

# Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output

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[1] Near-surface wind speeds ( $u$ ) measured by terrestrial anemometers show declines (a ‘stilling’) at a range of mid-latitude sites, but two gridded  $u$  datasets (a NCEP/NCAR reanalysis output and a surface-pressure-based  $u$  model) have not reproduced the stilling observed at Australian stations. We developed Australia-wide  $0.01^\circ$  resolution daily  $u$  grids by interpolating measurements from an expanded anemometer network for 1975–2006. These new grids represented the magnitude and spatial-variability of observed  $u$  trends, whereas grids from reanalysis systems (NCEP/NCAR, NCEP/DOE and ERA40) essentially did not, even when minimising the sea-breeze impact. For these new grids, the Australian-averaged  $u$  trend for 1975–2006 was  $-0.009 \text{ m s}^{-1} \text{ a}^{-1}$  (agreeing with earlier site-based studies) with stilling over 88% of the land-surface. This new dataset can be used in numerous environmental applications, including benchmarking general circulation models to improve the representation of key parameters that govern  $u$  estimation. The methodology implemented here can be applied globally. **Citation:** McVicar, T. R., T. G. Van Niel, L. T. Li, M. L. Roderick, D. P. Rayner, L. Ricciardulli, and R. J. Donohue (2008), Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output, *Geophys. Res. Lett.*, 35, L20403, doi:10.1029/2008GL035627.

## 1. Introduction

[2] Recent observations of near-surface wind speed ( $u$ ) trends measured by terrestrial anemometers have shown declines between  $-0.004 \text{ m s}^{-1} \text{ a}^{-1}$  to  $-0.017 \text{ m s}^{-1} \text{ a}^{-1}$  (with an average of approximately  $-0.010 \text{ m s}^{-1} \text{ a}^{-1}$ ) over the last 30 to 50 years for a range of mid-latitude regions including: Australia [Roderick *et al.*, 2007]; China [Xu *et al.*, 2006a, 2006b]; Europe [Pirazzoli and Tomasin, 2003]; North America [Hobbins, 2004; Klink, 1999; Tuller, 2004]; and Tibet [Shenbin *et al.*, 2006; Zhang *et al.*, 2007]. Others report different  $u$  metrics also showing decreases: (i) Pryor

*et al.* [2007] report that over the contiguous USA the annual median  $u$  decreased significantly ( $P = 0.1$ ) for 118 (out of 157) stations for 1973–2005; and (ii) Smits *et al.* [2005] show that the frequency of weak and moderate storm events at 13 Dutch stations for 1962–2002 decreased by approximately 20% and 10% per decade, respectively. In contrast, high-latitude ( $> 65^\circ$ ) sites in Antarctica [Aristidi *et al.*, 2005; Turner *et al.*, 2005] and Alaska [Lynch *et al.*, 2004] report increases of approximately  $0.005 \text{ m s}^{-1} \text{ a}^{-1}$ . This latitudinal dependence of  $u$  trends agrees with model projections showing decreasing  $u$  at mid-latitudes with increasing  $u$  at high-latitudes [Seidel *et al.*, 2008; Yin, 2005].

[3] In Australia, two studies recently illustrated that declining  $u$  from 1975–2004 is the primary factor reducing atmospheric evaporative demand, as measured by pan evaporation [Rayner, 2007; Roderick *et al.*, 2007]; with the term ‘stilling’ being coined to denote the negative  $u$  trend [Roderick *et al.*, 2007]. Rayner [2007] found that two gridded  $u$  datasets (NCEP/NCAR reanalysis output and a surface-pressure-based model) did not capture the observed stilling. Thus it remains possible that the site-based data used in the above-mentioned Australian pan evaporation studies are not representative of regional conditions because the non-uniform spatial distribution of the long record  $u$  observations makes their aggregation into an ‘Australia-wide’ trend questionable. More generally, the results from all other studies are only based on averaging across sites with no regard for the spatial representation of the sites. To address this limitation requires the generation of a time-series of surfaces, and as the  $u$  trends are of sufficient magnitude to be important for climate change, wind power generation and water resource assessments, more detailed investigation is warranted. Here we report the development of high-resolution ( $0.01^\circ$ ) daily  $u$  grids using an expanded anemometer database for the entire Australian land-surface covering  $7.6 \text{ million km}^2$  ( $10\text{--}45^\circ\text{S}$  and  $110\text{--}155^\circ\text{E}$ ). Annual  $u$  trends were calculated from these new surfaces and compared against trends from earlier studies and with outputs from three commonly used reanalysis systems (NCEP/NCAR, NCEP/DOE and ERA40).

