

A synoptic classification for wind power potential in the southwest of Western Australia

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A synoptic classification based on the criteria of gradient wind direction, curvature of isobars and pressure trends for the southwest of Western Australia is related to wind power potential. During summer, mesoscale sea-breeze circulations provide a significant contribution to wind power potential during periods of weak synoptic gradients. In winter, synoptic forcing is the dominant mechanism. Observations at Perth and Esperance infer that mesoscale forcing is an important source of wind power potential.

Introduction

Improvements in wind energy utilisation are critically dependent on a reliable knowledge of the available resource both in terms of its mean value as well as seasonal and/or diurnal variations. Within the Australian region, standard Bureau of Meteorology observations (Hutchinson et al. 1984) highlight the potential for wind energy conversion systems particularly in south coastal regions. These data tend to be based on stations located at low wind locations such as airports and consequently tend to underestimate the available wind energy (i.e. Bowden 1984; Cherry 1985; Lloyd and Yee 1985). Hence most wind energy resource studies within Australia (i.e. SECWA 1985; Crawford 1985; Barker et al. 1984; Barker et al. 1983; Bowden 1984; Carlin et al. 1987) have concentrated on site specific measurement programs to extend this data base. These clearly identify the available resource at a specific location but because of the topographical constraint cannot be extended beyond that site to infer wind power potential elsewhere. They do not represent a basis for assessing the regional wind resource and in fact may not represent an optimal location unless properly sited.

In recent years, diagnostic models (i.e. Dickerson 1978; Sherman 1978; Endlich et al. 1982; Erasmus 1986a,b; Adell et al. 1987) have been used to extend surface observations of mean flow over complex terrain. They use conservation of mass or other simplifications of the equations of motion, such as constant atmospheric density, in extrapolating surface observations to obtain an initial wind profile. Objective analysis can then be

used to estimate the wind field (Mahrer et al. 1985). Such models are capable of extending surface observations to provide a mesoscale (0-100 km) assessment but cannot predict wind fields in regions where observations are not available and are limited by the representativeness of the initial observed wind fields.

Alternatively, a numerical mesoscale model (NMM) provides the theoretical framework to extend observations taken at one site to a more general mesoscale assessment of wind power potential. Such a model uses numerical iterative techniques to solve the physical equations which describe wind flow in the lowest hundreds of metres of the atmosphere and can incorporate variations in topography. In particular, such a model (Pielke 1984, 1985; Mahrer et al. 1985) has been successfully used in assessing wind power potential in complex three-dimensional terrain (Snow 1981) in the United States as well as simpler two-dimensional terrain in South Africa (Diab and Garstang 1984). In all cases the models illustrate the potential to identify high and low centres of wind power density once they have been validated with representative profiles.

The bulk of wind data available in Australia is based on observations at selected times or daily wind run totals, neither of which indicate diurnal variations. This represents a significant lack in the standard data because diurnal variations are important for matching power output to electricity demand (Carlin and Diesendorf 1983). A NMM is able to provide a measure of the diurnal

variation in wind speed at all computational levels and once validated has the potential to overcome deficiencies in the standard meteorological data.

Such an assessment requires the NMM to be run under representative climatological situations wherein the model is initialised with representative but dynamically consistent synoptic-scale meteorological fields and then used to predict mesoscale features in the flow. The approach of Segal et al. (1982), using climatological averages, was shown to be valid for highly persistent surface climatology but has not been evaluated for less persistent seasons. Under these conditions, climatological fields are not necessarily dynamically consistent and the alternative approach of Diab and Garstang (1984), based on representative examples from a synoptic classification, should be considered.

Consequently, a synoptic classification has been undertaken for the southwestern region of Australia with particular emphasis on Perth and Esperance to identify the most persistent synoptic conditions and their relationship to wind power potential. Such a classification may be exploited to enable the extension of site specific measurement programs to a regional assessment of wind power potential.

Synoptic classification

Daily surface pressure maps can be classified subjectively or objectively. The former approach involves identifying common synoptic situations using features such as orientation and curvature of isobars and the location of major circulation centres. This can include consideration of winds and air masses affecting a particular station (Lindsey 1980; Pielke et al. 1987). Objective analysis, on the other hand, is composed of fitting polynomial surfaces to pressure patterns or correlating meteorological variables at several stations with synoptic charts to determine common situations. Synoptic categories can also be decided using discriminant analysis where factors such as wind speed, surface pressure and temperature are combined to produce statistically distinct classes (Diab 1983).

