Long-Term Wind Speed Trends over Australia

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ABSTRACT

Accurate estimates of long-term linear trends of wind speed provide a useful indicator for circulation changes in the atmosphere and are invaluable for the planning and financing of sectors such as wind energy. Here a large number of wind observations over Australia and reanalysis products are analyzed to compute such trends. After a thorough quality control of the observations, it is found that the wind speed trends for 1975–2006 and 1989–2006 over Australia are sensitive to the height of the station: they are largely negative for the 2-m data but are predominantly positive for the 10-m data. The mean relative trend at 2 m is \(-0.10 \pm 0.03\% \text{ yr}^{-1}\) (\(-0.36 \pm 0.04\% \text{ yr}^{-1}\)) for the 1975–2006 (1989–2006) period, whereas at 10 m it is \(0.90 \pm 0.03\% \text{ yr}^{-1}\) (\(0.69 \pm 0.04\% \text{ yr}^{-1}\)) for the 1975–2006 (1989–2006) period. Also, at 10 m light winds tend to increase more rapidly than the mean winds, whereas strong winds increase less rapidly than the mean winds; at 2 m the trends in both light and strong winds vary in line with the mean winds. It was found that a qualitative link could be established between the observed features in the linear trends and some atmospheric circulation indicators (mean sea level pressure, wind speed at 850 hPa, and geopotential at 850 hPa), particularly for the 10-m observations. Further, the magnitude of the trend is also sensitive to the period selected, being closer to zero when a very long period, 1948–2006, is considered. As a consequence, changes in the atmospheric circulation on climatic time scales appear unlikely.

1. Introduction

Long-term variations in near-surface wind speed, as measured by linear trends, have a marked impact on a variety of applications including wind energy, building construction, coastal erosion, evaporation rates, among others. Despite this, the robustness and causes of variations in near-surface wind remain poorly understood.

Several recent studies have reported significant linear wind speed trends, mostly toward declining winds, in the last decades around the globe. Guo et al. (2010) found that over the period 1969–2005 “the averaged rate of decrease in annual mean wind speed over China is \(-0.018 \text{ m s}^{-1} \text{ yr}^{-1}\),” and stated that “this decrease in strong winds also may lower the potential for wind energy harvest in China.” While Guo et al. noticed minor discrepancies in the behavior of records between rural and urban environments, most of the decrease in wind speed over China was attributed to the weakening of the lower-tropospheric pressure gradient force. Jiang et al. (2010) also reached a similar conclusion after analyzing a longer wind speed record over China (1956–2004). They, too, claim that the main cause of wind speed decline is modifications in atmospheric circulation due to climatic changes. They also note, however, that while annual and seasonal mean wind speeds are declining, the trend is uneven across wind speeds: strong winds (>8 m s\(^{-1}\)) are prone to decline whereas a light breeze (<4 m s\(^{-1}\)) actually show an increasing trend (this, they claim, would imply an increase in productivity for wind farms).

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Declines have also been observed for parts of the United States (Pryor et al. 2009) and southern Europe (Pirazzoli and Tomasin 2003). More specifically, Pryor et al. found observational evidence for an overall decline but noted that these trends are not consistent with some reanalysis products [notably, the National Centers for Environmental Prediction (NCEP) and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40)] and modeling studies with the regional spectral model. On the other hand, the declines in wind speeds observed by Pirazzoli and Tomasin in the Mediterranean region appear to be related to climatic variability: negative trends from the early 1950s to the mid-1970s are, in fact, followed by neutral or positive trends up to the end of their records (late 1990s).

A recent study by Vautard et al. (2010) showed that surface wind speeds have declined by 5%–15% over most continental areas in the Northern Hemisphere over 1979–2008: these trends are partly due to changes in atmospheric circulation, which would explain 10%–50% of the wind reduction, depending on the region, and partly to a generalized increase in surface roughness, owing to forest growth and expansion, land use changes, and urbanization, which would be responsible for 25%–60% of the observed changes.

Over Australia, McVicar et al. (2008, hereafter MV08) estimated a wind speed decline with an average decrease of 0.009 m s\(^{-1}\) yr\(^{-1}\) for the period 1975–2006 using about one hundred and fifty 2-m wind run observations. Taking this latter estimate at face value, this represents a 0.5% yr\(^{-1}\) decrease and, extrapolating this forward, would appear to suggest that the mean wind tends toward zero over a period of approximately 200 yr. While the wind speed climatology of the gridded surfaces produced by MV08 was generally consistent with three reanalysis products, the observed wind speed trends were not captured in any of these, even accounting for height differences (from the 2 m of the wind run observations to the 10 m of the reanalyses).

