south-southwest (obliquely-onshore) to south-southeast (obliquely-offshore), occurs around 21:00 hrs. At Perth and Swanbourne, weak land breezes quickly develop following the cessation of the sea breeze, however, relatively strong south-southeasterly winds prevail over most of the night on Rottnest Island.

Analysis of Wind Data Collected at Other Coastal Stations in Western Australia

We have found the sea breeze to be a prominent phenomenon along most of the Western Australian coast. Wind data were collected at nine additional coastal meteorological locations (Figure 8). Most of these sites were located some distance inland of the coastline at local airports, except for Ocean Reef and Cape Leeuwin which are directly situated on the coast, and Abrolhos, which is an island. One year of data (1995) was analyzed. Data were converted to hourly data for reasons of consistency.

Table 1 summarizes the time and frequency domain analysis of the ten Western Australian coastal weather sites. In the northern region (Derby, Broome, Karratha, Learmonth) the sea breeze is onshore and from the northwest. Obliquely-onshore and southwesterly sea breezes prevail in the central region (Carnarvon, Abrolhos, Ocean Reef, Perth). In the southern region (Cape Leeuwin and Esperance) the sea breeze blows predominantly onshore and from the southeast. 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. Except for 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).

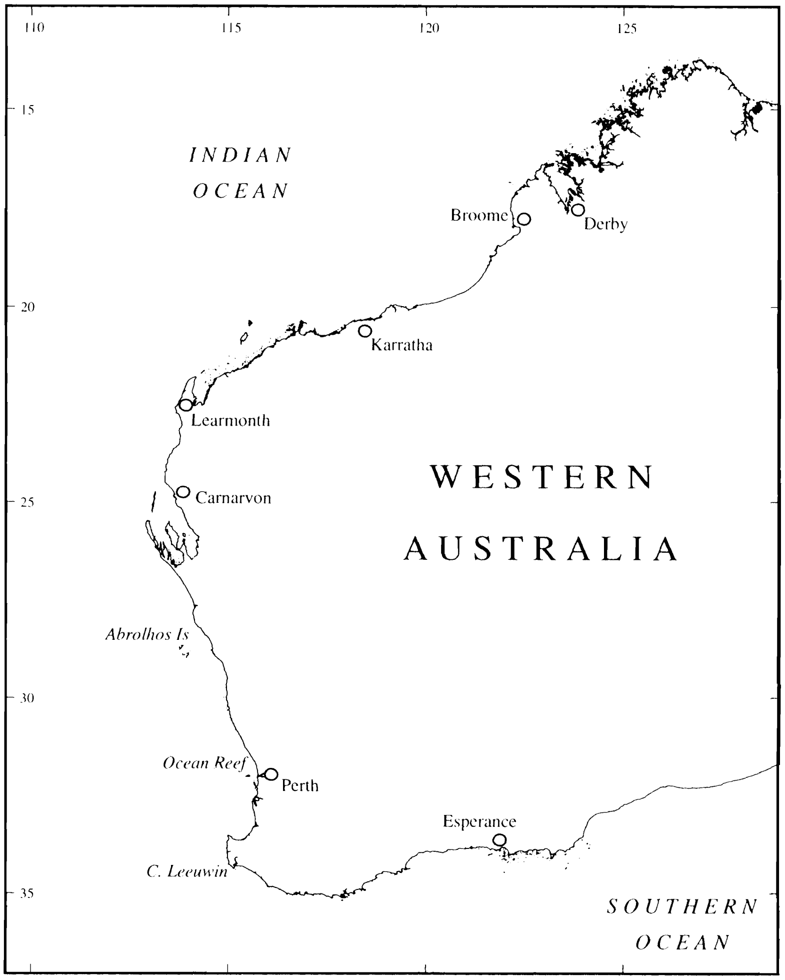

Figure 8. Map of Western Australia with ten coastal meteorological stations.

