The Potential Wind Power Resource in Australia: A New Perspective

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The Potential Wind Power Resource in Australia: A New Perspective

Willow Hallgren[*†], Udaya Bhaskar Gunturu[*], and C. Adam Schlosser[*]

Abstract

Australia is considered to have very good wind resources, and the utilization of this renewable energy resource is increasing. Wind power installed capacity increased by 35% from 2006 to 2011 and is predicted to account for over 12% of Australia's electricity generation in 2030. This study uses a recently published methodology to address the limitations of previous wind resource analyses, and frames the nature of Australia's wind resources from the perspective of economic viability, using robust metrics of the abundance, variability and intermittency of wind power density, and analyzes whether these differ with higher wind turbine hub heights. We also assess the extent to which wind intermittency can potentially be mitigated by the aggregation of geographically dispersed wind farms. Our results suggest that over much of Australia, areas that have high wind intermittency coincide with large expanses in which the aggregation of turbine output does not mitigate variability. These areas are also geographically remote, some are disconnected from the east coast's electricity grid and large population centers, and often are not connected or located near enough to high capacity electricity infrastructure, all of which would decrease the potential economic viability of wind farms in these locations. However, on the eastern seaboard, even though the wind resource is weaker, it is less variable, much closer to large population centers, and there exists more potential to mitigate its intermittency through aggregation.

Table of Contents

1. INTRODUCTION

The general climatology of the winds in Australia has been documented on a national basis (Gentilli, 1971; Parkinson, 1986; Mills, 2001) and at the state level (Dear, 1991; Dear *et al.*, 1990; ETSA, 1989; Blakers *et al.* 1991), using a variety of methodologies (Coppin *et al.*, 2003). Such climatologies indicate that Australia has wind resources that are in places comparable to

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those in northern Europe, and indicate that the location of the strongest winds is in western, southwestern, and southern Australia, and southeastern coastal regions (Coppin *et al*., 2003).

The physical quantity conventionally used to describe the wind energy potential in Australia is wind speed in m s^{-1}, whereas in the USA, wind atlases show maps of wind power density (WPD) to describe the quality of the wind resource. Most previously published studies use the mean to characterize the central tendency of the wind resource, however histograms of the wind resource measured using wind power density are characteristically skewed with long-tailed distributions (Gunturu and Schlosser, 2012). To add to this critique, wind power studies based only on the total mean WPD do not give a representative picture of the central tendency of the wind power potential and omit valuable information in terms of wind intermittency, variability and the temporal distribution of power generation (Hennessey Jr., 1977), which would affect estimates of power production and required backup (Gunturu and Schlosser, 2011).

Variability in the wind resource has major ramifications for the economics and therefore the feasibility of wind power generation and distribution, and hence measures of variability are useful for wind energy policymakers. Yet, very few atlases show maps of wind variability (Gunturu and Schlosser, 2012), and when they do it is typically in terms of the standard deviation of the wind speed or WPD. However, the economic viability of wind power as an alternative energy source strongly depends on how reliable the resource is, in terms of its availability and persistence, as well as other factors such as proximity to high-capacity power transmission lines, and how remote it is from population centers and the electricity grid. The reliability of wind power can in theory be increased by mitigating the natural intermittency of the wind resource, by aggregating power from wind farms that are geographically dispersed, with the aim of achieving a more continuous wind resource over large areas, and there have been several studies trying to address this issue (Kahn, 1979; Archer and Jacobson, 2007).

Wind power production doubled in the 5 years leading up to 2012, and has grown 340% since 1997, to meet 3.4% of Australia's total electricity demand and 26% of total renewable energy generated, which is a bit less than half that generated by hydropower (Clean Energy Council, 2012). Wind power will become economically competitive in the coming decades, and is projected to grow by 350% when wind power projects currently in development come online in the next few years [15]. This projected expansion of wind energy conforms to national government policies that have been designed to lower carbon emissions, including the Carbon Emissions Trading Scheme and the Renewable Energy Target of 20% by 2020 (Sinclair Knight Merz, 2010). In light of this policy directive, there is a need to increase the accuracy and practical relevance of the assessment of Australia’s wind power resource.

We assess Australia’s potential wind power resource with alternative metrics of abundance, variability and intermittency that provide deeper insights about the stability of the wind resource at a widespread deployment scale (Gunturu and Schlosser 2012, 2011), using a robust, multidecadal data set. Questions our study asks include: (1) What is the geographical distribution of the abundance, variability, availability, and persistence of wind power density (WPD); and do these differ with higher turbine hub heights? (2) Where can wind intermittency be mitigated by the aggregation of geographically dispersed wind farms?

2. METHODS

2.1 Data

We have sought to address some of the limitations of previous wind resource studies that used data that had a coarse spatial and temporal resolution, a relatively short record length, and sparse and uneven coverage (Pryor and Barthelmie, 2011; Gunturu and Schlosser, 2011). We used 31 years of hourly $0.5^{\circ} \times 0.75^{\circ}$ resolution MERRA (Modern Era Retrospective Analysis for Research and Applications (Rienecker *et al.*, 2011) data (from 0030 on January 1st, 1979 to 2330 on 31st December, 2009), to reconstruct the wind field at 50 m, 80 m, and 150 m. These heights were chosen to represent the recent 1990s (USA) 50 m standard wind turbine hub height (Elliott *et al.*, 1987, 1991), and the 80 m hub height, which has become more common as technology develops, and the potentially much higher hub heights in the future.

