# Observed Trends in Wind Speed over the Southern Ocean

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Received 19 March 2012; revised 8 May 2012; accepted 9 May 2012; published 7 June 2012.

[1] Most studies of trends in regional climate focus on temperature, however for maritime environments in particular, changes in the wind are equally important. An analysis of trends in the wind over Macquarie Island is performed with a radio-sonde database spanning nearly four decades. The results indicate that the surface wind speed is increasing, with the trend for the upper levels being less well defined. The surface wind is highly correlated with the upper level winds, and the wind at all levels are moderately correlated with the Southern Annular Mode. ECMWF ERA-Interim reanalysis data shows significant trends in wind speed over several levels, however slightly smaller than trends in the soundings over a similar time period. The correlations in ERA-Interim are similar to those in the soundings. A clustering analysis of the wind reveals four distinct regimes, with a trend towards a regime characterised by strong north westerly winds. **Citation:** Hande, L. B., S. T. Siems, and M. J. Manton (2012), Observed Trends in Wind Speed over the Southern Ocean, *Geophys. Res. Lett.*, *39*, L11802, doi:10.1029/2012GL051734.

## 1. Introduction

[2] Annually averaged, the oceanic wind speed over the Southern Ocean is the strongest on Earth [e.g., *Young*, 1999; *Tokinga and Xie*, 2011], which can be partly attributed to the absence of any significant landmass in the region. Correspondingly these winds drive the largest, annually averaged, wave height on Earth to establish a vast region (~15% of the Earth's surface) governed by an intense air-sea interaction. Climatologically, this interaction is fundamental in understanding the energy and water budgets over the Southern Ocean and, by extension, the Antarctic. *Trenberth and Fasullo* [2010] noted that the Southern Ocean displayed the greatest relative errors in the top of the atmosphere radiation budget between observations and both reanalyses and simulations.

[3] *Korhonen* [2010] proposed a climate feedback directly involving the oceanic wind speed over the Southern Ocean: it was argued that an increasingly strong jet stream over the Southern Ocean would lead to increasing strong winds at the ocean surface. This, in turn, would lead to greater sea spray and more CCN, thus changing the albedo of the clouds over the Southern Ocean. Not only are the oceanic wind speed and wave height greatest over the Southern Ocean, they have been observed to be increasing over the past 20+ years [*Young et al.*, 2011]. More broadly the region over the Southern Ocean has been noted to be undergoing a trend in the Southern Annular Mode (SAM) since the mid 1960s [*Marshall*, 2003]. While this trend in the SAM has been directly linked to changes in the ozone over the Antarctic and climate change through simulations [*Arblaster and Meehl*, 2005], it is not possible to convincingly attribute the trends in the wind speeds and wave height to climate change; decadal scale climate variability is a ready alternate explanation.

[4] Regardless of the factors leading to the positive trends in the SAM, oceanic wind speed and wave height over the Southern Ocean, it is of interest to note how wide spread these trends are observed through the atmosphere. This is a challenging task over the Southern Ocean due to the lack of observations. One long-standing platform for atmospheric observation over the Southern Ocean is the upper air soundings made from Macquarie Island (54°S, 158°E) beginning in 1973.

[5] The aim of this paper is to examine the trends (if any) in the long-term wind observations over the Southern Ocean and to compare these with the trends in oceanic wind speed observed by *Young et al.* [2011], as well as the trends in a state-of-the-art reanalysis data set.

## 2. Data

[6] Macquarie Island is ideally situated for this study, with the island being largely free of any orographic effects. Radio-sondes are routinely released twice daily from an elevation of 8 m above sea level, with direct exposure to the prevailing westerly winds. The data set of atmospheric soundings utilised in this study (MAC) cover the period from 1973 through to 2011. In this product, the raw measurements from the radio-sonde are interpolated onto standard pressure levels, and additional levels are included at temperature inversions, in order to resolve these features. Only data at certain standard pressure levels will be considered here, namely the surface (taken to be 8 m), 850 hPa, 700 hPa and 500 hPa. Measurements of the wind at these standard levels extend back to the beginning of the data set, except for the surface at 8 m, where the continuous measurements begin in 1987.

