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Supplement of

The impact of sea breezes on offshore wind energy resources in Australia

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Supplementary Material for: "The impact of sea breezes on offshore wind energy resources in Australia"

Contents:

S1. Sea breeze object filters

Several filters are used for identification of sea breeze objects. These attempt to filter our non-sea-breeze objects from a mask of candidate sea breeze objects, using physically-based criteria. These filters are listed in the table below, and are developed by Brown et al. (2026) except for the “temporal moisture increase” filter.

Filter	**Details**
Orientation relative to the coastline	The angle of orientation of the sea breeze object must broadly align with the orientation of the dominant coastline, within a tolerance of 45°. The dominant coastline angle of orientation is defined for each grid point in the BARRA-C2 domain, following the method described in Brown et al. (2026). For each grid point, the direction to the coastline is defined by calculating an inverse-distanced weighted average angle. This angle is then rotated to an orientation. For defining the coastline orientation associated with a sea breeze object, the angles for each grid point are averaged spatially over the object.
Aspect ratio	The aspect ratio of the sea breeze object must be greater than 2. The aspect ratio is estimated from an ellipse fitted to the object.
Area	The area of the sea breeze object must be at least 12 pixels
Land-sea temperature difference	The near-surface (2 m) air temperature over the land must be warmer than the temperature over the ocean. The land-surface temperature difference, ΔT, is calculated for each grid point as the difference between the closest ocean point and the maximum temperature within 50 km of the closest land point. For each object, the land-sea temperature contrast is then defined by the average ΔT over the object.
Onshore wind speed	The onshore component of the 10 m wind, averaged over the area of the candidate sea breeze object, must be positive. The onshore wind component is calculated by rotating the u and v wind components using the dominant coastline angle of orientation (described above in the Orientation filter)
Temporal moisture increase	An additional sea breeze filtering step is developed and applied in this study, compared with the method of Brown et al. (2026). That is, the change in specific humidity relative to the previous hour, averaged spatially over the candidate sea breeze object, must be positive. This is intended to remove synoptic-scale cold fronts, which are dry, and occur frequently over southern Australia during the cool season. The application of this filter did not significantly change the total spatial distribution of object occurrences, but did lower the amount of sea breeze objects during the winter, likely related to a reduction in the mis-classification of synoptic-scale cold fronts (not shown).

Table S1: A description of sea breeze object filters

S2: Comparison of sea breeze front days with previous studies

In this section, sea breeze front (SBF) days are defined for three regions over 1979–2024, following the methods outlined in Section 2.2 of the main text. The seasonal cycle of SBF days in these regions are then compared with the results of three previous studies on sea breeze occurrences in Australia, for the purposes of evaluating the accuracy of the sea breeze identification methods used in the main text. The three regions (and studies) are the southeast of the Australian state of Queensland near the city of Brisbane (Soderholm et al., 2017), the southwest of Australia near the city of Perth (Masselink and Pattiaratchi, 2001) and near the city of Adelaide in the Australian state of South Australia (Pazandeh Masouleh et al., 2016). The seasonal cycle from each of the three previous studies are approximately reproduced here, by manually extracting data from the relevant figures of each paper.

In the current study, SBF days are counted for each region by considering the occurrence of a sea breeze object in a broad coastal area (see shaded area in Figure S1), and compared with results from previous studies based on point observations within that area (see orange crosses in Figure S1). This discrepancy between area and point definitions is due to the characterisation of the sea breeze as a frontal object in the current paper, with the broader circulation around that front impacting local conditions away from the front. The number of sea breeze objects is sensitive to the size of the coastal area chosen, although the shape of the seasonal cycle remains consistent for any reasonably sized region (not shown). The size of the coastal areas shown in Figure S1 were subjectively chosen based on the expected area for which a detected sea breeze object could impact local surface conditions, as well as the agreement between the subsequent SBF counts with the previous results shown.

Figure S1 shows that the monthly distribution of mean SBF days per month in southeast Queensland agrees very well with the results from Figure 2b of Soderholm et al. (2017). This includes both the number of SBF days per month and the shape of the seasonal cycle, with a peak of 14–15 days per month during October–November (Austral Spring), and a minimum of around 3.5 days per month during June (Austral Winter). Sea breeze days are defined by Soderholm et al. (2017) at the Archerfield automatic weather station (indicated in Figure S1) over an 18-year period (1997–2014), based on a local observed increase in wind speed and relative humidity, and a change in wind direction.

