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Cover image: Wind roses for Rottnest Island in January (summer) and July (winter).

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Contents

Abstract

Monthly wind statistics have been derived for 23 weather stations along the Western Australian coast from Wyndham in the north-east of the state, down the west coast and around to Eucla in the south-east. The overall seasonal wind cycle at each site has been derived based on the 30-year period 1982 to 2011 (although a few stations had shorter records), and these show the major changes between the wind regimes along the Northwest Shelf, the west coast and the south coast. Within each of these 3 regions there are more localised variations in the seasonal wind pattern, largely because of the orientation of the coastline and latitudinal differences resulting from the seasonal migration of the subtropical high-pressure belt. As winds play a major role in driving near-surface currents, the current system in each of the 3 regions is briefly reviewed from historical current measurements. There is also a substantial inter-annual constituent in which the monthly anomalies from the seasonal cycle are of similar order of magnitude to the long-term monthly means, which may contribute to annual variability in recruitment of fish species with pelagic eggs & larvae. It appears that there are some inconsistencies in the records at a few sites but these have not been resolved here.

These seasonal/inter-annual wind and current variations have important implications for pelagic egg and larval transport along the continental shelf as well as for cross-shelf larval exchange between the continental shelf waters and the open ocean. An application of the wind statistics to understanding the variability in population of the silver-lipped pearl oyster (*Pinctada maxima*) is provided to illustrate the value of this information to marine population studies.

1.0 Introduction

The Western Australian coastline stretches from the tropics to the Southern Ocean, and there is accordingly a pronounced change in the seasonal wind patterns from north to south. The action of wind stress on the ocean surface plays a major role in the generation and maintenance of surface ocean currents, particularly in shallow near-coastal waters, and these have important implications for pelagic egg and larval transport. Direct current measurements along most of the Western Australian coast are sparse and in many regions non-existent, but those studies that have been undertaken over the years have shown a generally close relationship between the currents and winds in many nearshore areas on both monthly/seasonal and few-day time scales (*e.g*. Steedman & Associates 1981, Cresswell *et al*. 1989, Pattiaratchi *et al*. 1995, Fandry *et al.* 2006).

A suite of weather stations along the coast are maintained by the Bureau of Meteorology, stretching back many decades at some sites. This report has the following objectives:

1) Derive the seasonal mean wind pattern (“climatology”) at selected coastal sites using the past 30 years of records to show the changing wind regime between the far north coast (Wyndham) and the Great Australian Bight (Eucla);
2) Briefly consider inter-annual variability of the wind field;
3) Describe as a case study an application where winds play an important role in recruitment to the pearl oyster fishery.

It should be viewed as a preliminary analysis in that some apparent inconsistencies in the wind data have not been resolved.

2.0 Data and Methods

The wind data, covering many decades at most sites, were obtained from the Bureau of Meteorology on CD in text format. The sampling interval gradually improved over time from twice-daily observations (typically 9 am and 3 pm -- giving about 60 records per month) in the early days to 3-hourly measurements throughout the day and night (yielding 240 records per month) in more recent records.

23 sites have been selected as representative of the north-west coast, the west coast and the south coast of Western Australia (**Table 1**; **Figure 1**), based both on geographic location (seeking to cover the whole coastline at reasonable intervals) and on the data duration at each site. The 6 selected north coast sites fall into the North Coast Bioregion, the 12 west coast sites into the combined Gascoyne Coast and West Coast Bioregions, and the 5 south coast stations into the South Coast Bioregion (**Figure 1)**.

The bulk of the data processing was undertaken using an ACCESS database routine, in which the northward and eastward wind components were derived for all the records in each month and the monthly statistics (mean, standard deviation, minimum and maximum, and number of samples) calculated. The wind speeds were converted from the original km/hr to m/s using the conversion factor of 1 km/hr = 0.278 m/s. Continuity of the monthly records was checked, and individual missing months were linearly interpolated. Months with less than half the normal number of observations were omitted, being filled by interpolation where the adjacent months were valid.

From the monthly statistics, the overall seasonal cycle for the 30-year period 1982 to 2011 was derived by averaging the wind components for each month January to December (tabulated in the **Appendix**). As the resultant wind vectors in some seasons were comparatively small because of high directional variability during those months (hence giving a misleading impression of the seasonal variations in actual wind strength), the monthly mean scalar wind speeds were also calculated. An index of the "stability" (effectively the persistence or constancy in wind direction during the month) was then derived as the ratio of the vector mean speed to the scalar mean speed, multiplied by 100 (Neumann 1968).

The seasonal wind cycles at each site were plotted in the form of northward and eastward components as well as progressive vector diagrams (PVDs, in which the monthly vectors are linked nose-to-tail to depict the seasonal march of the winds over the calendar year) to provide a climatology of the near-shore/coastal wind field along the Western Australian coastline. Monthly anomalies were derived by subtracting the long-term mean annual wind cycle from the individual monthly winds, thus showing those months when the winds were higher or lower than the long-term pattern. To reduce small-scale variability, the anomalies were smoothed using a 3-month moving average.

By meteorological convention, winds are described by the directions *from* which they blow while currents are described as the direction *towards* which they are flowing (thus southerly winds generate northward currents); the northward and eastward components in this analysis are in the directions *towards* which the wind is blowing.

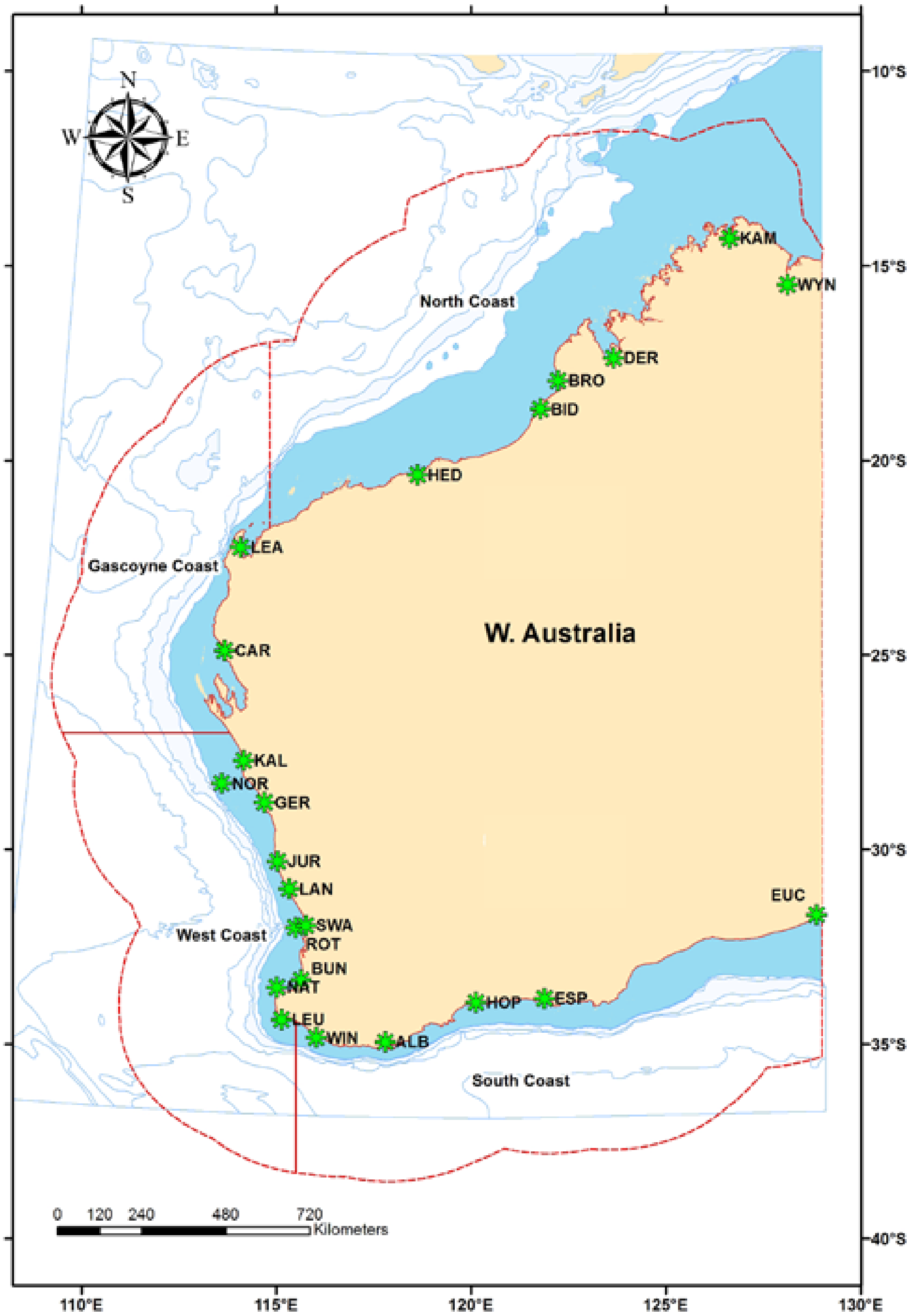

Figure 1: Location of the weather station sites used in this report, with bioregion zones (red lines) and bathymetry (blue lines) off Western Australia. Site codes are (anticlockwise from top right): WYN = Wyndham, KAM = Kalumburu Mission, DER = Derby, BRO = Broome, BID = Bidyadanga, HED = Port Hedland, LEA = Learmonth, CAR = Carnarvon, KAL = Kalbarri, NOR = North Island, GER = Geraldton, JUR = Jurien, LAN = Lancelin, SWA = Swanbourne, ROT = Rottnest Island, BUN = Bunbury, NAT = Cape Naturaliste, LEU = Cape Leeuwin, WIN = Windy Harbour, ALB = Albany, HOP = Hopetoun North, ESP = Esperance and EUC = Eucla.

Table 1: Weather stations along the Western Australian coast analysed in this report, running anti-clockwise from the north-east, down the west coast, to the south-east. The Start and End denote the first and last years processed although there were occasional (generally small) gaps in the data.

Station (abbreviation)	Code	Start	End	Latitude °S	Longitude °E
North-west coast					
Wyndham (WYN)	001013	1982	2011	15.4872	128.1247
Kalumburu Mission (KAM)	001021	1982	2005	14.2972	126.6417
Derby Airport (DER)	003032	1995	2011	17.3714	123.6592
Broome Airport (BRO)	003003	1982	2011	17.9492	122.2336
Bidyadanga (BID)	003030	1982	2011	18.6844	121.7803
Port Hedland Airport (HED)	004032	1982	2011	20.3736	118.6297
Gascoyne/West coast					
Learmonth Airport (LEA)	005007	1982	2011	22.2367	114.0872
Carnarvon Airport (CAR)	006011	1982	2011	24.8878	113.6700
Kalbarri (KAL)	008251	1982	2011	27.7119	114.1650
North Island (NOR)	008290	1990	2011	28.3031	113.6025
Geraldton Airport (GER)	008051	1982	2011	28.7953	114.6975
Jurien Bay (JUR)	009131	1982	2011	30.3081	115.0311
Lancelin (LAN)	009114	1982	2011	31.0175	115.3289
Swanbourne (SWA)	009215	1993	2011	31.9558	115.7619
Rottnest Island (ROT)	009193	1987	2011	32.0086	115.5000
Bunbury (BUN)	009965	1995	2011	33.3578	115.6433
Cape Naturaliste (NAT)	009519	1982	2011	33.5381	115.0183
Cape Leeuwin (LEU)	009518	1982	2011	34.3742	115.1344
South coast					
Windy Harbour (WIN)	009871	1984	2011	34.8361	116.0308
Albany Airport (ALB)	009741	1982	2011	34.9431	117.8008
Hopetoun North (HOP)	009961	1996	2011	33.9306	120.1283
Esperance (ESP)	009789	1982	2011	33.8308	121.8908
Eucla (EUC)	011003	1982	2011	31.6806	128.8769

3.0 Results and Discussion

There are distinctly different wind regimes between the Northwest Shelf (Wyndham to Port Hedland), the west coast (Learmonth to Cape Leeuwin) and the south coast (Windy Harbour to Eucla). These seasonally and latitudinally changing wind regimes in turn drive variations in the seasonally-reversing coastal current system, and so are important for the transport of fish eggs and early stage pelagic larvae.

The nearshore/coastal winds analysed here may not be representative of the wind field on the open continental shelf where larger-scale wind products such as those produced by the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) would be more appropriate (see **Section 3.5** below). Analyses of the larger-scale wind field (*e.g.* Godfrey & Ridgway 1985, *inter alia*), surface wind measurements (Holloway & Nye 1985) and comparison between the large-scale modelled and local measurements (Condie *et al*. 2006) show that the monthly/seasonal wind speeds and directions can be very different between the coast and the shelf-break.

3.1 Northwest coast (Wyndham to Port Hedland)

In general terms, the larger-scale winds along the Northwest Shelf are dominated by the seasonal monsoons (D'Adamo *et al.* 2009), with some substantial regional differences associated with the great latitudinal and longitudinal expanse of the Shelf between Wyndham and Port Hedland (**Figure 1**; see Figure 7 in Godfrey & Ridgway 1985; D'Adamo *et al*. 2009 citing Kronberg 2004).

At all the weather station sites, the PVDs show that north-westerly (south-eastward) winds generally blow during the Summer Monsoon centred on the months of January to March/April (**Figures 2a to 2f**) followed by strong easterlies/south-easterlies over winter (the "south-east trade winds", Holloway and Nye 1985) and then a gradual return to north-westerly conditions in spring at most sites. The regional differences apparent in the PVDs are partly a reflection of the varying coastal topography. At Wyndham, in the narrow south-trending Cambridge Gulf, the spring and summer winds are almost due north-to-south and the winter regime effectively due westward (**Figure 2a**). At Kalumburu and Port Hedland (**Figures 2b** and **2f**), there is a seasonally reversing south-eastward then north-westward pattern in the form of an inverted "S" (resulting in a net southward flow), while at Bidyadanga and adjacent Broome (**Figures 2d** and **2e**) the "S" shape has an overall north-eastward trend. At Derby (**Figure 2c**), the PVD follows a very tight NW-SE pattern probably because of its location at the head of the similarly-oriented King Sound.

The seasonality of the wind field is also evident in the northward and eastward wind components (upper panels in **Figure 2)**. At all sites, the northward components (solid bars) peak in winter while the winds at Wyndham and Kalumburu Mission are most strongly southward in spring (**Figures 2a** and **b**), extending through summer at both Derby and Port Hedland despite the large distance between these 2 sites (**Figures 2c** and **f**). At Broome and Bidyadanga, the monthly north-south components are effectively zero between October and March. The east-west components are strongly westward in winter at all sites and equally strongly eastward in spring/summer at all sites except at Wyndham, where there is minimal eastward wind in those seasons.

The monthly-averaged northward and eastward components tend to be weakest at the change of seasons (generally mid-autumn and mid-spring) as the wind directions are most variable at these times, but (as discussed above) this gives a misleading impression of the wind strength. The

actual wind speeds (*i.e*. the average wind speeds over the month regardless of wind direction -- depicted by the line graphs in the centre panels of **Figure 2**) vary seasonally but with somewhat different magnitudes and phases along the coast. At Wyndham, Kalumburu and Bidyadanga, the winds tend to be strongest during winter and into spring, whereas at the other 3 locations the highest wind speeds (at least on the monthly-averaged scale) are in spring and early summer.

These seasonal variations in the vector and scalar wind speeds result in interesting spatial and temporal variability in the wind stability (the bars in the central panels of **Figure 2**). The stability is strongly unimodal at Wyndham where the wind direction is most consistent in autumn/winter (note the strong westward movement in the PVD in **Figure 2a**), whereas the wind stability at all the other Northwest Shelf locations tends to be bimodal, being steadiest (highest stability) in mid-winter and spring/summer and far more variable in the transition seasons -- note Derby and Port Hedland (**Figures 2c** and **2f**) in particular.