Wind speed and wind power density were computed at these heights using boundary layer flux data (consisting of such parameters as surface roughness, displacement height and friction velocity) and similarity theory of the atmospheric boundary layer (Gunturu and Schlosser, 2012). By doing this, we sought to improve on previous wind resource constructions which used a constant scaling exponent (irrespective of surface roughness) to scale the wind speed from a lower altitude (usually 10 m) to that of the turbine hub height. We use WPD ($W \cdot m^{-2}$) to describe the wind resource as it is a function of not only wind speed but also density, which also varies in space and time. It indicates how much wind energy can be harvested at a location by a wind turbine but is independent of wind turbine characteristics. The domain considered for our study spans the entire Australian continent plus Tasmania, between 10° S and 45° S latitudes and 110° E and 155° E longitudes.

2.2. Comparison with Existing Wind Climatologies in Australia

We assessed the accuracy of the MERRA data by comparing a map of wind speed at 80 m that we constructed from this MERRA data, to an existing map of wind speed at the same height developed by the Australian Government Department of the Environment, Water, Heritage and the Arts (hereafter referred to as AGD), as detailed above (Sinclair Knight Merz, 2010:9). We chose to compare wind speed, as a continent-wide map of WPD was not available for Australia. We compare our construction of wind resource at an 80 m hub height with this data set, since it is a widely accepted published wind resource produced by the government (Sinclair Knight Merz, 2010).

2.3. Wind Resource Metrics

The metrics we use in our study are wind abundance, variability, and intermittency in the form of availability and persistence (Gunturu and Schlosser, 2011, 2012). Most previously published studies use the mean to characterize the central tendency of the wind resource. Since the mean is not a robust measure of the central tendency for distributions with long tails, we use the median, which is immune to the extreme values in the distribution, as a robust measure of the wind resource abundance.

Instead of using the standard deviation to represent the variability of the wind resource, we argue that the variability of the wind resource is better captured in terms of the robust coefficient of variation (RCoV), since it is calculated using the median, which we argue is a more accurate representation of the wind power at a given site than the mean. We also use the interquartile range (IQR) as a measure of the statistical dispersion, higher values of which can indicate the greater possibility of "swings" of the WPD at a location, and therefore the amount of backup power that needs to be maintained.

In addition to these measures of variability, we also look at two measures of the intermittency of the wind—availability (or lack of) and persistence—since these are important indicators of intermittency, which is recognized as one of the key limitations to large-scale installation of wind power. We apply the reliability theory concept of availability to wind power, as a measure of the temporal distribution of the wind resource, and therefore of the reliability of a wind power generation system. We calculate the percentage of hours in our time series where WPD is greater than 200 $W \cdot m^{-2}$, and use the inverse of this—unavailability—of non-useful WPD (i.e. proportion of hours where WPD is less than 200 $W \cdot m^{-2}$), to characterize the geographic distribution of the reliability of the wind resource (Gunturu and Schlosser, 2011), and as one measure of intermittency. Our rationale for choosing the 200 $W \cdot m^{-2}$ cut-off is the same as Gunturu and Schlosser (2011), and incorporates a number of contributing arguments, which are detailed in the Appendix. Mean episode lengths (i.e. number of hours of WPD above 200 $W \cdot m^{-2}$) were calculated as a measure of the persistence of the WPD, which is important in the planning and development of a robust deployment strategy for harvesting wind power.

We use Gunturu and Schlosser's (2011) technique to analyze the potential value of aggregating the power generated by geographically dispersed wind farms in a roughly 1000 km × 1000 km box (19 x 19 grid cells), in order to mitigate intermittency in the wind resource. Values of anticoincidence (Wiktionary, 2013), and null-anticoincidence were calculated for each grid cell (see Figure 5 in Gunturu and Schlosser, 2011) by converting the time series of WPD at each grid point into a binary sequence of 1s and 0s depending on if the WPD is greater or less than the 200 $W \cdot m^{-2}$ we use as the cut-off useful for viable commercial generation. We base our analysis of anti-coincidence on these binary sequences. Two grid points are said to be anticoincident when the hourly time series of WPD is greater than 200 $W \cdot m^{-2}$ at one of the two points, but not both, for 50% of the total length of the time series. We also calculate the null-anticoincidence, which offers a somewhat more relaxed criterion. Null-anticoincidence refers to the number of grid points in a roughly 1000 km × 1000 km area surrounding a central point which have usable wind power (less than 200 $W \cdot m^{-2}$), when the central point does not, for at least 50% of the time when there's no wind at the central point (Gunturu and Schlosser, 2011).

3. RESULTS AND DISCUSSION

Wind speed and wind power density were computed at several wind turbine hub heights using boundary layer flux data from the Modern Era Retrospective-analysis for Research and Applications (MERRA) (Reinecker *et al.*, 2011) and similarity theory of the atmospheric boundary layer (Gunturu and Schlosser, 2012). We use wind speed to compare our results to existing wind atlases (as the reference atlas for Australia uses wind speed instead of wind power density to measure wind power potential), as well as a range of metrics to analyze wind power density, including wind abundance, variability, and intermittency in the form of availability and persistence (Gunturu and Schlosser, 2011, 2012). Detailed descriptions of the data and methodology are described in the Section 2.