The seasonal cycle of mean SBF days per month in Perth broadly follows the results from Figure 4a of Masselink and Pattiaratchi (2001), shown in Figure S1. However, there are a larger number of SBF days identified per month from January–March (around 23–25) compared with the previous study (around 16–20), and fewer days per month from June–November. The peak of SBF days is also shifted to January (25 days per month), compared with December in previous study (23 days per month). Both the SBF days and previous study indicate a minimum during June, although with fewer SBF days per month (6) compared with the previous study (10). Masselink and Pattiaratchi (2001) identify sea breeze days using weather station observations at Perth Airport (indicated in Figure S1) from 1949–1997, using wind speed and direction only. Therefore, there is potential for large-scale changes in wind speed and direction to be falsely identified by sea breezes in that study, especially during the cool-season when synoptic-scale cold fronts can frequently impact the Perth region. It is acknowledged in that study that "the sea breeze selection algorithm works extremely well for the summer wind data, but is slightly less successful in identifying sea breezes during the winter".

The seasonal cycle is also broadly similar between the SBF days and results from Figure 4 of Pazandeh Ma-

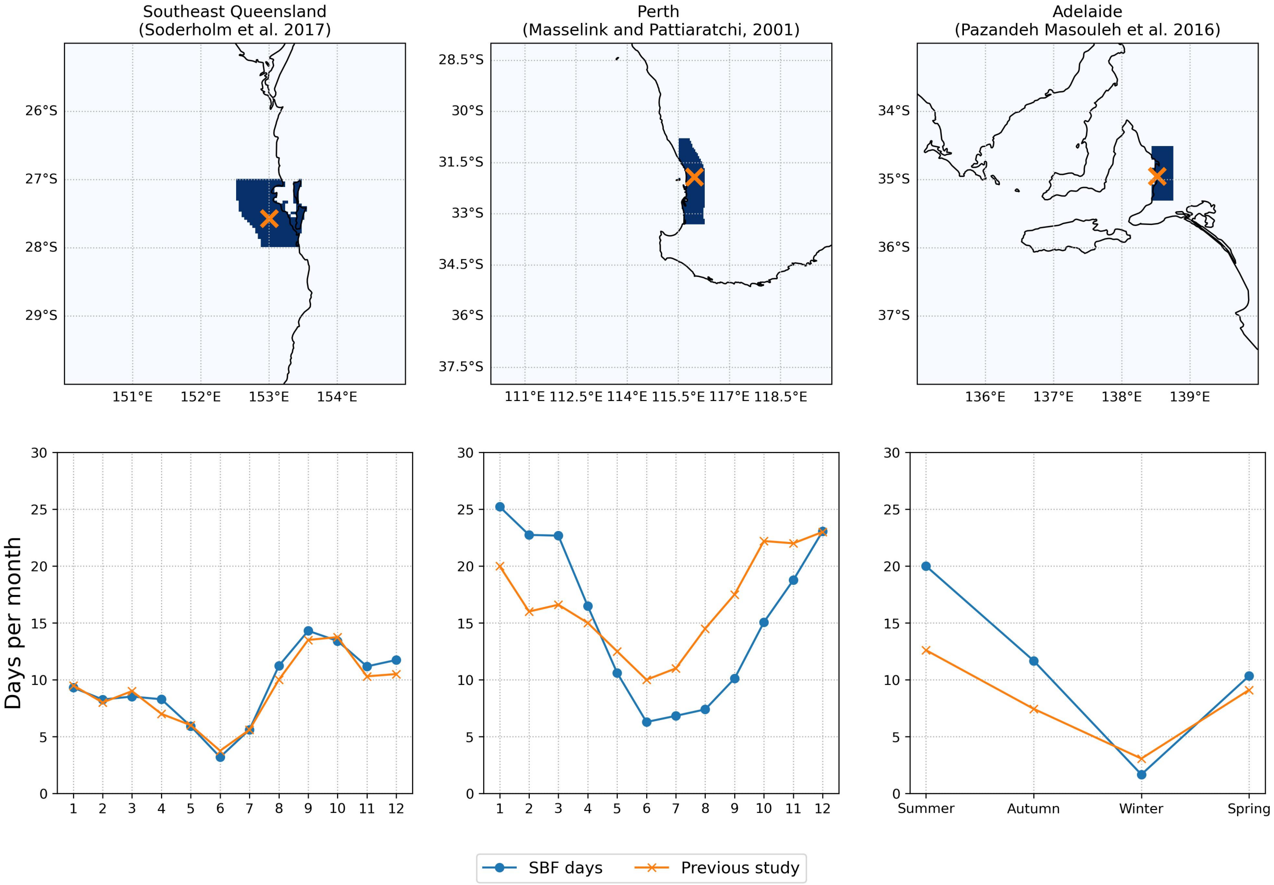


Figure S1: (bottom panels) Comparison between the (blue circles) seasonal cycle of sea breeze front (SBF) days, using methods described in Sections 2.1 and 2.2 of the main text, and (orange crosses) three previous studies for (left) southeast Queensland, (centre) the city of Perth and (right) the city of Adelaide. In each of the top panels, the areas used to define SBF days are shown with blue shading, while the locations of weather stations used to define sea breeze days in each of the previous studies are indicated with an orange cross.