Spectra of the wind speed were computed for all coastal stations. All locations except Cape Leeuwin exhibit a pronounced and significant spectral peak at the diurnal frequency with associated harmonics (Figure 9). Partitioning of the total spectral energy into the low-frequency synoptic band (periods larger than 1.5 days) and the high-frequency sea breeze band (periods smaller than 1.5 days) further demonstrates the dominance of the sea breeze for most of the coastal

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

	Dominant Sea Breeze Direction	u	N	u_{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

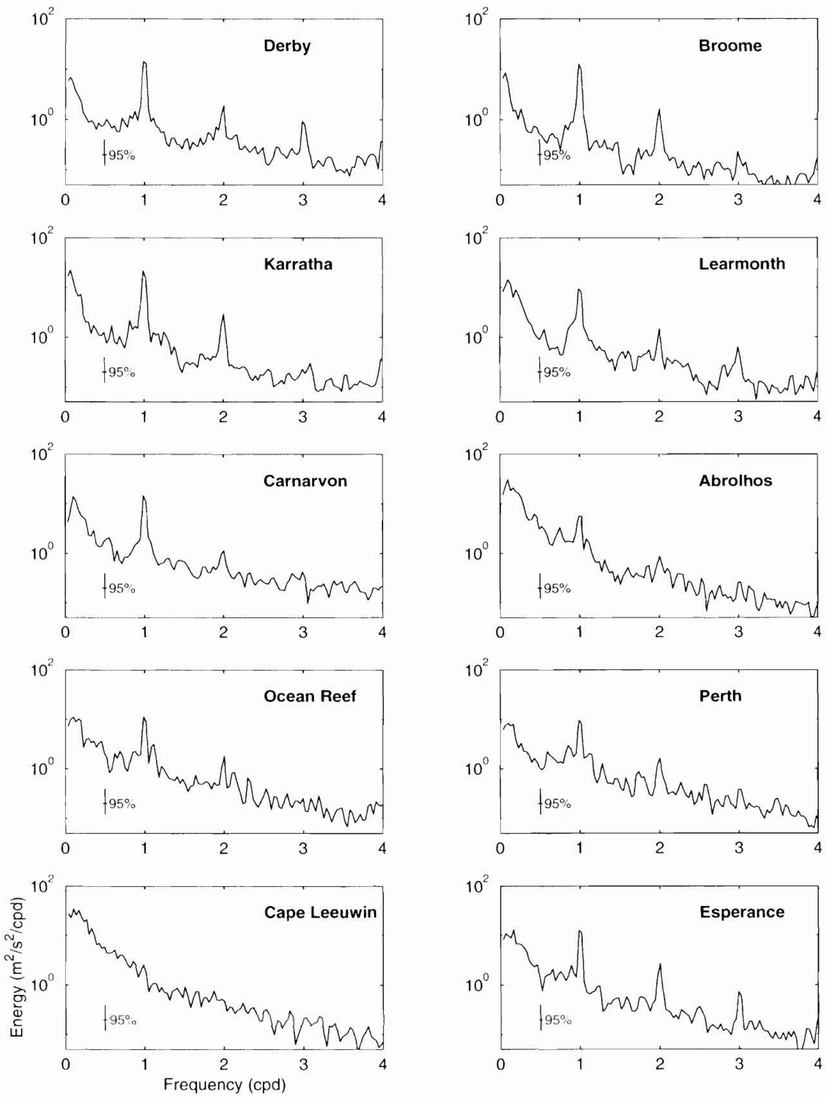

Figure 9. Average annual spectra of wind speed for ten Western Australian coastal stations. The 95% confidence limits are indicated by the scale bar and were calculated using 24 degrees of freedom and "cpd" refers to cycles per day. The spectra were computed using hourly wind speed data collected in 1995.

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. At both sites, 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.

