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The Royal Society of Victoria, 133, 82–92, 2021
10.1071/RS21011

WIND CLIMATE OF THE MELBOURNE METROPOLITAN AREA

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ABSTRACT: This paper describes a probabilistic analysis of data recorded by the Bureau of Meteorology (BoM) for the wind climate of the Melbourne metropolitan area. It is based on 10-minute average wind data from four automatic weather stations (AWS) — at Melbourne and Essendon airports, Fawkner Beacon in Port Phillip Bay, and Moorabbin Airport. Corrections to the data were made to adjust to standard terrain conditions and height. For the land stations, these were based on estimates of the surface roughness length at each site as a function of wind direction, making use of recorded gust factors. For the Fawkner Beacon, which is completely surrounded by open water, the surface roughness length is a function of mean wind speed, and the Charnock relationship was used in determining the corrections.

For each station the terrain-corrected wind data were fitted with Weibull probability distributions, as an all-direction group and for sixteen direction sectors. Directional probabilities were also determined. The parameters of the all-direction Weibull distributions are very similar for all four stations, but there are differences in directional probabilities for some directions, with a geographic trend from north to south in the region being apparent. Some possible explanations based on the general topography are given.

Keywords: probability, Melbourne, Weibull distribution, wind direction, wind speed

WIND CLIMATE DATABASE FOR THE MELBOURNE METRO REGION

Probabilistic modelling of a wind climate is useful for several applications, such as the assessment of windy conditions around building developments, dispersion of pollutants and for wind energy potential. It may also be useful for some wind-loading assessments, such as metallic fatigue.

This paper describes an analysis of data recorded by the Bureau of Meteorology (BoM) for the wind climate of the Melbourne metropolitan area. It is based on analysis of 10-minute average wind data, up to March 2021, from four automatic weather stations (AWS) operated by the Bureau of Meteorology — at Melbourne Airport, Essendon Airport, the Fawkner Beacon in Port Phillip Bay, and at Moorabbin Airport. Although there are several more AWS stations in the Melbourne area, these four stations were chosen because their surroundings have remained relatively constant over the last 20–30 years, and the corrections required to adjust the terrain and height of the wind speed readings to the standard conditions of 10-metres height, and flat open country are small.

The paper presents probability distributions of wind speed and direction for the four stations in the Melbourne area, and considers geographical variability, but does not attempt to separate the various sources of winds, such as large pressure systems, sea breezes, cold frontal storms or severe local thunderstorms (downbursts), or to distinguish winds by seasonal or diurnal cycles.

The coordinates of the four AWS anemometers are tabulated in Table 1 and their locations in relation to the central business district (CBD) of Melbourne are shown in Figure 1.

The closest AWS to the Melbourne CBD is at Essendon Airport, which is about 10 km northwest of the city centre. Melbourne Airport is further to the northwest,

Table 1: Anemometer stations with coordinates and dates of the 10-minute data.

Name	BoM station ID	Lat. /Long.	Dates
Melbourne Airport	86282	37.67°S, 144.83°E	6/3/97 – 25/3/21
Essendon Airport	86038	37.73°S, 144.91°E	30/1/03 – 25/3/21
Fawkner Beacon	86376	37.95°S, 144.93°E	11/3/92 – 25/3/21
Moorabbin Airport	86077	37.980°S, 145.096°E	4/8/92 – 23/6/04
″	″	37.977°S, 145.106°E	24/6/04 – 25/3/21

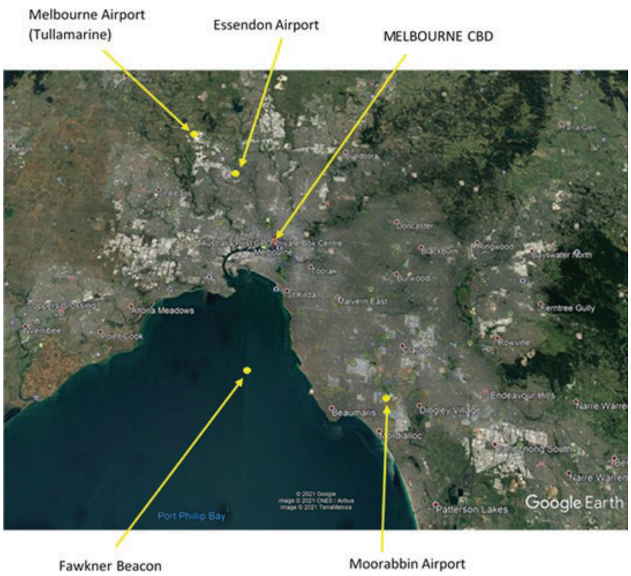

Figure 1: Location of the anemometers and the Melbourne CBD.

approximately 19 km from central Melbourne. The anemometer on the Fawkner Beacon is in Port Phillip Bay, about 6 km west of Sandringham beach, and 15 km from the CBD. The AWS at Moorabbin Airport is 21 km southeast of the city centre.

The anemometers at Melbourne and Essendon airports are well-sited, being located next to runways, with wind measurements taken at the standard height of 10 metres. However, small corrections for terrain are required for some directions, as discussed in the following section. The anemometer on the Fawkner Beacon is at a height above mean sea level of 17 metres, so that correction for height, as well as for the open water terrain, is required for all directions. Since 2004, the anemometer at Moorabbin Airport has been located on the western side of the airport, with some industrial buildings to the west affecting winds from that direction.