In this study we extend the analysis of long-term linear trends of wind speed observations over Australia to include 10-m observations and a relatively long time series from 40-m tower data. While some records, both at 2-m and 10-m heights, may be potentially very useful as climate indicators because of their length (some go as far back as the 1920s), there are several issues to be considered before carrying out statistical analyses on these data. As discussed in more detail later, factors to be taken into account include location, proximity to obstructions, length of continuous data record, and other data quality considerations, such as sudden steps caused by changes in instrumentation. To complement in situ observations, three reanalysis products have also been considered.

In section 2 we present the data used and discuss their quality control. Methods used to analyze wind speed observations are presented in section 3. Section 4 discusses the results of the linear trend analysis over Australia for different time periods, while section 5 provides physical explanations for some of the observed trends. Section 6 summarizes the results.

2. Availability and quality control of wind observations

A large network of wind observations at both 2-m and 10-m heights, the bulk of which starts from the 1970s, is available over Australia. We started by considering the 2-m height data, which has been used in previous studies of, for example, evapotranspiration (Roderick et al. 2007; MV08). These 2-m observations are daily wind run data (i.e., they only provide daily averages from continuous sampling over the 24 h) acquired from the Australian Bureau of Meteorology (BOM). Similar to MV08, the wind run data were excluded if quality control (QC) flags indicated that they were considered to be incorrect, suspect, or inconsistent with other known information and if the wind run exceeded five times the standard deviation of the entire time series. Unlike in MV08, wind run observations accumulated over a number of days were retained if information on the accumulation period were available. Also, only data with minimal gaps (up to three consecutive months) within the periods considered were retained. Three periods were considered: 1948–2006 (longest available period), 1975–2006 (for direct comparison with MV08) and 1989–2006 (overlap between reanalyses and observations). In addition to this QC based solely on flags and reasonable data filters, a supplementary QC was carried out for each station (cf. Muirhead 2000; Jakob 2010). This individual analysis included a visual analysis of the time series, an examination of the siting map of the station provided by the BOM, an analysis of satellite maps and satellite-derived products [e.g., Google maps, normalized difference vegetation index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR), Global Inventory Modeling and Mapping Studies (GIMMS, www.landcover.org/data/gimms/)], and interrogating other experts about data quality.

1 Data at 8-km resolution for the period 1982–2006 obtained from GIMMS.
2 Data at 1-km resolution for the period 1972–2010 obtained from the Australian Department of Climate Change and Energy Efficiency.
The additional issues encountered include the following.

- Accumulation spikes without information on the number of days that observations were accumulated over (for wind run data).
- Other outlying spikes with no suspect quality flag.
- Sudden steps or ramps, up or down or both.
- Steep overall trends (perhaps due to urbanization or vegetation changes rather than climate driven).
- Possible confusion about whether data is taken at 10 or 2 m (for wind run data).
- Data reported with inconsistent units.
- Many stations have not been sited according to the BOM specifications and are close to bluff bodies, vegetation, buildings, or on a hill or steep slope.
- Many stations do not have site diagrams and cannot be located easily.

As a result of our QC, the number of 2-m stations was reduced to about 50 stations, approximately a quarter of the original stations. Figure 1a shows the temporal evolution of the data availability, with the red line representing the selected 2-m wind run data and the black line its original total. By comparison, MV08 retained around 150 stations (their Fig. S1a).

Wind run observations are also available at a height of 10 m. The same QC procedures were applied to the 10-m data: of the total number of stations (given by the cyan line) very few were retained (green line) and only one station offered a continuous series covering the period pertinent to our analyses. For this reason, 10-m wind speed observations from automatic weather station (AWS)–type instruments were considered instead. With the extra requirement that the 10-m wind speed data should be close to the retained 2-m wind run stations whenever possible, between 20 and 30 stations were kept (blue line in Fig. 1a). Many of these stations were located at airport sites, which are usually considered as being of higher quality, because meteorology plays such a critical role in air traffic control and hence maintenance is often more reliable. However, even at some airports the observing stations have been affected by factors such as change of location, new construction near the station, among others, and our inspection of records at major airport sites showed several marked changes in time series characteristics. As a consequence, such airport sites have not been included in our analyses (see also Jakob 2010).

Since the installation of AWSs at many sites across Australia in the late 1980s to mid-1990s (e.g., Jakob 2010), Synchrotac cup anemometers have been used to measure both 2-m and 10-m observations, although there are some sites that still use Munro cup-counter anemometers to measure the 2-m wind run. Prior to the AWS installations, Synchrotac dial anemometers or Dines high-speed pressure tube anemometers were commonly used to measure the 10-m wind speed.