[7] An objective of this research is to assess the performance of reanalysis products when compared to in-situ observations. The European Centre for Medium range Weather Forecasts (ECMWF) provides a number of reanalysis products, the latest being ERA-Interim (ERA) which covers the period 1979–2010. Recent ECMWF products are dominated by observations from the Atmospheric InfraRed Sounder (AIRS) and the Infrared Atmospheric Sounding Instrument (IASI) over remote locations such as the Southern Ocean [*McNally et al.*, 2006]. The data is on a 1.5° × 1.5° grid, provided at six hour intervals, with 37 set pressure

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**Table 1.** Trends for the *u*-Wind, *v*-Wind and Wind Speed for Macquarie Island From 1991–2011, Along With Significance Level Given by the Two-Tailed p-Value[a]

| | Trend (cm/s/year) | p-Value | Correlation With SAM | Correlation With Surface |
|---|---|---|---|---|
| | | *u-Wind* | | |
| Surface | 0.528 | $7.63 \times 10^{-1}$ | **0.435** | **1** |
| 850 hPa | 4.597 | $1.08 \times 10^{-1}$ | **0.521** | **0.862** |
| 700 hPa | **6.099** | $5.50 \times 10^{-2}$ | **0.510** | **0.841** |
| 500 hPa | **7.649** | $6.29 \times 10^{-2}$ | **0.460** | **0.796** |
| | | *v-Wind* | | |
| Surface | **−3.825** | $1.62 \times 10^{-2}$ | **−0.396** | **1** |
| 850 hPa | −0.560 | $8.08 \times 10^{-1}$ | **−0.239** | **0.672** |
| 700 hPa | −0.658 | $8.10 \times 10^{-1}$ | **−0.225** | **0.638** |
| 500 hPa | −1.340 | $7.06 \times 10^{-1}$ | **−0.232** | **0.591** |
| | | *Wind Speed* | | |
| Surface | **2.999** | $1.13 \times 10^{-2}$ | **0.447** | **1** |
| 850 hPa | 2.879 | $1.61 \times 10^{-1}$ | **0.500** | **0.851** |
| 700 hPa | **5.148** | $3.87 \times 10^{-2}$ | **0.496** | **0.796** |
| 500 hPa | **7.290** | $2.95 \times 10^{-2}$ | **0.432** | **0.719** |

[a]Correlation coefficients for monthly mean winds and SAM are shown. The correlation coefficient between the surface wind and upper level winds are shown. Values in bold are significant.

**Table 2.** Trends for the *u*-Wind, *v*-Wind and Wind Speed for ERA-Interim From 1991–2010, Along With Significance Level Given by the Two-Tailed p-Value[a]

| | Trend (cm/s/year) | p-Value | Correlation With SAM | Correlation With Surface |
|---|---|---|---|---|
| | | *u-Wind* | | |
| Surface | 0.200 | $9.22 \times 10^{-1}$ | **0.422** | **1** |
| 850 hPa | 4.515 | $1.42 \times 10^{-1}$ | **0.503** | **0.957** |
| 700 hPa | 5.442 | $1.19 \times 10^{-1}$ | **0.474** | **0.937** |
| 500 hPa | 6.244 | $1.66 \times 10^{-1}$ | **0.432** | **0.897** |
| | | *v-Wind* | | |
| Surface | −1.957 | $2.27 \times 10^{-1}$ | **−0.375** | **1** |
| 850 hPa | −1.418 | $5.56 \times 10^{-1}$ | **−0.232** | **0.935** |
| 700 hPa | −1.166 | $6.87 \times 10^{-1}$ | **−0.224** | **0.901** |
| 500 hPa | −2.872 | $4.50 \times 10^{-1}$ | **−0.231** | **0.864** |
| | | *Wind Speed* | | |
| Surface | −0.221 | $8.54 \times 10^{-1}$ | **0.371** | **1** |
| 850 hPa | **3.806** | $8.96 \times 10^{-2}$ | **0.472** | **0.942** |
| 700 hPa | **4.952** | $6.59 \times 10^{-2}$ | **0.452** | **0.893** |
| 500 hPa | 5.163 | $1.59 \times 10^{-1}$ | **0.402** | **0.838** |

[a]Correlation coefficients for monthly mean winds and SAM are shown. The correlation coefficient between the surface wind and upper level winds are shown. Values in bold are significant.

levels which include the same standard levels as the MAC soundings.

[8] The main mode of climate variability at mid and high latitudes in the Southern Hemisphere is the Southern Annular Mode (SAM). Many definitions exist to describe this index, however the most convenient measures the difference in mean sea-level pressure (MSLP) between 40°S and 65°S. *Marshall* [2003] developed an observation based SAM index using the above definition, and it is this index which will be used in the current study to investigate any correlations between SAM and winds over Macquarie Island.