Currents on the Northwest Shelf

The water circulation along the Northwest Shelf is complex and poorly known (D'Adamo *et al.* 2009). The inner continental shelf is dominated by tidal currents because of the large tidal range prevailing along much of the coast (Pearce *et al*. 2003): the spring tidal range at Broome, for example, is about 10 m (Radok 1976) which results in spring tidal currents of up to 2 m/s near the coast, diminishing with distance offshore (Condie *et al.* 2006). The Leeuwin Current (or at least one of the sources of the Leeuwin Current) flows seasonally south-westward along the outer shelf partly but not wholly in response to the winds (Holloway & Nye 1985; Holloway 1995). A well-defined southward alongshore current along the mid-shelf during the autumn months has recently been identified and named the Holloway Current by D'Adamo *et al*. (2009) -- this appears, however, to be largely driven by an alongshore steric height gradient rather than the winds. Modelling by Condie *et al*. (2006) shows that there can be high spatial variability in the shelf current system, both along and across the shelf (and indeed down the water column), indicating that the local/regional topography has a large effect on the coastal circulation.

It may be concluded, therefore, that relationships between the currents and the wind field along the inner Northwest Shelf are as yet unresolved and are likely to be fairly complex.

Figures 2a to 2f (on successive pages): Top panels: The overall monthly-averaged northward (solid bars) and eastward (open bars) wind components for each site along the north-west coast Wyndham to Port Hedland.

Centre panels: The monthly mean wind speed (triangles) and wind stability (defined in the text -- bars).

Bottom panels: The progressive vector diagram (PVD), in which the origin on 1st January is at the zero point (0,0 km) and each monthly wind vector then follows nose-to-tail from January to December, with the end of each month depicted by the diamond -- this can be viewed (approximately) as the trajectory of a particle released at the origin at the start of the year and ending on 31st December. The PVD for Wyndham shows the months M(arch), J(une), S(eptember) and D(ecember). North is to the top of each diagram. The axis scales have been kept constant for all the sites to facilitate comparison of the wind regimes at each site.

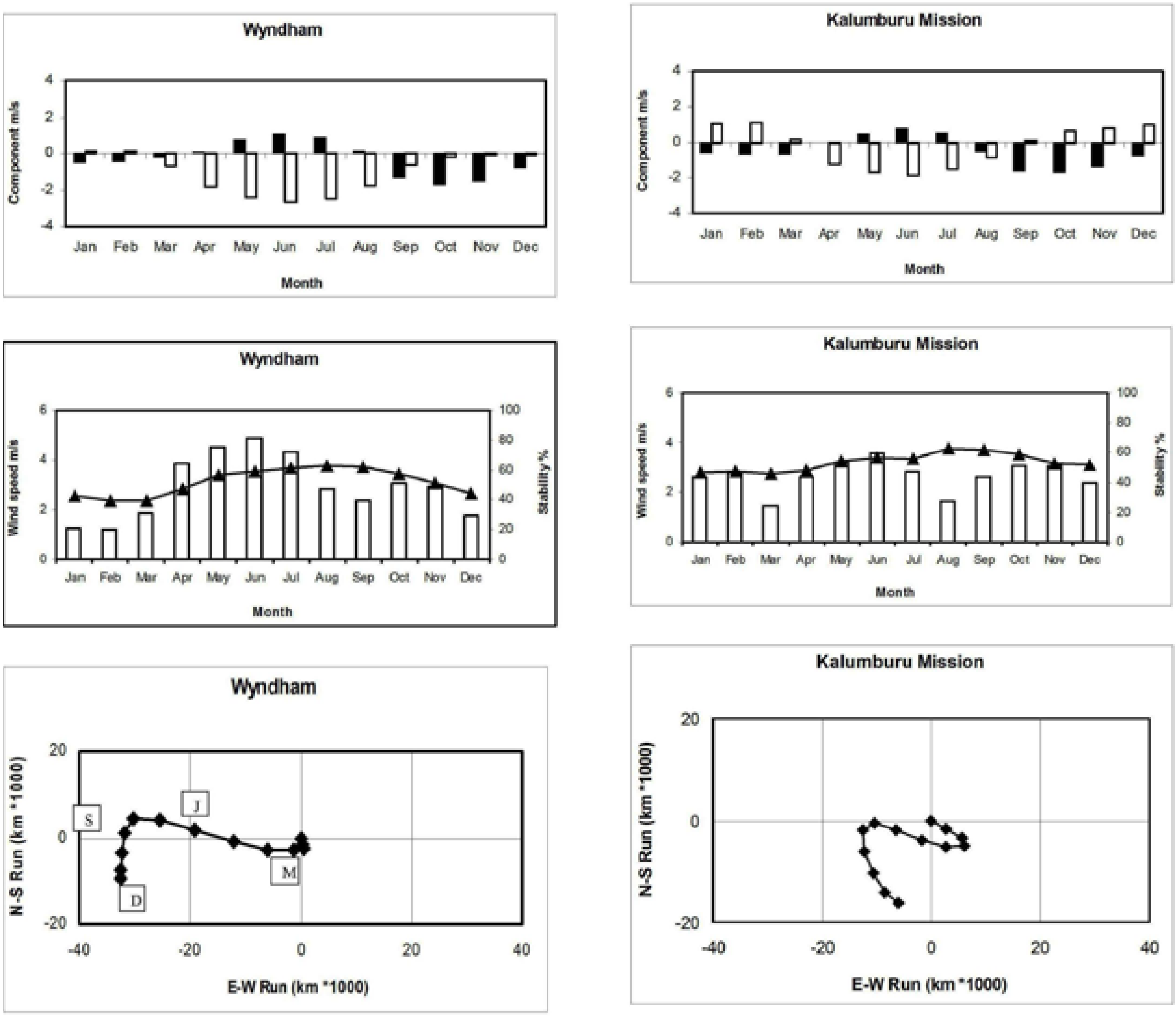

Figure 2: (a) Wyndham and (b) Kalumburu Mission.

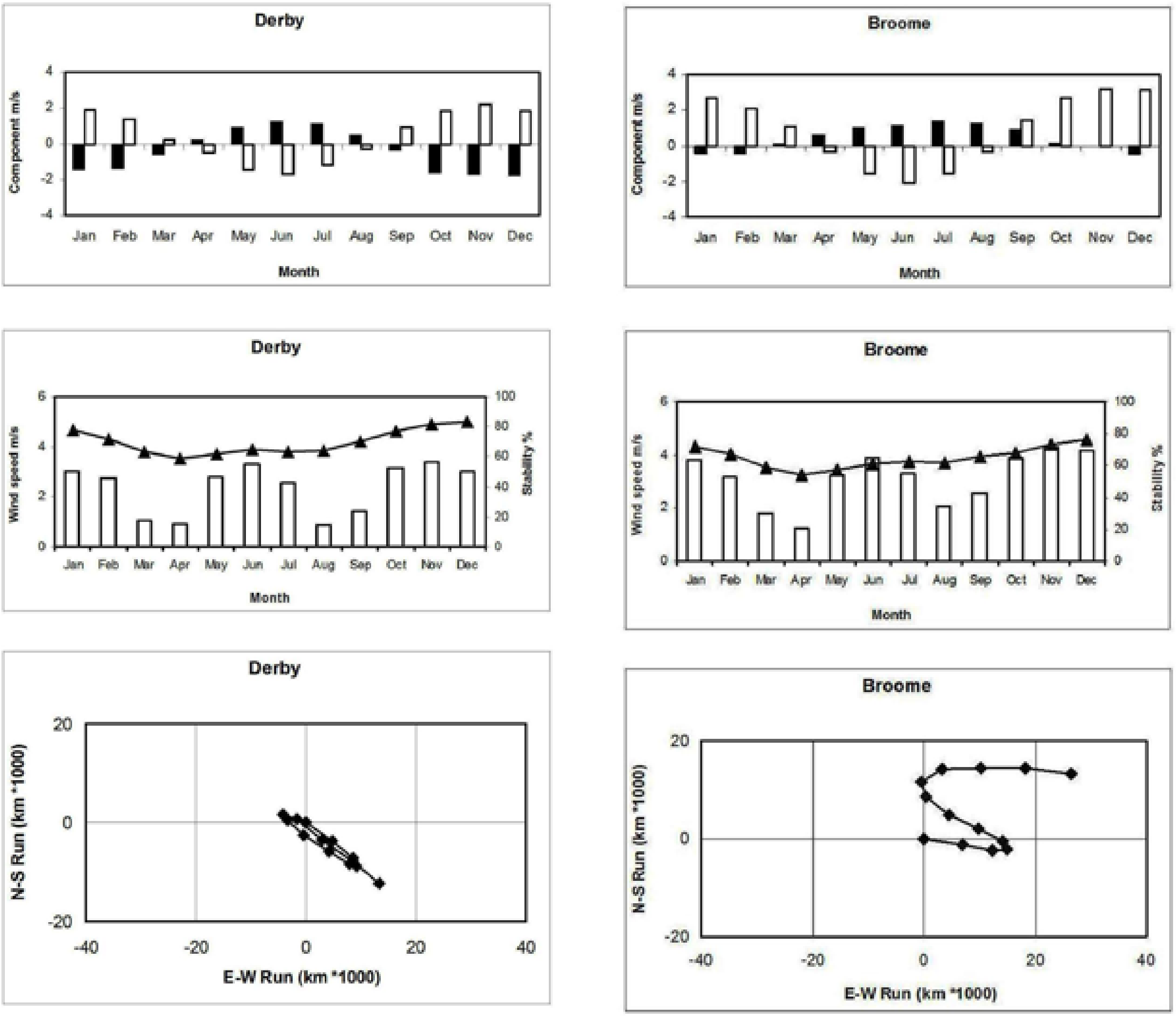

Figure 2: (c) Derby and (d) Broome.

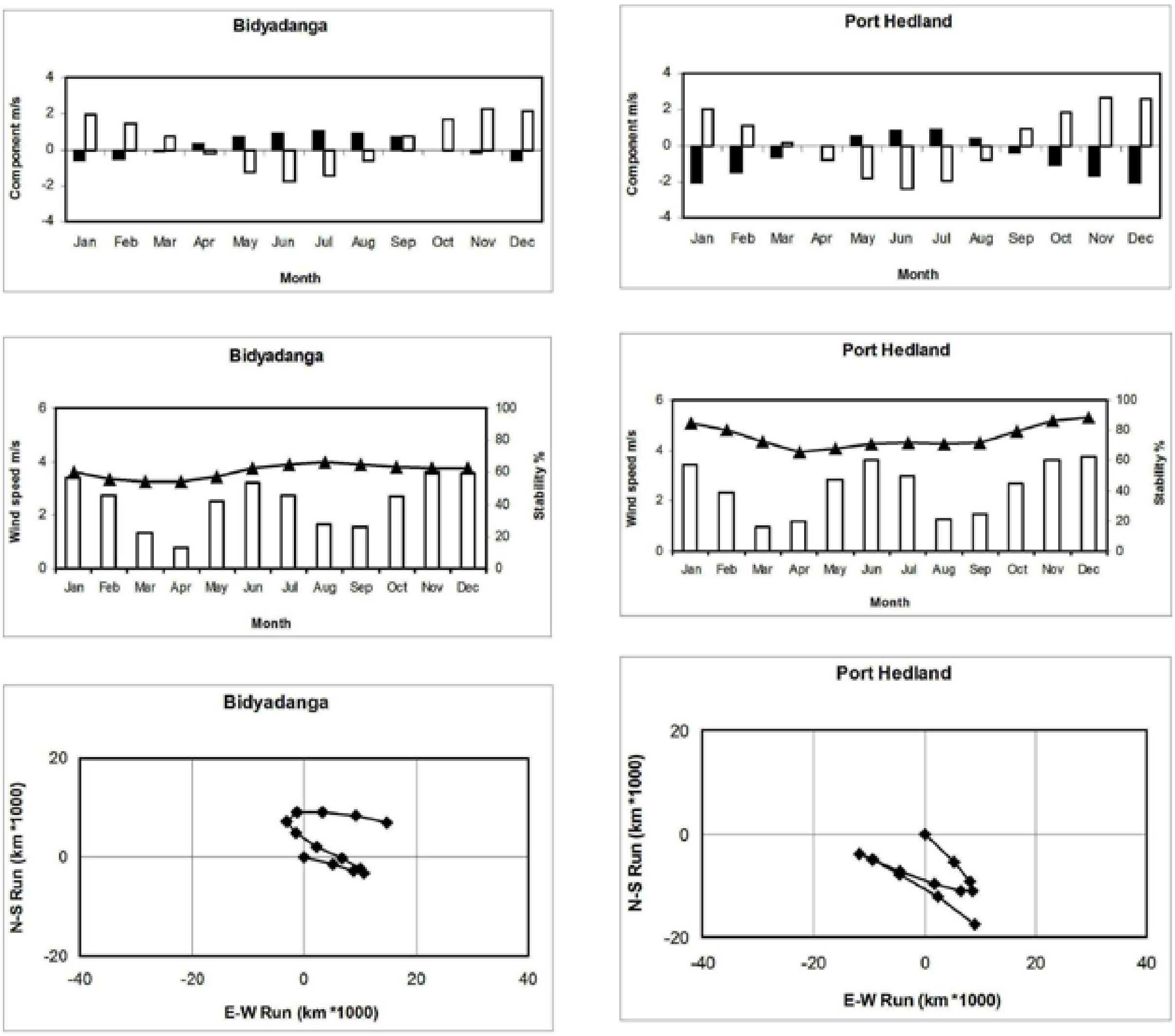

Figure 2: (e) Bidyadanga and (f) Port Hedland.

3.2 West coast (Learmonth to Cape Naturaliste)

From Learmonth southwards, where the coastline is largely meridional, the wind regime is very different from that along the north-west coast, with generally strong and persistent southerlies during the summer months and more variable winds in winter (**Figure 3**) (*e.g*. Forbes & Morrow 1989, Smith *et al*. 1991, Pattiaratchi & Woo 2009). The dominantly equatorward winds between Learmonth and Cape Leeuwin are "upwelling favourable" in the sense that these prevailing southerlies will tend to generate an offshore water movement in the upper layer of the water column (Ekman transport) with consequent replenishment by upwelling of cooler subsurface waters onto the continental shelf, although this seasonal upwelling process is largely suppressed by the southward-flowing Leeuwin Current (Smith *et al*. 1991, Pattiaratchi & Woo 2009). Because of the seasonal migration of the subtropical high pressure (HP) ridge between about 35°S (Cape Leeuwin, in January) and Shark Bay (25°S, in July) (Gentilli 1971, Southern 1979), there is also a progressive phase-shift in the seasonal wind pattern with latitude which is outlined below. Furthermore, regional differences in the wind regime result from variations in the coastline orientation and local coastal topography.

The seasonal wind cycles are most easily visualised in the PVDs for each site (the right panels in **Figure 3**). Overall, the net southerly (northward) wind field is experienced throughout the year north of Geraldton but is briefly interrupted further south by a weak southward component during the winter months when the HP belt is at its northernmost extent and weather frontal systems brush through the southern regions of Western Australia. Variations in the actual wind velocity (reflected in the monthly PVD excursions in **Figure 3**) are partly associated with the change in latitude but probably more so by local variability such as inshore-offshore differences.

Examining in more detail these regional wind shifts with latitude, it is evident from the PVDs in **Figure 3a** to **3d** that the winds between Learmonth and North Island are persistently from the south throughout the year, most strongly between spring and late autumn, with a weak south-easterly tendency during winter. The "bunching" of the vectors during the winter months is indicative of the more variable wind vectors in that season -- at Kalbarri, in particular, the monthly-averaged winds are virtually zero in June and July.

From Geraldton southwards (**Figure 3e**), the net southerly (northward) wind pattern continues to dominate for most of the year, but the winter wind regime switches from an easterly (westward) direction at Geraldton to westerly (eastward, or onshore) at Jurien (**Figure 3f**) and further south down the coast, thus forming a "cusp" in the PVD. This winter cusp continues to develop to the south as the zonal wind component becomes progressively stronger and more westerly with latitude, becoming dominant at Bunbury and the two Capes locations (**Figures 3j** to **3l**). The southerly pattern then resumes into spring and summer.