souleh et al. (2016) for the city of Adelaide, shown in Figure S1. In that study, results are reported as the median sea breeze days per season, and are converted here to median days per month within each season by dividing by three. The median number of SBF days per season are very similar to the previous study for the Austral Winter (June–August) and Spring (September–November), although a larger number of SBF days per month are observed during Summer (December–February, 20 compared with 12.5) and Autumn (March–May, 12 compared with 7.5). Pazandeh Masouleh et al. (2016) identify sea breeze days using wind speed and direction data from the Adelaide Airport weather station, over a period of 1955–2008, constrained to days with a climatologically average land-sea temperature contrast above 0 °C, as well as days without a strong offshore wind observed by radiosonde. The observations used include 3-hourly surface wind observations and 12-hourly radiosonde data, and the study notes that "the (method) is likely to underestimate the frequency of sea breeze days as some potential sea breeze days with shorter duration might not be detected". This could contribute to the lower sea breeze days per month in that study compared with the SBF days used here.

In summary, the SBF days for three selected regions broadly agree with three different previous studies for each region, in terms of the approximate magnitude and shape of the seasonal cycle. This provides confidence that the sea breeze identification methods and SBF days used in the main text are able to accurately represent the observed variability in sea breeze days around Australia. There are also some differences between the seasonal cycle in SBF days and previous studies for Perth and Adelaide. Some differences are to be expected given the very different methods used between those previous studies (based on station wind data) and the current study (based on moisture frontogenesis from atmospheric model data).

S3: Average daily profile of wind capacity factor and energy demand (seasonal)

In this section, the average daily cycle in wind energy capacity factor is compared between sea breeze front (SBF) days and other days, as well as regional energy demand. This is done for eight different offshore wind areas, as well as each season of the year, extending on the results for December–February (DJF, austral summer) from the main text.

The key findings for DJF, as reported in the main text, are that:

- For six out of eight offshore wind areas (Illawarra, Newcastle, South Australia, Southern Ocean, Bunbury nearshore and offshore), average wind capacity factors are higher in the afternoon on SBF days compared with other days.
- For all regions besides Tasmania, average energy demand (for the broader state region) is higher on SBF days compared with other days.
- The afternoon peak in wind energy tends to occur at a similar time of day to peak energy demand.

Figure S2 shows that some of these results may not extend to other seasons of the year. For example, the energy demand pattern is similar between SBF days and other days for each of the other seasons, across all regions. In addition, for regions where the wind capacity factor is enhanced in the afternoon on average in DJF (for example, Illawarra, Figure S2b.1), this behaviour is reduced in other seasons (for example, Figure S2b.2–b.4). However, the diurnal cycle of wind capacity factor in other seasons besides DJF still appears to broadly peak in the afternoon, at a similar time as energy demand, besides in the winter (June–August, JJA) and spring in some regions (September–November, SON).

As in Table 2 of the main text, Table S2 shows the difference in average capacity factor throughout the day, between sea breeze front days and other days, as well as the corresponding difference in integrated wind energy (GWh per day) based on a 2.2 GW wind farm.