## 3. Results

### 3.1. Trend Analysis

[9] Table 1 presents the trends in wind over the period 1991 to 2011, in order to afford a direct comparison to the results presented by *Young et al.* [2011] The trend was calculated using a simple linear regression on the monthly mean values of *u* and *v* wind components, as well as the wind speed, after the seasonal cycle was removed. Also shown in Table 1 is the correlation coefficient between the monthly mean values of wind and the monthly SAM index, and the correlation coefficient between the monthly mean surface wind and monthly mean upper level winds at 850 hPa, 700 hPa and 500 hPa. Again, the seasonal cycle in the wind and SAM index were removed prior to calculating the statistics. The two-tailed p-value describing the significance of the trends is also shown. For this study, a p-value of less than $1 \times 10^{-1}$, which indicates significance to the 10% level, will be considered a significant trend, and a p-value greater than this will be considered insignificant. All the correlation coefficients shown through Tables 1–4 are significant.

[10] For the period 1991 to 2011, positive trends exist for MAC in the *u* wind, and increase with height. The only significant trends are those at 700 hPa and 500 hPa which are the greatest trends of 6.1 and 7.6 cm/s/year respectively. The trends in the *v* component are all negative, however the only significant trend is at the surface which is −3.8 cm/s/year. On average, *v* is negative, so a negative trend in the *v* component implies a strengthening of the northerlies. Put together, these result in overall positive trends for the wind speed, with the only insignificant trend being at 850 hPa. The surface wind speed shows an increase in magnitude of approximately 3 cm/s/year, with the trends at 700 hPa and 500 hPa increasing to 5.1 and 7.3 cm/s/year respectively.

[11] The correlation coefficient of the winds with SAM indicate positive correlations of between 0.43 and 0.52 for

**Table 3.** Same as Table 1 but for Macquarie Island From 1973–2011

| | Trend (cm/s/year) | p-Value | Correlation With SAM | Correlation With Surface |
|---|---|---|---|---|
| | | *u-Wind* | | |
| Surface | 1.094 | $4.47 \times 10^{-1}$ | **0.469** | **1** |
| 850 hPa | 0.124 | $9.22 \times 10^{-1}$ | **0.505** | **0.861** |
| 700 hPa | 0.969 | $4.97 \times 10^{-1}$ | **0.493** | **0.838** |
| 500 hPa | 2.072 | $2.62 \times 10^{-1}$ | **0.454** | **0.787** |
| | | *v-Wind* | | |
| Surface | **−5.899** | $6.81 \times 10^{-6}$ | **−0.417** | **1** |
| 850 hPa | 0.399 | $6.85 \times 10^{-1}$ | **−0.163** | **0.673** |
| 700 hPa | 0.141 | $9.03 \times 10^{-1}$ | **−0.147** | **0.624** |
| 500 hPa | 1.067 | $4.69 \times 10^{-1}$ | **−0.153** | **0.571** |
| | | *Wind Speed* | | |
| Surface | **4.259** | $1.59 \times 10^{-5}$ | **0.454** | **1** |
| 850 hPa | **−1.611** | $7.17 \times 10^{-2}$ | **0.433** | **0.798** |
| 700 hPa | −0.390 | $7.16 \times 10^{-1}$ | **0.448** | **0.746** |
| 500 hPa | 1.452 | $3.30 \times 10^{-1}$ | **0.408** | **0.672** |

**Table 4.** Same as Table 2 but for ERA-Interim From 1979–2010

| | Trend (cm/s/year) | p-Value | Correlation With SAM | Correlation With Surface |
|---|---|---|---|---|
| | | *u-Wind* | | |
| Surface | 1.528 | $1.46 \times 10^{-1}$ | **0.440** | **1** |
| 850 hPa | **2.951** | $6.48 \times 10^{-2}$ | **0.510** | **0.964** |
| 700 hPa | **3.151** | $8.38 \times 10^{-2}$ | **0.483** | **0.942** |
| 500 hPa | 3.802 | $1.07 \times 10^{-1}$ | **0.441** | **0.902** |
| | | *v-Wind* | | |
| Surface | −0.139 | $8.58 \times 10^{-1}$ | **−0.380** | **1** |
| 850 hPa | 0.614 | $5.92 \times 10^{-1}$ | **−0.209** | **0.928** |
| 700 hPa | 0.997 | $4.68 \times 10^{-1}$ | **−0.197** | **0.889** |
| 500 hPa | 1.006 | $5.77 \times 10^{-1}$ | **−0.206** | **0.844** |
| | | *Wind Speed* | | |
| Surface | 0.638 | $2.54 \times 10^{-1}$ | **0.375** | **1** |
| 850 hPa | **2.314** | $3.99 \times 10^{-2}$ | **0.473** | **0.948** |
| 700 hPa | **3.010** | $2.83 \times 10^{-2}$ | **0.456** | **0.897** |
| 500 hPa | **3.722** | $4.77 \times 10^{-2}$ | **0.408** | **0.843** |