The amplitude and phase of the seasonal alongshore wind cycle may be more clearly seen in the monthly mean wind components (solid bars in the upper left panels in **Figure 3**; positive is northward) showing the consistently strong northward pattern between October and March throughout the year, and the very much weaker and more variable tendency in winter, including the southward reversal in June and July which commences in Geraldton and continues southward to Cape Leeuwin. The months of peak northward wind are November/December at Learmonth and Carnarvon and then in January all the way southward to Cape Leeuwin (open symbols in **Figure 4a**). The weakest northward (*i.e.* strongest southward) flow is in mid-winter (solid symbols in **Figure 4a**). The alongshore wind component is thus effectively in phase for the whole west coast.

The eastward components (open bars in **Figure 3** left upper panel; positive is eastward) are equally seasonal but there is a phase shift down the coast (**Figure 4b**). At Learmonth and Carnarvon, the wind is most strongly eastward in December and westward in June. A marked transition then commences at the latitude of Kalbarri (~28°S) where the peak easterlies are in November and the highest westerly components in April. With increasing distance southward, the seasonal cycle progressively shifts forward in time until the peak easterlies and westerlies at Cape Leeuwin occur in August and February respectively (**Figure 4b**) -- a 4-month phase advance.

The total length of the trajectory in the PVD is an indication of the overall wind strength. The monthly-averaged wind speed (regardless of direction -- the line graph in **Figure 3** lower left panels) displays a strong seasonality in the northern portion of the coast where it is far higher in summer than in winter, but this seasonal pattern weakens towards the south and by the latitude of the Capes the winds in fact blow most intensely in winter (Pearce & Pattiaratchi 1999). The peak monthly-averaged wind speeds along the west coast are encountered at North Island (8.6 m/s) and Rottnest Island (8.4 m/s) in January (**Appendix**) and at Cape Naturaliste (8.3 m/s) and Cape Leeuwin (9.2 m/s) in July. The weakest winds are at Bunbury, probably due to some "sheltering" by the coastline topography in Geographe Bay. The wind strength at the two island locations is appreciably higher than that at the adjacent mainland coast: the ratio between the monthly wind speed at Geraldton versus North Island varies between about 0.60 in winter and 0.75 in summer (compare **Figures 3d** with **Figure 3e**) while the Swanbourne winds are about 0.70 to 0.75 of those at Rottnest Island (**Figures 3h** and **3i**). The mainland wind measurements are applicable to nearshore waters while the (stronger) island winds are more appropriate for the outer shelf.

The wind stability index (the bars in the lower left panels of **Figure 3**) neatly illustrates the seasonal persistence of the wind patterns down the west coast. Because of the strong southerlies during the summer months with little variability in wind direction, the stability is high between October and March (exceeding 80% at Carnarvon and North Island, **Figures 3b** and **3d** respectively). By contrast, the stability index in the more southern locations falls to < 20% in the winter months as a result of the highly variable wind directions under the influence of the passing westerly frontal systems. At the southernmost location of Cape Leeuwin (**Figure 3l**), the stability displays a bimodal structure due to the more constant winter westerlies at that latitude.

Current system along the west coast

With the increasing development of coastal infrastructure and industry along the lower west coast in recent times, the continental shelf circulation at a number of sites has been investigated, particularly in the Perth metropolitan area. While a detailed review of these studies is beyond the scope of this report (see Pearce 2010 for more detail), they have revealed the generally strong influence of the wind in generating and maintaining the coastal current system on monthly/seasonal time scales and also the wind-forcing of hourly-to-daily wind events. It should be borne in mind that the current measurements are of necessity undertaken at some depth below the water surface, often 10 or 20 m deep, and so do not reflect the actual movement of the very surface layer which is more closely associated with the surface wind stress -- this has a direct bearing on the likely movement and dispersal of floating (buoyant) eggs and larvae.

The Leeuwin Current flows southward along the outer shelf and upper slope (Cresswell & Golding 1980, Cresswell *et al.* 1989, Pearce *et al.* 2006), being primarily driven by the alongshore steric height gradient seasonally modulated by the alongshore wind stress (Godfrey

& Ridgway 1985, Smith *et al*. 1991, Pattiaratchi *et al*. 1995). The shallower inner shelf waters tend to be dominated by local wind forcing (Steedman & Associates 1981, Cresswell *et al*. 1989, Pattiaratchi *et al*. 1995, Fandry *et al*. 2006), and the development and movement of Leeuwin Current meanders may at times have a direct influence on the coastal current system (Mills *et al*. 1996, Cresswell 2009).

At monthly-to-seasonal time-scales, the persistently southerly winds which prevail during the summer months generate northward coastal currents which have been given regional names: the narrow Ningaloo Current flows northward along the Ningaloo Reef coast (Taylor & Pearce 1999, Woo *et al*. 2006, Pattiaratchi & Woo 2009) and the Capes Current likewise flows northward from the Capes region to the Abrolhos Islands and Shark Bay (Steedman & Associates 1981, Pearce & Pattiaratchi 1999, Gersbach *et al*. 1999, Pattiaratchi & Woo 2009). The winter circulation is less clearly defined because of the more variable winds in winter but the flow tends to be southwards in that season. In general, the transitions between northward and southward flow and vice versa occur in March-May and August-October respectively (Steedman & Associates 1981, Cresswell *et al*. 1989, Pearce *et al*. 2006, Fandry *et al*. 2006) although this seasonal switch can occur in other months (*e.g.* Cresswell 2009, Pattiaratchi *et al*. 1995). Because the seasonal wind pattern has a greater effect on the shallow nearshore waters than out near the shelf break (Cresswell 2009), there can be large differences in the monthly-averaged current speeds and directions across the continental shelf as the alongshore pressure gradient and bottom friction also contribute to the current dynamics (Smith *et al*. 1991, Fandry *et al*. 2006, Zaker *et al*. 2007).

Superimposed on the seasonal circulation are higher-frequency current reversals which occur throughout the year (Cresswell *et al*. 1989), generally associated with changes in the alongshore wind on periods of a few days. During the Perth Coastal Waters Study (PCWS), the nearshore currents were found to respond "almost instantaneously" to changes in the winds (Pattiaratchi *et al*. 1995); earlier current measurements by Cresswell *et al*. (1989) indicated that the current change lagged the wind by a few hours. It appears that a minimum wind speed of 3-5 m/s over shallow water (Pattiaratchi *et al* 1995) or 6.2 m/s on the outer shelf (Cresswell 2009) is required to overcome the southward pressure gradient and reverse the currents to northward.

In summary, the strong seasonal wind pattern prevailing along the west coast plays a dominant role in driving the coastal current system, with a consistent northward flow during the summer months and a less well defined southward tendency in winter. The inner shelf waters are more closely linked with the winds at both monthly/seasonal and few-day time-scales than is the outer shelf region where the Leeuwin Current is usually encountered. Because of other driving factors (including the alongshore pressure gradient and shelf intrusions of the Leeuwin Current), however, the continental shelf circulation is complex and caution must be exercised in using the wind field to estimate the alongshore current. Floating eggs and near-surface larvae will be more directly under the influence of the wind than are subsurface objects.

Figures 3a to 3l (on successive pages): Upper left panels: The overall monthly-averaged northward (solid bars) and eastward (open bars) wind components for each site along the west coast Learmonth to Cape Leeuwin. Note the differing y-axis scales necessitated by the greatly varying wind component magnitudes at different sites.

Lower left panels: The monthly mean wind speed (triangles) and wind stability (defined in the text -- bars).

Right panels: The progressive vector diagram (PVD), in which the origin on 1st January is at the zero point (0,0 km) and each monthly wind vector then follows nose-to-tail from January to December, with the end of each month depicted by the diamond -- this can be viewed (approximately) as the trajectory of a particle released at the origin at the start of the year and ending on 31st December. The axis scales have been kept constant for all the sites to facilitate comparison of the wind regimes at each site.