EFFECT OF SEA BREEZE ON OFFSHORE AND INSHORE WAVE CONDITIONS

Generation of Wind Waves by the Sea Breeze

Local sea breeze activity is expected to have a significant impact on the incident waves due to the generation of local wind waves that become superimposed on the background wave field. For example, PRITCHETT (1976) noted a 10% increase in visually estimated breaking wave heights recorded in the late afternoon, presumably as a result of sea breeze activity. Figure 10 illustrates the effect of the three sea breeze cycles shown in Figure 2 on the offshore wave field measured south of Rottnest Island in 48 m water depth (refer to Figure 1) and is typical of summer oceanographic conditions. During each of the sea breezes, the significant wave height (determined using $4\sqrt{m_0}$, where m_0 is the zeroth moment of the energy spectrum) increased by 0.5 m, whereas the significant wave period (determined using m_0/m_1, where m_0 and m_1 are the zeroth and first moment of the energy spectrum, respectively) decreased by 5 s. The offshore wave energy was partitioned into swell ($f < 0.15$ Hz) and wind waves ($f > 0.15$ Hz) to more clearly demonstrate the effect of sea breeze activity. Over the three-day period, the significant

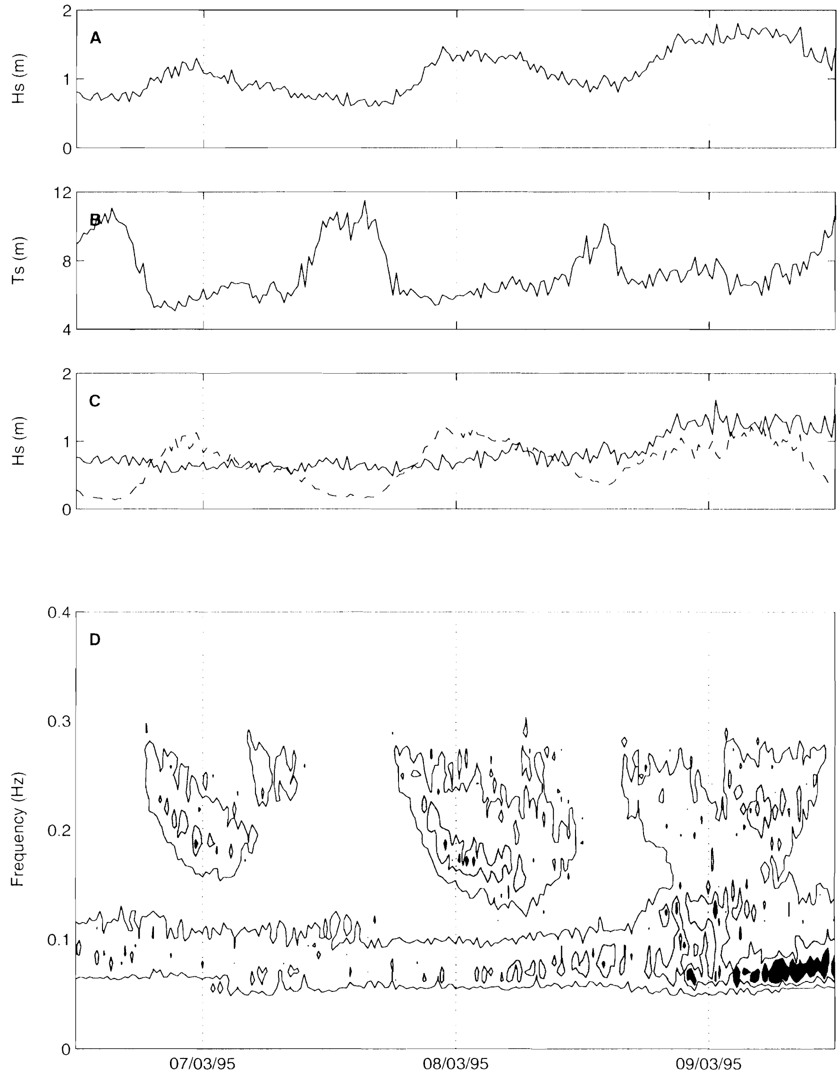

Figure 10. Three-day time series of offshore wave data: (A) significant wave height H_s; (B) significant wave period T_s; (C) significant wave height H_s of swell (solid line; <0.15 Hz) and sea breeze-generated wind waves (dashed line; >0.15 Hz); and (D) frequency-time spectrum. The contour lines represent 0.1, 0.5 and 1 m^2/Hz and the intensity of the shading increases with the spectral energy level. The spectra were calculated with 14 degrees of freedom. Wave data were collected at 1 Hz for 8 minutes every 20 minutes south of Rottnest Island in 48 m water depth. The date labels on the x-axis are placed at midnight (00:00 hrs).