Ten-minute average wind speeds and directions are currently recorded at half-hourly intervals by the BoM from each station (i.e. on the hour and 30 minutes after the hour), although when the wind speed increases, samples are often taken at intermediate times. The range of dates used for the present study are shown in Table 1.

TERRAIN CORRECTIONS

Corrections for the airport stations

For each of the three airport stations, effective roughness lengths for sixteen wind directions were determined, making use of measured gust factors (maximum 3-second gust speed/10-minute mean wind speed), for samples for which the 10-minute mean wind speed was 31 km/h or greater, and the gust factor was less than 2.0. A lower limit on wind speed was required to limit the gust-factor

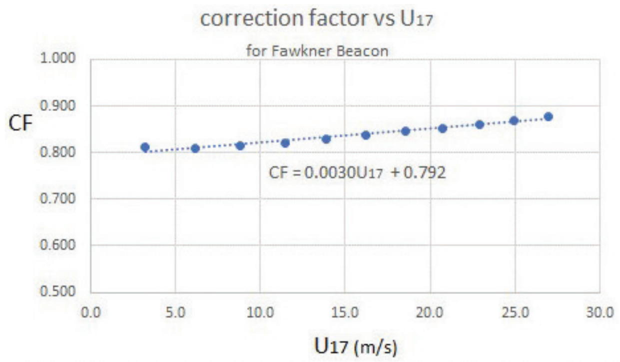

Figure 2: Correction factors for over-water mean wind speeds at Fawkner Beacon.

calculations to boundary-layer winds with neutral thermal stability, but allowing for sufficiently large numbers of gust factors for averaging purposes for all wind directions. A sensitivity analysis showed that a reduction in the wind speed threshold by 20% resulted in an average variation (averaged over the sixteen directions) in the calculated correction factors of less than 1%.

The limit of 2.0 on the measured gust factors excluded winds from thunderstorms and other transient events, which are affected differently by the upwind terrain. However, there is little sensitivity of calculations of roughness lengths to this limit. For example, varying the gust factor limit by +/- 10% (i.e. 1.8 to 2.2) for the Essendon Airport data resulted in an average variation in correction factors over the sixteen directions of less than 0.4%.

The general approach to the determination of terrain correction factors is as follows:

- For each sample with known mean wind speed, a theoretical 'expected' peak factor g_u was calculated using the approach described by Holmes et al. (2014), based on random processes, and assuming the spectral density given in the Australian Standard for Wind Actions, AS/NZS 1170.2 (Standards Australia 2021), with an integral length scale of 85 m.
- A turbulence intensity was then calculated for each sample from Equation (1).

$$I_u = \frac{G-1}{g_u} \qquad (1)$$

  where G is the recorded gust factor for that sample.
- The resulting turbulence intensities were then averaged over all the samples available for each station-direction set, typically several hundred samples for most directions.
- Equation (2) was then used to get an estimate of aerodynamic roughness length, Z_O, from the turbulence intensity.

$$I_u(z) = \frac{1}{\log_e (z/z_0)} \qquad (2)$$

For z equal to 10 metres, and inverting Eq. (2):

$$z_0 \cong 10.\exp\left(\frac{-1}{I_u}\right) \tag{3}$$

Correction factors for mean wind speeds were then determined from Equation (4), assuming the logarithmic law applies for the mean wind speed variation with height,

$$CF_i = \frac{u_* \, log_e(10/0.02)}{u'_{*,i} \, log_e(z_m/z_{0,i})} \tag{4}$$

in which z_m is the anemometer height, and $z_{0,i}$ is the roughness length determined from analysis of gust factors for wind direction i. The friction velocities u_* and $u'_{*,i}$ are in open country and at the anemometer site, respectively.

In order to determine the ratio of friction velocities u_*/u'_* for Equation (4), an empirical relationship in Equation (5) between the geostrophic drag coefficient u_*/U_g and the surface Rossby Number $Ro = U_g/fz_o$ was applied to both the anemometer site and standard open country terrain, assuming that the geostrophic wind speed U_g is independent of terrain roughness. f is the Coriolis parameter, involving the rotational velocity of the Earth, and the angle of latitude.

$$u_*/U_g = 0.12\, Ro^{-0.085} \tag{5}$$

An alternative approach to Equation (5) would be to use a relationship based on 'asymptotic similarity theory' (e.g. Csanady 1967; Deaves & Harris 1978). However, this theory gives an implicit relation for the roughness length, which must be solved by iteration, and is inconvenient for the over-water data from Fawkner Beacon, as the roughness length is also a function of mean wind speed, (see next section). However, Equation (5) matches measurements of geostrophic drag coefficient and surface Rossby Number quite adequately for the present purposes (see Figure 3.4 in Holmes and Bekele 2021).

For the three airport stations, the calculated roughness lengths, and resulting correction factors to the anemometer readings are tabulated in Tables 2 to 5, as a function of wind direction. Two sets of factors are given for Moorabbin Airport, as the anemometer was moved in mid-2004 from the north-east corner to the western side of the airport.

Table 2: Roughness lengths, and correction factors to standard conditions (10 m, TC2), for mean wind speeds at Melbourne Airport.