In addition to the 2-m and 10-m data, just for one location (in southeast Australia) we were able to obtain a wind speed record from a 40-m tower that provides a long enough time series, and it is located in the neighborhood of both a 2-m and a 10-m station.

To complement these in situ observations, wind speed data from three reanalysis products were used:
1) NCEP–National Center for Atmospheric Research (NCEP–NCAR, www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html; Kalnay et al. 1996); 2) ECMWF reanalysis ERA-Interim (www.ecmwf.int/research/era/do/get/index; Berrisford et al. 2009); and 3) Japanese 25-year reanalysis (JRA-25) (http://jra.kishou.go.jp/; Onogi et al. 2007). NCEP–NCAR is available from 1948 to present, ERA-Interim from 1989 to present, and JRA-25 from 1979 to present. For ease of comparison, the overlapping period between the three reanalyses and the observations is taken, namely, 1989–2006, except for the 1948–2006 analyses for which only the NCEP–NCAR reanalysis is available.

Figure 2 provides an example of two sites that failed to meet the QC criteria that also demonstrate how changes in land use and urbanization contribute to reducing the quality of the long-term wind time series. For Kyancutta (Fig. 2a), both 2-m and 10-m wind time series have a step in 1978. For the 2-m data this step imposes a negative trend when fitted over the whole period. An examination of the NCAS forest extent data identified that this step corresponds to an increase in vegetation at the site and surrounding region over the period from 1977 to 1980. This site also has buildings and trees located within a 10-m radius that influence the quality of the observations. Post-1980 the 10-m time series increases; however, an examination of the NCAS forest extent and the NDVI data do not suggest any decrease in the surface vegetation to contribute to this increase. The Sydney Observation Hill site (Fig. 2b) illustrates the influence of urbanization on the observed surface wind with steep decreasing trends from 1955 to 1990 in both the 2-m (−0.031 m s⁻¹ yr⁻¹) and 10-m data (−0.038 m s⁻¹ yr⁻¹). The proximity of this site to the central business district and buildings located adjacent to the site has contributed to the steep decreasing trend.

The Port Lincoln site (Fig. 3) provides another example of vegetation and buildings located close to the station, thus influencing wind observations. The time series shows a steady decline in the 2-m wind run observations from 1973 to 1981, which coincides with an increase in the forest extent for the site during this period. This trend is less clear in the 10-m data, possibly because the 10-m mast is less influenced by changes in the adjacent vegetation than the 2-m instrument.

For all three examples (Figs. 2 and 3), there is some overlap in the wind speed values between the 2-m and

**FIG. 2.** Wind speed time series (a) for Kyancutta (33.1°S, 135.6°E) and (b) for Sydney Observation Hill (33.9°S, 151.2°E): wind run observations at 2 m (black) and wind speed observations at 10 m (gray).

**FIG. 3.** Aerial photograph of the Port Lincoln observational site (135.9°E, 34.5°S) located with trees and buildings adjacent to the site. Inset: wind time series for Port Lincoln for 2-m wind run (black) and 10-m wind speed observations (gray).
3. Methodology

As noted, 2-m wind run data are continuous averages over the 24 h. Daily values for 10-m data are averages of observations taken at regular intervals. The number of intervals varies from station to station (from a minimum of two, i.e., at 0900 and 1500 local time, to a maximum of eight, i.e., every 3 h), but they generally remain constant over time and therefore the individual site statistics are internally consistent.

The daily averages were processed to obtain monthly statistics: mean, 10th, and 90th percentiles. Monthly statistics were computed only for months in which more than 20 days were available. The requirement of a maximum temporal gap (3 months) was also enforced. Figure 1b shows the number of stations with a continuous record between an arbitrary year and 2006 (the red line is for 2-m wind run data; the blue line for 10-m observations). All subsequent analyses are based on the monthly statistics (mean, 10th, and 90th percentiles).

The trends were computed by means of two methods: (i) the standard linear regression (function lm in the statistical software package R, http://cran.r-project.org/) and (ii) a 12th-order autoregressive model applied to unfiltered monthly mean time series to take into account temporal autocorrelations including the annual cycle (function arima in R), and residuals were inspected to ensure they were within the error bounds. The trends computed with these two methods were compared with each other at each site and in most cases differences between the two estimates were the same within the error estimates [Tables 1 and 2; see also Pryor and Ledolter (2010) for an analogous discussion]. For this reason, the more common linear regression (function lm) was preferred.

4. Analysis of wind speed trends

a. Linear trends of observed 2- and 10-m mean wind speeds

Relative wind speed trends (i.e., trend divided by the mean wind) rather than the absolute wind speed trends are considered here, as we regard the former to be more informative for a long-term analysis. This is especially true when the geography is such that considerable differences in mean wind speeds are present within a considered domain, as is the case here.