3.1. Comparison of MERRA and Australian Government Maps of Wind Speed

Our approximately 50 km × 67 km ($0.5^{\circ} \times 0.75^{\circ}$) map of 80 m above ground level wind speed (**Figure 1**) is quantitatively and geographically similar to the 9 km × 9 km resolution map of wind speed at the same height produced by AGD (Sinclair Knight Merz, 2010). This map was created by WindLab (www.windlab.com) for the AGD and is derived from observed weather station data taken from Bureau of Meteorology weather stations for the years 1995–2005, for the entire continent, and supplemented with commercially produced meteorological data sets, which are then assimilated into a high resolution broad-area wind mapping model called WindScape (Steggle *et al*., 2002). WindScape uses a regional scale weather model, The Air Pollution Model (TAPM) (Hurley, Blockley and Rayner, 2001), to improve the resolution of the observed data, and also a fine scale computational fluid dynamics model Raptor and/or Raptor-NL to create fine scale resolution maps of the wind resource over broad areas. The maps created are validated and adjusted to achieve consistency with observational data at ground level (International Renewable Energy Agency, 2012).

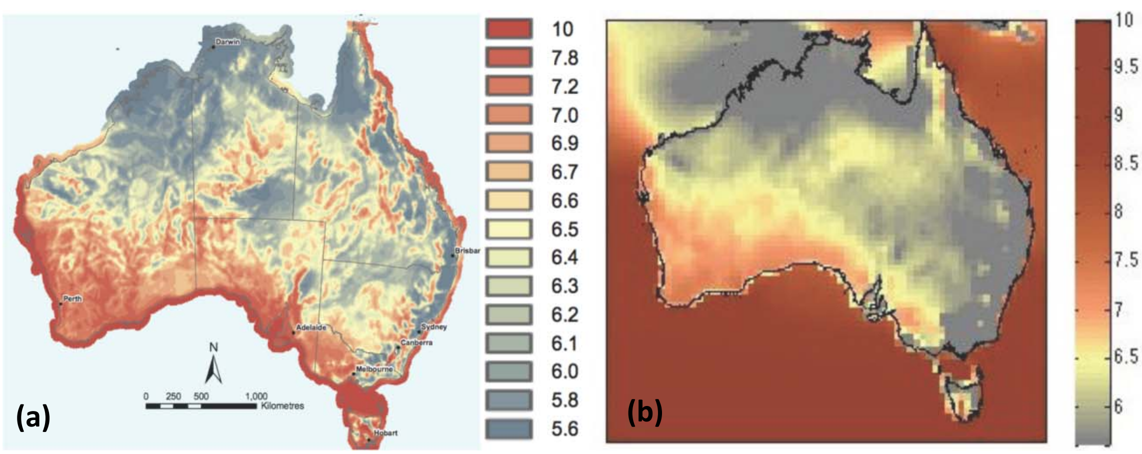

Figure 1. Comparison of mean wind speed (m·s) at an 80 m turbine hub height across Australia. (a) Map developed by the Australian Government Department of the Environment, Water, Heritage and the Arts in 2008, and (b) the map constructed from MERRA data.

While our construction of the wind resource matches qualitatively and quantitatively very well with that of the AGD, there are differences between the two maps in some regions. Our results mostly show slightly lower values for most areas compared to the AGD map (**Table 1**). Reasons for the differences seen in these two maps could be due to the lower spatial resolution of our constructed map and the lower temporal record length of the AGD map. Since the AGD wind resource map has been constructed by running a mesoscale model (TAPM) for 11 years, the record length of the construction is short compared to the record length of our construction (31 years). Short record lengths do not represent interannual variability and climate scale oscillations like the El Niño Southern Oscillation (ENSO) robustly.

Table 1. Comparison of the range of values (m·s) in many areas of the 80 m wind speed map constructed from MERRA data to the one produced by the Australian Government. The first region encompasses much of the East coast, and includes southeast and northeast QLD, and Tasmania.

Regions of similarity	MERRA data map	Australian government map
East coast, Tasmania	5.6–7.0	6.5–7.8
Western Victoria	6.5–7.0	Mostly >7.0
Southeast South Australia	6.4–7.2	Up to 7.8
Central Australia	5.6–7.0	5.8–6.6

3.2. Measures of Abundance and Variability

Reflecting the wind speed patterns of previous Australian wind atlases, our constructed map of mean WPD at 50 m (**Figure 2a**) shows that the strongest wind resources occur in southwest Western Australia, southern South Australia, and Tasmania, and southwestern Victoria. It is lowest in mountainous areas along the Great Dividing Range in eastern Australia, in northwest Australia, and northwest Queensland. Most of the continent has mean WPD values below 300, and most of the populated east coast of the country has values below 200 W·m^{-2} at this resolution, which is the cutoff for the production of usable power that turbines can produce, the rationale for which is detailed in the Appendix. As turbine hub height increases to 80 (**Figure 2b)** and 150 m (**Figure 2c**), there is an increase in mean WPD of up to about 40 and 100 W·m^{-2} in the northern two-thirds of Australia and 80 and 160 W·m^{-2} (and higher in Tasmania) in the south respectively. While the mean WPD construction reflects the other known data sets which illustrate wind speed, we extend the analysis that has historically been done, and look at other metrics of the resource that could be useful for assessing the economics of wind power generation and also for operational stability.

The map of median WPD at 50 m (**Figure 2d**) indicates that a greater part of the continent has WPD below the 200 W·m^{-2} value. Compared with the mean WPD in Figure 2a, the median values are almost half of the mean values throughout much of the country. This implies that the distribution is very skewed, and hence we argue that the median is a much more robust measure of central tendency and therefore a more appropriate metric to represent WPD.