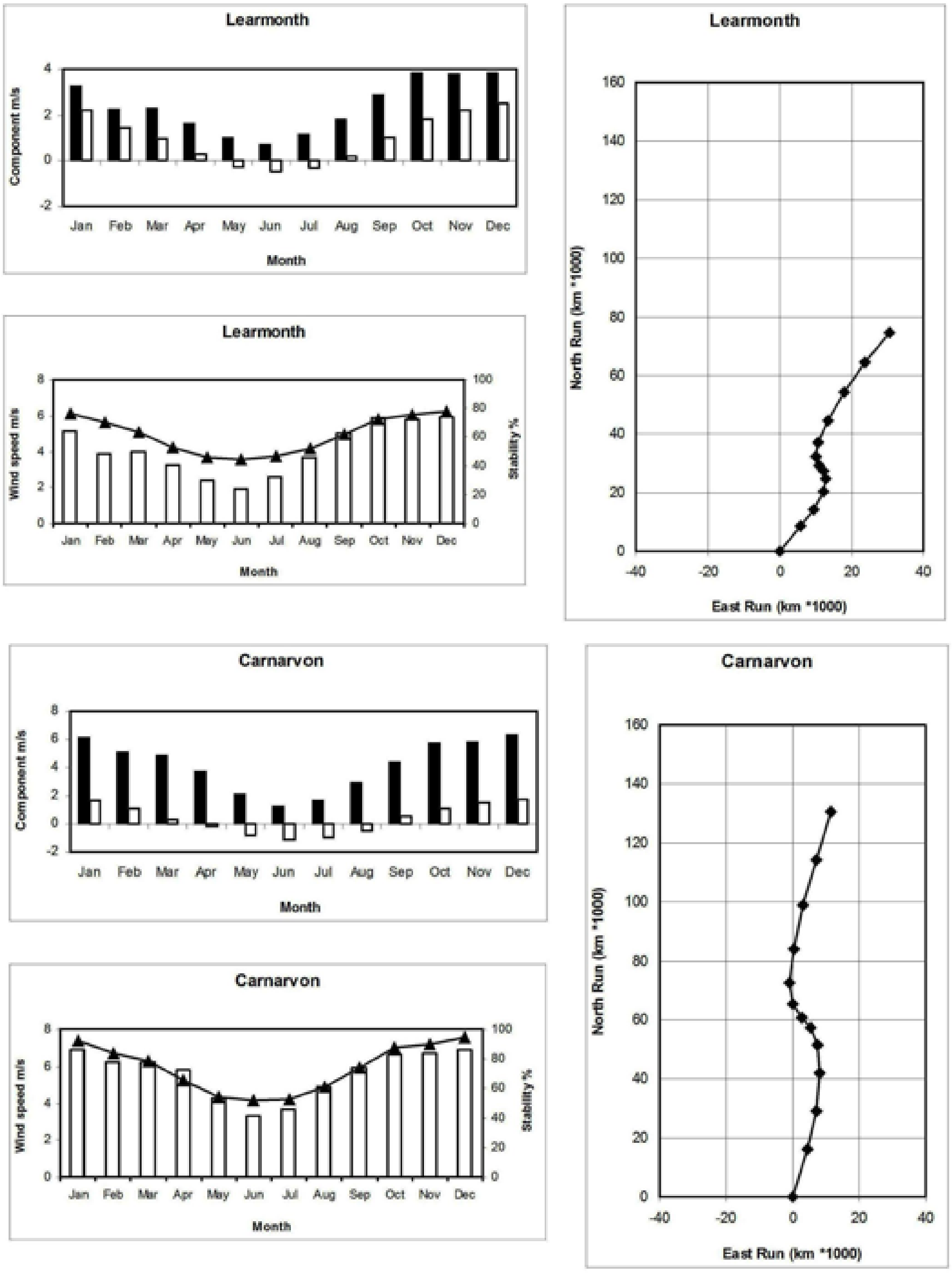

Figure 3: (a) Learmonth and (b) Carnarvon

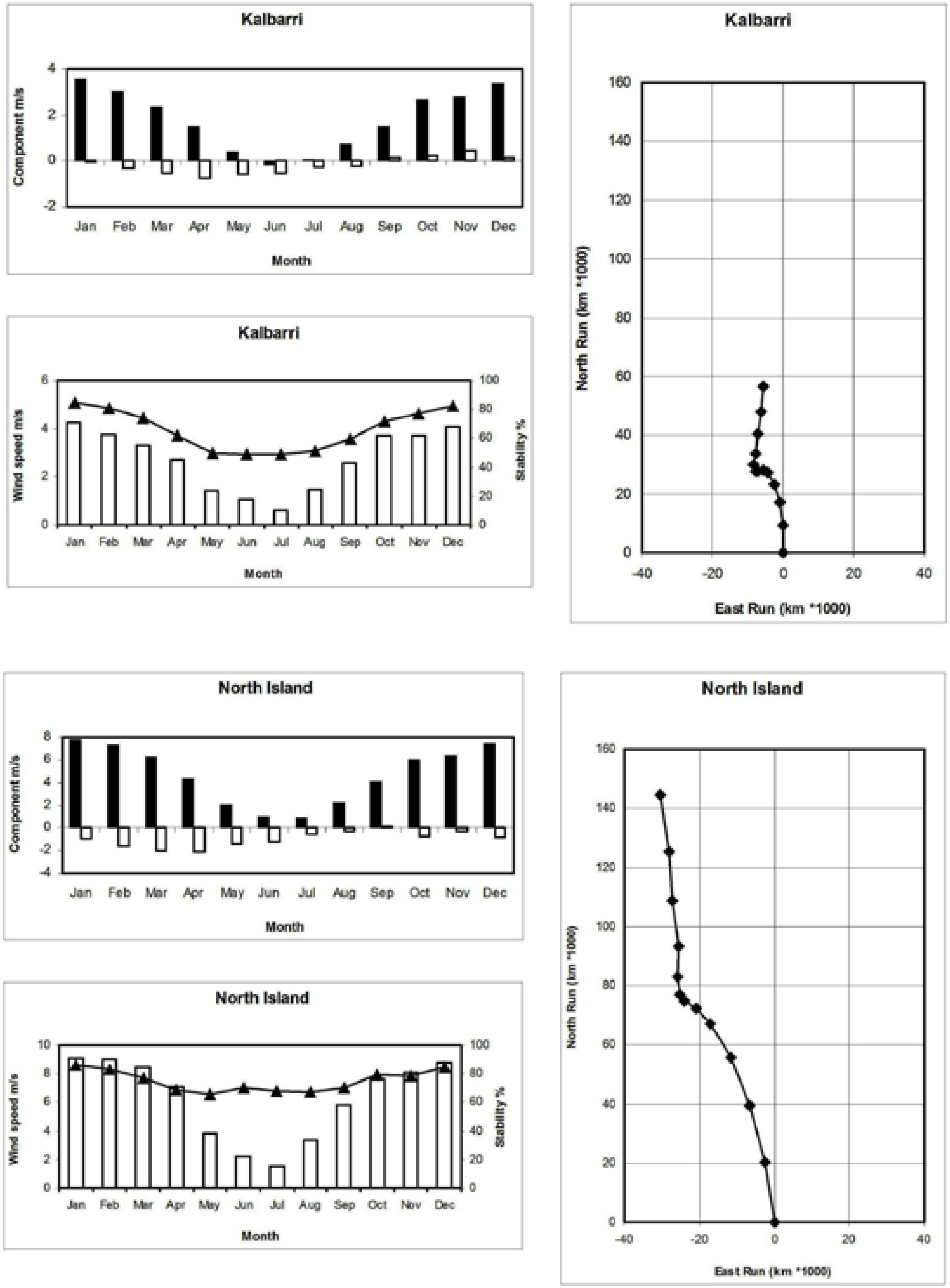

Figure 3: (c) Kalbarri and (d) North Island

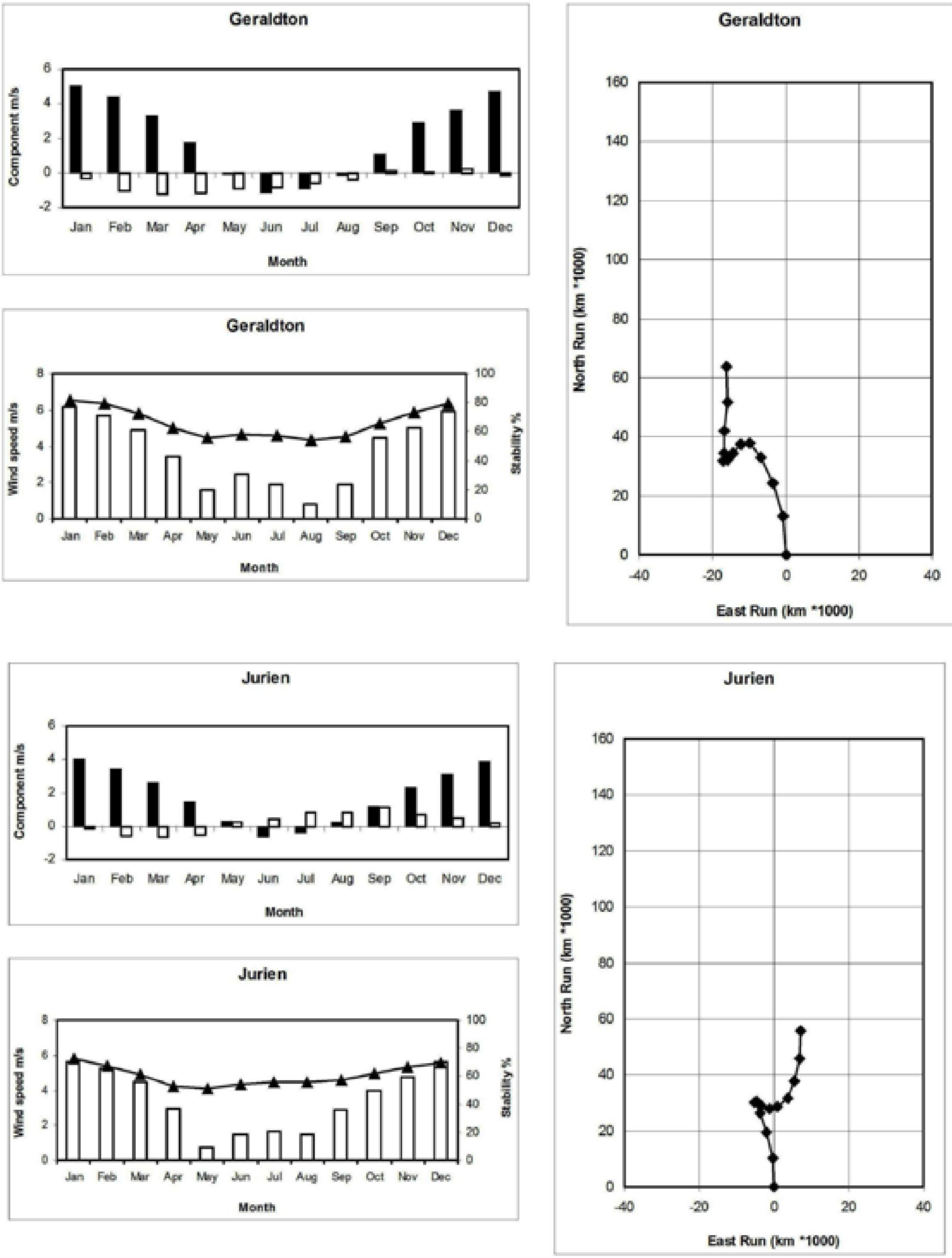

Figure 3: (e) Geraldton and (f) Jurien

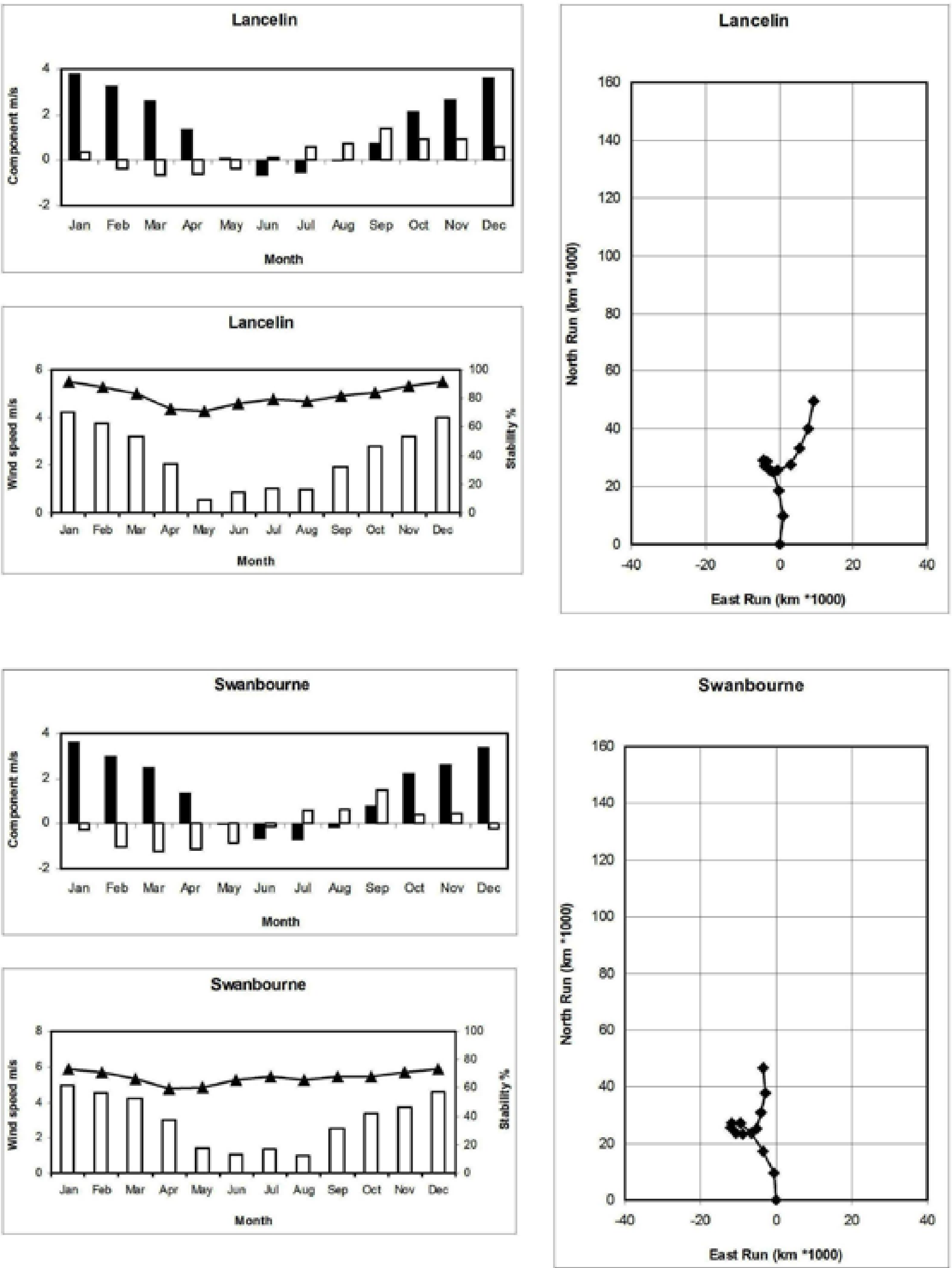

Figure 3: (g) Lancelin and (h) Swanbourne.

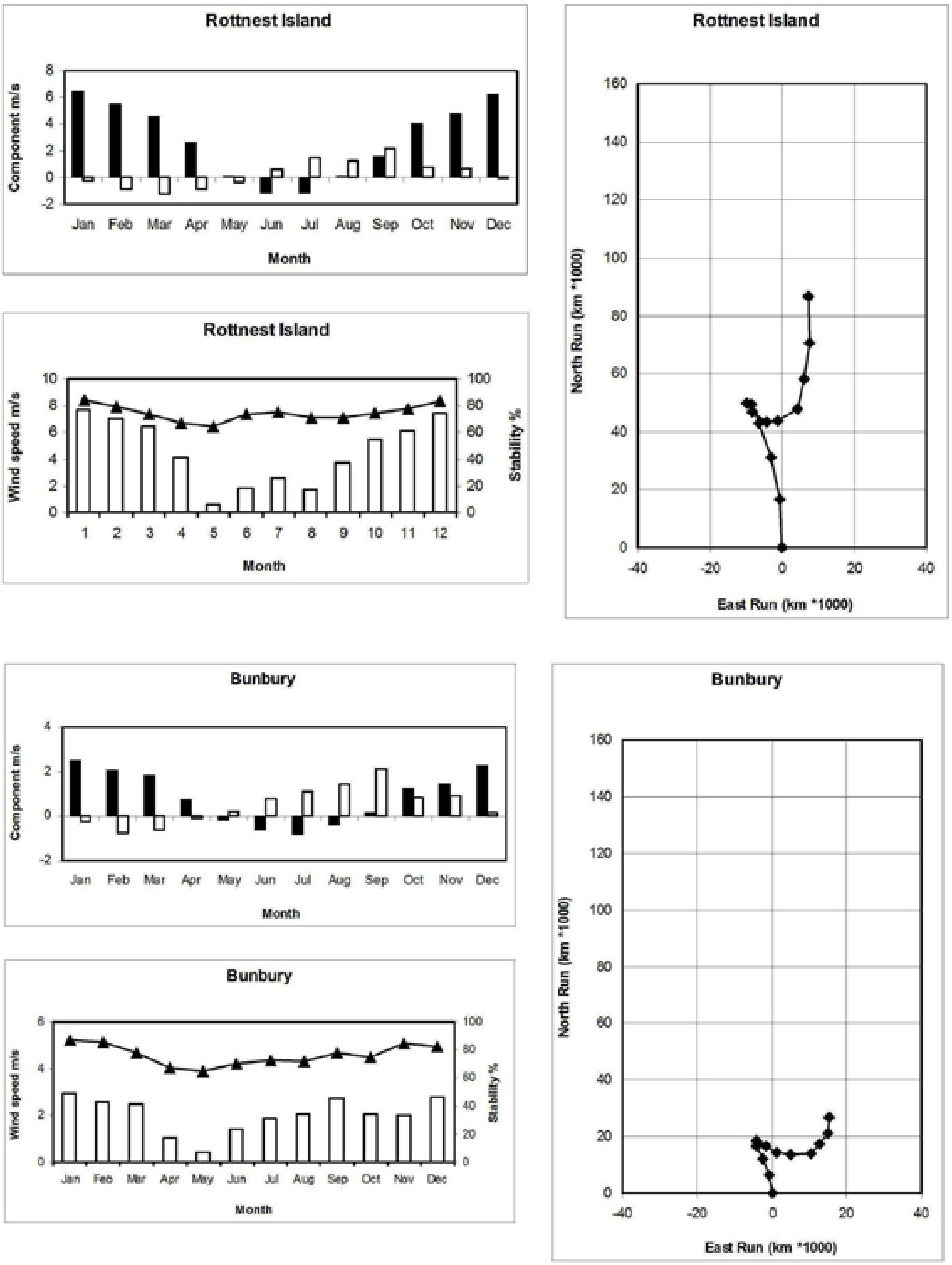

Figure 3: (i) Rottnest Island and (j) Bunbury.

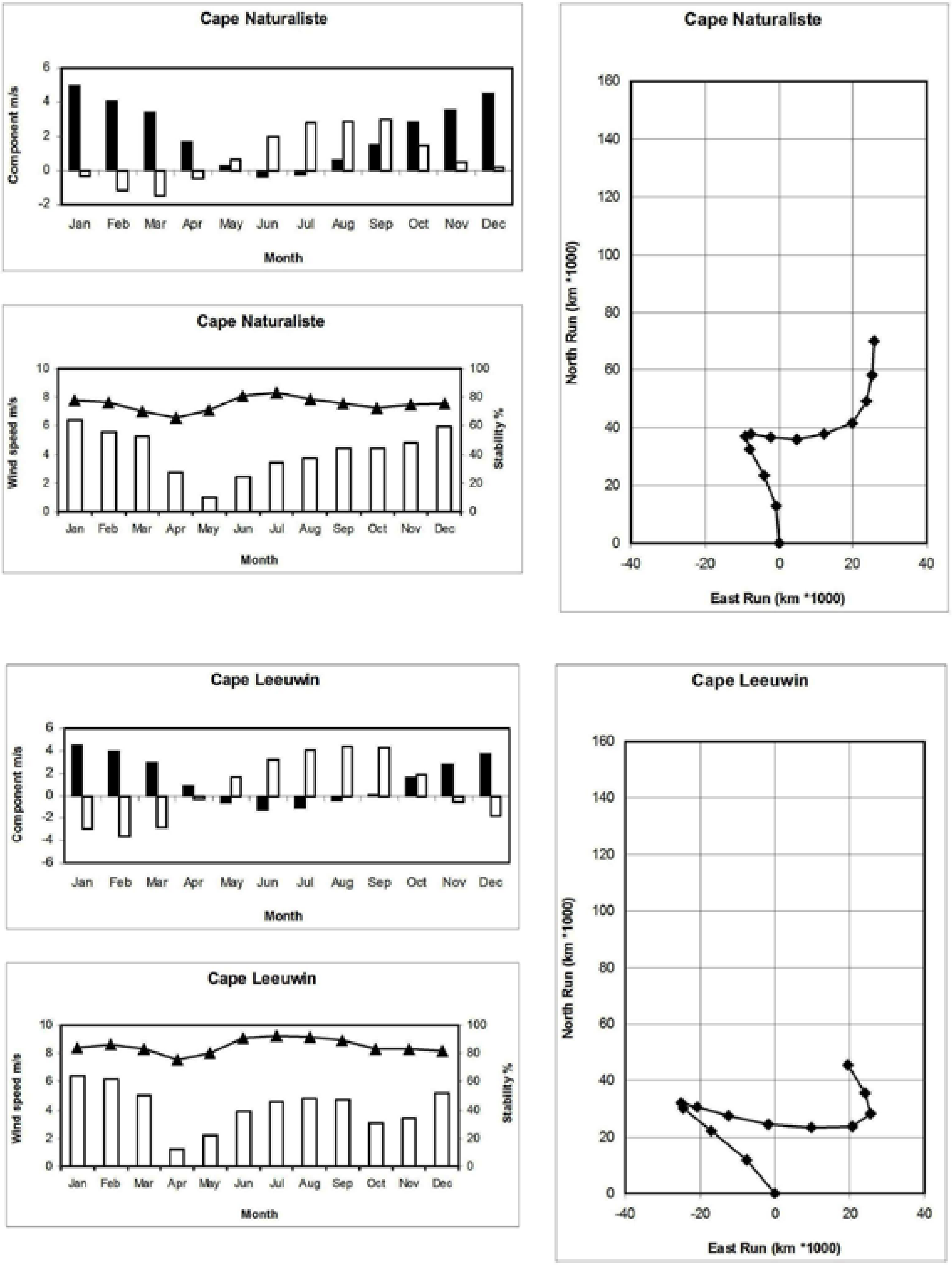

Figure 3: (k) Cape Naturaliste and (l) Cape Leeuwin.

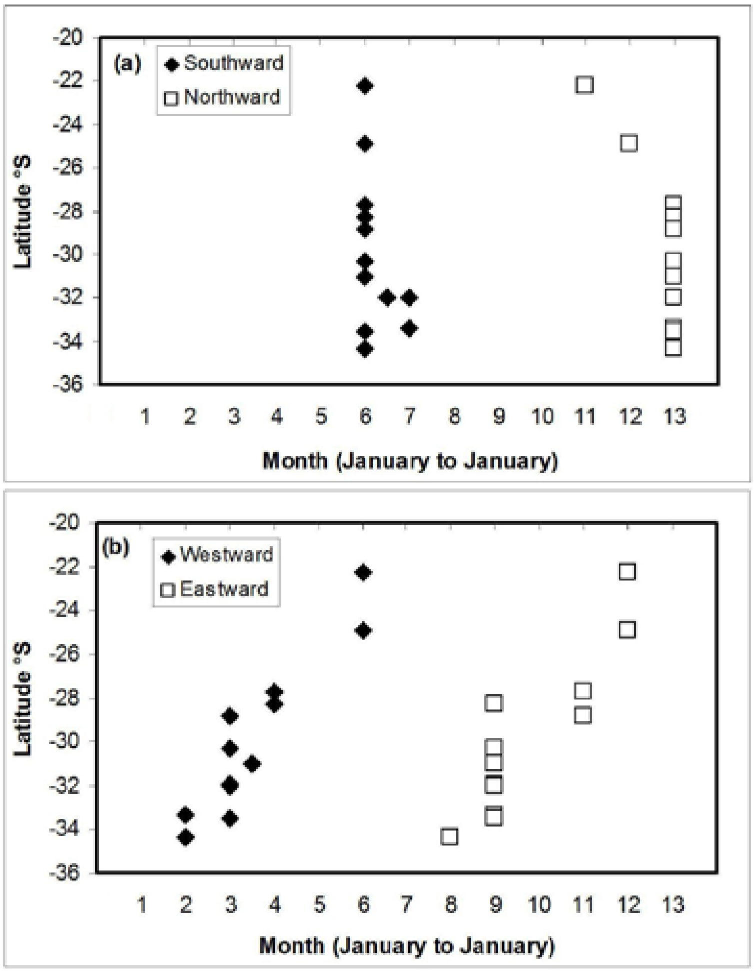

Figure 4: (a) The months at which the maximum southward (solid diamonds) and northward (open squares) wind components occurred by latitude of each west coast site, derived from the Table in the Appendix. Because some of the maxima occurred between December (month 12) and January (month 1), the latter month has been coded as 13 to retain continuity. (b) The months at which the maximum westward (solid diamonds) and eastward (open squares) wind components occurred by latitude of each site. The sites are (north-to-south, see Table 1): Learmonth, Carnarvon, Kalbarri, North Island, Geraldton, Jurien, Lancelin, Swanbourne, Rottnest Island, Bunbury, Cape Naturaliste and Cape Leeuwin.