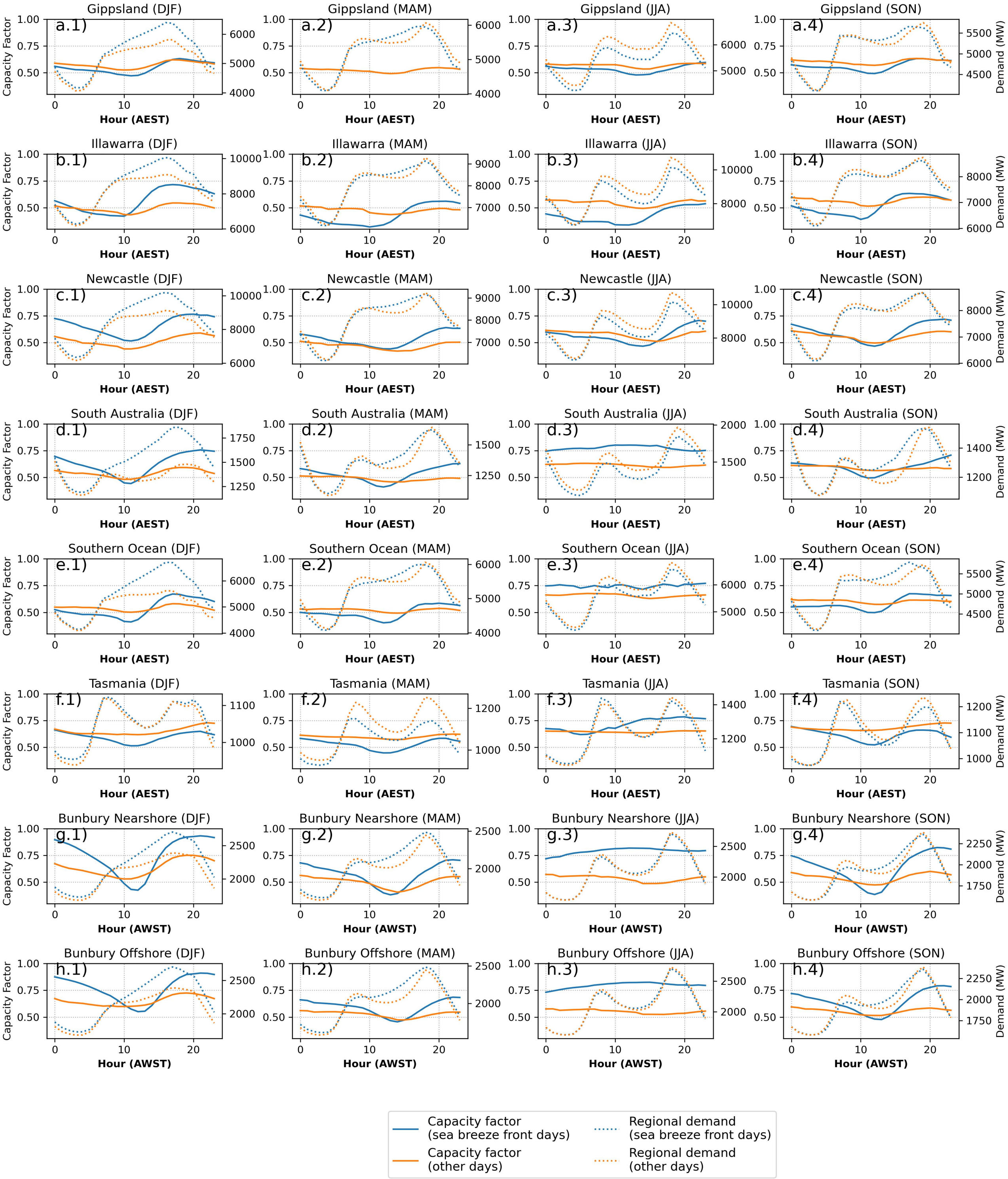


Figure S2: The average daily profile of (solid lines) wind energy capacity factor and (dotted lines) regional energy demand. Each row is the average over a different offshore wind area, and each column is a different season of the year, including December–February (DJF, as in Figure 5 of the main text), March–May (MAM), June–August (JJA) and September–November (SON). For each panel, results are subset into (blue) days with sea breeze fronts and (orange) other days. Times shown are Australian Eastern Standard Time (a.1–f.4, AEST, UTC+10) and Western Standard Time (g.1–h.4, AWST, UTC+8).

Table S2: Difference in average daily capacity factor (CF) and theoretical wind energy generation (in GWh per day) between days with a sea breeze front and other days, using data from all months of the year. Positive values represent surplus CF or GWh on sea breeze front days. Calculated separately using all daily data, as well as just for the morning (00:00–11:59 local standard time) and afternoon/evening (12:00–23:59 local standard time). Theoretical wind energy generation is based on a 2.2 GW capacity wind farm.

	CF (entire day)	CF (morning)	CF (afternoon)	GWh per day (entire day)	GWh per day (morning)	GWh per day (afternoon)
Gippsland	-0.035	-0.057	-0.012	-1.802	-1.387	-0.237
Illawarra	-0.013	-0.091	**0.064**	-0.714	-2.270	**1.684**
Newcastle	**0.074**	**0.042**	**0.106**	**3.632**	**1.004**	**2.639**
Southern Ocean	-0.045	-0.095	**0.006**	-2.309	-2.298	**0.265**
South Australia	**0.033**	-0.001	**0.067**	**1.507**	-0.024	**1.695**
Tasmania	-0.049	-0.044	-0.054	-2.531	-1.046	-1.237
Bunbury Nearshore	**0.142**	**0.112**	**0.171**	**6.992**	**2.782**	**4.292**
Bunbury Offshore	**0.139**	**0.126**	**0.152**	**6.889**	**3.096**	**3.741**

S4: Average daily profile of surface air temperature on sea breeze front days and other days

Figure S3 shows the average daily profile of surface air temperature for each coastal land region, adjacent to each offshore wind area during the summer. Daily profiles are shown separately for days with a sea breeze front (SBF) identified in the same area, and other days. Figure S3 demonstrates that on SBF days, air temperatures over the land tend to be higher, providing enhanced sea breeze forcing and regional cooling demand (see main text).