Wind direction	**Melbourne AP (Tullamarine)**		
	z_0 (m)	u_*/u_*'	*CF*
N	0.013	1.04	0.97
NNE	0.025	0.98	1.02
NE	0.028	0.97	1.03
ENE	0.006	1.10	0.93
E	0.006	1.11	0.93
ESE	0.014	1.03	0.98
SE	0.009	1.07	0.95
SSE	0.006	1.11	0.93
S	0.013	1.04	0.97
SSW	0.034	0.96	1.05
SW	0.023	0.99	1.01
WSW	0.026	0.98	1.02
W	0.023	0.99	1.01
WNW	0.035	0.95	1.05
NW	0.092	0.88	1.16
NNW	0.093	0.88	1.17

Table 3: Roughness lengths, and correction factors to standard conditions (10 m, TC2), for mean wind speeds at Essendon Airport.

Wind direction	**Essendon AP**		
	z_0 (m)	u_*/u_*'	CF
N	0.074	0.89	1.13
NNE	0.094	0.88	1.17
NE	0.075	0.89	1.14
ENE	0.061	0.91	1.11
E	0.024	0.99	1.01
ESE	0.026	0.98	1.02
SE	0.046	0.93	1.08
SSE	0.049	0.93	1.08
S	0.024	0.98	1.01
SSW	0.033	0.96	1.04
SW	0.033	0.96	1.04
WSW	0.030	0.97	1.03
W	0.045	0.93	1.07
WNW	0.068	0.90	1.12
NW	0.063	0.91	1.11
NNW	0.086	0.88	1.15

Table 4: Roughness lengths, and correction factors to standard conditions (10 m, TC2), for mean wind speeds at Moorabbin Airport (1992–2004).

Wind direction	**Moorabbin Airport (1992–2004)**		
	z_0 (m)	u_*/u_*'	*CF*
N	0.071	0.90	1.13
NNE	0.094	0.88	1.17
NE	0.099	0.87	1.18
ENE	-	-	1.26*
E	0.229	0.81	1.34
ESE	0.193	0.82	1.30
SE	0.170	0.83	1.27
SSE	0.076	0.89	1.14
S	0.035	0.95	1.05
SSW	0.022	0.99	1.01
SW	0.019	1.00	1.00
WSW	0.038	0.95	1.05
W	0.058	0.91	1.10
WNW	0.046	0.93	1.08
NW	0.057	0.91	1.10
NNW	0.067	0.90	1.12

* interpolated value

Table 5: Roughness lengths, and correction factors to standard conditions (10 m, TC2), for mean wind speeds at Moorabbin Airport (2004–2021).

Wind direction	**Moorabbin Airport (2004–2021)**		
	z_0 (m)	u_*/u_*'	*CF*
N	0.041	0.94	1.06
NNE	0.037	0.95	1.05
NE	0.040	0.94	1.06
ENE	-	-	1.03*
E	0.018	1.01	0.99
ESE	0.027	0.98	1.02
SE	0.022	0.99	1.01
SSE	0.029	0.97	1.03
S	0.047	0.93	1.08
SSW	0.047	0.93	1.08
SW	0.079	0.89	1.14
WSW	0.149	0.84	1.25
W	0.182	0.83	1.29
WNW	0.189	0.83	1.29
NW	0.144	0.85	1.24
NNW	0.094	0.88	1.17

* interpolated value

The correction factors are in the range of 0.93 to 1.34. The higher values account for the rough forested terrain north-west of the anemometer at Melbourne Airport, and the built-up terrain comprising industrial buildings, for some wind directions, at Moorabbin Airport.

Corrections for the Fawkner Beacon (over-water winds)

For the Fawkner Beacon, data corrections were made individually for each 10-minute mean speed, based on the Charnock (1955) relationship of Equation (6) for roughness length over water.

$$z_0 = \frac{a u_*^2}{g} \quad (6)$$

in which g is the gravitation acceleration (9.8 m/s^2), and a is the Charnock 'constant'.

A previous study for Port Phillip Bay (Holmes, 2017) indicated a value for a of 0.04. By combining Equations (5) and (6), the following relationship between Z_O and U_g is obtained.

$$z_0 = \left[\sqrt{\frac{a}{g}}\, U_g^{\,0.915}\, 0.12 f^{0.085}\right]^{1/0.415} \quad (7)$$

Then from Equation (6),

$$u_* = \sqrt{\frac{g z_o}{a}}$$

By application of the logarithmic law, relationships between u_*, U_{17}, U_g, and z_o were obtained. Application of Equation (4) then gave the correction factors to 10 m height over rural terrain as a function of the mean wind speed U_{17} at 17 m height over Port Phillip Bay. An empirical linear function for the correction factor was finally fitted (Equation (8) and Figure 2):

$$CF = 0.00299U_{17} + 0.7918 \quad (8)$$

in which U_{17} is in m/s.

Equation (8) was applied to every recorded value of 10-minute mean wind speed from the Fawkner Beacon, in order to correct to the equivalent values for the standard terrain conditions (z_o = 0.02 m) at a height of 10 m. The correction factors are between 0.8 and 0.9, so that the recorded wind speeds are reduced to adjust for the lower surface roughness of the over-water winds, and for the height of the Fawkner Beacon anemometer above mean sea level.

The average tidal range in Port Phillip Bay is 0.8 metre; the effect of this height variation on wind speeds at the anemometer level at the Fawkner Beacon is negligible compared to the corrections for the over-water terrain, and was ignored in this study.