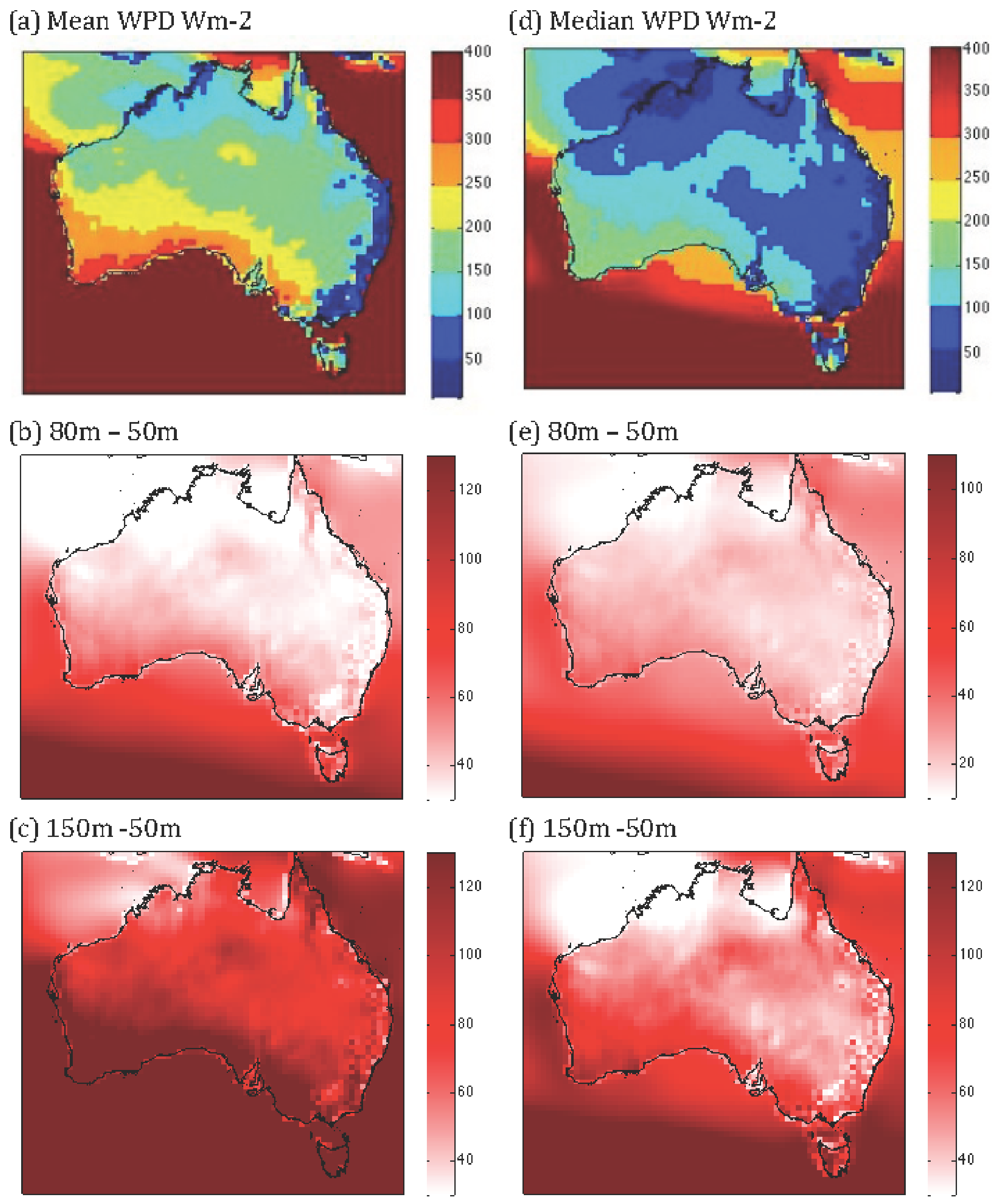

Figure 2. Measures of abundance. (a) The mean WPD at 50 m, (b) the change in the mean from 50 m to 80 m, (c) the change in the mean from 50 m to 150 m, (d) median wind power density at 50 m, (e) the change in the median from 50 m to 80 m, (f) and the change in the median from 50 m to 150m. All units are W·m^{-2}.

As turbine hub height increases to 80 m (Figure 2e) and then 150 m (Figure 2f), there is less of an increase in median WPD compared to mean; up to about 30 and 80 W·m^{-2} in the northern half of Australia, and up to about 50 and 120 W·m^{-2} (and higher in Tasmania) along the southern part of the country. This scenario implies that the number of hours which show an increase in WPD are about the same as those which show a decrease, however the increase of WPD in those hours which show an increase is greater than the decrease of WPD in the hours which show a decrease. We infer from this that variability and intermittency of the resource are increasing while the median resource is increasing.

Most maps of the variability of the wind resource use the standard deviation. We do not use the normal standard deviation. In line with our argument that the median is a better metric, being non-parametric, we use the 'robust coefficient of variation' (RCoV) which is the ratio of median deviation about the median to the median. Our results show that the highest RCoV values occur in southwest Tasmania and WA, and in southern South Australia, but inland from the coastline, which indicates these areas have relatively higher variability compared to the abundance in terms of the median (**Figure 3a**). The lowest values, indicating a less variable, more reliable wind resource, occur along the southeastern seaboard and in parts of northern Australia near the coast.