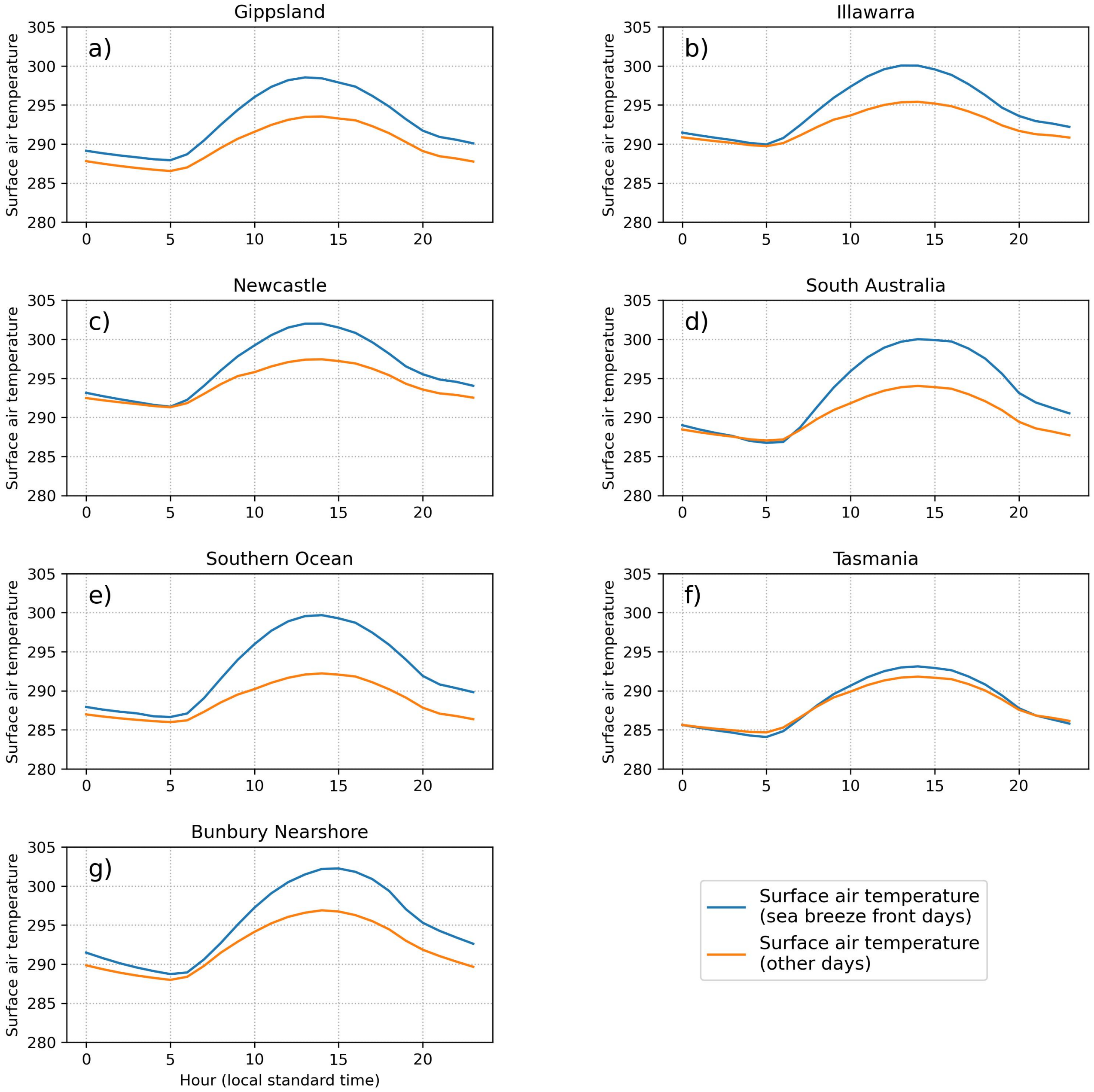


Figure S3: The average surface air temperature over coastal land regions adjacent to each offshore wind area, during the summer, on (blue) sea breeze front (SBF) days and (orange) other days.