PROBABILITY DISTRIBUTIONS OF WIND SPEED AND DIRECTION

For the terrain-corrected all-direction winds at each station, the Weibull probability distribution, of Equation (9), was fitted.

$$p(> U) = \exp\left[-\left(\frac{U}{c}\right)^k\right] \quad (9)$$

Fitting was carried out using a simple least-squares fit to a linearized form of Equation (9), and also by the maximum likelihood method. For the latter method, the log-likelihood function for the 2-parameter Weibull distribution was given by Nielsen (2011). The maximum likelihood method is generally regarded as superior by statisticians, but the differences in the shape and scale factors obtained by the two fitting methods were found to be quite small for the Melbourne stations.

The directional sector wind-speed distributions were also fitted to the recorded and corrected data, by a modified form of the Weibull distribution as shown in Equation (10).

$$p(>U,\theta_i) = p(\theta_i).\exp\left[-\left(\frac{U}{c_i}\right)^{k_i}\right] \qquad (10)$$

where $p(\Theta_i)$ is the probability that the wind speed comes from a particular 22.5° direction sector i, and c_i and k_i are scale and shape factors, respectively.

Equation (10) defines the combined probability that the wind direction falls within the sector centred on Θ_i, and that a wind speed U is exceeded.

All-direction distributions

Figures 3 to 6 show the fitted all-direction probability distributions for the wind speeds from the four stations, obtained using the maximum likelihood method.

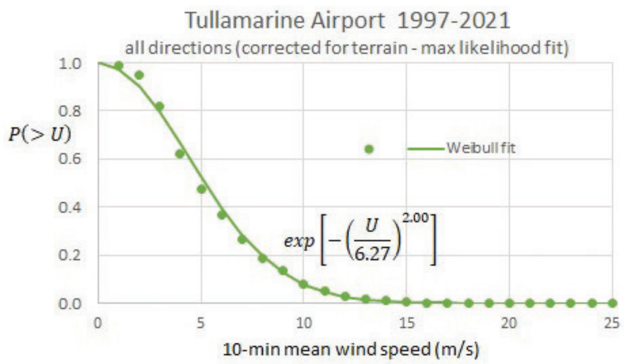

Figure 3: Weibull distribution fitted to terrain-corrected data from Melbourne AP.

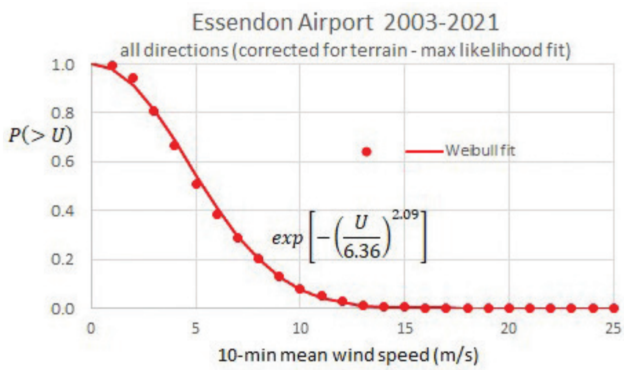

Figure 4: Weibull distribution fitted to terrain-corrected data from Essendon AP.

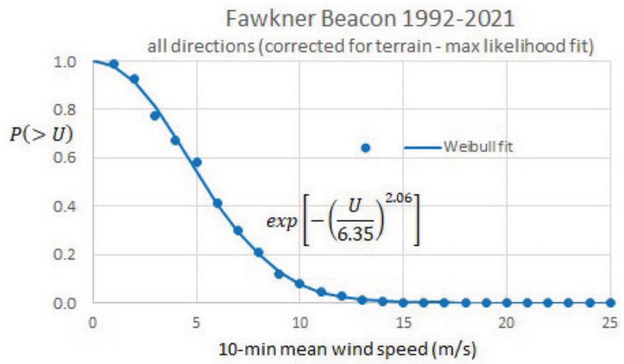

Figure 5: Weibull distribution fitted to terrain-corrected data from Fawkner Beacon.

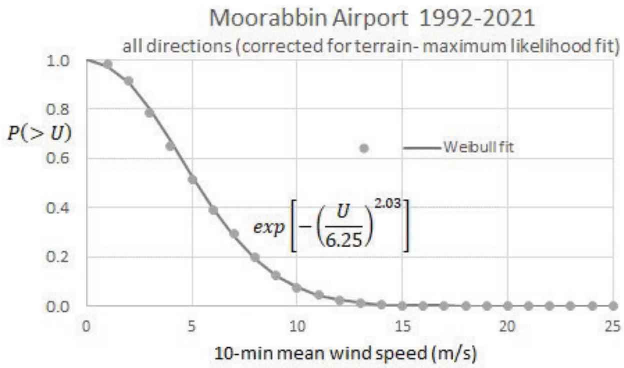

Figure 6: Weibull distribution fitted to terrain-corrected data from Moorabbin AP.

The fits are all good, and the all-direction distributions in Figures 3 to 6 are almost identical across the four stations, giving some support to the terrain-correction approaches. The shape factors are all close to 2.0 (for which the Weibull distribution is also the 'Rayleigh' distribution). The scale factors vary only slightly, with Essendon Airport and Fawkner Beacon having the highest values and Moorabbin Airport the lowest.