swell height (determined using $4\sqrt{m_0}$, where m_0 was computed over $f < 0.15$ Hz) gradually increased from 0.8 to 1.2 m, but was not affected by sea breeze activity. The significant wind wave height (determined using $4\sqrt{m_0}$, where m_0 was computed over $f > 0.15$ Hz), however, directly responded to the daily sea breezes and attained maximum heights of 1–1.2 m around midnight. The frequency-time spectrum of the offshore wave energy shows the evolution of the wave field during sea breeze activity. During the sea breeze, a progressive increase in the peak wave period of the wind waves occurred from 3–4 s to 5–6 s, while the peak swell period remained constant at 12 s. At the end of the three-day period, the arrival of energetic swell and wind wave energy, unrelated to sea breeze activity, is apparent in the frequency-time spectrum.

The effect of the same three sea breeze cycles on the inshore wave field measured 5 km offshore in 17 m water depth (refer to Figure 1) is shown in Figure 11. At this location, sea breeze-generated wind waves with significant heights of up to 0.5 m were superimposed on a 0.3 m swell. During the sea breezes, the overall significant wave height increased by 0.2–0.3 m and the significant wave period decreased by 4 s.

The measured offshore and inshore wave conditions during the sea breeze can be compared with those predicted using the Sverdrup-Munk-Bretschneider method (CERC, 1984). The wind speed at Perth u_{Perth} is taken as a starting point