S5: Sensitivity to prevailing wind direction

Daily sea breeze occurrence frequencies and afternoon capacity factors are presented here based on different prevailing wind directions for each region. These are shown for the December–February period only. The prevailing wind is defined using the u and v wind components at 850 hPa and 05:00 in the morning (local standard time). Four different prevailing wind quadrants are defined relative to the coastline in BARRA-C2. These include offshore or offshore flow with land to the right or left. To calculate the onshore/offshore and left/right components, we define coastline angles in BARRA-C2 and rotate the u and v wind components to be coastline-relative, following the methods of Brown et al. (2026).

Results are shown in Figures S4 and S5, supporting the findings in the main text that the prevailing wind direction has a large impact on sea breeze occurrence frequency and the associated afternoon wind energy capacity factor. In particular, sea breezes tend to occur most frequently with offshore prevailing winds (Figure S4). The relationship between prevailing wind direction and afternoon capacity factor depends on the region, and if there are sea breeze identified or not (Figure S5).

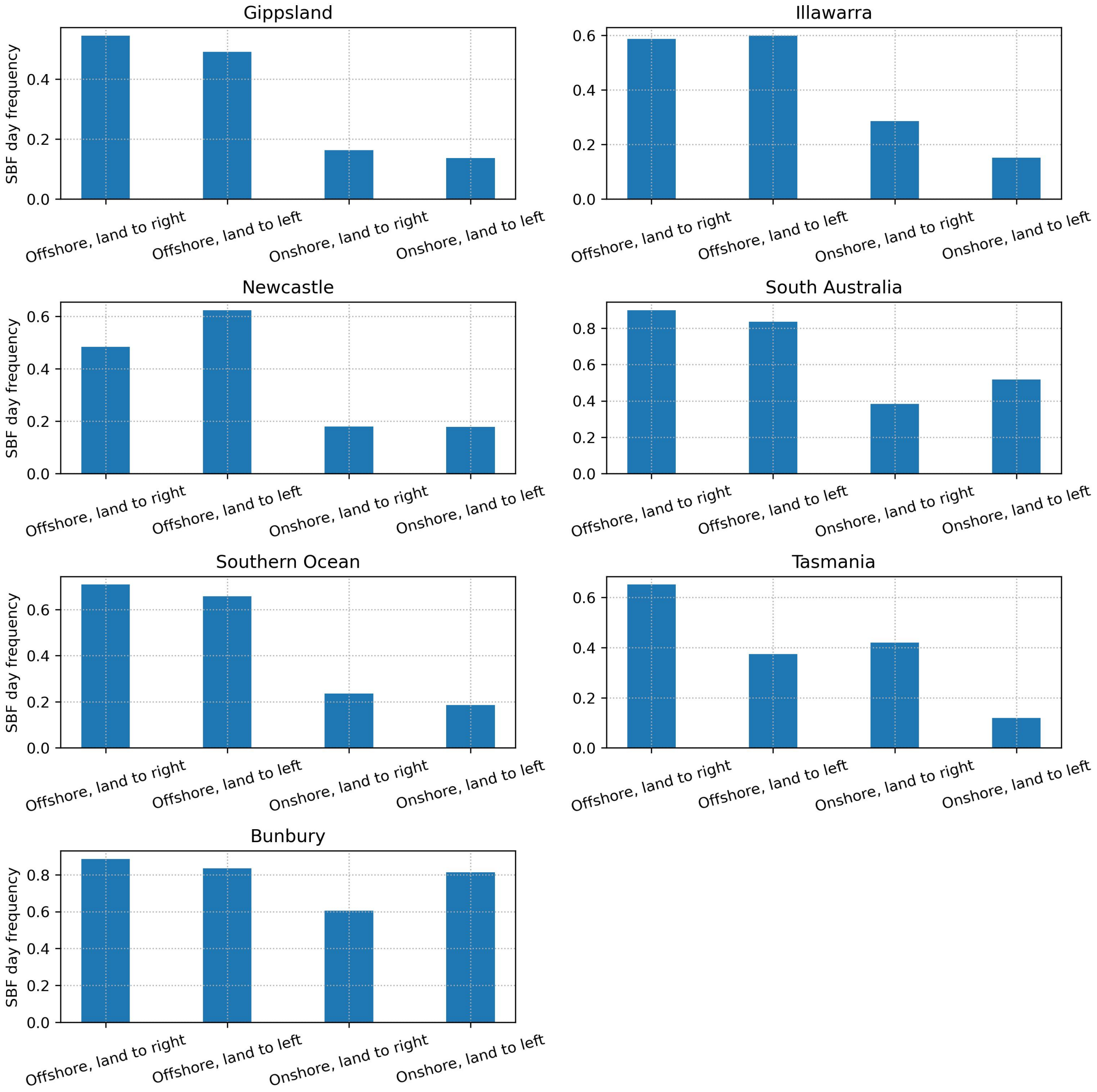


Figure S4: The daily December–February occurrence frequency of a sea breeze front in each coastal land area (see main text Figure 1), for four different prevailing wind quadrants.