the *u* component, and weaker negative correlations of between −0.22 and −0.39 for the *v* component. This yields correlations with SAM of between 0.43 and 0.5 for the wind speed over the 4 levels. Correlation coefficients between the surface wind and upper level wind are all large. For the wind speed, the size of the correlations are between about 0.72 and 0.85, and decrease with height.

[12] These results agree very well with those presented by *Young et al.* [2011] for the trend in surface wind speed in the area around Macquarie Island, who find a trend of between 2–3 cm/s/year over the past two decades. *Young et al.* [2011] also note a correlation between SAM and significant wave height of up to 0.4 over large areas of the Southern Ocean.

[13] The same analysis was performed on the ERA data set, with the results shown in Table 2, for the period 1991 to 2010, in order to compare to the MAC data set over a similar time period. In general, ERA reproduces similar trends to MAC, with slightly lower magnitudes, however none of the trends in the *u* and *v* wind components are significant. The trend in the surface wind speed for ERA is insignificant with a p-value of 0.85, hence one can not even infer the sign of the trend. The size of the trends for 850 hPa to 500 hPa wind speed are similar to MAC, however only the 850 hPa and 700 hPa trends are significant. ERA produces similar correlations between the winds and SAM, having similar values for *u*, *v* winds, and wind speed to those found in MAC. The correlations between the surface wind and upper level winds are higher in ERA than the ones in MAC, approximately equal to or greater than 0.9, and show the same pattern of decreasing with height.

[14] Both the MAC and ERA data sets extend back earlier than 1991, so the same statistics were calculated again using the full time periods in order to assess the longer term trends in each individual data set. Table 3 presents the trends and correlation coefficients for MAC for the period 1973 to 2011, a total of 39 years. Again, note that the continuous record of surface wind measurements is from 1987 to 2011, and hence represents a shorter time series. The only significant trend in the *u* and *v* components is for the surface *v* wind. Here we find a trend of −5.9 cm/s/year, which again implies the surface wind is becoming more northerly. The wind speed trends at the surface and 850 hPa are significant, and the trend at 850 hPa actually changes sign with the additional 18 years data. The surface trend shows an increase in magnitude and maintains the same sign with the addition of 4 extra years of data, resulting in a surface wind speed trend of 4.2 cm/s/year.

[15] All the correlation coefficients with the extended MAC wind data set and SAM remain between about 0.45 and 0.5 for the *u* component, and between −0.14 and −0.41 for the *v* component. This results in little change of the correlation coefficients of wind speed and SAM with the additional MAC data. Similarly, the correlations between surface wind and upper level winds remains high, typically between 0.67 and 0.8 for wind speed.

[16] Table 4 shows the same statistics for the ERA data set from 1979 to 2010. The only significant trends here are in the *u* wind at 850 hPa and 700 hPa, which show increases of 2.9 and 3.2 cm/s/year respectively. This results in the wind speed trends in ERA increasing from about 0.64 to 3.72 cm/s/year from the surface to 500 hPa, however the surface is insignificant. The correlation coefficients between the winds and SAM, and surface wind and upper level winds change very little with the additional reanalysis data.

### 3.2. Clustering Analysis

[17] A K-means clustering analysis [*Anderberg*, 1973; *Pope et al.*, 2009] was performed on the MAC data set in order to identify naturally occurring regimes in the wind over Macquarie Island. The variables chosen for the clustering analysis were the *u* and *v* wind components at the surface, and 500 hPa, along with the surface pressure, totalling 5 variables. The aim is to determine if there is a shift in meteorological regimes rather than the mean state of the atmosphere.

[18] The initial number of clusters was chosen by employing a series of objective and subjective criteria, similar to those used by *Rossow et al.* [2005]. The most appropriate number of clusters was found to be K = 4. Only soundings from 1987 onwards were included in the cluster analysis. Figure 1 shows histograms of the variables for the 4 cluster centroids. In all panels, the *y*-axis represents wind speed in $ms^{-1}$, or pressure anomaly from the mean in hPa, where the mean pressure is 998.63 hPa.