3.3 South coast (Windy Harbour to Eucla)

Along the south coast, the eastward wind component is effectively alongshore and the northward component in an onshore direction. The wind pattern along the western south coast (typified by Windy Harbour -- see the PVD in **Figure 5a**) is very similar to that at Cape Leeuwin, with south-easterlies between October and April and westerlies in winter: the autumn transition in March/April is very pronounced. From Albany eastwards, however, there is a very distinct seasonally reversing south-easterly/north-westerly pattern illustrated by the "tight" PVDs (**Figures 5b to 5e**) indicative of relatively constant winds during the mid-summer and mid-winter months and a sharp transition between the two regimes in March/April and September/October.

At all sites, the northward wind components (upper left panels in **Figure 5**) are strongest onshore between October and March and offshore in winter. The alongshore wind components are eastward in winter and westward in summer, with a clearly defined seasonal pattern. The monthly mean wind speeds are between 4 and 6 m/s, with a minor weakening in autumn (lower left panels in **Figure 5**), and the stability is distinctly bimodal with the winds being most consistent in summer and winter.

Currents along the south coast

There have been very few current measurements along the south coast. A short-term record near Windy Harbour in spring 1986 found dominantly eastward alongshore currents of up to 20 cm/s (Boland *et al.* 1988, Pearce 1992). A mid-shelf mooring in 80 m water depth south-west of Esperance (Cresswell & Domingues 2009) showed that the current was dominantly eastward over the whole year of measurement, probably associated with the Leeuwin Current, albeit with a consistent offshore component which was attributed to the nearby ("downstream") presence of the Recherche Archipelago south of Esperance. Wind had an important influence on the variability of the continental shelf currents on time scales of a few days (Cresswell & Domingues 2009).

Figures 5a to 5e: Upper left panels: The overall monthly-averaged northward (solid bars) and eastward (open bars) wind components for each site along the south coast Windy Harbour to Eucla.

Lower left panels: The monthly mean wind speed (triangles) and wind stability (defined in the text -- bars).

Right panels: The progressive vector diagram (PVD), in which the origin at 1st January is at the zero point (0,0 km) and each monthly wind vector then follows nose-to-tail from January to December, with the end of each month depicted by the diamond -- this can be viewed (approximately) as the trajectory of a particle released at the origin at the start of the year and ending on 31st December. North is to the top of each diagram. The PVD axis scales have been kept constant between the sites to facilitate comparison of the wind regimes, but the y-axes for the other panels have been varied to suit the appropriate wind scales.

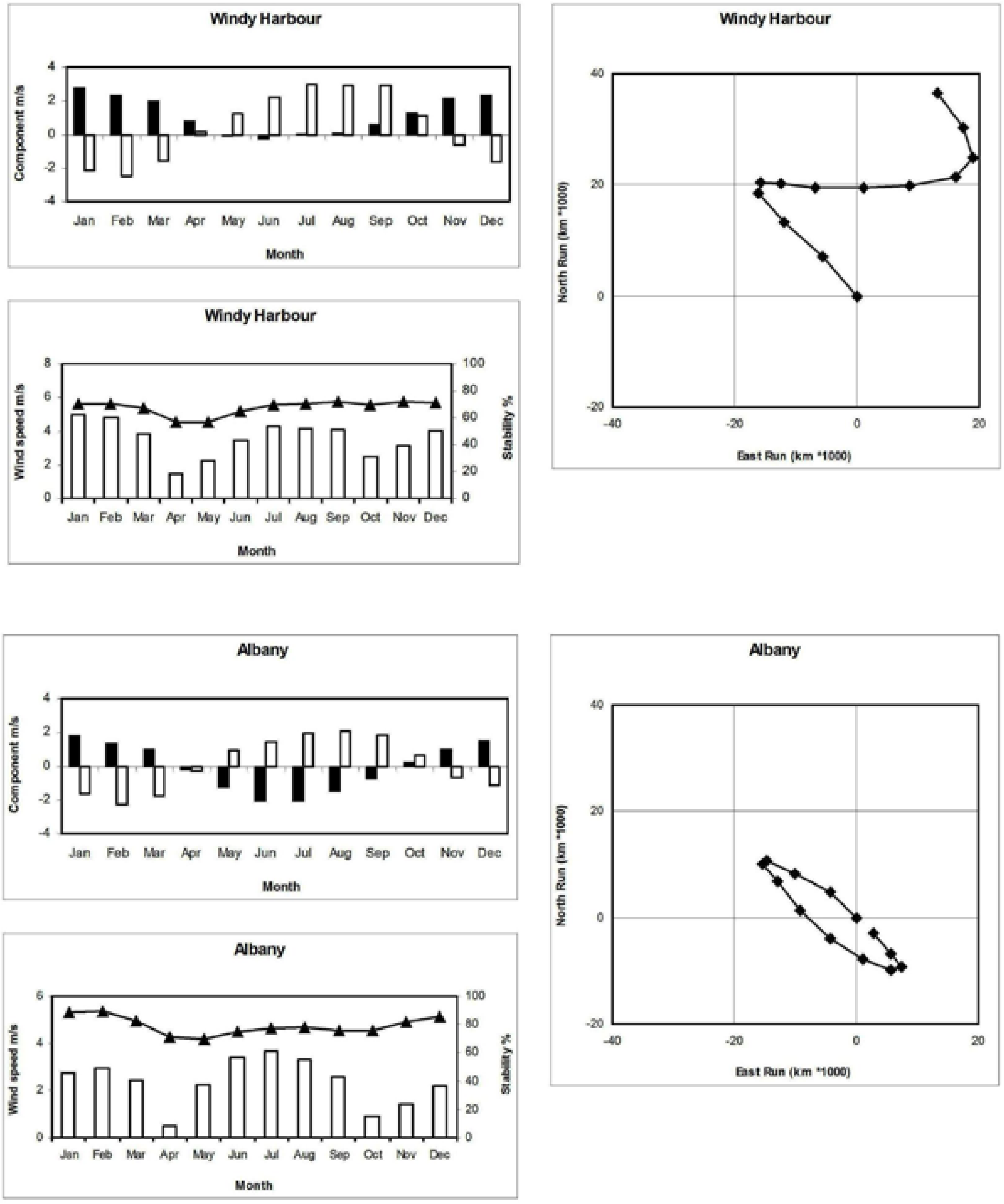

Figure 5: (a) Windy Harbour and (b) Albany.

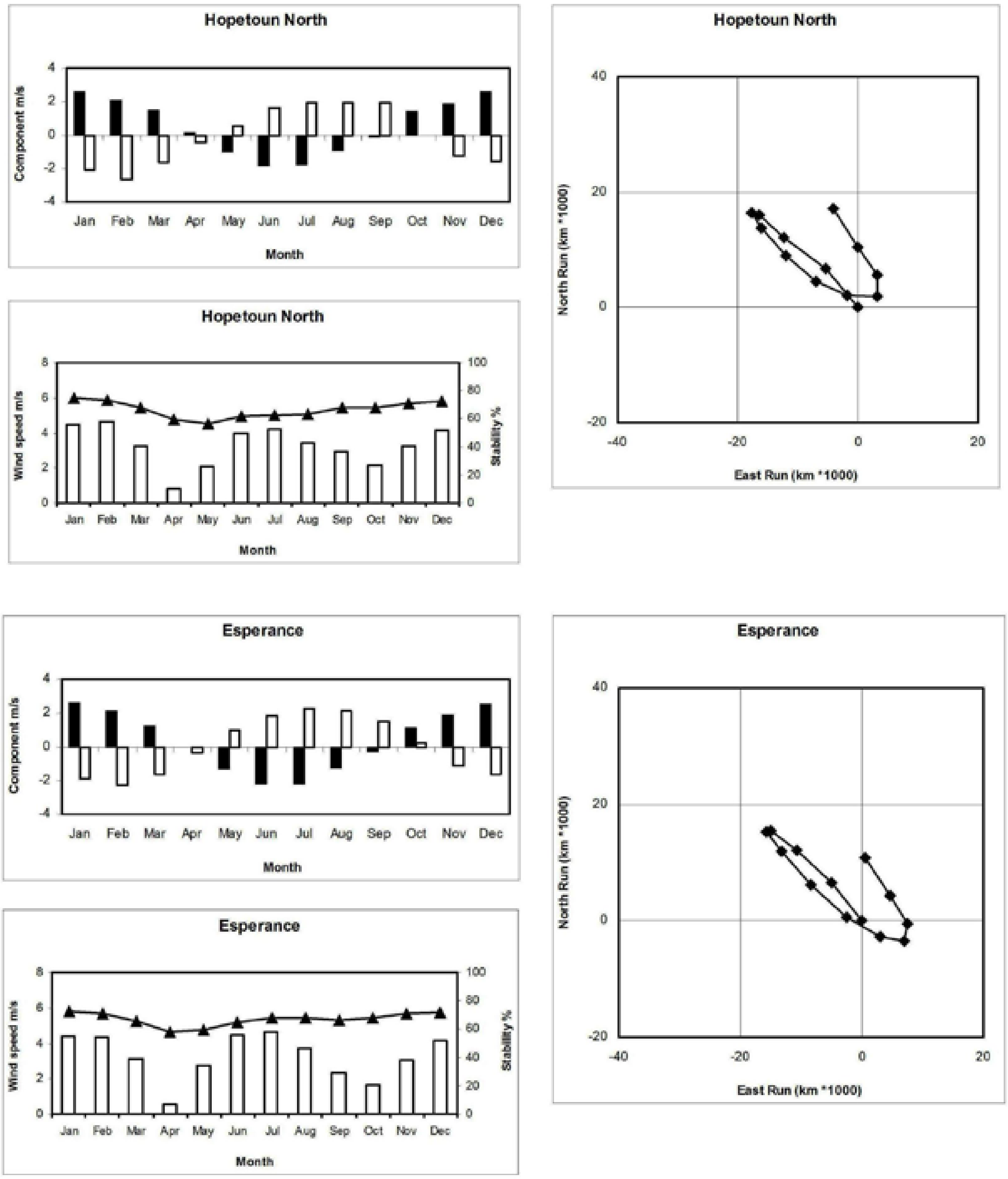

Figure 5: (c) Hopetoun North and (d) Esperance.

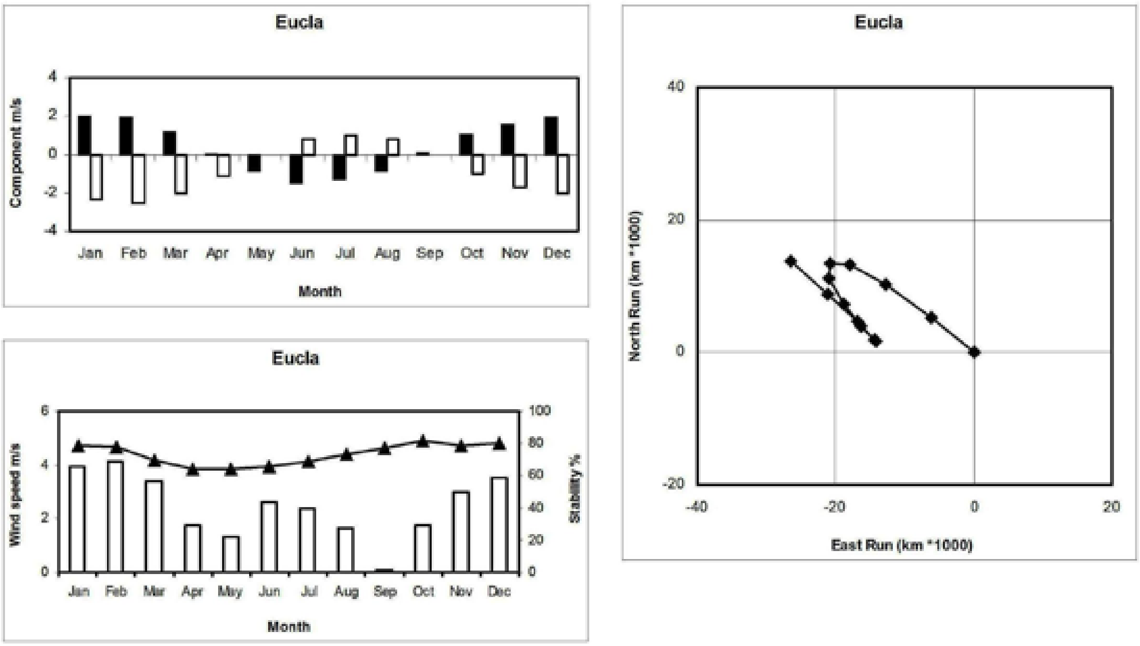

Figure 5: (e) Eucla.

3.4 Inter-annual variability

Inter-annual fluctuations in both the northward and eastward wind components are evident in the monthly anomalies over the 30-year period (**Figure 6**), indicating a generally high level of variability from year to year which may well have an influence on local oceanographic conditions (more specifically, the nearshore currents and the wind-driven wave field) and therefore on annual levels of recruitment to particular fisheries. The magnitudes of the anomalies varied spatially and temporally, the adjacent inter-site variations being partly a result of the varying coastline topography at the different sites.

Both the northward and eastward anomalies were typically between 1 and 2 m/s along most sections of the coastline: these were of similar magnitude to the actual wind components at many sites and so could have a major influence on the wind-driven currents at those locations. The larger anomalies occurred irregularly over time, many carrying across to adjacent sites and further along the coast while others were regionally limited. For example, the westward anomalies along the north-west coast in summer 1997 (the “dip” in early 1997 in **Figure 6b**) extended along the entire coast from Wyndham to Port Hedland and were in phase, whereas the large southward anomaly at Jurien in early 2002 (**Figure 6c**) was not evident at either of the adjacent stations Geraldton to the north (**Figure 6c**) or Lancelin to the south (**Figure 6e**). There was an eastward anomaly along the lower west coast in summer 2006 (a positive value in **Figure 6f**) which was only weakly recorded at Lancelin but progressively increased southwards to peak at Cape Leeuwin as well as at some of the south coast locations (**Figure 6h**). At most of the west coast stations, there were consistent northward and (strong) westward anomalies in 2010 (**Figures 6c** to **f**). These were followed by an extremely strong southward anomaly from Learmonth southwards in early 2011 (**Figure 6c**) which was associated with the strong cyclonic wind circulation and the “Ningaloo *Niña*” identified by Feng *et al*. (2013) as contributing to a unusually strong Leeuwin Current and the record heat wave conditions in February/March of that year (Pearce *et al*. 2011, Pearce & Feng 2013, Caputi *et al.* 2014). Some of the inter-annual

wind variability occurring during the winter and spring months is associated with larger scale oceanographic and atmospheric features including easterly anomalies off Western Australia related to the Indian Ocean Dipole and the southern annular mode (Weller *et al*. 2012).