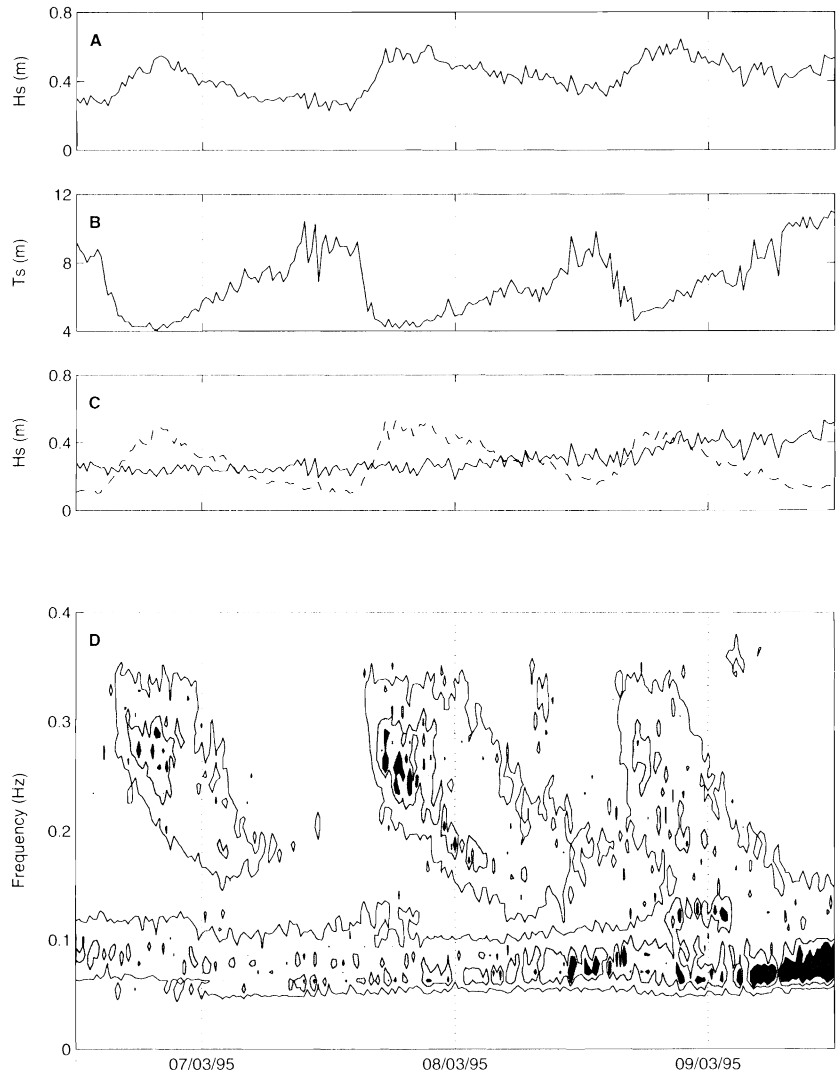

Figure 11. Same as Figure 10, but the contour lines represent 0.01, 0.05 and 0.1 m²/Hz. The spectra were calculated with 14 degrees of freedom. Wave data were collected offshore of Fremantle in 17 m water depth.

and three types of sea breezes are considered: (1) a weak sea breeze with u_{Perth} = 3 m/s; (2) an average sea breeze with u_{Perth} = 5 m/s; and (3) a strong sea breeze with u_{Perth} = 7 m/s. The wind speeds at Swanbourne u_{Swanb} and Rottnest Island u_{Rottn} are approximated by $1.4u_{Perth}$ and $1.7u_{Perth}$, respectively (refer to Figure 7). It is assumed that the inshore waves are generated by wind speeds represented by u_{Swanb} whereas the offshore waves are generated by wind speeds represented by u_{Rottn}. It is further assumed that the duration of the sea breezes is 6 hours.

The offshore wave conditions generated during sea breeze activity are straightforward to predict because due to the dominant alongshore component of the sea breeze the fetch is virtually unlimited. It is predicted that an average sea breeze (u_{Perth} = 5 m/s) generates offshore waves with H_s = 1.2 m and T_p = 5.2 s (Table 2). This is in excellent agreement with the offshore wave observations shown in Figure 10 which indicate H_s = 1–1.2 m and T_p = 5–6 s. Prediction of the inshore wave conditions is less straightforward because it is not quite clear whether the wave generation process is fetch-limited by the presence of Garden Island and Five Fathom Bank (refer to Figure 1). In addition, the contribution of refraction and diffraction of offshore waves into the inshore region to the inshore energy level is not known. Under the assumption of unlimited fetch, an average sea breeze (u_{Perth} = 5 m/s) generates inshore waves with H_s = 0.9 m and T_p = 4.5 s (Table 2). However, the inshore wave measurements shown in Figure 11 are considerably less and indicate H_s = 0.5 m and T_p = 3–4 s. If a fetch length of 15 km is assumed, corresponding to the approximate distance from the inshore wave rider buoy to Garden Island and Five Fathom Bank, predicted wave conditions are H_s = 0.5 m and T_p = 3.2 s which is in close agreement with the observations. This strongly suggests that the inshore waves are fetch-limited.