## 2. Materials and Methods

[4] Daily wind run data ( $\text{km day}^{-1}$ ) for low-set anemometers (2 m) were acquired from the Australian Bureau of Meteorology [2007] from 1 Jan 1975 through 31 Dec 2006 (32 years totalling 11,688 days). The data and associated quality control flags were shuffled backward one day, as observations were made at 0900 local time each day with the

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majority of the wind-run generally occurring in the afternoon of the previous day [Archer and Jacobson, 2003; Rehman and Ahmad, 2004]. Daily wind run data were excluded if: (i) quality control flags indicated that they were considered wrong, suspect, or inconsistent with other known information; (ii) data were accumulated over two or more days; or (iii) wind run exceeded  $1200 \text{ km day}^{-1}$  [Rayner, 2007]. The data were converted from  $\text{km day}^{-1}$  to daily average  $u$  with units of  $\text{m s}^{-1}$ . The number of sites available on any given day varied from 112 to 194, having an overall average of 163 stations. Most sites were located within 45 km of the coast (input data are characterised in Figures S1 and S2 and Table S1).<sup>1</sup>

[5] Daily data were spatially interpolated using ANUSPLIN (version 4.3) [Hutchinson, 2004]. The wide-spread use of ANUSPLIN for interpolating hydrometeorological and climatological data, and its advantages over other approaches, are summarised by McVicar *et al.* [2007]. To fit the daily  $u$  data, four models were tested with the tri-variate thin-plate spline as a function of longitude, latitude and distance inland from coast [Hutchinson *et al.*, 1984] providing the best statistical fits (see Text S1, Figure S3, and Tables S2, S3, and S4 for details). The 11,688 daily  $u$  surfaces were output with a  $0.01^\circ$  (approximately 1 km) resolution to accurately represent sea-breezes and to match similar resolution remotely sensed data that are used in actual and potential evapotranspiration modelling.

[6] Monthly average  $u$  surfaces were derived from the daily surfaces for each of the 384 months, and from these, monthly, seasonal and annual climatologies were generated for the 32 years. Trend analysis was performed on monthly, seasonal and annual time series by fitting a linear regression (ordinary least squares) to each grid-cell with significance ( $P = 0.05$ ) being determined using a two-tailed t-test.

[7] Annual climatologies and trend statistics were developed for: (1) the new surfaces generated herein; and 10 m high reanalysis winds from (2) the National Centers for Environmental Prediction Department of Energy (NCEP/DOE [Kanamitsu *et al.*, 2002]; <http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis2.html>); (3) NCEP National Center for Atmospheric Research (NCEP/NCAR [Kalnay *et al.*, 1996]; <http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html>); and (4) European Centre for Medium-range Weather Forecasts (ECMWF) 40 Years Re-Analysis (ERA40 [Uppala *et al.*, 2005]; [http://data.ecmwf.int/data/d/era40\\_daily](http://data.ecmwf.int/data/d/era40_daily)). For (2) to (4), we downloaded sub-daily, non-averaged wind vectors and created sub-daily  $u$ . These were then averaged to monthly  $u$  and resampled to a common  $2^\circ$  resolution, then annual  $u$  climatologies and trends were derived. The reanalysis products were all 10 m height, whereas the anemometer observations were at 2 m. Assuming: (i) a logarithmic  $u$  profile [Robeson and Shein, 1997; Stull, 1988]; (ii) that the profile is constant through time; (iii) neutral atmospheric stability; and (iv) a typical range of roughness values (i.e., varying from 0.1 m [Stull, 1988] to 0.65 m [Stull, 1994]), it is expected that 10 m  $u$  and  $u$  trends will be between 1.5 to 2.4 times larger than those at 2 m. To minimise sea/land-breeze effects [Stull, 1988], we also calculated climatologies and trends using ‘land-only’ grid-cells, with our data resampled to the common  $2^\circ$  resolution. Finally, the  $u$  trends observed at 41 BoM stations [Roderick

*et al.*, 2007] across Australia were compared against data extracted from (1) to (4) above. All the above comparisons were made for the period 1979–2001 (the ERA40 data extent). Rayner [2007] used NCEP/NCAR 0.995-sigma surfaces, transferred to 2 m height using a static wind power profile relationship to assess  $u$  trends at points. Our research extends this by: (i) assessing output from all three reanalysis systems; (ii) implementing a vertical transfer based only on height (not a mixed height-pressure transfer that does not account for surface pressure changes); and (iii) performing analyses using both grids and points.