For the present study, a subjective synoptic classification scheme was devised using daily mean sea level (MSL) pressure charts, and applied to Perth and Esperance. The climate of the region is dominated by the subtropical ridge (Gentili 1971). During summer, heat troughs form along the Western Australian coast and move inland in accordance with a regular progression of anticyclones (Watson 1980). Winter rainfall comes with northward movement of the ridge and incursions of mid-latitude cyclones and cold fronts. Accordingly, synoptic categories were broadly divided between ridge and cold front

events. These classes are listed in Table 1 with their characteristics. Curvature of isobars and expected wind directions were the main criteria applied, as well as the location of major circulation centres with respect to Perth or Esperance.

Daily MSL pressure charts valid for 0800 WST (local standard time equivalent to 2400 UTC), published in the 'Monthly Weather Summaries' of the Australian Bureau of Meteorology, were examined for 1976 to 1986. Synoptic situations at Perth and Esperance were then classified according to the criteria of Table 1. Over 98 percent of days could be successfully classified, giving a data base of some 3950 observations for each station.

Most of the synoptic classes are variants or subsets of more general wind regimes and so have been combined into synoptic groups, as shown in Table 2. Since we are seeking to group classes in

Fig. 1 Distribution of synoptic groups with respect to (a) observed surface wind speed and (b) direction.

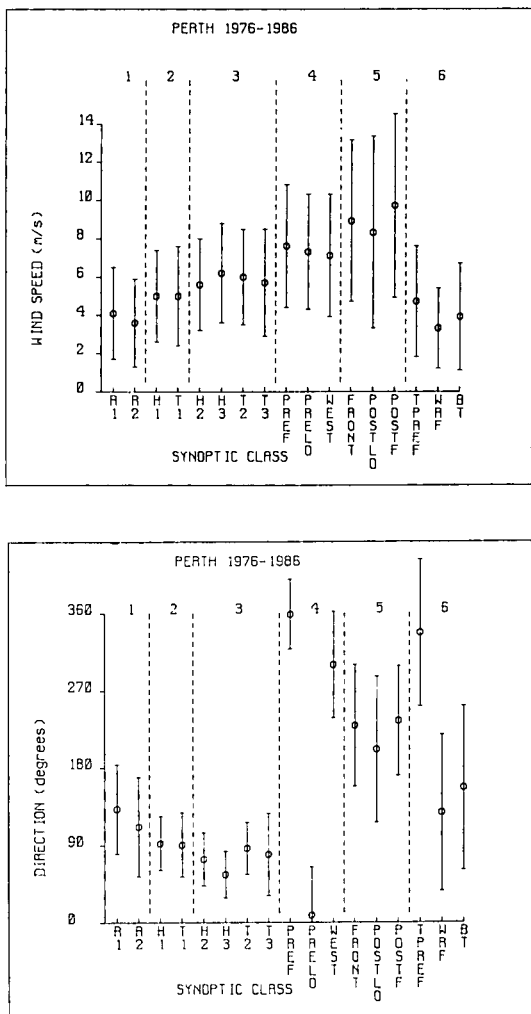


Table 1. Description of synoptic classes.

<i>Class</i>	<i>Description</i>	<i>Gradient winds</i>	<i>Pressure trend</i>	<i>Curvature of isobars</i>
R1	First stage in progression of ridge or anticyclone across WA Ridge or high to south of station.	S - SE	Rising	Straight or anticyclonic
R2	Advanced progression, cell develops in the Great Australian Bight or inland in winter.	E	Rising or steady	Straight or anticyclonic
H1	Anticyclone to the south.	E	Rising	Anticyclonic
H2	Anticyclone to the east or southeast.	NE	Steady or falling	Anticyclonic
H3	Anticyclone 10 degrees longitude or more to the east.	NE-N	Falling	Anticyclonic
T1	Weak heat trough along WA coast.	NE	Slight fall	Cyclonic or straight
T2	Stronger heat trough. Often follows T1.	NE	Falling	Cyclonic or straight
T3	Late stage of development - deep trough. Often follows T2.	NE - N	Falling	Cyclonic
BT	Broad trough over station. Often follows T3.	Var.	Falling	Weak gradient
TPREF	Trough preceding a cold front.	W - Var.	Falling	Cyclonic - weak gradient
PREF	Prefrontal. Prior to passage of a cold front.	NW - N	Large fall	Cyclonic or straight
FRONT	Passage of cold front over station.	W	Falling	Cyclonic
POSTF	Post cold front passage.	SW	Rising	Cyclonic or straight
PRELO	Prior to passage of low pressure circulation. May be mid-latitude or subtropical in origin.	N - NW	Falling	Cyclonic
POSTLO	Post passage of low pressure circulation, usually to the south.	SW	Rising	Cyclonic
WRF	Weak ridge, often eroded by cold front to the south.	Var.	Steady	Weak gradient
WEST	Broad mid-latitude trough well to the south.	SW - W	Falling	Cyclonic