Table 2. *Inshore and offshore wave conditions generated by three types of sea breezes predicted using the Sverdrup-Munk-Bretschneider method (CERC, 1984). The duration of the sea breezes is assumed to be 6 hours.* u_{Perth} *= wind speed at Perth;* u_{Swanb} *= wind speed at Swanbourne;* u_{Rottn} *= wind speed at Rottnest Island;* H_s *= significant wave height;* T_p *= spectral peak wave period.*

			Offshore Waves With Unlimited Fetch		Inshore Waves With Unlimited Fetch		Inshore Waves With a Fetch of 15 km	
u_{Perth} (m/s)	u_{Swanb} (m/s)	u_{Rottn} (m/s)	H_s (m)	T_p (s)	H_s (m)	T_p (s)	H_s (m)	T_p (s)
3	4.2	5.1	0.5	3.7	0.5	3.5	0.3	2.6
5	7	8.5	1.2	5.2	0.9	4.5	0.5	3.2
7	9.8	11.9	1.9	6.3	1.4	5.5	0.8	3.6

A comparison between the offshore and inshore wave conditions indicates that the inshore wave height was about half the offshore wave height, whereas the wave periods were rather similar (*cf.*, WNI, 1998). The reduction in wave height was, however, dependent on the wave frequency; the swell height decreased by 60%, whereas the reduction in wind wave height was 50%. The inshore coastal region off the coast of Perth is sheltered by submerged reef systems and islands (Five Fathom Bank, Rottnest and Garden Islands; refer to Figure 1) and the reduction in swell height from offshore to inshore is primarily due to wave attenuation processes (refraction, diffraction, bed frictional effects). The reduction in wind wave height, however, is considered the result of the weaker wind speed and the shorter fetch length associated with the sea breeze in the inshore coastal region.

Quantifying the Effect of Sea Breeze Activity on Incident Wave Conditions

Sea breeze activity has a significant effect on the offshore wave conditions and it is useful to be able to quantify this effect. One approach has been discussed above and uses spectral analysis of raw wave data to separate the total wave energy in swell and wind waves. Under the assumption that the wind waves are principally generated by the sea breezes, the importance of sea breeze activity can then simply be expressed as the relative contribution of wind wave energy to the total wave energy. For example, the contribution of wind-wave energy (generated by the sea breeze) to the total wave energy for the entire three-day period shown in Figures 10 and 11 is 40% for the offshore region and 50% for the inshore region. It is reasonable to assume that the majority of wind wave energy in summer is generated by sea breeze activity. However, for the remainder of the year, winds associated with the passage of mid-latitude depressions (storms) should also be taken into account, especially in the winter months. In the analysis of the wind climate, the relative contributions of storm and sea breeze activity to the overall variance in the wind record was assessed by comparing the amounts of energy present in the synoptic (periods larger than 1.5 days) and sea breeze (periods smaller than 1.5 days) frequency bands, respectively. A similar methodology can be applied to quantify the significance of sea breeze activity for the nearshore wave climate.

Spectral analysis was conducted on four years (1995–1998) of hourly significant wave height data collected in the offshore and inshore regions. 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 spectrum was determined for each of the seasons (Figure 12). The spectra show considerably more offshore wave energy than inshore wave energy as a result of the attenuation of the incident wave energy by the offshore reef systems and islands. The offshore wave conditions experience clear sea breeze forcing in summer as indicated by a significant peak in the spectrum at a frequency of one cycle per day (*i.e.*, the diurnal frequency). The spectra for the remainder of the year do not suggest that sea breezes significantly affect the offshore waves. The summer and autumn spectra of the inshore wave height exhibit a significant diurnal peak, and an insignificant, albeit distinct, diurnal peak in the spring spectrum. It is apparent that the sea breeze has a larger impact on the inshore waves than on the offshore waves.

Monthly spectra of the offshore and inshore wave conditions were computed and an average spectrum was determined for each month using the four years of wave height data. The total spectral energy was then partitioned into the synoptic and sea breeze frequency bands to allow investigation of the seasonal variation in the importance of these components (Figure 13). Despite the substantial wave heights (H_s > 1 m) generated by the sea breeze in the offshore region (refer to Figure 10), diurnal forcing of the offshore wave height only accounts for 10–20% of the total variance in the wave height record in the summer and *c.* 5% for the remainder of the year. In contrast, in the inshore region, the diurnal frequencies contribute 20–40% to the total variance in the wave height record in the summer, 10–20% in spring and autumn and *c.* 5% in winter. In contrast to the spectra of the wind speed (refer to Figure 6), the synoptic band in the spectra of the wave height is of greater importance than the sea breeze band. This indicates that the variability in wave conditions due to local and remote storm activity is greater than the variations in wave height generated by sea breezes.