The interquartile range (Figure 3d) is a measure of an important measure of dispersion in the wind resource since it is immune from the effect of outlying extreme values. Thus it is one of the robust measures of dispersion. As such, it can provide insight into the possibility of swings in the wind resource and therefore the amount of backup power that needs to be maintained. At 50 m, the areas that show high IQR (**Figure 3d**) tend to coincide with areas that have the highest mean and median WPD (Figures 2a and 2d, southwest and southern parts of the continent), and increases more with turbine hub height in these areas (Figure 3f). The regions that have low mean WPD also have the lowest IQR (e.g., east coast). IQR increases with turbine hub height across the country, but RCoV increases with hub height in some areas (e.g. southeastern Australia), and decreases in others (much of inland Southern Australia) (**Figures 3b,c**). This is because although the median increases with height everywhere, variability decreases in some regions and increases in others.

When the median increases with the hub height, and the variability also increases as much or more, RCoV (which is the ratio of deviation to central tendency) also increases. The RCoV decreases when the median increases but the variation does not increase so much (i.e. the ratio decreases). A scenario where RCoV decreases with height indicates that raising the hub height would better harvest the greater wind resources at higher hub heights, with lowered variability and intermittency. With greater surface friction, the standard deviation of the wind in the boundary layer increases (Panofsky and Dutton, 1984). Therefore, the boundary layer roughness predominantly determines the impact that raising the hub height has on the RCoV of the wind resource.

If we consider just abundance and variability, regions that have high WPD and low variability (as shown by IQR) are areas where the wind resource could potentially be harnessed economically. Unfortunately, in Australia, our analysis indicates that at the resolution of this study, the areas which have mean WPD > 200 $W \cdot m^{-2}$ also have an IQR of at least the same magnitude if not greater, though undoubtedly there are isolated areas where this would not be the case – but our relatively coarse data set is unable to show this. However an additional very important consideration for harnessing wind power economically at a widespread deployment scale is the extent of its episodic nature— or intermittency.