Close examination of the anomalies reveals some apparent inconsistencies, mainly through changes in the anomaly patterns over time -- by their very nature, seasonal anomalies should oscillate irregularly around a constant mean value. These inconsistencies include:

1) periods when the anomalies over a number of years seemed to exhibit a strong regular seasonal cycle (for example, the eastward components at Wyndham followed a very regular cycle between 1988 and 1998 (**Figure 6b**), and both component anomalies at Bunbury from 1988 to 1995 (**Figure 6e,f**));

2) a sudden shift in the anomaly level and/or a sudden change in the amplitude of the anomalies (for example, the eastward component at Kalbarri in 1992 (**Figure 6d**), and the eastward component at Cape Naturaliste in 1997 (**Figure 6f**)). Resolving these inconsistencies, which could be due to a change in the location or height of the anemometer at a site or sheltering by a growing tree or new building, is beyond the scope of this preliminary report but should be followed up in any important use of the data.

The inter-site relationships can be analysed in 2 ways: (a) correlating each site with its immediate neighbour to the north (or, for the south coast, to the west), and (b) correlating each site with a geographical "central" site for each region, selected as Broome, North Island and Esperance. The inter-site correlations (**Table 2**) were very "patchy", partly due to the varying along-coast distances between the sites but also the greatly varying local topography at each site (**Figure 1**), nevertheless they were almost all statistically significant ($p < 0.01$), indicating a high level of coherency along the coast for monthly-scale wind events. For the north and south coasts as well as many of the west coast locations, the correlations were higher for the eastward components than for the northward components (**Table 2**). The lower correlations at Bunbury were probably due to the effect of large coastline changes around Geographe Bay on the local wind field.

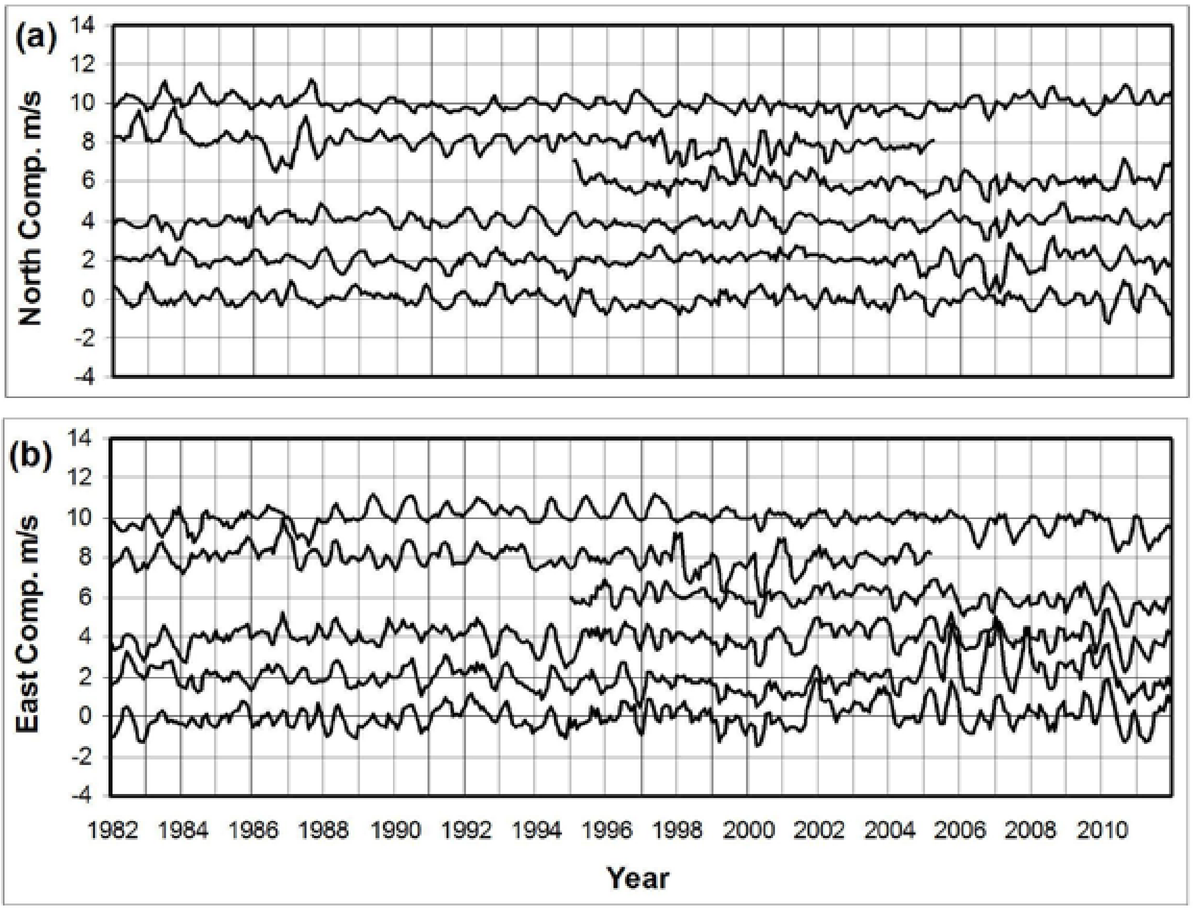

Figure 6a,b: Monthly (a) northward and (b) eastward wind component anomalies between 1982 and 2011 at the 6 weather station sites along the Northwest Shelf: from top to bottom WYN, KAM, DER, BRO, BID and HED (see Figure 1). The anomalies have been derived by subtracting the long-term (30-year) seasonal mean wind cycle from the individual years of record and have been smoothed by a 3-month moving average to reduce small-scale variability and thus improve clarity of the inter-site relationships. The graphs are progressively offset by 2 m/s to avoid overlap.

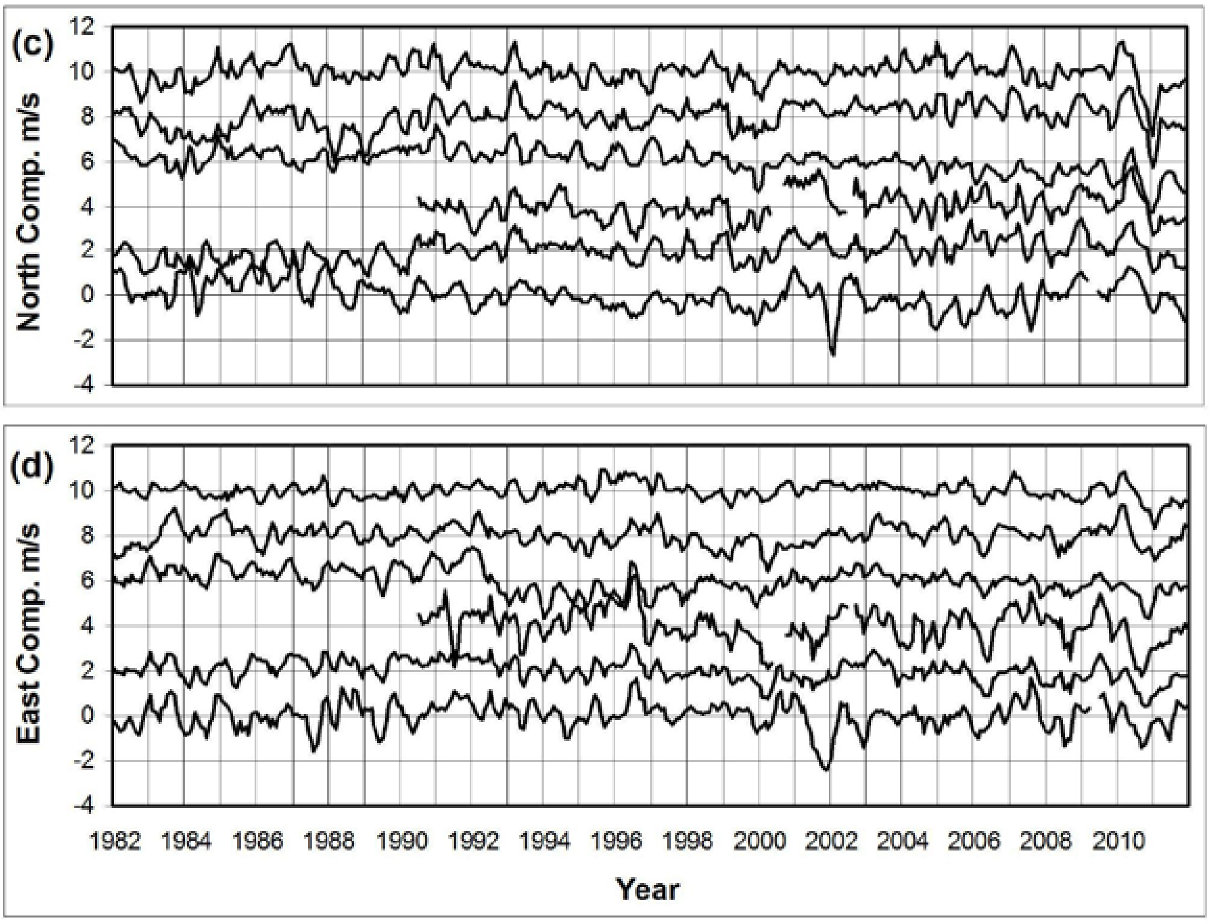

Figure 6c,d: Monthly (c) northward and (d) eastward wind component anomalies between 1982 and 2011 at the 6 weather station sites along the upper west coast: from top to bottom LEA, CAR, KAL, NOR, GER and JUR (see Figure 1). The anomalies have been derived by subtracting the long-term (30-year) seasonal mean wind cycle from the individual years of record and have been smoothed by a 3-month moving average to reduce small-scale variability and thus improve clarity of the inter-site relationships. The graphs are progressively offset by 2 m/s to avoid overlap.

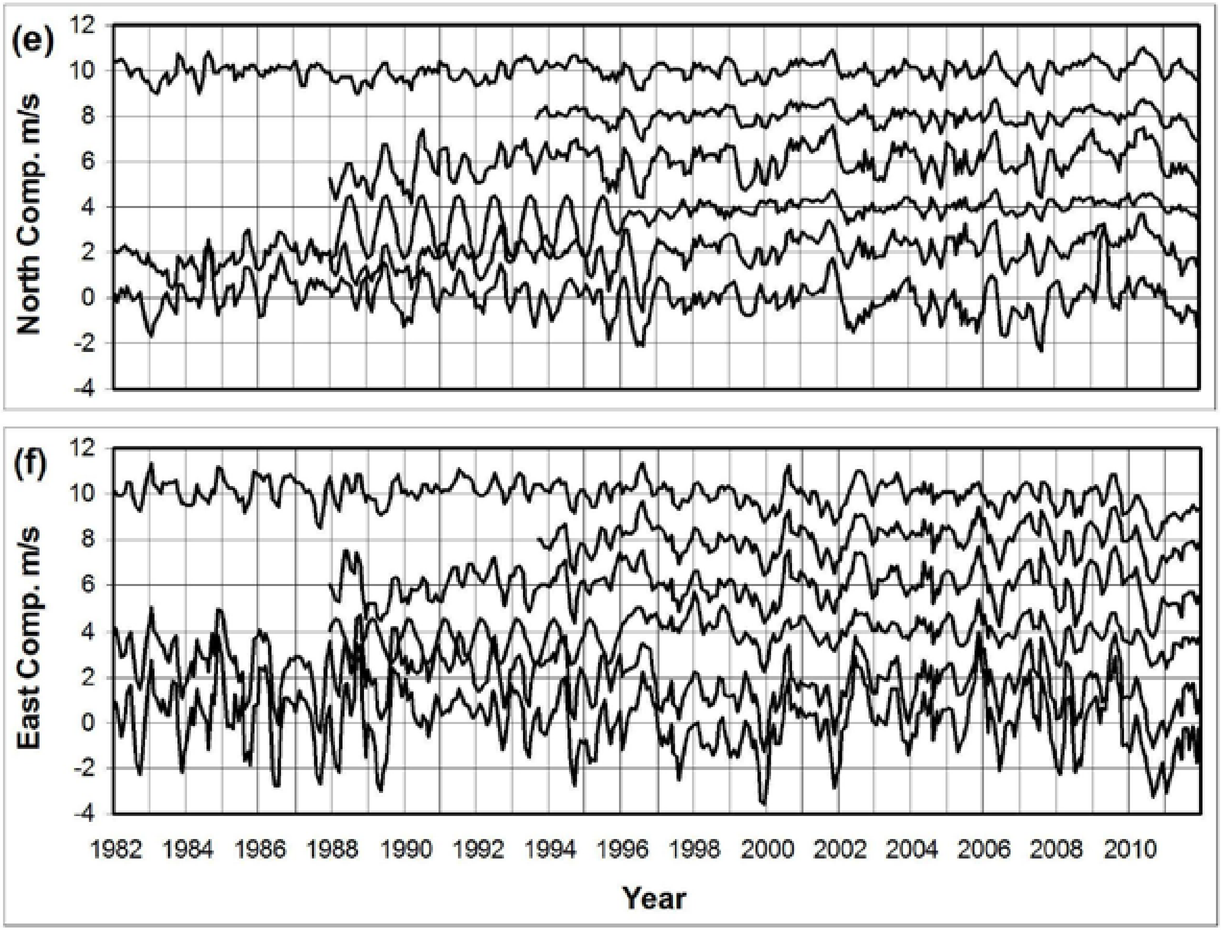

Figure 6e,f: Monthly (a) northward and (b) eastward wind component anomalies between 1982 and 2011 at the 6 weather station sites along the lower west coast: from top to bottom LAN, SWA, ROT, BUN, NAT and LEU (see Figure 1). The anomalies have been derived by subtracting the long-term (30-year) seasonal mean wind cycle from the individual years of record and have been smoothed by a 3-month moving average to reduce small-scale variability and thus improve clarity of the inter-site relationships. The graphs are progressively offset by 2 m/s to avoid overlap.

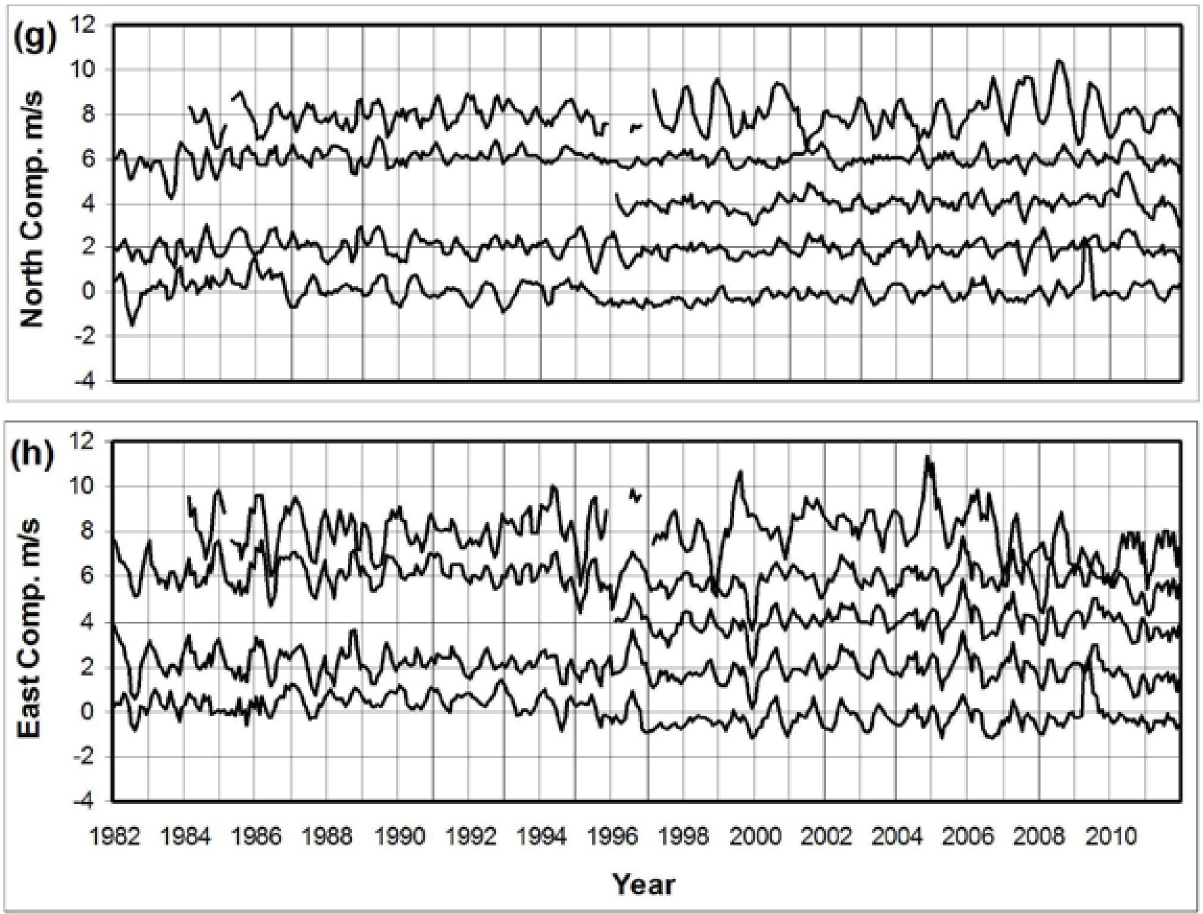

Figure 6g,h: Monthly (a) northward and (b) eastward wind component anomalies between 1982 and 2011 at the 5 weather station sites along the south coast: from top to bottom WIN, ALB, HOP, ESP and EUC (see Figure 1). The anomalies have been derived by subtracting the long-term (30-year) seasonal mean wind cycle from the individual years of record and have been smoothed by a 3-month moving average to reduce small-scale variability and thus improve clarity of the inter-site relationships. The graphs are progressively offset by 2 m/s to avoid overlap.