CONCLUSIONS

The diurnal sea breeze system in Perth, Western Australia, is a very important contributor to the overall wind climate. Using forty-nine years of wind data collected at Perth airport, 20 km inland, it was found that almost 200 sea breezes are experienced per year with an average wind velocity at 15:00

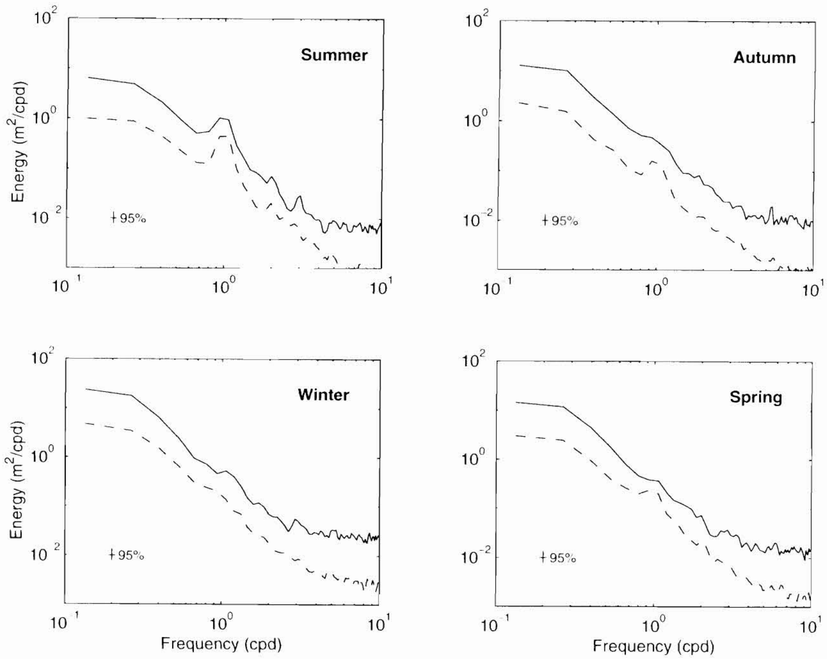

Figure 12. Average seasonal spectra of offshore (solid line; 48 m water depth) and inshore (dashed line; 17 m water depth) wave height. The 95% confidence limits are indicated by the scale bar and were calculated using 96 degrees of freedom and "cpd" refers to cycles per day. Based on hourly significant wave height collected from 1995–1998.