terms of their wind power potential, those exhibiting similar wind direction and speed have been combined. This is shown in Fig. 1 for Perth where 10-year averages of surface winds at 0800 WST are correlated with the respective synoptic class. The Perth wind data were based on hourly ten-minute averages, centred on the hour, from

the Fremantle Port Authority (FPA) anemometer located near the coast at a height of 60 m. This data has an accuracy of 3° azimuth for direction and 1.0 m s⁻¹ for speed and the anemometer has a starting speed of approximately 1.0 m s⁻¹. Good correlation with synoptic situations is expected because of the elevation (away from building

Table 2. Grouping of synoptic classes.

Group	Predominant gradient Wind direction regime	Classes included
1	Southeasterly	R1 R2
2	Easterly	H1 T1
3	Northeasterly	T2 T3 H2 H3
4	Northwesterly to westerly	PREF PRELO WEST
5	Southwesterly	POSTF POSTLO FRONT
6	Variable	BT WRF TPREF

effects) and an observation time that is too early for development of local sea-breezes. Mean standard deviation of wind speed within each classification is $> 3 \text{ m s}^{-1}$, so there is some overlap between classes but the discrimination between synoptic groups is evident.

Synoptic group 1 is representative of a ridge of high pressure advancing over the southwest of Western Australia, giving rise to southeasterly gradient winds. Group 2 is an easterly regime characteristic of an anticyclone to the south or early stage of heat trough development along the Western Australian coast. Group 3 is associated with anticyclones to the east of the station or well-developed west coast troughs, generating northeasterly gradient winds. Groups 4 and 5 represent conditions prior to and following the passage of cold fronts or cyclonic centres. Group 6 exhibits small pressure gradients, producing light and variable winds, and occur under the presence of a weak ridge or broad trough of low pressure.

Results and discussion

Table 3 shows the frequency of occurrence of the synoptic groups during the years 1976 to 1986. Perth exhibits a typical Mediterranean climate with almost total dominance by anticyclones in summer, and the resultant mesoscale forcing of the surface wind field (Lyons 1975; Carlin and Diesendorf 1983). Cold fronts and cyclones occur nearly 40 per cent of the time in winter but ridge and anticyclonic categories still dominate. At Esperance, a very similar summer distribution prevails but winter brings a higher proportion of cold fronts and cyclonic activity. Maher and Lee (1977), in an analysis of 2300 UTC wind profiles from Bureau of Meteorology observations, illustrate that the surface wind at Perth is very constant during the summer whereas it is more constant during the winter on the south coast. Such variation is governed mainly by the position of the subtropical ridge which lies to the south of Perth during the summer, leading to mainly easterly gradient winds. With the onset of winter, the subtropical ridge moves further north and the south coast is more frequently exposed to the prevailing westerlies.

Table 3. Percentage frequency of occurrence of each synoptic group at Perth and Esperance for 1976-1986 on a monthly basis.