The similarity of the distributions across the four stations is further illustrated by Figure 7, which shows all four fitted Weibull distributions together on the one plot. If a single Weibull distribution is required to cover the whole of the Melbourne metropolitan area, an average shape factor, $k = 2.05$, and scale factor, $c = 6.30$ could be adopted. The shape factor is applicable at 10 m height in flat, open country, and would need adjustment for other conditions.

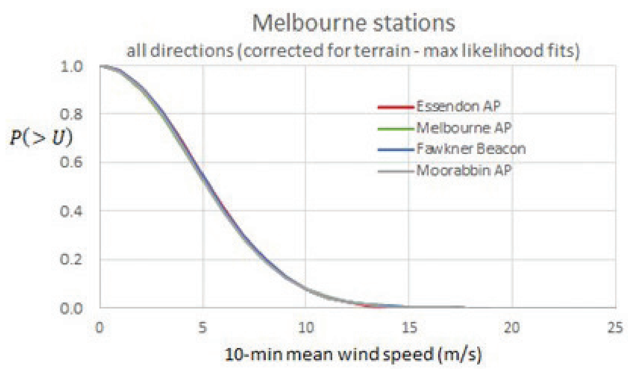

Figure 7: Weibull distributions fitted to data from four stations.

Distributions by direction sector

Probability distributions for sixteen direction sectors, for all four stations, have been fitted with the form of Equation (10), using the simple least-squares method. The directional probabilities $p(\Theta_i)$ and the parameters for the fitted distributions are tabulated in Tables 6 to 9. These tables also show the scale and shape factors for the all-direction distributions.

Table 6: Parameters for directional distributions for Melbourne AP.

Wind direction	$p(\Theta_i)$	Scale factor, c_i	Shape factor, k_i
N	0.247	7.78	2.30
NNE	0.039	6.55	1.99
NE	0.012	4.04	1.50
ENE	0.008	2.61	1.24
E	0.007	2.86	1.58
ESE	0.008	4.14	1.99
SE	0.022	4.73	2.17
SSE	0.056	5.31	2.52
S	0.125	6.09	2.79
SSW	0.075	5.66	2.24
SW	0.080	5.91	2.04
WSW	0.086	6.41	1.98
W	0.083	6.26	1.98
WNW	0.057	5.59	1.78
NW	0.043	5.94	1.79
NNW	0.053	6.45	1.83
All directions	1.000	**6.27**	**2.00**

Table 7: Parameters for directional distributions for Essendon AP.

Wind direction	$p(\Theta_i)$	Scale factor, c_i	Shape factor, k_i
N	0.195	8.11	2.41
NNE	0.039	6.04	1.89
NE	0.020	3.92	1.91
ENE	0.015	3.19	1.67
E	0.011	2.97	1.72
ESE	0.015	3.87	1.77
SE	0.032	5.01	2.16
SSE	0.053	5.29	2.50
S	0.130	6.46	2.91
SSW	0.077	6.43	2.38
SW	0.064	6.13	2.12
WSW	0.092	6.93	2.15
W	0.076	6.87	2.00
WNW	0.063	6.00	1.98
NW	0.056	5.78	1.83
NNW	0.062	6.41	1.98
All directions	1.000	**6.36**	**2.09**

Table 8: Parameters for directional distributions for Fawkner Beacon.

Wind direction	$p(\Theta_i)$	Scale factor, c_i	Shape factor, k_i
N	0.165	7.32	2.19
NNE	0.045	5.26	1.72
NE	0.020	3.31	1.48
ENE	0.018	3.03	1.73
E	0.036	5.13	1.78
ESE	0.054	5.73	2.11
SE	0.065	5.65	2.29
SSE	0.079	5.62	2.49
S	0.102	6.46	2.38
SSW	0.073	6.69	2.22
SW	0.057	6.76	2.10
WSW	0.067	7.20	2.24
W	0.069	7.19	2.30
WNW	0.054	6.59	2.13
NW	0.046	6.16	1.89
NNW	0.050	6.18	1.94
All directions	1.000	**6.35**	**2.06**

Table 9: Parameters for directional distributions for Moorabbin AP.

Wind direction	$p(\Theta_i)$	Scale factor, c_i	Shape factor, k_i
N	0.174	7.05	2.10
NNE	0.044	5.08	1.73
NE	0.016	3.19	1.43
ENE	0.012	2.48	1.52
E	0.019	2.96	1.37
ESE	0.062	5.15	1.74
SE	0.073	4.91	2.09
SSE	0.063	4.84	2.41
S	0.059	5.40	2.40
SSW	0.107	6.74	2.71
SW	0.082	7.11	2.64
WSW	0.051	7.17	2.44
W	0.066	7.71	2.52
WNW	0.061	7.07	2.37
NW	0.049	6.32	2.14
NNW	0.063	6.25	1.98
All directions	1.000	**6.25**	**2.03**

The directional probabilities $p(\Theta_i)$ are also compared in graphical form in Figures 8 and 9. Some directional features stand out in Tables 6 to 9, and in Figures 8 and 9.

- Northerly winds are the most common, and the strongest, at all stations, but they are more common and stronger at Melbourne and Essendon airports than they are at the other stations.

- South is the second most common direction (after north) at Melbourne and Essendon airports, and at Fawkner Beacon, but at Moorabbin Airport, SSW is the more frequent direction than south.
- Winds from the SW to NNW sector, with moderate strength, are fairly frequent at all stations.