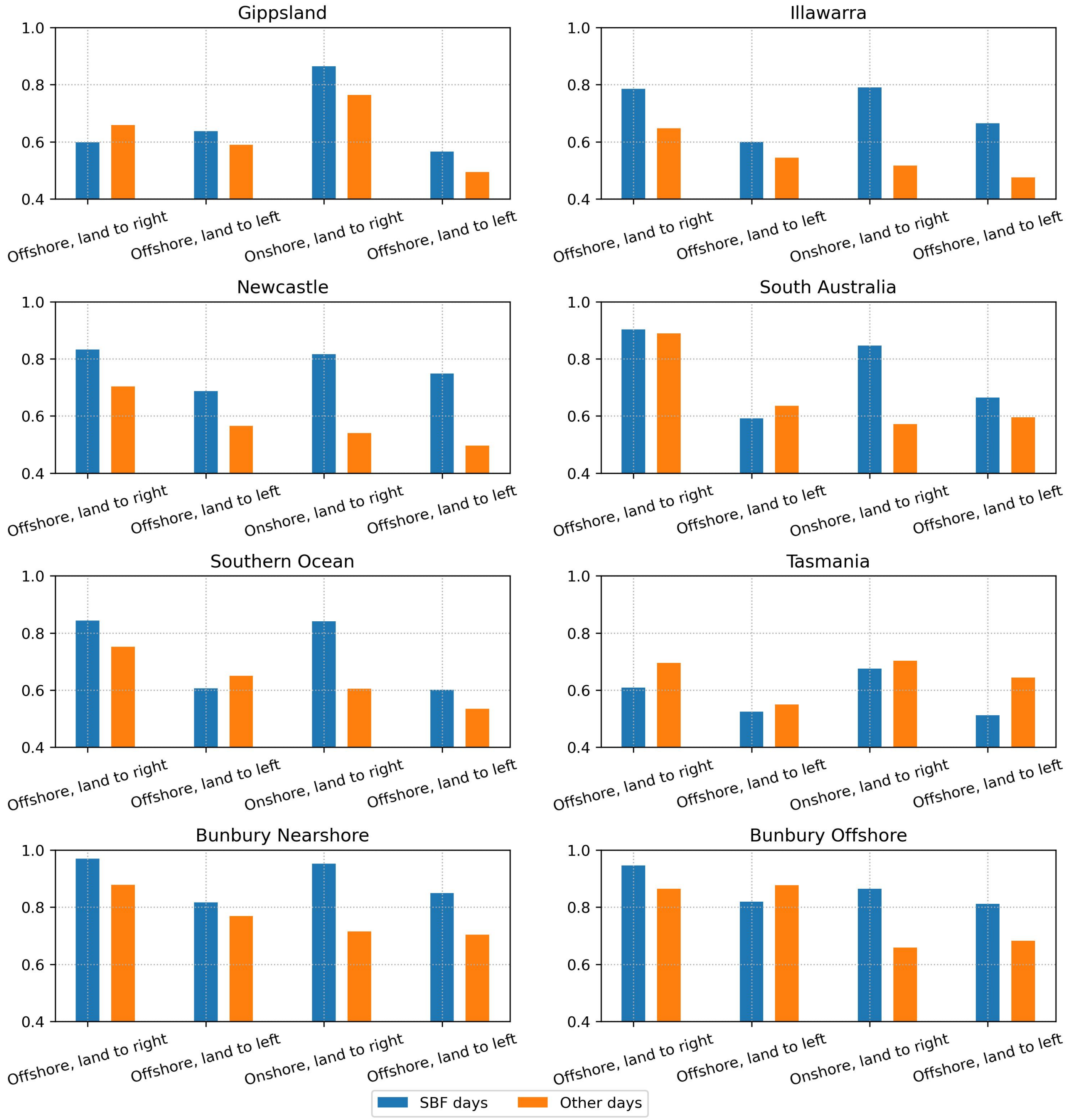
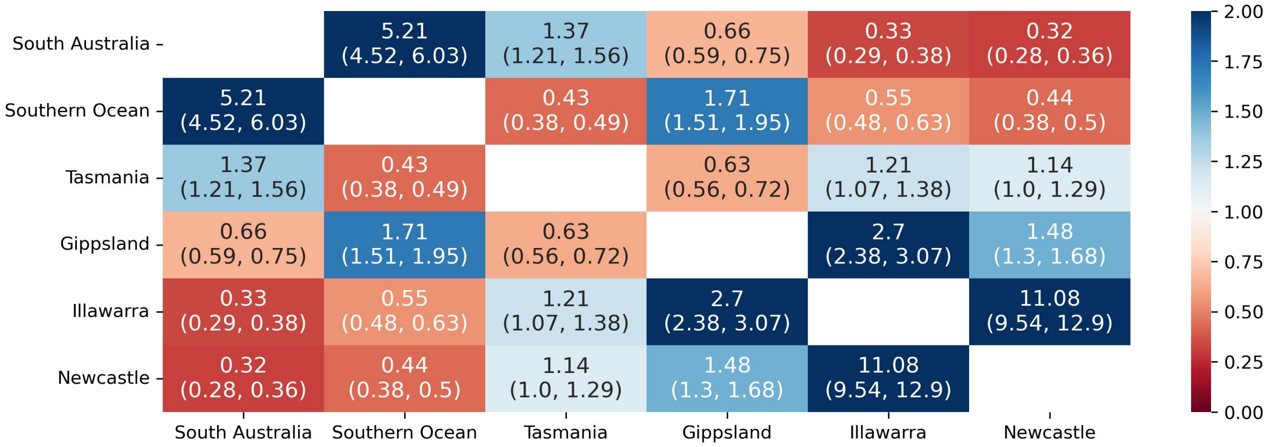