Month	Synoptic Group					
	1	2	3	4	5	6
Perth						
Jan	35.6	16.8	18.7	1.0	1.6	26.3
Feb	31.7	19.9	17.0	1.0	2.0	28.4
Mar	28.7	17.0	19.9	1.2	3.2	30.1
Apr	23.5	15.6	20.5	6.1	5.2	29.1
May	20.1	8.8	20.1	13.6	12.4	25.1
Jun	15.2	5.5	22.0	22.3	16.5	18.6
Jul	18.2	7.4	20.0	17.9	17.1	19.4
Aug	25.4	7.4	12.7	20.1	16.5	18.0
Sep	29.4	11.0	8.9	12.2	10.4	28.1
Oct	36.2	9.2	10.7	6.8	6.5	30.6
Nov	37.9	12.5	11.9	2.2	6.0	29.5
Dec	40.4	13.1	10.3	0.9	3.3	31.9
Annual	28.4	11.9	16.1	9.0	8.5	26.2
Esperance						
Jan	37.7	13.3	23.7	1.0	3.6	20.8
Feb	33.0	17.3	21.9	0.3	2.9	24.5
Mar	26.8	12.7	29.8	4.7	5.6	20.4
Apr	21.5	12.1	28.7	8.5	6.9	22.4
May	15.5	6.6	26.9	21.8	14.9	14.3
Jun	9.4	7.6	27.9	25.2	18.5	11.5
Jul	10.8	9.3	25.0	24.4	21.1	9.3
Aug	18.3	5.6	16.8	29.2	20.4	9.7
Sep	22.7	7.5	18.7	18.1	14.3	18.7
Oct	31.1	6.8	18.3	10.4	10.9	22.5
Nov	30.0	8.5	23.3	5.2	7.6	25.5
Dec	38.9	7.5	19.3	3.3	3.3	27.7
Annual	24.5	9.5	23.4	12.8	10.9	18.9

Annual frequencies for the two stations show the most common groups to be 1, 3 and 6, that is southeasterly, northeasterly and variable gradient wind regimes. The synoptic groups associated with the highest wind speeds, 4 and 5 (see Fig. 1) had frequencies of only 17.5 per cent at Perth and 23.7 per cent at Esperance.

The average wind power at Perth for each synoptic group was calculated by combining the power curve of a Westwind 55 Kw turbine (see Fig. 2), as currently deployed at South Fremantle and Esperance, with the 24 hourly FPA wind observations for each individual day classified in the corresponding group. As well these hourly observations were converted to a corresponding daily wind run to enable a direct comparison with wind power estimates for Esperance, where wind observations were only available as 24-hour wind run at 2 m.

The results are presented as percentage contributions of the annual total power for 1976 to 1986. Table 4 shows contributions from each synoptic group for Perth using hourly wind data. Groups 1 and 6 generate the highest proportion of power from October to March, consistent with domination by the subtropical ridge. Accordingly, groups representing frontal activity, 4 and 5, contribute little power during those months.

Fig. 2 Power curve for the Westwind 55 Kw wind turbine (after Steketee 1987).

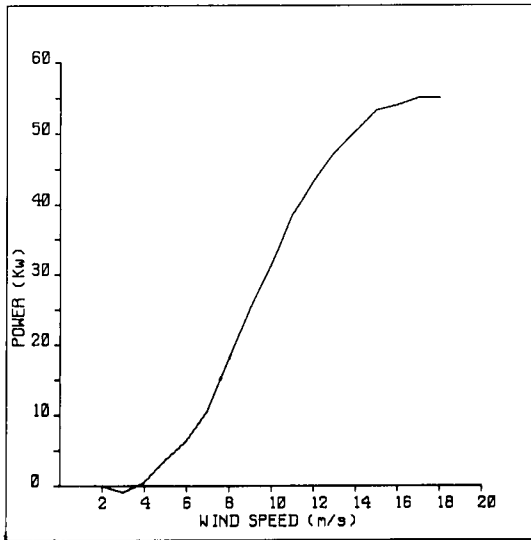


Table 4. Wind power at Perth as a percentage of the total annual estimated power production.