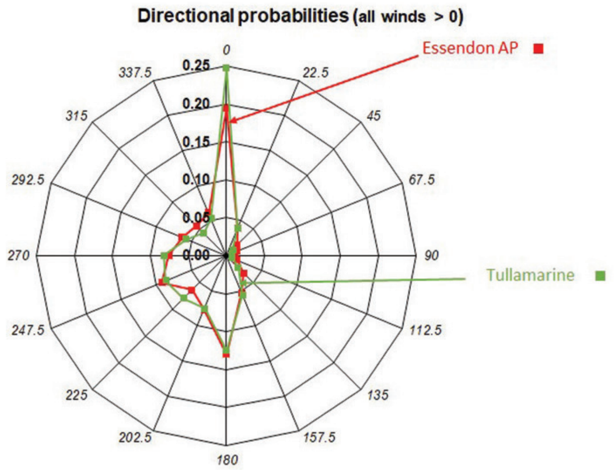

Figure 8: Directional probabilities for Melbourne Airport (Tullamarine) and Essendon Airport.

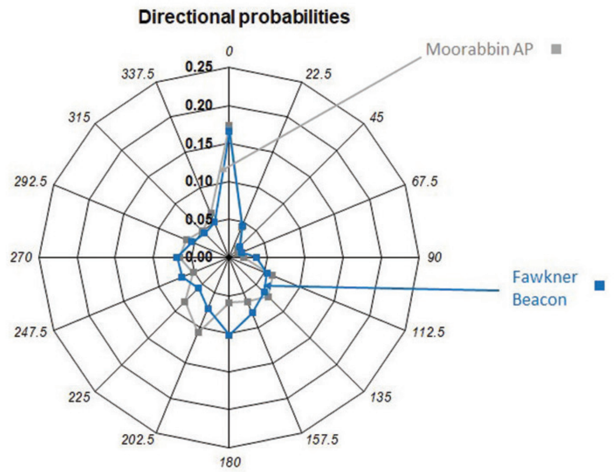

Figure 9: Directional probabilities for Fawkner Beacon and Moorabbin Airport.

The directional probabilities for Melbourne and Essendon airports (Figure 8) are quite similar to each other, with high values for north, south and to a lesser extent WSW. The northerly peaks are usually attributed to channeling through the Kilmore Gap in the Great Dividing Range, about 40 km north of the Melbourne Airport. That feature may also reinforce the southerly winds as well.

Fawkner Beacon and Moorabbin Airport show lower peaks for both north and south winds, but have contributions from the southeast (Figure 9). The SSW peak at Moorabbin Airport is likely due to the prevailing sea breeze over Port Phillip Bay that occurs almost daily during the summer months.

The direction/windspeed distributions have been replotted in a different form in Figures 10 and 11. The directional probabilities are shown for four wind speed ranges: > 0, > 6 m/s, > 12 m/s and > 18 m/s. These present the same information as in Tables 6 to 9 and Figures 8 and 9, but show more clearly the changes in prevailing wind directions as the wind speed increases. Also, the differences in directional characteristics between the northern stations (Melbourne and Essendon airports), and the southern stations (Fawkner Beacon and Moorabbin Airport), as discussed above, are shown to be present for all speed ranges.

ADJUSTED WIND CLIMATE FOR OTHER PARTS OF MELBOURNE

To obtain a wind climate for other parts of Melbourne, the parameters of the Weibull distributions can be adjusted according to the height and terrain of the site of interest. The adjustment factor to the Weibull scale factor is given by a similar equation to Equation (4):

$$AF = \frac{u'_* \log_e(h/z_0')}{u_* \log_e(10/0.02)} \quad (11)$$

in which h and z_0' are, respectively, the height and roughness length in metres for the site of interest. To obtain the ratio of friction velocities u_*' / u_*, the method described earlier can be used. This method relates the surface winds to the upper-level mean wind speeds U_g, which is assumed to be independent of the terrain roughness. Then the Weibull scale factor c′ for a site in central Melbourne can simply be obtained from Equation (12).

$$c' = c \times AF \quad (12)$$

For example, Table 10 shows the adjusted all-direction scale factors for a range of heights and roughness lengths in central Melbourne, using the method described, and the scale factor from Essendon Airport (Table 7), which is nearly identical to that at Fawkner Beacon (Table 8).

Adjustment for the varying directional probabilities for other parts of Melbourne could be attempted by linear interpolation, or by a weighted average based on weighting factors inversely proportional to the distance of the site from two anemometer stations. For the directional Weibull probabilities in central Melbourne, a weighted average of the directional distributions for Essendon Airport and Fawkner Beacon (Figure 12) could be used, but that has not been done here. In any case, wind directions near ground level in urban areas are likely to be heavily distorted by the presence of large buildings and street orientations.