### 3. Results

[8] Annual climatology (Figure 1a) shows higher  $u$  associated with arid regions and lower  $u$  associated with wetter coastal regions. The Australian-average  $u$  (Figure 1b) ranged between  $2.3 \text{ m s}^{-1}$  in summer (DJF) to  $1.7 \text{ m s}^{-1}$  in winter (JJA); see Table S5 and Figure S4. While all-Australian monthly averages are fairly constant (Figure 1b), some local differences associated with processes governing Australia’s climate (e.g., the summer-winter latitudinal movement of the sub-tropical ridge) are clearly seen (Figure 1c).

[9] Figure 1d shows the distribution of annual  $u$  trends for 1975–2006. The majority (88.6%) of Australia exhibits stilling, with 57.5% of grid-cells having negative and significant ( $P = 0.05$ ) trends; the majority of annual, seasonal and monthly significant trends are negative (Table S6). The average annual trend of  $-0.009 \text{ m s}^{-1} \text{ a}^{-1}$  is very similar to the  $-0.010 \text{ m s}^{-1} \text{ a}^{-1}$  calculated by Roderick *et al.* [2007] by averaging the results across 41 BoM stations for 1975–2004. Monthly average (Figure 1e), point (Figure 1f), and extreme monthly grid-cell (Table S6)  $u$  trends are similar to those reported for other mid-latitude sites. The seasonal (Figure S5) and annual (Figure 1d)  $u$  trends have similar spatial patterns except for increasing  $u$  trends in autumn and winter found in north-eastern Queensland, which are associated with a positive phase of the Southern Annular Mode [Gillett *et al.*, 2006; Hendon *et al.*, 2007].

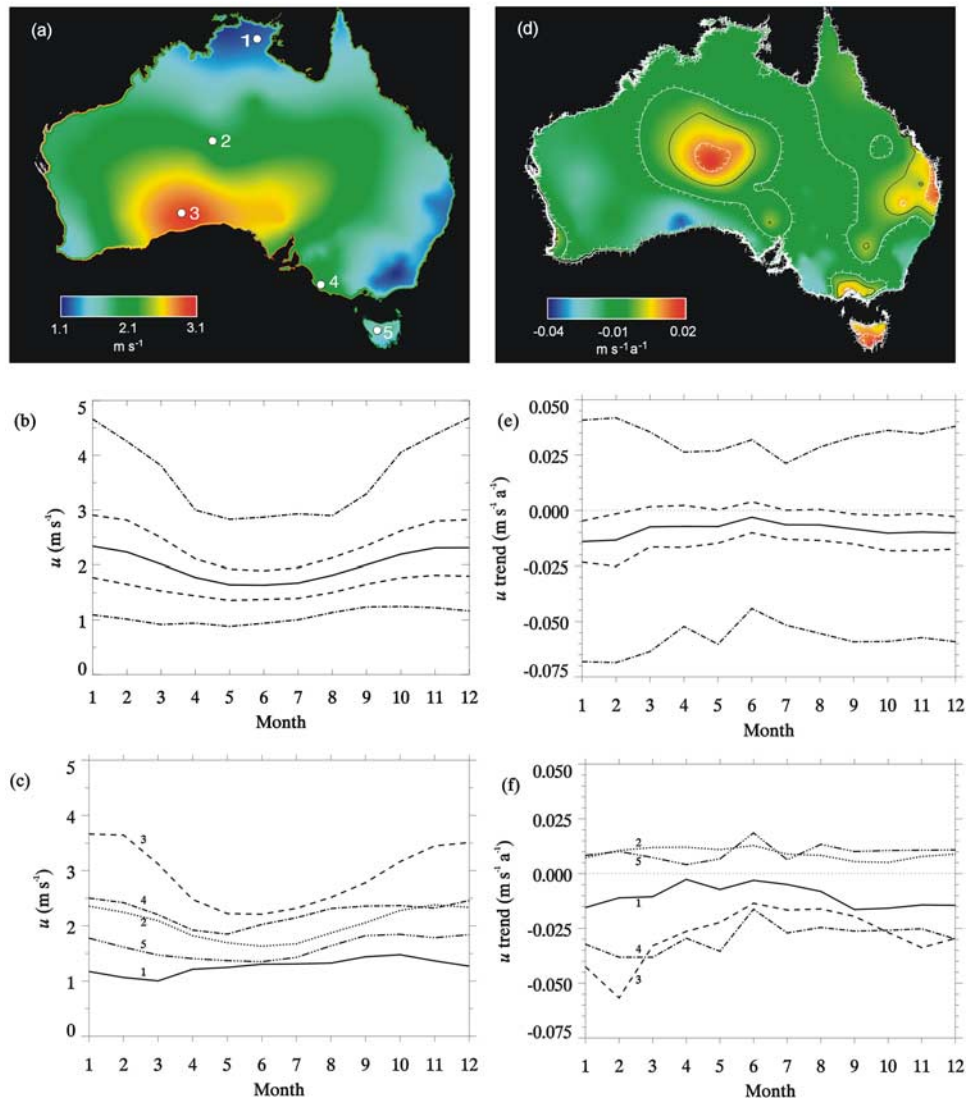
[10] The reanalysis-based  $u$  climatologies are 1.85 to 2.25 times larger than our data (Table 1), as expected given the height differences (see above). Table 1 also shows that the Australian-averaged reanalysis-based  $u$  trends are three to six times smaller than for our data. The results are similar when comparing land-only grid cells of equal  $2^\circ$  resolution (Table S7), so this reanalysis-based  $u$  trend underestimation cannot be explained as a sea/land-breeze effect.