Figure 4 shows the linear trends for the 1975–2006 period (as in MV08) for the 2-m wind runs (left) and 10-m wind speed (right), with solid circles used for stations where the trend is significant at the 95% confidence level. Only stations covering the entire 32-yr period were considered: 15 for the 2-m wind runs and 14 for the 10-m wind speed (cf. Fig. 1b). Even though the number of stations retained following our QC procedures is certainly not sufficient to produce a homogeneous mean wind speed trend for the whole of Australia, there appears to be general agreement between our trends as shown in Fig. 4a and those computed by MV08 (their Fig. 1d). Indeed, there are more stations showing statistically significant declining trends than those with statistically significant increasing trends. Therefore, it may appear somewhat surprising that the results are different when the 10-m daily averaged wind speed data are used (Fig. 4b). Now almost all of the computed trends are nonnegative, with several of them significantly larger than zero at the 95% confidence level. In addition, where 2-m and 10-m observations are available at the same site (Carnarvon, Albany, Ceduna, Williamtown, and Rockhampton; see Fig. 4 and Tables 1 and 2), the 10-m data have a trend that is equal to or more positive than that for the 2-m data. Even if there is no complete overlap among 2-m and 10-m stations, the overall mean of the available stations is also consistent with the above analysis: the mean of the 15 2-m stations is $-0.10 \pm 0.03\% \text{ yr}^{-1}$, whereas it is $0.90 \pm 0.03\% \text{ yr}^{-1}$ for the 14 10-m stations (last rows in Tables 1 and 2).

A shorter period, 1989–2006, has also been considered to allow for a direct comparison with reanalysis data later. With this shorter period, the number of stations increases considerably: from 15 to 30 for the 2-m data and from 14 to 22 for the 10-m data (Fig. 1b). Despite the shorter record, linear trends of mean wind speeds for
Table 1. Trends for the 2-m wind run stations (% yr⁻¹) with associated error (95% confidence level): standard linear regression (LM) and autoregressive linear trend (AR). Means of all stations (last line) are computed as weighted averages with associated error. Two asterisks by a station name indicate that the station is geographically collocated with a 10-m station and the records available overlap for both periods 1975–2006 and 1989–2006 (Table 2) and one asterisk indicates a geographical collocation and the records available overlap for the 1989–2006 period only.

<table>
<thead>
<tr>
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<tr>
<td></td>
<td>LM trend</td>
<td>AR trend</td>
</tr>
<tr>
<td>Broome Air</td>
<td>−0.76 ± 0.56</td>
<td>−0.82 ± 0.25</td>
</tr>
<tr>
<td>Port Hedland Air</td>
<td>−0.87 ± 0.42</td>
<td>−0.99 ± 0.22</td>
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<tr>
<td>Learmonth Air*</td>
<td>0.03 ± 0.64</td>
<td>0.01 ± 0.08</td>
</tr>
<tr>
<td>Carnarvon Air**</td>
<td>−1.48 ± 1.26</td>
<td>−0.88 ± 0.71</td>
</tr>
<tr>
<td>Meekatharra Air*</td>
<td>0.03 ± 0.44</td>
<td>0.02 ± 0.34</td>
</tr>
<tr>
<td>Albany Air**</td>
<td>0.86 ± 1.24</td>
<td>0.79 ± 0.23</td>
</tr>
<tr>
<td>Giles MET*</td>
<td>0.89 ± 0.93</td>
<td>0.87 ± 0.16</td>
</tr>
<tr>
<td>Loxton RES CNT</td>
<td>0.25 ± 0.46</td>
<td>0.23 ± 0.21</td>
</tr>
<tr>
<td>Mount Isa Aero*</td>
<td>−2.19 ± 0.75</td>
<td>−2.21 ± 0.33</td>
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<tr>
<td>Cairns Aero</td>
<td>0.61 ± 0.47</td>
<td>0.59 ± 0.25</td>
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<td>Townsville Aero</td>
<td>−0.26 ± 0.98</td>
<td>−0.09 ± 0.47</td>
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<tr>
<td>Longreach Aero</td>
<td>0.11 ± 0.48</td>
<td>0.13 ± 0.24</td>
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<tr>
<td>Rockhampton Aero**</td>
<td>−0.03 ± 0.36</td>
<td>0.04 ± 1.12</td>
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<tr>
<td>Brian Pastures*</td>
<td>0.37 ± 0.41</td>
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<tr>
<td>Charleville Aero*</td>
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<tr>
<td>Trangie Res Stn</td>
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<td>−0.64 ± 0.15</td>
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<tr>
<td>Pindari Dam</td>
<td>−0.85 ± 0.37</td>
<td>−0.86 ± 0.09</td>
</tr>
<tr>
<td>Williamburg Town RAAF**</td>
<td>−1.03 ± 0.51</td>
<td>−0.82 ± 0.48</td>
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<tr>
<td>Bathurst AG Stn</td>
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<td>Orange AG INST</td>
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<td>Hume Reservoir</td>
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<tr>
<td>Wagga Wagga AMO</td>
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</tr>
<tr>
<td>Mean</td>
<td>−0.10 ± 0.03</td>
<td>−0.16 ± 0.01</td>
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1989–2006 (Figs. 5a,b) are consistent with the 1975–2006 period (Fig. 4), with the majority of 2-m data showing declining wind speeds and, instead, most of the 10-m data showing positive trends. In particular, the 14 stations available at both heights (stations with asterisks in Tables 1 and 2) clearly indicate that the 10-m wind speed trends tend to be greater than the 2-m trends. Also, analogous to the shorter period, the mean of the 30 2-m stations is −0.36 ± 0.04% yr⁻¹, whereas for the 22 10-m stations it is 0.69 ± 0.04% yr⁻¹ (last rows in Tables 1 and 2), confirming the contrasting overall negative trend for the 2-m stations and positive trend for the 10-m stations.