Month	Synoptic Group						Monthly Total
	1	2	3	4	5	6	
Perth - hourly wind observations							
Jan	3.8	1.2	1.5	0.1	0.3	2.4	9.3
Feb	3.1	1.4	1.0	0.1	0.3	2.9	8.8
Mar	2.2	1.3	1.4	0.1	0.3	2.5	7.8
Apr	1.0	0.7	0.9	0.6	0.4	1.5	5.1
May	0.7	0.3	1.5	1.4	1.2	1.0	6.1
Jun	0.8	0.3	1.2	2.6	1.8	1.1	7.8
Jul	0.7	0.4	1.7	2.0	1.6	1.1	7.5
Aug	1.2	0.3	1.3	3.1	2.5	1.3	9.7
Sep	1.4	0.7	0.5	1.5	1.0	2.2	7.3
Oct	2.6	0.9	0.9	1.1	0.9	2.9	9.3
Nov	4.0	1.0	1.0	0.3	1.1	3.2	10.6
Dec	4.4	1.3	1.1	0.2	0.4	3.3	10.7
Annual	25.9	9.8	14.0	13.1	11.8	25.4	100.0
Perth - daily wind run							
Jan	4.5	1.4	1.3	0.1	0.2	1.7	9.2
Feb	4.2	1.5	1.0	0.1	0.4	1.6	8.8
Mar	3.2	1.3	1.0	0.1	0.4	1.1	7.1
Apr	1.3	0.6	0.8	0.5	0.8	0.5	4.5
May	0.9	0.2	0.9	1.4	2.6	0.2	6.2
Jun	0.9	0.1	0.5	2.2	3.9	0.4	8.0
Jul	0.9	0.2	0.8	1.8	3.5	0.6	7.8
Aug	2.1	0.2	0.4	2.9	4.6	0.4	10.6
Sep	2.4	0.4	0.4	0.9	2.2	0.7	7.0
Oct	3.8	0.9	1.1	1.0	1.4	1.5	9.7
Nov	4.9	1.2	1.2	0.3	1.3	2.1	11.0
Dec	5.4	1.5	0.8	0.1	0.5	2.0	10.3
Annual	34.5	9.5	10.2	11.4	21.8	12.8	100.2

During winter, however, they are the major sources of power. Most power (for all synoptic groups) is generated in summer, as well as one month (August) in winter. Least power is generated in April. Annually, groups 1 and 6 dominate wind power generation, contributing as much as the other four groups combined.

Power calculated from daily wind run and the power curve of Fig. 2 is also shown in Table 4. On this basis, the percentage contribution from Group 1 is enhanced while that from Group 6 is decreased. Also, the proportion of power generated by the frontal and post-frontal Group 5 is doubled. Such changes are a direct result of the unequal weighting of wind speeds given by the power curve (Fig. 2). The total estimated power decreased some 17 per cent compared to that estimated from hourly observations but monthly trends are preserved. As before, greatest power occurs in summer and during August and least power during April. Synoptic group 1 still contributes most power annually but now Group 5 is a major contributor. The estimated contribution of Group 6 has been halved because, in averaging out the diurnal variations in wind speed, wind run statistics do not account for the power inherent in the high speed on shore flows of the sea-breeze circulation.

A statistical measure of the average power available under a given synoptic group can be obtained from corresponding Weibull parameters where the cumulative distribution of wind speeds is expressed as

$$F(v) = 1 - \exp[-(v/c)^k]$$

where v is wind speed (m s^{-1}), k a dimensionless shape parameter and c a scale parameter (m s^{-1}). This distribution has been used extensively in describing wind speed data (Justus et al. 1978; Hennessey 1977; Conradsen et al. 1984; Pavia and O'Brien 1986) whereby the mean is given by

$$\langle v \rangle = c \Gamma(1 + 1/k)$$

and the mean energy of the flow, assuming an average air density of 1.23 kg m^{-3} , is

$$\langle E \rangle = 0.615 \langle v^3 \rangle = 0.615 c^3 \Gamma(1 + 3/k)$$

where Γ is the gamma function (Petersen et al. 1981; Pavia and O'Brien 1986).

Table 5 gives the Weibull parameters and associated wind energy for each synoptic group based on the FPA data for 1976-1986 inclusive. Obviously the higher wind speed groups 4, 5 yield a greater energy density, with the easterly and northeasterly gradient winds yielding the lowest. Synoptic groups 1, 6 have higher energy densities than might be expected from their mean wind speeds at 0800 WST (Fig. 1) because of stronger winds generated during afternoon sea-breezes. The larger pressure gradients associated with groups 2, 3 delay development of a sea-breeze circulation resulting in a lower daily energy

density despite their exhibiting stronger mean wind speeds in the morning. Group 6 achieves its higher energy density because the weak synoptic pressure gradients allow the earlier development of mesoscale circulations whereas for group 1 the synoptic pressure gradient strengthens the sea-breeze circulation. Despite their relatively lower energy density, groups 1, 6 are the major contributors to the wind power potential through their greater frequency of occurrence and longer duration.