For other parts of the metropolitan area, a distribution with a shape factor of 2.05, and a scale factor of 6.30, as suggested in an earlier section, can be used. The scale

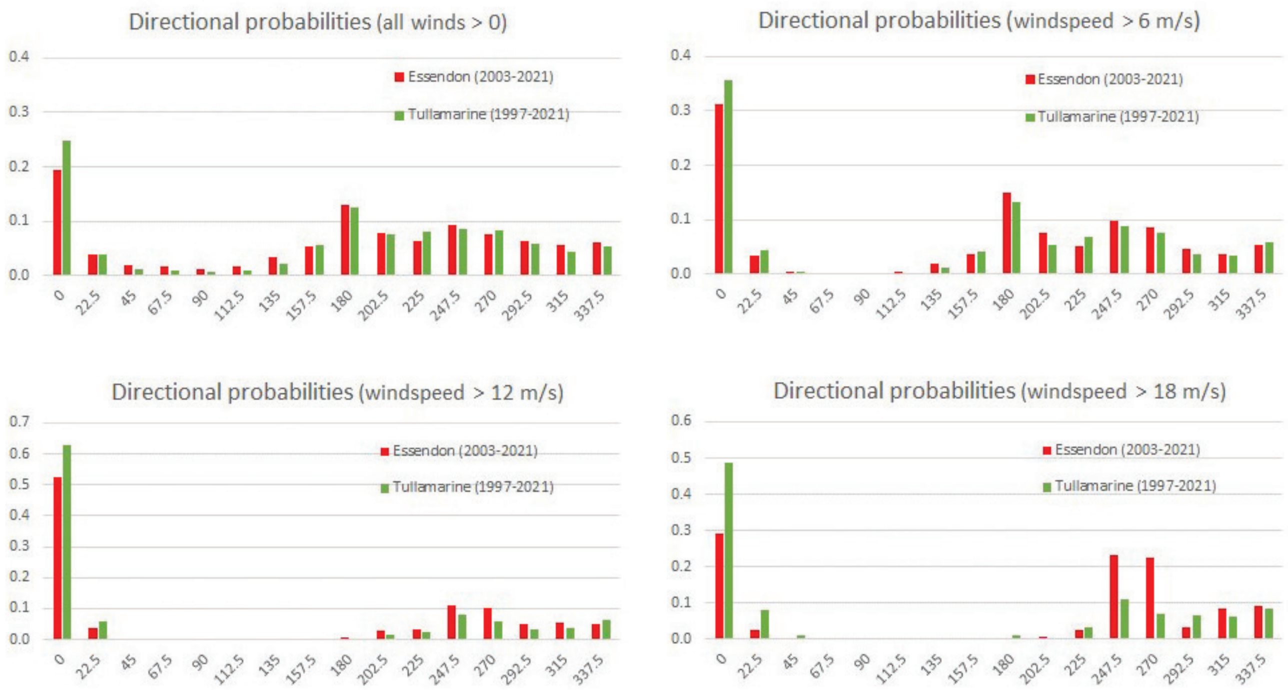

Figure 10: Directional probabilities as a function of wind speed — Melbourne and Essendon Airports.

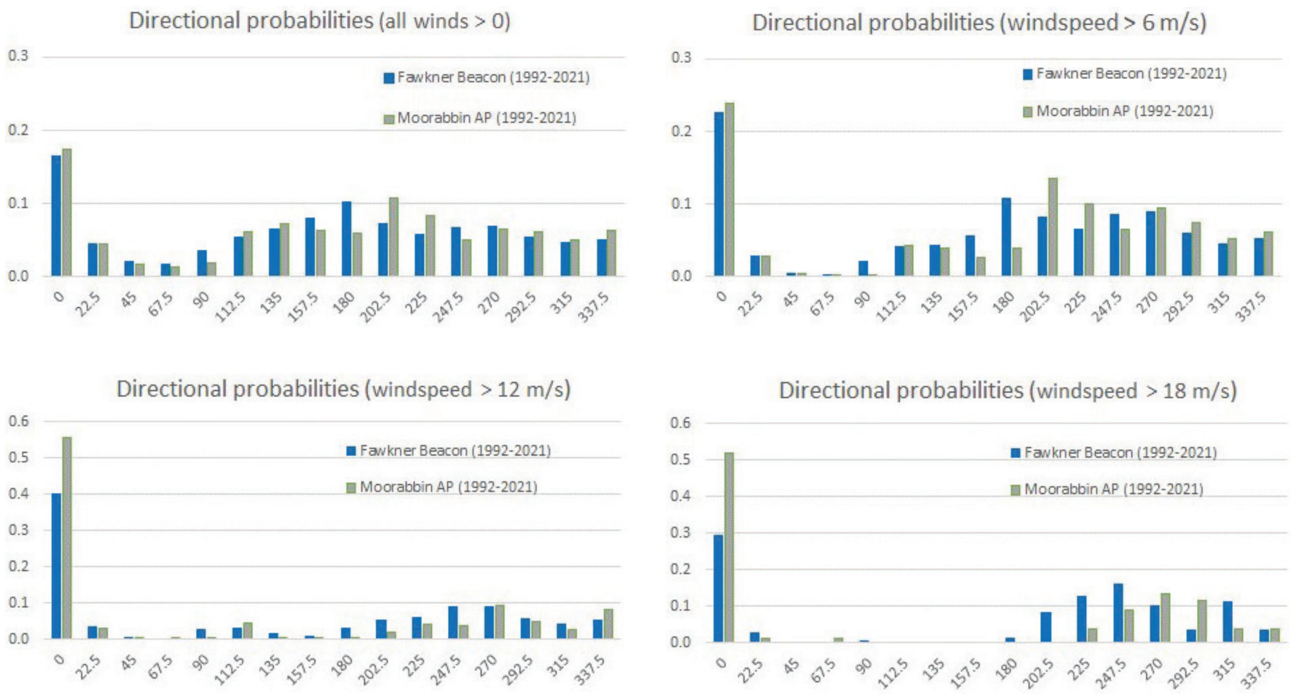

Figure 11: Directional probabilities as a function of wind speed — Fawkner Beacon and Moorabbin Airport.