It is not immediately obvious why the trends at 2 m are so different, and often with opposite sign, from those observed at 10 m. Although there is no firm evidence to support this systematic difference, it is noted that the 2-m wind run stations are often sited near vegetation, buildings, or other obstructions (our QC only removed data with obvious external influence). As such, a declining wind speed trend is not unexpected. On the other hand, 10-m stations are normally better sited, including being higher from the ground and hence less directly affected by obstructions. In addition, the wear on mechanical parts and possible other instrumentation ageing factors may contribute to the records showing decreasing trends over a long period of time. Clearly, both 2-m wind run and 10-m wind speed could be affected by these mechanical factors in a similar fashion; however, as mentioned earlier, 10-m wind instruments are normally better serviced. Overall, it would appear as if the 10-m data should provide a better representation of the actual near-surface wind trends, but firmer conclusions can be drawn based on the following analyses.
Comparison between observed 2-, 10-, and 40-m tower wind speeds

The temporal behavior of wind speed for the same nominal location in southeast Australia at three heights—2, 10, and 40 m—was investigated to gain a better understanding of the relationship among observed wind speeds at different heights. Figure 6 shows the standardized wind speed with the annual cycle removed for 2 m (red line), 10 m (blue), and 40 m (green). Although the three time series seem to show similar interannual variations (e.g., all have a low in the decade from the late 1990s to early 2000s), a quantitative analysis indicates that the correlation with the 40-m wind speed over the common period (August 1995–July 2005) is considerably higher for 10 m than it is for 2 m (Table 3).

The linear trends for the observations, also computed over the common period, are progressively larger with
height: 0.25% yr\(^{-1}\) at 2 m, 0.43% yr\(^{-1}\) at 10 m, and 0.55% yr\(^{-1}\) at 40 m, where only the latter is significantly different from zero (Table 3). Even though only for one specific location—we could not obtain collocated observations such as these covering a sufficiently long period—this analysis indicates that the wind speed at 10 m provides a much better representation of the long-term trend of near-surface wind, as given by the wind at 40 m, than that at 2 m.

c. **Linear trends of observed 2- and 10-m wind speeds for two percentiles**

Further evidence of the different characteristics between the 2-m and 10-m wind speed is provided by the linear trends of the 10th and 90th percentiles computed from the monthly probability distribution functions of daily wind speeds: these two percentiles provide an assessment of changes in light and strong winds, respectively. The linear trends for the 10th percentile (Figs. 5c,d) clearly indicate that light winds have increased more rapidly than mean winds for almost all 10-m stations (contrast Figs. 5b and 5d). On the other hand, the 2-m stations do not show a distinctive difference in the linear trend between the 10th percentile and the mean (contrast Figs. 5a and 5c), with two stations even displaying a marked decrease (Cairns and Pindari Dam).
Similar to the linear trends for the 2-m 10th percentile, the 90th percentile for the 2-m wind speeds is very similar to the one for the mean (contrast Figs. 5a and 5e), with Cairns again displaying a different tendency, namely, a more positive increase than its mean. Instead, the 90th percentile trends for the 10-m wind speed have generally lower values than for the mean trends (contrast Figs. 5b and 5f).