Calculation of wind power for Esperance required a slightly different approach. After converting the daily wind runs to mean daily wind speeds, the mean wind at 10 m was estimated from

$$u_1/u_2 = (z_1/z_2)^{0.14}$$

where $z_1 = 10$ m, $z_2 = 2$ m and u_1, u_2 are wind speed at those heights (Irwin 1979). Initially, wind power was obtained from the Westwind power curve. However, mean wind speeds derived from wind run data were often so low that negative power was derived. Potential wind power was then calculated using

$$P = 0.615u^3A$$

where an average air density of 1.23 kg m^{-3} is assumed and A is the swept area of the turbine blades. Assuming the Westwind rotor diameter of 16 metres, monthly contributions over the ten years by synoptic group are presented in Table 6. In common with Perth synoptic groups 1 and 6 generate most power during summer, with groups 2 and 3 also making significant contribution. During winter, groups 4 and 5 (frontal activity) are prominent but, except for July, group 1 synoptic events still contribute most power. Monthly trends of power potential follow those at Perth with spring and summer having most power. A peak of power potential is also apparent during August at Esperance. As at Perth, April is the month of least power potential.

It can be seen from Tables 4 and 6 that synoptic group 1, southeasterly regime, is the major annual contributor to wind power at both Perth and Esperance. During summer, it is responsible for 50 percent of the potential wind power. The next most significant contributor, group 6, is composed of weak pressure gradients and variable winds. Under these conditions, mesoscale phenomena dominate the flow patterns and are clearly important in terms of the available energy. Thus the extension of single site observations, for wind power estimations, is critically dependent on mesoscale forcing and requires the use of a NMM. For winter, synoptic group 5 (west-southwesterly regime) is the most important in terms of wind power potential for both Perth and Esperance. These situations are associated with strong pressure gradients and consistent winds.

Table 5. Estimated Weibull parameters and corresponding wind energy based on Fremantle (FPA) anemometer observations as a function of synoptic group.

Synoptic Group	Weibull parameters		$\langle v \rangle$ $m s^{-1}$	$\langle E \rangle$ W^{-2}
	c $m s^{-1}$	k		
1	6.26	1.93	5.6	209
2	5.91	2.28	5.2	150
3	5.92	2.20	5.3	155
4	8.13	2.16	7.2	406
5	8.73	1.91	7.8	573
6	5.44	1.63	4.9	171

Table 6. Wind power at Esperance as a percentage of the total annual estimated power production.

Month	Synoptic Group						Monthly Total
	1	2	3	4	5	6	
Esperance - daily wind run							
Jan	5.2	2.4	3.1	0.2	0.2	3.0	14.1
Feb	3.4	2.2	1.7	0.0	0.1	2.2	9.6
Mar	3.3	1.0	1.2	0.0	0.2	2.0	7.7
Apr	1.5	0.7	0.5	0.3	0.4	1.1	4.5
May	2.4	0.4	0.5	1.7	2.3	1.2	8.5
Jun	2.0	0.5	0.2	1.1	1.7	0.5	6.0
Jul	1.7	0.7	0.3	0.6	1.7	0.8	5.8
Aug	3.8	0.6	0.3	1.8	1.7	0.8	9.0
Sep	3.8	0.5	0.3	0.8	1.1	1.3	7.8
Oct	3.9	1.0	0.6	0.5	0.5	1.8	8.3
Nov	3.7	1.2	0.8	0.2	0.5	2.3	8.7
Dec	4.9	1.0	1.0	0.1	0.3	2.8	10.1
Annual	39.6	12.2	10.5	7.3	10.7	19.8	100.1

Consequently, these observations are more directly dependent on synoptic forcing rather than mesoscale and can be more readily extrapolated (Petersen et al. 1981).

Conclusion

A synoptic classification scheme, using gradient wind direction, curvature of isobars and pressure trends as criteria, has been applied to estimating wind power potential at two locations in the southwest of Western Australia. Wind power potential was estimated using the power curve of a Westwind 55 kW turbine, as well as through the estimation of associated Weibull parameters.

The largest annual power contribution at both stations during summer was from synoptic situations where the subtropical ridge was beginning its passage across Western Australia and under conditions of weak synoptic pressure gradients. These situations provide a major contribution to annual wind power potential through the development of mesoscale flows and their high frequency of occurrence. In winter, mid-latitude systems provide the greatest contribution to wind power potential.

This study illustrates the importance of mesoscale circulations in estimating wind power potential over the southwest of Western Australia. The extension of observations at a single site requires an account of the contribution of mesoscale circulations to provide an adequate assessment of the regional wind power potential.

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