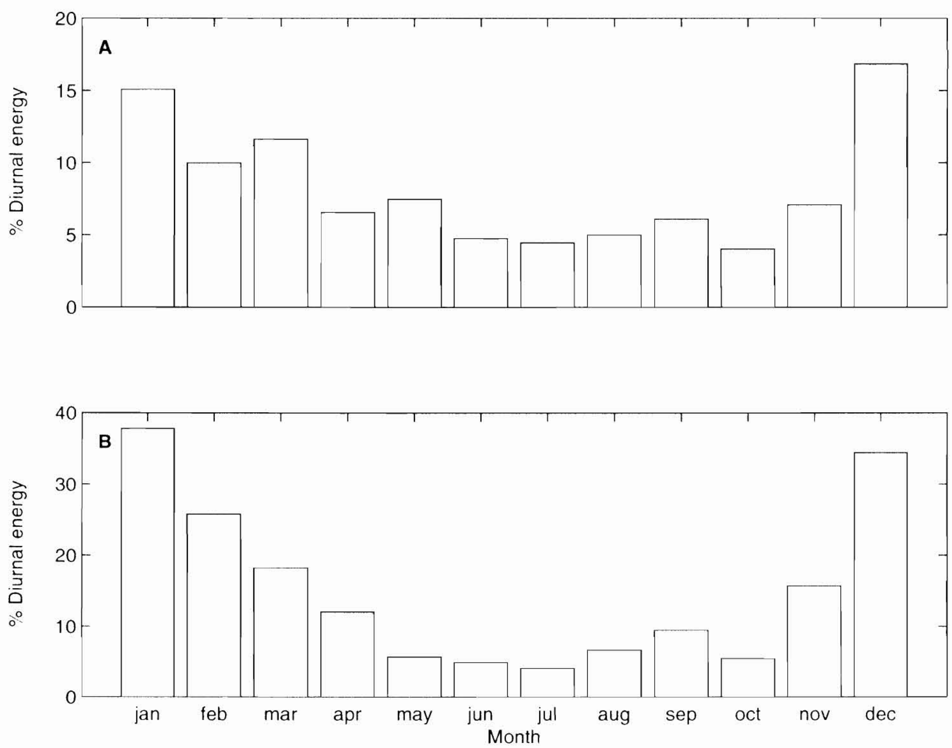

Figure 13. Monthly variation in the relative contribution of the sea breeze band (periods smaller than 1.5 days) to the total variance in the wave height record: (A) offshore (48 m water depth); and (B) inshore (17 m water depth). Based on hourly significant wave height collected from 1995–1998.

hrs of 5.7 m/s and a mean direction of 240°. The sea breeze starts around mid-afternoon and usually subsides after 18:00 hrs. In summer, more than 20 sea breezes occur on a monthly basis, but also in winter, sea breezes are not uncommon. Throughout the year, more than half the variance in the wind speed record can be attributed to the sea breeze frequency band (periods less than 1.5 days). Along the coastline, sea breeze velocities are 1.4 times stronger than inland, and in addition, the sea breeze blows from a more southerly direction (200°). Some distance offshore on Rottnest Island (20 km offshore), the winds during the sea breeze are 1.7 times stronger than inland, but from the same direction as on the coast. Analysis of wind data collected at nine other coastal meteorological stations in Western Australia indicate similar results, demonstrating that the sea breeze system is highly significant state-wide.

The strength and persistence of the sea breezes has important implications for the offshore wave climate in the area. Spectral analysis of wave data collected off the coast of Perth revealed considerable amounts of spectral energy present within the sea breeze band, in particular during summer when the sea breeze system is best developed. The importance of waves generated by the sea breeze is particularly significant in regions that are protected from the direct impact of swell. The inshore region of the Perth metropolitan coastline is partly sheltered and in the summer up to 40% of the variability in the inshore wave height record can be attributed to sea breeze activity.

The diurnal sea breeze system is a worldwide phenomenon that is particularly prevalent along tropical and subtropical coasts, but is also commonplace in temperate coastal environments (SIMPSON, 1994). In sheltered, low wave energy environments, sea breeze activity has a significant impact on nearshore processes and morphology, as demonstrated by the investigations conducted along the Perth metropolitan coastline (MASSELINK *et al.*, 1997; PATTIARATCHI *et al.*, 1997; MASSELINK and PATTIARATCHI, 1998a, b). It is surprising, therefore, that only a handful of studies have been carried out concerning sea breeze effects in other parts of the world, namely the Gulf of California (INMAN and FILLOUX, 1960), the Gulf of Mexico (SONU *et al.*, 1973), the Caribbean (HENDRY, 1983; HUNTLEY *et al.*, 1988) and Sri Lanka (PATTIARATCHI and MASSELINK, 1996). It is expected that the importance of sea breeze activity for nearshore environments is far greater than that suggested on the basis of the amount of attention it has received in the literature.

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