Table 2: Correlation coefficients for the northward and eastward monthly anomalies (1982 to 2011) between (a) adjacent sites, and (b) against a geographical central site for each region (bolded: Broome, North Island and Esperance respectively). The number of months of valid data and the site latitude (or for the south coast, the longitude) are indicated.

Site	Number Months	Lat./Long. °S/°E	a) Corr. with neighbour		b) Corr. with central site	
			North	East	North	East
NorthWest Shelf						
Wyndham	360	15.5			0.135	0.413
Kalumburu	279	14.3	0.393	0.339	0.030	0.480
Derby	204	17.4	0.254	0.435	0.684	0.849
Broome	360	17.9	0.684	0.849	**1.000**	**1.000**
Bidyadanga	360	18.7	0.515	0.654	0.515	0.654
Port Hedland	360	20.4	0.340	0.648	0.137	0.788
West coast						
Learmonth	360	22.2			0.250	0.334
Carnarvon	360	24.9	0.654	0.501	0.604	0.475
Kalbarri	252	27.7	0.428	0.456	0.453	0.475
North Island	360	28.3	0.453	0.475	**1.000**	**1.000**
Geraldton	360	28.8	0.833	0.773	0.833	0.773
Jurien	357	30.3	0.585	0.769	0.734	0.619
Swanbourne	220	31.0	0.893	0.890	0.777	0.632
Rottnest Island	289	32.0	0.933	0.947	0.790	0.641
Bunbury	193	33.4	0.450	0.583	0.409	0.342
Cape Naturaliste	360	33.5	0.439	0.481	0.688	0.514
Cape Leeuwin	360	34.4	0.645	0.916	0.511	0.424
South coast						
Windy Harbour	323	116.0			0.168	0.331
Albany	360	117.8	0.236	0.356	0.590	0.876
Hopetoun North	191	120.1	0.705	0.880	0.820	0.921
Esperance	360	121.9	0.820	0.921	**1.000**	**1.000**
Eucla	360	128.9	0.317	0.696	0.317	0.696

For the west coast, the island/mainland pairings were highly correlated (north component 0.833, east component 0.773 between North Island and Geraldton, and 0.933 northward and 0.947 eastward between Rottnest Island and Swanbourne), indicating a close relationship between variations in the inshore and offshore winds even though the magnitude of the offshore winds was greater than that near the coast (**Appendix**).

To assess whether there has been a gradually-varying shift in wind regimes over time, the slopes of the trend lines were derived seasonally for each location (**Table 3**). The results were inconclusive because of the very patchy nature of the slopes (both regionally and seasonally, partly a result of the data inconsistencies described above, and possibly also due to site-specific topographic features) so the significance levels have not been included here. The only general patterns appear to have been a negative slope in the eastward anomalies along most of the west coast in all seasons (implying weakening westerly winds throughout the year) -- this was also true for the north coast in autumn and winter and the south coast in spring and summer.

Table 3: Slopes (proportional changes per year) of the trend lines for each season and site for the northward and eastward wind components. Positive slopes indicate an increase in the wind speed over time.

Site	Summer		Autumn		Winter		Spring	
	North	East	North	East	North	East	North	East
NorthWest Shelf								
Wyndham	0.004	0.004	-0.011	-0.022	-0.011	-0.024	-0.006	-0.007
Kalumburu	-0.032	0.014	-0.005	-0.054	-0.045	-0.017	-0.033	-0.019
Derby Airport	-0.024	-0.011	0.001	0.010	0.026	-0.056	0.005	-0.047
Broome	-0.019	0.023	0.008	-0.015	0.004	-0.009	0.006	0.003
Bidyadanga	-0.025	0.028	0.014	-0.023	0.022	-0.018	-0.020	0.034
Port Hedland	-0.018	0.037	0.014	-0.015	0.009	0.008	-0.022	0.031
West coast								
Learmonth	0.002	-0.004	0.007	0.001	0.006	0.000	-0.029	-0.011
Carnarvon	0.029	0.011	0.029	-0.016	0.027	-0.011	0.007	-0.003
Kalbarri	-0.054	-0.025	-0.018	-0.015	-0.021	-0.012	-0.051	-0.047
North Island	0.005	-0.039	0.021	-0.022	0.022	-0.022	0.019	-0.038
Geraldton	0.040	-0.028	0.011	-0.017	0.003	-0.009	0.032	-0.038
Jurien	-0.048	-0.001	0.002	-0.003	-0.016	0.011	-0.042	-0.032
Lancelin	0.011	-0.018	0.022	-0.021	-0.004	0.000	0.004	-0.050
Swanbourne	-0.024	-0.007	0.016	-0.020	-0.005	-0.005	-0.014	0.004
Rottnest Is.	0.044	0.011	0.017	-0.027	0.001	-0.004	0.019	-0.007
Bunbury	0.009	-0.079	0.037	-0.049	0.016	-0.050	0.027	-0.040
Cape Nat	0.035	-0.075	0.041	-0.052	0.008	-0.011	0.033	-0.094
Cape Leeuwin	0.015	-0.051	-0.019	-0.030	-0.067	0.027	-0.002	-0.062
South coast								
Windy Harbour	-0.012	-0.073	0.023	0.002	0.026	0.027	0.012	-0.068
Albany	-0.013	-0.048	0.011	0.006	0.006	0.010	0.002	-0.039
Hopetoun Nth	-0.003	-0.010	0.064	0.016	0.020	-0.029	-0.013	0.014
Esperance	0.010	-0.048	-0.011	-0.008	-0.011	0.005	0.002	-0.028
Eucla	0.000	-0.059	-0.017	-0.021	-0.014	-0.018	-0.009	-0.040

3.5 Comparison with NCEP winds for Rottnest Island

Most oceanic modelling studies use global wind products such as those derived by the NOAA National Centers for Environmental Prediction (NCEP), typically on spatial (grid) scales of a degree or more and therefore representative of comparatively large oceanic areas. This section compares the NCEP monthly-averaged winds for the block containing Rottnest Island with those derived in the present report from the weather stations on Rottnest Island and the coastal location of Swanbourne to illustrate the difference between the *in situ* measurements and the larger scale NCEP product.

The current version of the NCEP winds is the DOE Reanalysis 2 dataset (Website http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html). Monthly mean winds are available from January 1979 to August 2013. The grid size varies latitudinally; the Rottnest block is from 30°29’ to 32°23’S and 113°26’ to 115°19’E (approximately 210 by 175 km rectangle).

The annual PVDs show very similar characteristics (**Figure 7**), with a dominantly northward wind for most of the year interrupted briefly by the highly variable westerly winds mid-year (the "cusp" in the PVDs in April/May/June). As would be expected, the NCEP open-ocean winds were much stronger than those at Rottnest Island, which in turn were about twice the strength of the coastal winds at Swanbourne. Clearly, these cross-shelf differences in the alongshore wind field should be allowed for when applying coastal or island wind measurements to estimates of wind-forced current movements as the wind stress on the water (which varies as the square of wind speed) will increase greatly between the nearshore region and the outer shelf. Likewise, the larger-scale NCEP wind regime would be more relevant for wider-ranging circulation systems and larval migrations (such as the western rock lobster).

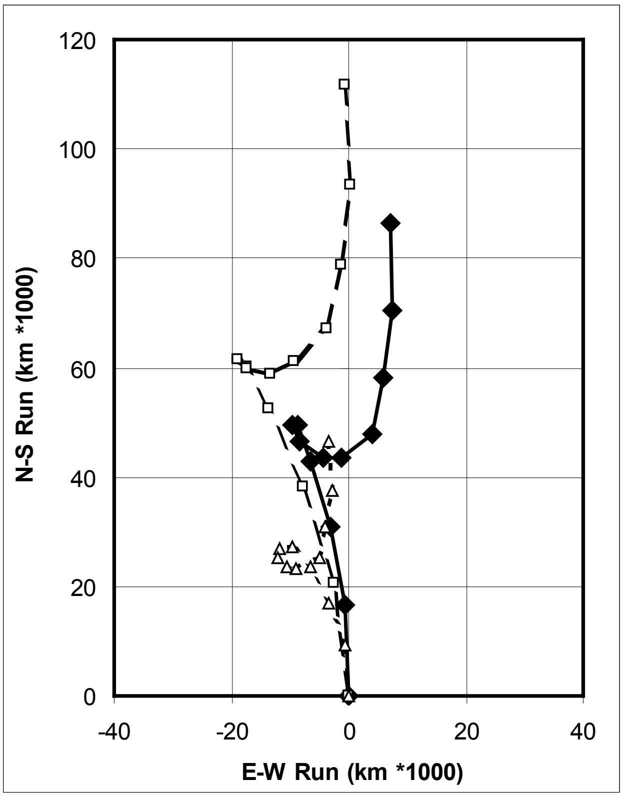

Figure 7: Progressive vector diagram (PVD) comparing the overall monthly wind cycle for the Rottnest Island weather station (solid line and symbols) with that for Swanbourne (open triangles) and the NCEP winds for the block containing Rottnest Island (open squares and dashed line; see text). The PVD is explained in the caption to Figure 2.

4.0 Applications in fisheries analysis

4.1 Background

In sustainably managed fisheries where sufficient reproductive capacity exists to replenish the population, environmental factors are the main source of annual variability in population numbers. In particular, ocean currents, which are often driven by wind (especially in shallower coastal waters), are hypothesised to have a major influence on the timing and magnitude of annual recruitment in fish stocks because they directly affect the distribution and abundance of fish larvae during their pelagic stage. In addition, wind-induced upwelling may also increase vertical mixing and plankton production in the water column (Legget & Frank 2008). Werner *et al.* (1997) identified wind as the most intensively studied abiotic factor contributing to recruitment variability in fish populations. It is often studied in combination with sea surface temperature (SST), another highly influential factor in the early life history phase of fish.

Coastal winds have been shown to affect a number of finfish and invertebrate species in Western Australia (summarised in Caputi *et al*. 2010). For example, the southerly winds in summer at the time when the early stage larvae of western rock lobster rise to the surface, can carry the lobster larvae offshore at the start of their 9-11 month larval life. The summer southerly winds influence the nearshore Capes Current which may affect the recruitment of dhufish and tailor. In this section, a case study is presented of the direct role of wind in recruitment to the pearl oyster fishery.

4.2 Biological hypothesis related to wind

The main biological hypothesis tested is that wind strength during the critical period of spawning and larval drift has a significant influence on numbers of fish juveniles settling and/or recruiting into the population. The influence may be positive or negative, depending on the direction of wind relative to the location of the main fish populations, nursery and spawning sites. A number of nearshore fish species in the West Coast Bioregion, such as tailor (*Pomatomus saltatrix*), spawn to the north of their range in winter and in the south of their range in summer, when water temperatures in these areas are suitable (Lenanton *et al.* 1996). The predominant wind regimes at these times assist the transportation of the pelagic eggs and larvae through the extent of their range. However, the wind anomalies during these critical spawning periods, particularly in winter, may drive annual variation in recruitment.

4.3 Data preparation and analysis techniques

The essential ingredient is a substantial time series of matching wind strength and fish abundance and fishing efficiency data sets. These are generally annual data points summarised from the hourly and daily wind data, but may also be monthly or weekly summaries as many life cycle characteristics have a seasonal aspect. The fish abundance data should come from a standardised survey of the size-class of interest, while changes in fishing efficiency are usually calculated as a component of a standardised catch-per-unit effort. Correlation and regression analyses, including multiple regression, can be used to examine the influence of wind and other environmental variables.

4.4 Example – pearl oyster settlement analysis

Hart *et al.* (2011) examined the effect of the environment on pearl oyster stock abundance in the Broome fishery (zones 2 and 3), including the effects of SST and wind. The dataset of interest is the Age 0+ "spat", which are recently-hatched oysters usually between 3 and 6 months of age, that settle onto adult shells which are later caught in the fishery. Hart & Joll (2006) describe the nature of this dataset, and an annual settlement index is derived by Hart *et al*. (2011). The wind data were from Bidyadanga over the period 1980 to 2012, and the SST for the Reynolds temperature block covering the pearl oyster fishing grounds (latitude 19–20°S; longitude 121–122°E) (Reynolds & Smith 1994).

The strength of the northward wind component during summer (December to February) was significantly negatively correlated with 0+ spat settlement, and positively correlated with sea surface temperature (**Table 4**). A multiple regression model for December–February environmental conditions of rainfall, SST, and the northward wind component provided a satisfactory description of settlement trends in *P. maxima*, with a model fit (r^2) of 0.68 (**Table 5**). The model revealed SST to be the most important and highly significant variable, alone explaining 56% ($r^2 = 0.56$) of settlement variability (**Table 4**). The northward wind component and rainfall were negatively related to settlement, and their addition to the model improved the fit by 7% for wind ($r^2 = 0.63$) and a further 5% ($r^2 = 0.68$) for rainfall (**Table 5**).

Examining the data trends, it would appear that the exceptional spat settlement in 2005 was also a year of relatively unusual environmental conditions during the spawning months of December to February (**Figure 8**). It simultaneously had the highest SST (**Figure 8a**), the second strongest northerly winds (**Figure 8d**), and the third lowest rainfall (**Figure 8b**) for the past 30 years. In the case of the winds, there is a biologically plausible hypothesis as to how strong southward winds could enhance settlement by pushing larvae onto the shallow water habitat where the most productive pearling grounds are (Hart *et al.* 2011), whereas northward winds in the opposite direction would push larvae away from the main habitat areas.

Table 4: Correlation matrix for annual 0+ spat settlement and environmental variables in December-February in the *P. maxima* fishery (adapted from Hart *et al.* 2011). Rainfall is the total rainfall at Bidyadanga, SST the average sea surface temperature, Northward and Eastward the mean wind components.
* Significant correlation ($p < 0.05$).

Variable	SST	Rainfall	Northward	Eastward
Rainfall	0.11			
Northward	-0.58*	-0.10		
Eastward	0.38	-0.34	-0.45*	
0+ spat	0.75*	-0.37	-0.66*	0.38

Table 5: Multiple regression results for the effect of environment on settlement (0+ spat abundance) of *P. maxima*, with variables arranged in descending order of importance (adapted from Hart *et al*. 2011). β = partial regression coefficient, Beta = standardized partial regression coefficient. The significance of the final model and the proportion of variance explained is F(3,12) = 8.36; p = 0.003; r^2 = 0.68. SST is the average SST between December and February, Northward is the mean northward wind component for the months December–February, and Rainfall the total rainfall at Bidyadanga between December and February.