The above visual analysis is corroborated by paired $t$ tests for two-tailed distributions. For the 10-m wind speed trends the 10th percentile is significantly different from both the mean and the 90th percentile at the 95% (and even 99%) confidence level, and the same holds true for the mean 90th percentile pair. Instead, none of the pairs for the 2-m wind speed trends are significantly different from each other, in agreement with the analysis above. A two-sample (both equal and unequal variances) $t$ test was also performed on 2-m versus 10-m analogous distributions (mean–mean, and 10th–10th and 90th–90th percentiles): while the mean pair and the 10th percentile pair are significantly different from each other (even at the 99% level), the two 90th percentiles are not. This is a confirmation of the sluggish increase in the 90th percentile of the 10-m wind speed trends, compared to the mean and 10th percentile.

d. Linear trends of observed seasonal mean wind speeds at 2 and 10 m

Given the pronounced seasonality in wind speeds over a large portion of Australia, especially south of 20°S, where winds are typically stronger in December–February (DJF), the austral summer, than in June–August (JJA), austral winter, it is also important to decompose the linear trend analysis into seasons. The linear trends of mean wind speeds for DJF (Figs. 7a,b) show some marked differences with respect to the annual mean trend (Figs. 5a,b). Although the changes are less distinct in the case of the 2-m winds (contrast Fig. 5a with 7a) than for the 10-m winds (contrast Fig. 5b with 7b), there appears to be a distinct tripole structure in the summer changes along the eastern coast of Australia, with a positive sign over part of Queensland and over Tasmania/south Victoria and a negative sign between these two regions (see highlighted areas in Figs. 7a,b). One or two changes are also present over Western Australia (Albany for the 2 m and Meekatharra for 10 m) but, possibly because of the sparsity of the data, there is no clear pattern there.

Changes in linear trends are also observed for JJA (Figs. 7c,d). Again, changes in the 10 m (contrast Fig. 5b with 7d) appear to be more pronounced than in the 2 m (contrast Fig. 5a with 7c), even if both display a similar bipolar pattern of change over the eastern side of Australia, with a positive sign over Queensland and a negative sign south of it (see highlighted areas in Figs. 7c,d). Similar to DJF, for JJA changes are present over parts of west Australia but again with no definite pattern (Broome for 2 m and Carnarvon for 10 m).

As with the two percentiles, a two-tailed paired $t$ test was applied to the DJF–annual pair and JJA–annual pair for both 2-m and 10-m wind speed data. In all cases, the distributions were not significantly different, suggesting that, although evident, the seasonality in wind speed trends displayed by the tripolar and bipolar patterns may not be very robust. In any case, more discussion on the causes of these observed patterns is discussed in section 5.

e. Linear trends of analyzed 10-m wind speeds

Wind speed linear trends based on the three reanalyses—NCEP–NCAR, ERA-Interim and JRA-25—at 10 m have also been computed for the period 1989–2006. There is broad agreement among the three reanalyses over the oceanic part of the Australasian region (Fig. 8):
all three have an average positive linear trend with an average of 0.17% yr\(^{-1}\) (Table 4). Over mainland Australia, however, there are large discrepancies with average trends ranging from the near zero for ERA-Interim to the negative for NCEP–NCAR to the very positive for JRA-25, with an overall mean of 0.09% yr\(^{-1}\) (Fig. 8 and Table 4).

Normally reanalyses are extremely useful references for the observed climate. However, given their disparity, it is difficult to establish which of the three reanalyses...
better represents reality in terms of 10-m wind speed trends over Australia. It should be noted that modeled 10-m winds are often derived quantities (computed using model data from other heights) and assumptions such as surface conditions and atmospheric stability are required. Therefore, such large differences are not entirely unexpected, even if there is good agreement among the three reanalysis on more robust variables such as mean sea level pressure (not shown).

f. Linear trends of 10-m wind speeds over 1948–2006

Despite the consistency between wind speed trends for the 32-yr period 1975–2006 and the shorter 18-yr period 1989–2006 (contrast Figs. 4a,b with 5a,b), the robustness of the observed trends should be tested also over longer periods if possible. In fact, wind speeds may be affected by changes in the relative importance of atmospheric circulation patterns on different time scales (decades or longer).

Of the 10-m wind speed observations, seven stations cover a period of nearly 60 years, 1948–2006 (Fig. 9a, no station is available for the 2-m data over this long period). These generally show reduced trend values compared to the shorter periods considered above, with four stations displaying trends significantly different from zero, and positive: Ceduna, Rockhampton, Charleville, and Laverton. The NCEP–NCAR reanalysis (the only one available over this long period) also shows weaker trends (Fig. 9b) and mostly with the same sign of the observed trends, with an overall mean of 0.009% yr\(^{-1}\) over Australia. Thus, the analysis of this longer period suggests that there is no indication of marked long-term changes in atmospheric circulation.