[11] Figure 2 shows that the  $u$  trends determined using our interpolation and analysis process captured the trend better than the three reanalysis products ( $r^2 = 0.380$  compared with  $r^2$  from 0.001 to 0.008). Table 1 also shows that the observed  $u$  trends are poorly captured in the reanalysis output. This suggests: (i) changes in the reanalysis data assimilation have acted to mask the observed  $u$  changes; and/or (ii) an inadequate representation of key boundary-layer parameters in the reanalysis systems that govern  $u$  estimation.

### 4. Discussion

[12] After spatial interpolation using an expanded database, we found similar stilling as reported previously using

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2008GL035627.



**Figure 1.** Climatology and trends for  $u$  1975–2006: (a) annual climatology; (b) continent-averaged monthly climatology; (c) monthly climatology for the five points shown in Figure 1a; (d) annual trend; (e) continent-averaged monthly trends; and (f) monthly trends for the five points shown in Figure 1a. In Figure 1a the locations are: (1) 134.5°E, 13.5°S; (2) 130.0°E, 22.5°S; (3) 127.0°E, 30.5°S; (4) 140.5°E, 37.5°S; and (5) 146.0°E, 42.0°S. In Figure 1b and 1e the 32-year mean (solid line),  $\pm 1$  standard deviation (dashed lines), and the minimum and maximum (dash-dot lines) are shown. In Figure 1d the black line shows where the trend is  $0.0 \text{ m s}^{-1} \text{ a}^{-1}$  and the white lines show where the trends change from being non-significant to significant ( $P = 0.05$ ); the white bars are in the direction of significance.