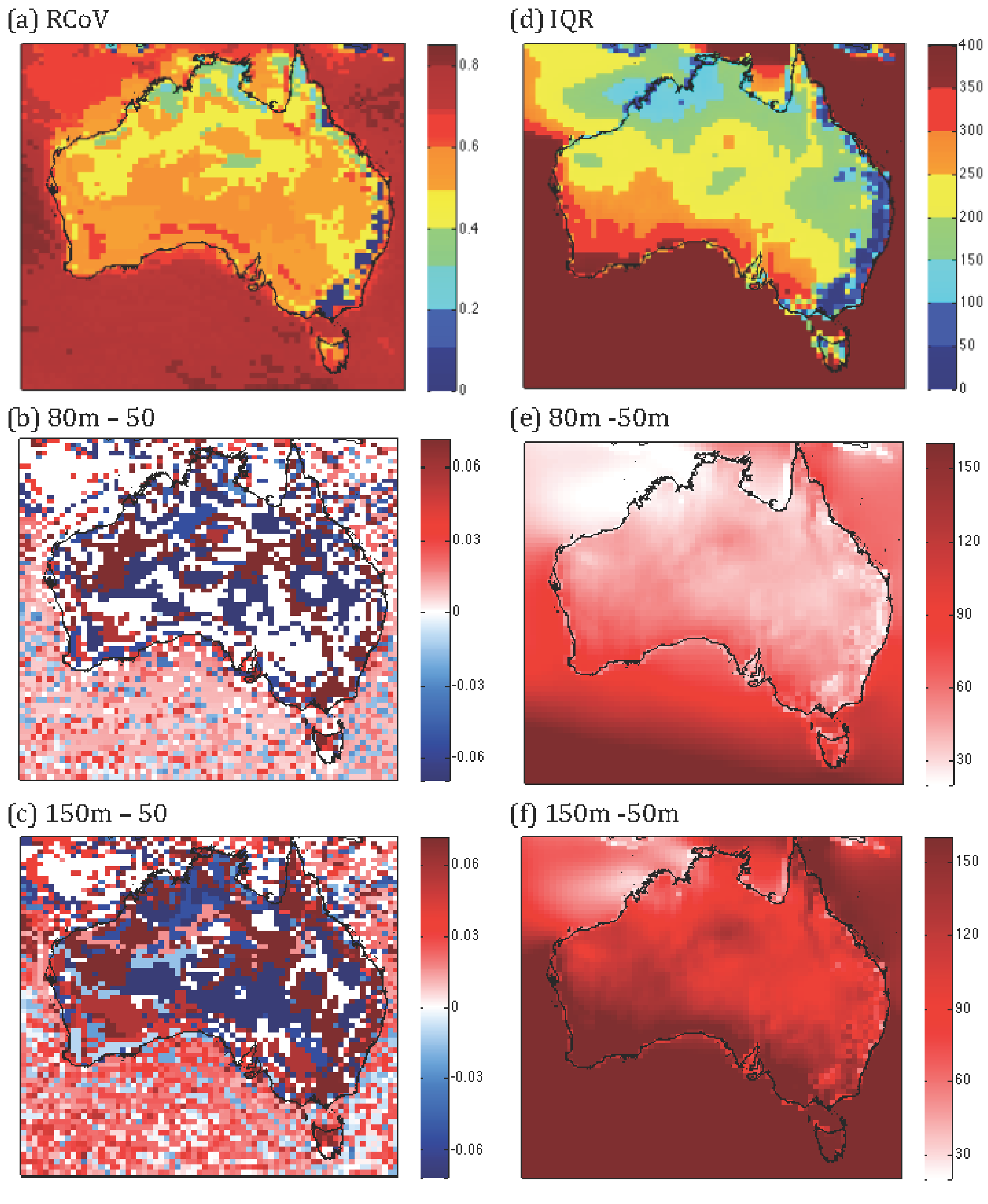

Figure 3. Measures of variation. (a) The robust coefficient of variation (RCoV—unitless) of WPD at 50 m, (b) the change in the RCoV from 50 m to 80 m, (c) the change in RCov from 50 m to 150m, (d) interquartile range (IQR, W·m^{-2}) at 50 m, (e) the change in the IQR from 50 m to 80 m, (f) the change in the IQR from 50 m to 150m.

3.3. Measures of Intermittency and the Potential for its Mitigation

To explicitly gauge the intermittency of WPD, we first consider a metric of unavailability (given as fraction of time WPD is less than a minimum threshold—see Section 2.1). We find that unavailability, which decreases with height, is generally highest in the areas where mean (or median) WPD is low (far northwest Australia, northern Tasmania, and just west of the Great Dividing Range on the eastern seaboard). The lowest values are seen along the eastern seaboard, indicating more reliable winds in these areas. Large areas scattered throughout northern and eastern Australia exhibit relatively high values (above 0.65), with the southwestern third of the country exhibiting moderate values (**Figure 4a**). Unavailability decreases with height, as might be expected (WPD increases, so given the 200 $W{\cdot}m^{-2}$ threshold of availability, it also increases), except for the areas which have the lowest mean WPD values—higher altitude areas along the eastern seaboard—which show a negligible change in unavailability with a change in height (**Figures 4b,c**).

The availability of WPD as a continuous resource over time is also considered. The spatial pattern of mean episode length (defined as the average time that WPD is continuously above the same threshold) closely resembles that of the mean WPD. We found that the mean episode length at 50 m hub height (**Figure 4d**) is lowest in parts of the Great Dividing Range in the east of the country, where WPD is low, and highest in the southern Australia, southwest Western Australia, and Tasmania, where WPD is highest. Mean episode length increases with height most where the mean WPD is lowest, along the Great Dividing Range in the east (**Figures 4e,f**). Conversely, areas where mean episode length is highest show only small increases (less than 2 hours) with increasing hub height to 80 m (Figure 4e), and raising the hub height to 150 m results in a near linear response in terms of additional episode length (Figure 4f).

The coincidence (or lack thereof—see Section 2) of intermittent wind power in different places sets the scope of installed backup generation capacity required to maintain a steady power supply, as well as the benefits of the aggregation of wind resources. The areas with the lowest unavailability (suggesting low wind intermittency, or more reliable, steady winds), coincide with areas of moderate to high anticoincidence at 50 m, such as along the eastern seaboard.

"Anticoincidence" denotes the occurrence of one event without the simultaneous occurrence of another (Wiktionary, 2013). The greatest intensity of anticoincident points is in the southeast of the continent, including northeast Tasmania (**Figure 5**). However, these areas also have a small episode length (suggesting less persistent winds), which suggests that the aggregation of wind farms may indeed help mitigate wind intermittency in the more densely populated southeast of Australia.

There are areas in Australia with relatively high intermittency—high unavailability and quite low mean episode length—such as northern and northwest Australia, that overlap a vast swathe of the continent west of the Great Dividing Range that shows little anticoincidence of WPD. These are the areas where aggregating turbines would be least effective, at the spatial and temporal scales analyzed. However, an analysis of the null-anticoincidence (Figure 5) across