### 5. Effect of circulation changes on near-surface wind speed linear trends

Having analyzed several features of wind speed linear trends, we summarize here some of the main changes in linear trends and then attempt an explanation of their physical causes. We have observed that

1) mean wind speeds at 2 m display an overall negative trend, whereas those at 10 m generally show an increasing trend;
2) for the 10-m wind speed, the 10th percentile tends to increase more rapidly than the mean, whereas the 90th percentile increases less rapidly than the mean; for the 2-m wind speed, both the 10th and 90th percentile trends vary in line with the mean trends; and
3) changes between seasonal wind speed trends, for DJF and JJA, and the (annual) mean wind speed trends show broad agreement between the 2-m and 10-m observations, particularly over the eastern part of Australia—a negative–positive–negative tripole for DJF and a dipole for JJA.

Regarding item 1, as discussed especially in sections 4a and 4b, the wind speed at 10 m appears to better represent the near-surface wind characteristics than those at 2 m. The fact that the trends of the tails (10th and 90th

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<tr>
<td>Average</td>
<td>0.17</td>
<td>0.09</td>
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**Table 4.** Linear trend for 10-m wind speed (% yr\(^{-1}\)) over Australia for three reanalysis products computed on a common 2.5\(^\circ\) × 2.5\(^\circ\) grid.
percentiles) of 2-m wind speed distributions do not show distinct features [section 4c and item 2 above] may be further evidence that 2-m observations could be affected by factors such as local obstructions and changes in land use (at least to a greater extent than 10-m observations could be). Although it is difficult to assess the relative reliability of 2-m and 10-m observations solely based on the trends of the 10th and 90th percentiles, a plausible mechanism for changes in these trends is discussed later in this section. A possible physical cause of the changes in trends in response to seasonal variations [section 4d and 3 above], which appear similar in the 2-m and 10-m observations, is also addressed here.

Considering that our analysis is based on daily mean observations, it is not straightforward to identify the physical mechanism responsible for possible changes in the trends for the 10th and 90th percentiles (higher frequency data, e.g., from model simulations, may be used in future studies to analyze these issues further). One hypothesis is that intensification of the land–sea contrast as measured by differences in mean sea level pressure (MSLP) may be causing an increase in light winds: this would explain the observed increase in the 10th percentile trend (e.g., Crosman and Horel 2010). The trend in MSLP from the NCEP–NCAR reanalysis for the 1989–2006 period (Fig. 10a) shows how the well-documented poleward shift of the Hadley circulation (e.g., Archer and Caldeira 2008) manifest itself in the Australasian region: a decrease in MSLP in the subtropics and an increase in MSLP at midlatitudes. Of relevance here, the MSLP tends to increase more rapidly over the ocean than over land, as seen especially over eastern and southern parts of Australia (Fig. 10a). Such a land—sea MSLP differential may, therefore, be responsible for a possible strengthening of sea breezes and therefore of light winds observed along the eastern and southern Australian coasts.

It is also tantalizing to draw a parallel with similar results documented by Guo et al. (2010) and Jiang et al. (2010): they reported an increase of light winds over
several parts of China. The region that they analyzed, China, is clearly distinct from ours and therefore the reason for the apparent similarity between their results and our analysis of the 10th percentiles for the 10-m winds may be unrelated. We just note that a similar pattern of change in land–sea MSLP is present in the case of China too.

Possible changes in the 90th percentile are better analyzed by means of upper-air fields, as they are more appropriate indicators for large-scale circulation, likely drivers of changes in strong winds. The relative trend in 850-hPa wind speed displays a distinct zonal pattern over Australia, with an increase in upper-air winds north of 20°S, a decrease in the band 20°–35°S, and again an increase south of 35°S (Fig. 10b). As noted, the trends in the 90th percentile for the 10-m wind observations (most of which fall in the band 20°–35°S) are characterized by a negative difference compared to the trends in the mean (contrast Fig. 5a with 5f). Thus, even if a quantitative estimate is not straightforward, the smaller increase in strong 10-m wind speeds compared to the mean 10-m winds appears to be explained, with the exception of Tasmania, by the trends in the wind speed at 850 hPa (contrast Fig. 5f with 10b). By contrast, the trend in the 90th percentile for the 2-m winds did not show any significant change compared to the mean trend, with the only exception of Broome and Cairns, which display larger increases than their means. For these two stations the change in trend would also be consistent with the trend increase in the winds at 850 hPa (contrast Fig. 5e with 10b).