Variable Intercept	***β***	**Beta**	**Partial Correlation**	**P**	**Cumulative r^2**
(-14.02)					
SST	0.52	0.55	0.62	0.02	0.56
Northward	-0.12	-0.28	-0.36	0.21	0.63
Rainfall	-0.0007	-0.21	-0.34	0.23	0.68

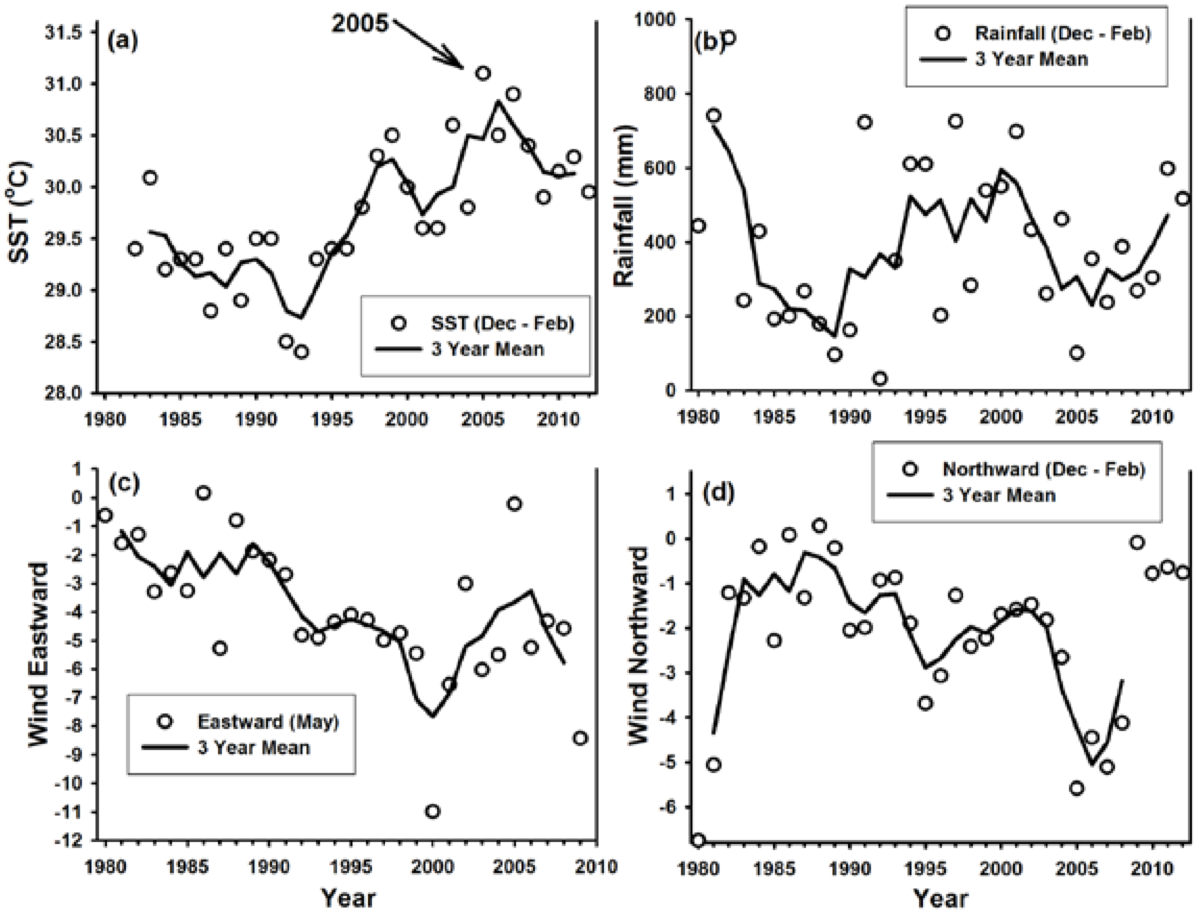

Figure 8: Environmental variables for the *P. maxima* fishery from 1980 to 2009. (a) SST, (b) Rainfall (mm), (c) eastward wind component during May at Bidyadanga, and (d) northward wind component at Bidyadanga, with 3-year running means shown for all variables. After Hart *et al.* (2011).

5.0 Summary and Conclusions

The seasonal wind patterns along the north-west coast, the west coast and the south coast are all distinct, being largely governed by the annual latitudinal migration of the subtropical high-pressure belt as well as by the general orientation of the coastline in each region. Superimposed on these regional wind patterns, however, are smaller-scale wind differences largely due to the effects of the local topography, especially in the north-west where the coastline is highly convoluted.

The derived wind charts provide a comprehensive climatology of the seasonal wind field along the coastline of Western Australia. Surface currents are largely driven by the winds, especially in the shallow nearshore waters of the inner- to mid-continental shelf, and play an important role in the alongshore and cross-shelf transport of pelagic eggs and larvae with consequences for the distribution and abundance of many commercial fish. The wind regime therefore has direct application in fisheries and marine population analysis, as has been demonstrated for the silver-lipped pearl oyster fishery on the North Coast.

For the west coast in particular, current measurements over the past 3 decades have shown a strong relationship with the coastal wind field, particularly during the summer months when the persistently southerly wind stress drives the Capes and Ningaloo Currents northward along the inner shelf. Where no current measurements are available, therefore, the wind field may be used as a first proxy for coastal currents in shallow nearshore waters on monthly to seasonal time scales, although other influences such as tides (on the north-west shelf), pressure gradients and the intrusion of Leeuwin Current meanders onto the continental shelf can also be important. Further out on the continental shelf, the southward movement of the Leeuwin Current becomes increasingly dominant and the wind effect is correspondingly reduced.

The ratio of the surface current speed to the wind speed (the “wind factor” -- Beer 1983) is traditionally about 3% (*e.g*. Fandry *et al.* 2006) and somewhat to the left of the wind direction in the Southern Hemisphere, with the wind effect decreasing with depth. Beer (1983) quotes wind factors of 3 to 4% while current measurements near the Abrolhos Islands by Cresswell *et al*. (1989) suggested between 2.2% and 4.3% of the wind speed with an average of 3.4%. Typically, therefore, any eggs or larvae at the water surface could be transported at about 30 cm/s in a 10 m/s (20 knot) wind, superimposed on the surface current produced by other dynamic forcings.

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Appendix

Overall site summaries of the monthly-averaged northward (upper line at each site, NC) and eastward (centre line, EC) wind components as well as the scalar mean wind speed (lower line, SPD). The data period is 1982 to 2011 at most locations; some sites had shorter records

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a) North-west coast												
Wyndham (001003)												
NC	-0.3	-0.3	-0.1	0.1	0.5	0.8	0.6	0.1	-0.8	-1.2	-1.0	-0.5
EC	0.1	0.1	-0.4	-1.2	-1.6	-1.8	-1.6	-1.2	-0.4	-0.2	0.0	0.0
SPD	1.6	1.4	1.4	1.8	2.2	2.3	2.3	2.4	2.4	2.4	2.0	1.6
Kalumburu Mission (001021)												
NC	-0.5	-0.6	-0.6	0.0	0.5	0.7	0.4	-0.5	-1.5	-1.5	-1.2	-0.6
EC	0.8	0.9	0.1	-1.1	-1.6	-1.7	-1.4	-0.8	0.1	0.6	0.7	0.8
SPD	2.3	2.3	2.3	2.5	3.0	3.1	3.1	3.4	3.4	3.1	2.8	2.7
Derby Airport (003032)												
NC	-1.4	-1.4	-0.6	0.2	0.9	1.2	1.1	0.5	-0.3	-1.6	-1.7	-1.7
EC	1.8	1.4	0.2	-0.5	-1.4	-1.6	-1.1	-0.3	0.9	1.8	2.1	1.8
SPD	4.6	4.2	3.7	3.3	3.5	3.7	3.6	3.7	4.0	4.5	4.8	4.9
Broome Airport (003032)												
NC	-0.4	-0.4	0.0	0.4	0.7	0.9	1.1	0.9	0.8	0.1	0.0	-0.4
EC	2.5	1.9	0.9	-0.3	-1.2	-1.7	-1.2	-0.3	1.2	2.4	3.0	3.0
SPD	4.0	3.6	3.0	2.5	2.6	2.9	2.9	2.9	3.3	3.7	4.1	4.3
Bidyadanga (003030)												
NC	-0.5	-0.5	-0.1	0.3	0.7	0.9	1.0	0.9	0.7	0.0	-0.2	-0.6
EC	1.9	1.4	0.7	-0.2	-1.2	-1.7	-1.4	-0.6	0.7	1.6	2.2	2.1
SPD	3.4	3.1	3.1	3.1	3.3	3.6	3.7	3.8	3.7	3.6	3.6	3.7
Port Hedland Airport (004032)												
NC	-1.9	-1.4	-0.6	0.0	0.5	0.8	0.9	0.4	-0.4	-1.0	-1.6	-2.0
EC	1.9	1.0	0.1	-0.7	-1.7	-2.3	-1.8	-0.8	0.9	1.7	2.5	2.4
SPD	4.8	4.5	3.9	3.5	3.7	4.0	4.1	4.0	4.1	4.5	4.9	5.0
b) West coast												
Learmonth Airport (005007)												
NC	3.2	2.2	2.2	1.6	1.0	0.6	1.0	1.8	2.8	3.8	3.8	3.8
EC	2.2	1.4	1.0	0.3	-0.3	-0.4	-0.3	0.2	1.0	1.8	2.2	2.5
SPD	6.0	5.4	4.9	4.0	3.4	3.2	3.4	3.9	4.8	5.7	6.0	6.2
Carnarvon Airport (006011)												
NC	6.1	5.0	4.8	3.7	2.1	1.2	1.6	2.8	4.3	5.7	5.8	6.3
EC	1.7	1.1	0.3	-0.2	-0.8	-1.0	-0.9	-0.4	0.5	1.1	1.5	1.7
SPD	7.3	6.6	6.2	5.1	4.1	3.9	4.0	4.7	5.8	6.9	7.2	7.6
Kalbarri (008251)												
NC	3.4	2.9	2.3	1.4	0.4	-0.1	0.0	0.7	1.4	2.5	2.7	3.2
EC	0.0	-0.3	-0.5	-0.7	-0.5	-0.4	-0.3	-0.2	0.2	0.3	0.4	0.2
SPD	4.9	4.6	4.2	3.5	2.7	2.7	2.7	2.9	3.4	4.1	4.4	4.8

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Island (008290)												
NC	7.8	7.4	6.2	4.4	2.0	0.7	0.8	2.2	3.9	5.8	6.3	7.4
EC	-0.9	-1.6	-2.0	-2.1	-1.4	-1.0	-0.6	-0.4	0.2	-0.5	-0.3	-0.9
SPD	8.6	8.3	7.7	6.8	6.5	6.8	6.7	6.7	7.0	7.8	7.8	8.5
Geraldton Airport (008051)												
NC	4.9	4.2	3.2	1.7	-0.1	-1.1	-0.9	-0.1	1.0	2.8	3.5	4.6
EC	-0.3	-1.0	-1.2	-1.1	-0.8	-0.8	-0.5	-0.4	0.1	0.0	0.2	-0.2
SPD	6.3	6.1	5.5	4.7	4.1	4.4	4.3	4.1	4.2	5.0	5.6	6.2
Jurien Bay (009131)												
NC	4.1	3.4	2.7	1.5	0.4	-0.7	-0.5	0.2	1.0	2.3	3.0	3.9
EC	-0.1	-0.6	-0.7	-0.4	0.0	0.3	0.8	0.7	1.2	0.6	0.6	0.1
SPD	5.8	5.3	4.9	4.1	3.9	4.3	4.4	4.4	4.5	4.8	5.2	5.5
Lancelin (009114)												
NC	3.8	3.2	2.6	1.3	0.1	-0.7	-0.6	0.0	0.7	2.1	2.6	3.6
EC	0.4	-0.4	-0.6	-0.6	-0.4	0.1	0.6	0.7	1.4	0.9	0.9	0.6
SPD	5.4	5.2	4.9	4.3	4.2	4.5	4.7	4.6	4.8	5.0	5.2	5.4
Swanbourne (009215)												
NC	3.6	3.0	2.5	1.4	0.0	-0.6	-0.7	-0.2	0.8	2.2	2.6	3.4
EC	-0.3	-1.1	-1.2	-1.1	-0.8	-0.1	0.6	0.6	1.5	0.4	0.4	-0.2
SPD	5.9	5.6	5.3	4.7	4.8	5.2	5.4	5.2	5.4	5.4	5.6	5.9
Rottnest Island (009193)												
NC	6.5	5.5	4.5	2.6	0.0	-1.2	-1.2	0.1	1.6	4.0	4.7	6.2
EC	-0.3	-1.0	-1.2	-0.9	-0.4	0.6	1.5	1.2	2.1	0.7	0.5	-0.1
SPD	8.4	7.9	7.3	6.6	6.4	7.3	7.4	7.0	7.1	7.5	7.8	8.3
Bunbury (009965)												
NC	2.5	2.0	1.7	0.7	-0.1	-0.5	-0.7	-0.3	0.2	1.2	1.4	2.2
EC	-0.2	-0.7	-0.6	-0.1	0.2	0.7	1.0	1.3	2.0	0.8	0.6	0.1
SPD	5.2	5.0	4.5	3.7	3.4	3.7	3.8	3.8	4.3	4.3	4.8	4.8
Cape Naturaliste (009519)												
NC	5.0	4.1	3.4	1.7	0.3	-0.4	-0.3	0.6	1.5	2.9	3.5	4.5
EC	-0.3	-1.2	-1.5	-0.5	0.6	2.0	2.8	2.8	3.0	1.5	0.5	0.2
SPD	7.8	7.6	7.0	6.5	7.0	8.1	8.3	7.8	7.5	7.2	7.5	7.6
Cape Leeuwin (009518)												
NC	4.5	3.9	3.1	0.9	-0.6	-1.3	-1.1	-0.5	0.1	1.7	2.8	3.8
EC	-2.9	-3.6	-2.9	-0.3	1.7	3.2	4.1	4.4	4.2	1.9	-0.6	-1.8
SPD	8.4	8.6	8.3	7.5	8.0	9.1	9.2	9.1	8.9	8.3	8.3	8.2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
c) South coast												
Windy Harbour (009871)												
NC	2.7	2.3	2.0	0.8	-0.1	-0.2	0.0	0.1	0.6	1.5	2.1	2.3
EC	-2.2	-2.4	-1.6	0.1	1.2	1.9	2.9	2.9	2.9	0.7	-0.5	-1.6
SPD	5.7	5.5	5.3	4.5	4.4	4.9	5.4	5.6	5.7	5.4	5.7	5.6
Albany Airport (009741)												
NC	1.7	1.3	0.9	-0.2	-1.1	-1.9	-1.9	-1.4	-0.7	0.2	0.9	1.4
EC	-1.6	-2.2	-1.7	-0.3	0.8	1.4	1.8	2.0	1.7	0.6	-0.6	-1.1
SPD	5.0	5.1	4.7	3.9	3.7	4.1	4.3	4.4	4.2	4.3	4.6	4.8
Hopetoun North (009961)												
NC	2.6	2.1	1.5	0.2	-1.0	-1.8	-1.8	-0.9	-0.1	1.4	1.9	2.6
EC	-2.1	-2.6	-1.6	-0.4	0.6	1.6	1.9	1.9	1.9	0.0	-1.2	-1.5
SPD	5.9	5.8	5.4	4.7	4.5	4.9	5.0	5.0	5.4	5.3	5.6	5.8
Esperance (009789)												
NC	2.5	2.0	1.2	-0.1	-1.2	-2.1	-2.1	-1.2	-0.3	1.1	1.8	2.4
EC	-1.9	-2.2	-1.6	-0.3	0.9	1.8	2.2	2.1	1.5	0.2	-1.1	-1.6
SPD	5.6	5.5	5.0	4.4	4.5	4.9	5.2	5.2	5.1	5.2	5.5	5.6
Eucla (011003)												
NC	2.0	1.9	1.2	0.1	-0.8	-1.5	-1.3	-0.9	0.1	1.1	1.6	2.0
EC	-2.3	-2.5	-2.0	-1.1	0.0	0.8	1.0	0.8	0.0	-1.0	-1.7	-2.0
SPD	4.7	4.6	4.1	3.8	3.8	3.9	4.1	4.3	4.6	4.8	4.7	4.7