Table 10: Weibull all-direction scale factors for sites in central Melbourne.

Height (m)	z_o' *(m)*	**Scale factor,** $u'*/u*$	**Shape factor,** c'
15	0.50	1.31	4.58
20	0.50	1.31	4.96
30	0.50	1.31	5.51
50	0.50	1.31	6.20
100	0.50	1.31	7.13
15	1.00	1.39	3.86
20	1.00	1.39	4.28
30	1.00	1.39	4.85
50	1.00	1.39	5.58
100	1.00	1.39	6.57
15	2.00	1.48	3.05
20	2.00	1.48	3.49
30	2.00	1.48	4.10
50	2.00	1.48	4.87
100	2.00	1.48	5.92

factor, of course, applies to the standard conditions of 10-m height in flat, open country, and would need to be adjusted for other heights, and terrain and topographic situations.

DISCUSSION AND CONCLUSIONS

Probability distributions of wind speed and direction, based on the Weibull distribution, have been derived for the mean (10-minute average) wind speeds from four anemometer stations with reliable data in the Melbourne area. Corrections to standard height and terrain have been made, but the correction factors are mostly within 20% of 1.0, so that the errors in the corrected values should be small. The only correction factors greater than 1.20 were found for some directions at Moorabbin Airport (Tables 4 and 5); these were the result of industrial buildings providing additional surface roughness, and hence reduced mean wind speeds, for those directions. However, the all-direction probability distributions, based on the terrain-corrected data, are very similar for all four stations, including Moorabbin Airport. This consistency gives some confidence in the validity of the terrain corrections.

If required, the probability density functions (p.d.f.) can easily be obtained by differentiation of Equations (9) or (10). For example from Equation (10) for winds from a direction i, the p.d.f. is given by Equation (13).

$$f(U,\theta) = p(\theta_i).\frac{k_i U^{k_i-1}}{{c_i}^{k_i}}\,exp\left[-\left(\frac{U}{c_i}\right)^{k_i}\right] \tag{13}$$

The well-known northerly winds in the Melbourne area, which are closely related to the surrounding topography, particularly the Kilmore Gap, are prominent in the data, but they are clearly more prominent in the Melbourne Airport (Tullamarine) distributions, and to a lesser extent the winds at Essendon Airport. There is some indication of the effects of sea breezes over Port Phillip Bay in the southerly and south-westerly peaks, particularly at Moorabbin Airport.

Possible sources of error in the analysis are:

- Sampling and fitting errors in the wind database. Sampling errors should be small, given that 18–30 years of data from each station were used. The Weibull distributions used were very good fits to the bulk of the wind speed data for all wind directions, so that errors from that source are also likely to be small. However, it is clear that the wind climate in the Melbourne area is contributed to by a number of different phenomena and events, and representing them by a single-2-parameter distribution is an approximation. The 'double' Weibull distribution (Xu et al., 2008) may improve the fitting to the upper tails in the data.
- Errors in the corrections for the terrain to the standard open country conditions. However, since the corrections have been limited to ±30% of 1.0, with most of differences from 1.0 being considerably less, these errors are expected to be small. However, although the terrain corrections have been derived for large-scale boundary-layer winds, they have been used for winds from all sources — this would clearly be a source of some errors for winds from thunderstorms and frontal changes.

There is variation in the directional probability distributions with the magnitude of the wind speed itself, as some phenomena such as the coastal sea breezes only produce low to medium strength wind speeds; this is presented for the Melbourne stations in Figures 10 and 11. In general, the differences in the directional characteristics of winds in the Melbourne area can be attributed to the topographic effects of the Kilmore Gap to the north, and Port Phillip Bay to the south.

Future work could consider seasonal and diurnal variations in wind speed, and their geographical variations within the Melbourne area. The possible effects of cyclical variations in weather on wind speeds, due to the El Nino Southern Oscillation (ENSO), could also be investigated. Extreme wind speeds with very low probabilities of occurrence are of interest for wind loading applications, and these have been discussed elsewhere for Melbourne (e.g. Holmes 2020, 2021). Any long-term changes in the parameters of the distributions with time, as a result of climate change, are also of great interest, but the length of the database may be too short to discern any clear trends.

Conflict of interest: The author declares no conflicts of interest.

Figure 12: The Fawkner Beacon (the anemometer with direction vane is at the highest point on the tower — shown ringed in red).

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Appendix: Glossary of terms

Term	**Meaning**
(aerodynamic) roughness length	A measure of surface roughness; it is also equal to the height at which the wind speed becomes zero
anemometer	An instrument for measuring wind speed – commonly by the speed of rotating cups
friction velocity	A scaling velocity for boundary layers equal to the square root of the stress on the surface divided by the air density
geostrophic wind speed	The wind speed well above the earth's surface, not affected by terrain roughness
gust factor	Ratio between the peak gust wind speed and the mean (average) wind speed
logarithmic law	A mathematical relationship between wind speed and height above the earth's surface
probability density	The probability that a wind speed falls within a narrow range of values
spectral density	A measure of the distribution of turbulence (gustiness) over frequencies
turbulence intensity	A measure of wind gustiness — equal to the ratio of the root-mean square velocity fluctuation to the mean wind speed