Figure S5: The average afternoon (18:00 local standard time) December–February capacity factor in each offshore wind area (see main text Figure 1), for four different prevailing wind quadrants, and for (blue) days with a sea breeze front (SBF), as well as (orange) other days.

S6: Odds Ratios for sea breeze front days across regions

The correlation of daily sea breeze occurrences between regions is quantified using the Odds Ratio in Figure S6. For two regions (say, region A and B), the Odds Ratio describes the ratio of the odds that a SBF day occurs in region A given a SBF day in region B, compared to a SBF day in region A without a SBF day in region B. An Odds Ratio significantly greater than 1 indicates that the odds of a SBF day occurring in region A are enhanced if there is a SBF day in region B, suggesting that SBF occurrences between the two regions are positively correlated. Similarly, an Odds Ratio significantly less than 1 suggests that SBF day occurrences between regions are anti-correlated, with values around 1 suggesting no correlation.

Figure S6 further quantifies the findings in the main text, with Odds Ratios > 1 between coastlines of similar orientations, and Odds Ratios < 1 for coastlines that are opposite-facing. For example, the odds of an SBF day in Illawarra is 2.7 times higher when there is a SBF day in Gippsland (as they are both east-facing coastlines), and vice versa. In contrast, the odds are reduced by 50% when there is a SBF day in the Southern Ocean region (as the Illawarra and Southern Ocean coastlines are opposite-facing). Similarly, for the South Australia region, the odds of an SBF day is 5.2 times greater if there is a SBF day in the neighbouring Southern Ocean region, while the odds are reduced by around 70% if there is a SBF day in the Illawarra or Newcastle regions.



	South Australia	Southern Ocean	Tasmania	Gippsland	Illawarra	Newcastle
South Australia		5.21 (4.52, 6.03)	1.37 (1.21, 1.56)	0.66 (0.59, 0.75)	0.33 (0.29, 0.38)	0.32 (0.28, 0.36)
Southern Ocean	5.21 (4.52, 6.03)		0.43 (0.38, 0.49)	1.71 (1.51, 1.95)	0.55 (0.48, 0.63)	0.44 (0.38, 0.5)
Tasmania	1.37 (1.21, 1.56)	0.43 (0.38, 0.49)		0.63 (0.56, 0.72)	1.21 (1.07, 1.38)	1.14 (1.0, 1.29)
Gippsland	0.66 (0.59, 0.75)	1.71 (1.51, 1.95)	0.63 (0.56, 0.72)		2.7 (2.38, 3.07)	1.48 (1.3, 1.68)
Illawarra	0.33 (0.29, 0.38)	0.55 (0.48, 0.63)	1.21 (1.07, 1.38)	2.7 (2.38, 3.07)		11.08 (9.54, 12.9)
Newcastle	0.32 (0.28, 0.36)	0.44 (0.38, 0.5)	1.14 (1.0, 1.29)	1.48 (1.3, 1.68)	11.08 (9.54, 12.9)	

Figure S6: Odds Ratios describing the relationship of sea breeze front (SBF) day occurrences between regions. Values greater than 1 indicate that a region has greater odds of a SBF day if a SBF occurs in another region, with the oppostie true for values less than 1. A 95% confidence interval is also shown.

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