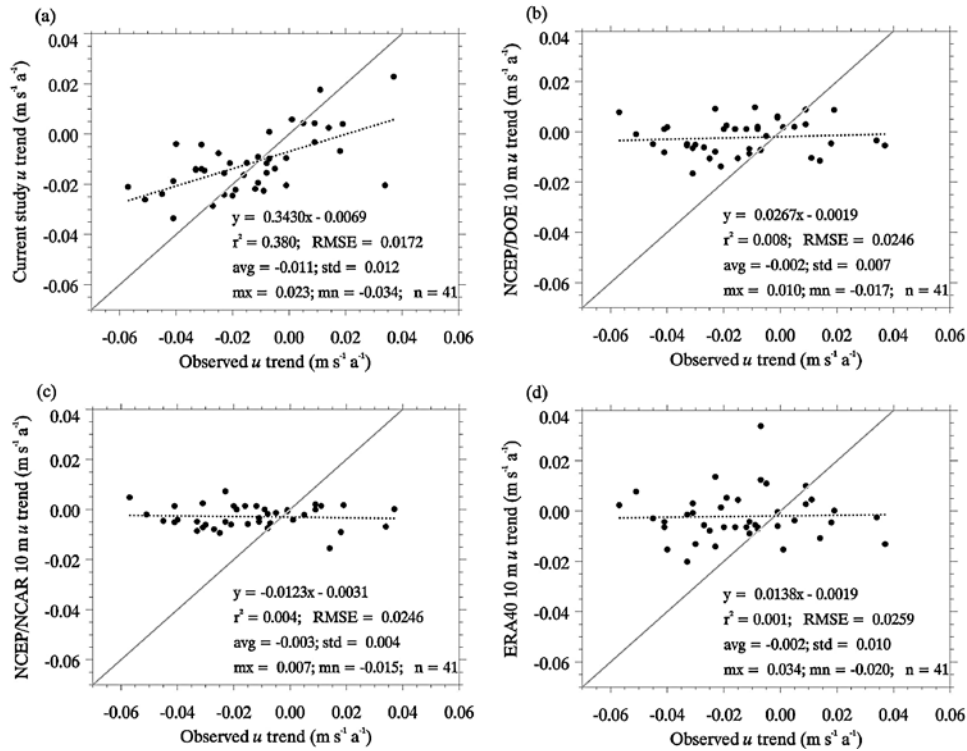
individual station data from 41 BoM sites across Australia [Roderick *et al.*, 2007]. Over the 1975–2006 period, the majority of Australia ( $\sim 88\%$  of the continental surface) experienced stilling (Table S6). Over the remaining 12% of the continent, our results show increasing  $u$  in three distinct regions (Figure 1d): (i) central Australia; (ii) southeast Queensland and northeast New South Wales; and (iii) southern Victoria and Tasmania. In arid central Australia, there was exceptionally high precipitation during the mid-1970s coincident with the start of the period analysed here. During the mid-1970s, more of the available energy would have been partitioned into the latent heat flux (and associated with increased vegetation growth) than the sensible heat flux (and associated turbulent transport) [Roderick *et al.*, 2007, Figure S3c] resulting in lower  $u$  [Ozdogan *et al.*,

**Table 1.** Australian-Average Annual  $u$  Climatology and Trends for 1979–2001<sup>a</sup>

Source	Mean	Std Dev	Max.	Min.	Num Grid-Cells	Mean Relative to Our Mean
<i>Climatology</i>						
Our study	1.99	0.40	3.44	1.14	6,979,336	1.00
NCEP/DOE	4.48	0.96	8.68	2.52	185	2.25
NCEP/NCAR	3.67	0.99	8.68	1.91	185	1.84
ERA40	3.80	0.67	7.21	2.38	185	1.91
<i>Trends</i>						
Our study	−0.013	0.010	0.047	−0.059	6,979,336	1.00
NCEP/DOE	−0.002	0.007	0.012	−0.038	185	0.15
NCEP/NCAR	−0.004	0.004	0.007	−0.019	185	0.31
ERA40	−0.002	0.007	0.034	−0.020	185	0.15

<sup>a</sup>The units of the climatology data are  $\text{m s}^{-1}$  and the units of the trend data are  $\text{m s}^{-1} \text{ a}^{-1}$ .





**Figure 2.** Comparison of wind speed trends at the 41 BoM sites used by *Roderick et al.* [2007] for 1979–2001 with trends extracted from: (a) this study; (b) NCEP/DOE 10 m output; (c) NCEP/NCAR 10 m output; and (d) ERA40 10 m output. At the 41 BoM sites, statistics for 1979–2001 are average (avg) =  $-0.013$ , standard deviation (std) =  $0.022$ , maximum (mx) =  $0.037$ , and minimum (mn) =  $-0.057$ ; all units are  $\text{m s}^{-1} \text{a}^{-1}$ . For each plot, the line of best fit is the dotted black line defined by the equation, the 1:1 line is gray, and the avg, std, mx and mn (all units are  $\text{m s}^{-1} \text{a}^{-1}$ ) of the Y-axis data are shown. The units of all offsets and RMSE statistics are  $\text{m s}^{-1} \text{a}^{-1}$ , whereas  $r^2$  and slope statistics are unitless.