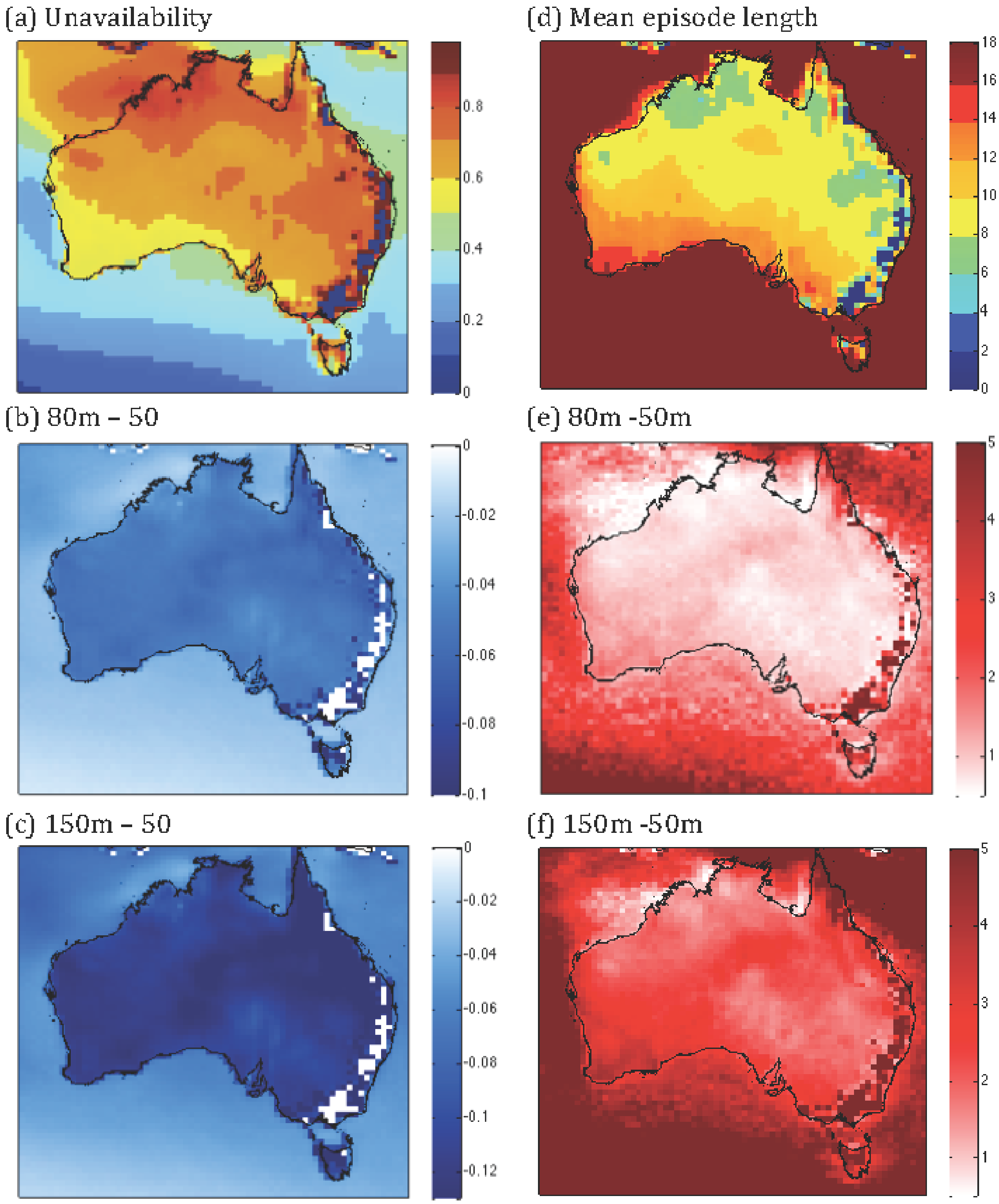

Figure 4. Measures of intermittency. (a) The unavailability of WPD at 50 m (fraction of time), (b) the change in the unavailability from 50 m to 80 m, (c) the change in the unavailability from 50 m to 150m, (d) the mean episode length at 50 m (hours) (e) the change in the mean episode length from 50 m to 80 m (f) the change in the mean episode length from 50 m to 150m.

Australia suggests that there may be some merit in linking wind farms across large areas to increase the reliability of the power supply in areas which show low anticoincidence and moderate to high intermittency, such as parts of the northern Queensland coast, inland New South Wales, and parts of western Victoria and Tasmania, all of which show high values of null-anticoincidence. This may improve the reliability of wind farms in these areas.

These results agree well with previous research which has shown the coexistence of higher values of anticoincidence with regions which have high topographical inhomogeneity (i.e. mountain ranges) and proximity to the sea. This research has also co-located low anticoincidence areas to low surface roughness (flat terrain), semiarid climate and terrains, with climate characterized by anticyclones which occur over large areas, leading to a large coincidence of low wind states across these high pressure systems (Gunturu and Schlosser, 2011).

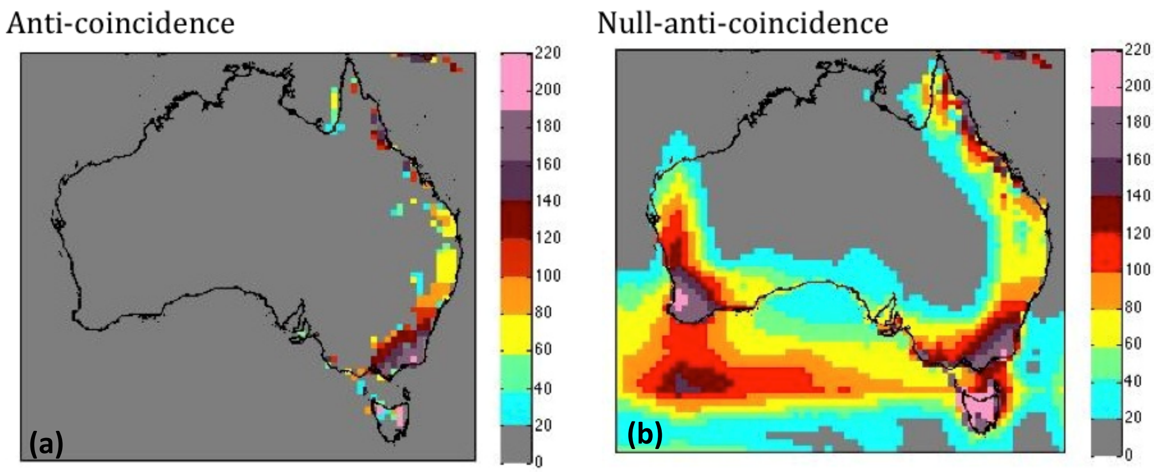

Figure 5. Anticoincidence (a) and Null-anticoincidence (b) of wind power density, at 50 m. Units indicate the number of grid points in a ~1000 km × 1000 km box surrounding the gridpoint in question which are anticoincident to the central gridpoint, which is when the hourly time series of WPD is greater than 200 W·m^{-2} at one of the two points, but not both, for 50% of the total length of the time series.