The seasonal patterns of the changes in wind speed trends, item 3 above, also appear to be (partly) attributable to changes in the large-scale atmospheric circulation. As indicated by the trends in geopotential height at 850 hPa (Fig. 10c), an anticyclonic anomaly near the eastern coast of Australia is superimposed on the mostly zonal flow in the atmospheric circulation for DJF. Such an anticyclonic signal induces a decrease in geostrophic wind speeds north of about 20°S and a corresponding increase between 25° and 35°S. Similarly, the negative trend (anomaly) south of about 35°S would be responsible for a slowdown of winds south of Victoria and Tasmania. The tripole pattern just described clearly fits with the patterns for the 2-m and 10-m data highlighted in Figs. 7a,b.

An analogous correspondence is present for JJA winter season (Fig. 10d). In this case the mean circulation over Australia is characterized by an anticyclonic flow, now superimposed by a large positive trend (note the different scale from Fig. 10c) with a maximum over the oceanic region between Australian and New Zealand. Such a trend induces a reduction on wind speed over southeast Australia and a smaller increase north of about 25°S. Again, these variations match well the dipole patterns for both the 2-m and 10-m data observed in Figs. 7c,d.

The analysis of seasonal variations therefore suggests that there is qualitative correspondence between seasonal changes in the upper-air circulation flow and in near-surface winds (both at 2 and 10 m). A quantitative analysis aimed at partitioning the causes of the observed changes, whether due to changes in atmospheric circulation, land use, vegetation, or instrumentation, would require some extensive modeling simulations, and these are currently underway for a separate study.

6. Conclusions

In this paper a large number of wind observations over Australia have been analyzed for their long-term trends. An extensive quality control procedure, which included visual analysis of the time series, examination of the siting map of the stations, analysis of satellite maps and satellite-derived products, in addition to more standard checks based on flags and reasonable data filters, was carried out. It was found that the wind speed trends for the 1975–2006 and 1989–2006 periods are sensitive to the height of the station, to the extent that the sign of the trend changes from being largely negative in the 2-m data (as in MV08) to predominantly positive in the 10-m data. As broad references, the mean trend of the 15 (30) retained 2-m stations is $-0.10 \pm 0.03% \text{ yr}^{-1}$ ($-0.36 \pm 0.04% \text{ a}^{-1}$) for the 1975–2006 (1989–2006) period, whereas the mean trend of the 14 (22) retained 10-m stations is $0.90 \pm 0.03% \text{ yr}^{-1}$ ($0.69 \pm 0.04% \text{ a}^{-1}$) for the 1975–2006 (1989–2006) period.

The character of the linear trends for two percentiles close to the tails of the wind speed distributions, the 10th and 90th percentiles, also showed different behavior between the 2-m and 10-m observations. For the 10-m wind speed, the 10th percentile tends to increase more rapidly than the mean, whereas the 90th percentile increases less rapidly than the mean; for the 2-m wind speed, both 10th and 90th percentiles trends vary in line with the mean trends.

However, changes between seasonal wind speed trends, for December–February (DJF) and June–August (JJA), and the (annual) mean wind speed trends show broad agreements between the 2-m and 10-m observations, particularly over the eastern part of Australia: a negative–positive–negative tripole for DJF and a dipole for JJA.

Overall, we conclude that wind speed observations collected by 2-m stations are often more affected by changes in vegetation, obstacles, and construction of nearby buildings than for the 10-m stations. Clearly, a measurement closer to the surface is more affected by surface roughness and
hence less representative of the large-scale atmospheric circulation. The comparison between 2, 10, and 40 m provided confirmation of this assertion, with the 10-m data highly correlated with the 40-m data. It is apparent, therefore, that to assess changes in the atmospheric circulation the use of 10-m (or higher) wind speed data should be strongly preferred to the 2-m dataset.

Further, we found that a qualitative link could be established between the observed features in the linear trends and some atmospheric circulation indicators (mean sea level pressure, wind speed at 850 hPa, and geopotential at 850 hPa), particularly for the 10-m observations. A quantitative partitioning of the causes of the observed linear trends, whether due to changes in atmospheric circulation, land use, vegetation, or instrumentation, would require extensive modeling simulations, and these are currently underway in a separate study.

Wind speed linear trends based on the three reanalyses—NCEP–NCAR, ERA-Interim, and JRA-25—at 10 m indicate large discrepancies among them over mainland Australia, with average trends ranging from the near zero for ERA-Interim to negative for NCEP–NCAR to very positive for JRA-25, with an overall mean of 0.09% yr\(^{-1}\). It is therefore difficult to establish which of the three reanalyses better represents reality in terms of 10-m wind speed trends over Australia.

Finally, it was noted that the magnitude of the trend is also sensitive to the period selected, being closer to zero when a very long period is selected, the 1948–2006. As a consequence, changes in the atmospheric circulation on climatic time scales appear unlikely.

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