2006] at the start of the period. If the analysis period had begun in 1980, instead of 1975, the increase in central Australia would not be present. The two other regions identified in Figure 1d warrant further investigation: increasing  $u$  trends in southeast Queensland and northeast New South Wales could be associated with decreased precipitation and/or rapid urbanisation changing local circulation patterns, and trends in southern Victoria and Tasmania are likely influenced by the Southern Annular Mode [Gupta and England, 2006; Hendon et al., 2007].

[13] The finding that annually over 88% of Australia showed stilling, with 57% (Table S6) being statistically significant ( $P = 0.05$ ), demonstrates a high degree of spatial coherence in the input  $u$  observations, which suggests that regional (or global) processes dominate the ‘potential local factors’ (e.g., growing trees or other obstacles progressively obstructing the air flow) discussed by *Roderick et al.* [2007]. This raises a very interesting question because there is a wealth of evidence from terrestrial anemometer records showing that regionally-averaged declines in  $u$  are prevalent at mid-latitudes with increases typical at high-latitudes (see Introduction). This basic pattern of change is also shown by climate change projections [Lorenz and DeWeaver, 2007; Yin, 2005] and has been associated with poleward expansions of the Hadley cell [Lu et al., 2007; Seidel et al., 2008].

[14] In contrast, *Wentz et al.* [2007] reported that  $u$  averaged over the global oceans increased by  $0.008 \text{ m s}^{-1}$

$\text{a}^{-1}$  for 1987–2006, based on passive microwave satellite retrievals. Closer to the equator (oceans between  $30^\circ\text{S}$  and  $30^\circ\text{N}$ ), they report a lower but still increasing trend of  $0.004 \text{ m s}^{-1} \text{a}^{-1}$ . Hence those data also suggest latitudinally-dependent  $u$  changes, although there is still no reconciliation on how  $u$  could increase over the ocean while decreasing over the land in the mid-latitudes.

[15] The importance of  $u$  trends for predicting the interacting feedbacks between trends of precipitation, temperature and vapor pressure has recently been highlighted by the climate change community [Allan and Soden, 2007; Held and Soden, 2006; Wentz et al., 2007]. Therefore further measurement and modelling in other regions are needed to place terrestrial stilling in a wider context: focussing on spatial (e.g., tropical latitudes for terrestrial- and oceanic-surfaces); vertical (e.g., to at least 80 m, the typical height of commercial wind turbines [Archer and Jacobson, 2003; Pérez et al., 2005]); and temporal aspects.

[16] It is concerning that the terrestrial stilling is so poorly represented by the reanalysis outputs, as the representation of the key boundary layer parameters that govern  $u$  estimates in the reanalysis models is likely similar to the circulation models used to predict climate change. A recent validation study of ERA40 and NCEP/DOE near-surface outputs did not consider  $u$  [Betts et al., 2006] whereas our validation results of  $u$  for Australia suggests further measurement and modelling need to be extended to a wider

context (see above) as a matter of high priority. The methodology used here can be implemented to the global land-surface and so can play an important role in providing verification data for such a study.

## 5. Conclusion

[17] Using anemometer observations from approximately 160 sites, daily surfaces of  $u$  have been interpolated for the Australian continent for 1975–2006. The results showed reductions in  $u$  over some 88% of the continent. Averaged over the continent, the trend was  $-0.009 \text{ m s}^{-1} \text{ a}^{-1}$ , in general agreement with earlier site-based studies. Taking into account height differences, the  $u$  climatology of the gridded surfaces was generally consistent with the NCEP/NCAR, NCEP/DOE and ERA40 reanalysis products, but the observed  $u$  trends were essentially not captured in any of these. Densities of anemometers similar to that of Australia are likely found for many other parts of the global land-surface, so our methodology provides an avenue to develop daily  $u$  grids elsewhere. By capturing the stilling trends in Australia, the resultant surfaces provide a benchmark retrospective dataset that general circulation model output can be compared with. Additionally, the surfaces can be used in numerous applications including the estimation of evapotranspiration [McVicar and Jupp, 1999], wind erosion studies, and to locate wind turbines.

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