4. SUMMARY AND CONCLUSIONS

Our study suggests that many areas with the strongest widespread wind resource, in terms of both mean and median WPD (southwest Western Australia, southern South Australia and Tasmania, and southwest Victoria) also score relatively highly on measures of variability (IQR, RCoV) and exhibit moderate levels of intermittency, in terms of reliability (i.e. unavailability) and persistence (mean episode length). Many of the areas which have moderate to high wind intermittency also have very low anticoincidence, as defined in the Section 2, suggesting that there are large expanses of the continent in which aggregating turbines would be less effective, based on our study , at the spatial and temporal scales analyzed (keeping in mind the limitations of this study, as described next). These areas also tend to be geographically remote from the bulk of the Australian population on the east coast (certainly in Western Australia, Northern Territory and South Australia), disconnected from the east coast's electricity grid (Western Australia, Northern Territory), and often are not connected or located near enough high capacity electricity infrastructure (parts of South Australia) (Geoscience Australia and ABARE, 2010: 240), all of which would decrease the potential economic viability of wind farms in these locations.

However, in eastern Australia (along the Great Dividing Range and the eastern seaboard), many areas exhibit a relatively poorer wind resource (in terms of the mean and median), and the broad scale mean WPD is below the 200 $W \cdot m^{-2}$ cutoff. However, the variability is also lower in these areas, the reliability is better, and the potential to mitigate intermittency (in the form of relatively low persistence) by the aggregation of wind farms, is larger; these areas tend to have higher values of anticoincidence, and null-anticoincidence. Our results broadly agree with those of Davy and Coppin (2003), who demonstrated that variability in the total wind power output in southeast Australia can be reduced to some extent by wider distribution of numerous wind farms.

There are several assumptions and limitations of our study which require articulating, the most important being the mapping scale issues that this study raises, whereby coarser resolution maps can overestimate the area available at a given wind speed, and will also potentially fail to depict many areas with good resources which occur at a scale smaller than the resolution our study employs ($0.5^{\circ} \times 0.75^{\circ}$, or about 55 $km^2 \times 73$ km^2) (Coppin *et al*., 2003). That being said, the continuous assimilation of observations to run the model enhances the efficacy of the MERRA data, i.e. if there are many sites that have good subgrid scale wind resources, this will be taken into consideration because the observations at these point locations are fed into the data assimilation cycle.

The temporal resolution of the MERRA data set is one hour, and as such, subhourly wind intermittency cannot be studied, even though this type of shorter scale intermittency can impact the voltage and frequency stability of a power grid (Gunturu and Schlosser, 2011). Also, the MERRA data is created from the assimilation of observational data and satellite remote sensed data into a global model, and will reflect any imperfections of the model and the assimilation procedure, and will have an influence on the results presented here. These limitations notwithstanding, the multidecade span of the MERRA data provides a more robust assessment of the temporal characteristics (i.e. mean, median, availability, intermittency, etc.) of wind power than that used in other studies, as described previously.

Future studies would be able to use our constructed wind resource data to analyze the variability of the resource at different time scales (like the intraseasonal and ENSO cycle time scales) and in response to different atmospheric oscillations like the El Nino Southern Oscillation and the Madden Julian Oscillation. This data will also be useful for analyzing the economic viability and the levelized costs of wind power compared to other energy sources, as well as for developing strategies for deployment such as the best pattern for aggregation. Studies such as this can conceivably delineate how much intermittency can be mitigated by aggregation and could play a role in the faster deployment of wind farms.

Acknowledgments
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Appendix: Rationale for the Cut-Off Employed to Calculate the Intermittency Metrics

Our rationale for choosing the 200 $W \cdot m^{-2}$ cut-off for the calculation of the intermittency metrics, is the same as Gunturu and Schlosser (2011), and incorporates a number of contributing arguments. The ReEDS (Renewable Energy Deployment System) model uses an annual mean WPD of 300 $W \cdot m^{-2}$ to filter the sites for commercial scale power production. ReEDS is a model used by the National Renewable Energy Laboratory (NREL) in the United States. Gunturu and Schlosser (2011) reason that given the value of annual mean WPD of 300 $W \cdot m^{-2}$, which is the value used as a lower cutoff for the viability of commercial power generation, 200 $W \cdot m^{-2}$ would be a reasonable cut-off for the instantaneous value. Also relevant in their rationale was the observation of very low power generation for typical wind turbines below a WPD of 200 $W \cdot m^{-2}$ —typically, the power curve of a wind turbine increases very slowly up until about 200 $W \cdot m^{-2}$ but rises quickly thereafter.

In addition to this, the estimation of the power that any individual wind turbine will produce must include numerous losses from availability (i.e. the wind turbine is stopped for reasons other than a lack of wind, e.g. down time for the maintenance of the turbine), electrical resistance and array interference when groups of turbines are clustered together. For example, electrical losses can be as high as 3% in large projects with long cable runs, and interference can cut production by up to 10% or more if the turbines are too close together, due to wake effects. When considered together, these losses can be significant; actual electricity delivery may be only 85-90% of a simple calculation of the potential power of a turbine (Gipe, 2004).

For our study we use an estimate of 3% of the rated power that the wind turbine itself uses for its own operation and maintenance, which means that this 3% power is not available to an end user. The turbine has to generate at least that amount of power in order to ‘break even’ in terms of the net electricity generated. For a 1.5 MW turbine, this corresponds approximately to 200 $W \cdot m^{-2}$.

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