[19] The first cluster represents 30.3% of the data, and is characterised by nearly average pressure and a strong surface westerly with a small northerly component. The strong westerlies persist aloft, and the *v*-component changes to a relatively large positive value. This represents an anticlockwise rotation in the wind field from the surface to 500 hPa. Cluster 2 represents 24.5% of the data, and is characterised by high pressure and moderately strong winds. There is a moderate north westerly at the surface turning to mostly westerly, with a small northerly component at 500 hPa. The third cluster represents 28.3% of the data, and indicates low surface pressure is associated with this regime. Here there exists persistent and strong north westerlies from the surface to 500 hPa. There appears to be little change in the wind direction with height for the soundings associated with this cluster. The final cluster is also the smallest, representing 16.9% of the MAC data. Again, this cluster is characterised by low pressure, however with weak winds. The wind is mostly southerly at the surface, changing to

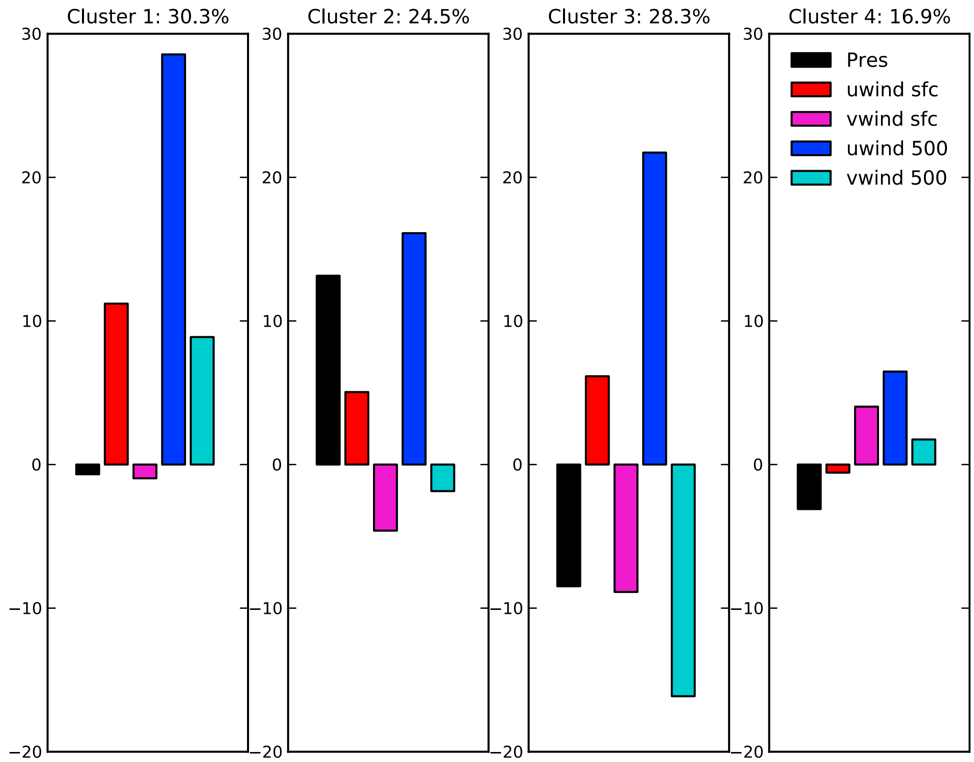


**Figure 1.** Magnitude of each variable for each cluster centroid.

mostly westerly with a smaller southerly component at 500 hPa.

[20] To elucidate any trends in the occurrence of these clusters, the frequency with which they occur from 1987 was evaluated. The result is shown in Figure 2. For visual clarity, the time series for Cluster 3 has been offset by +0.1. There appears to be no trend in the occurrence of Cluster 1, and there are weak negative trends in Clusters 2 and 4, however these are insignificant with p-values of 0.18 and 0.16 respectively. The trend in Cluster 3 shows a clear increase in occurrence of 0.19 % per year, which is statistically significant with a p-value of 0.02. Thus, there appears to be a shift in the meteorological regimes over Macquarie Island, towards strong north westerly winds at the surface and 500 hPa.

## 4. Conclusions

[21] Analysis of trends in Macquarie Island sounding data reveal the surface wind speed is increasing, and is consistent with the trends highlighted in *Young et al.* [2011]. The overall trend in the upper levels is not consistent when examined over different periods of time, and not as significant as at the surface. When analysed over similar time periods, ERA mostly underestimates the size of the trends in

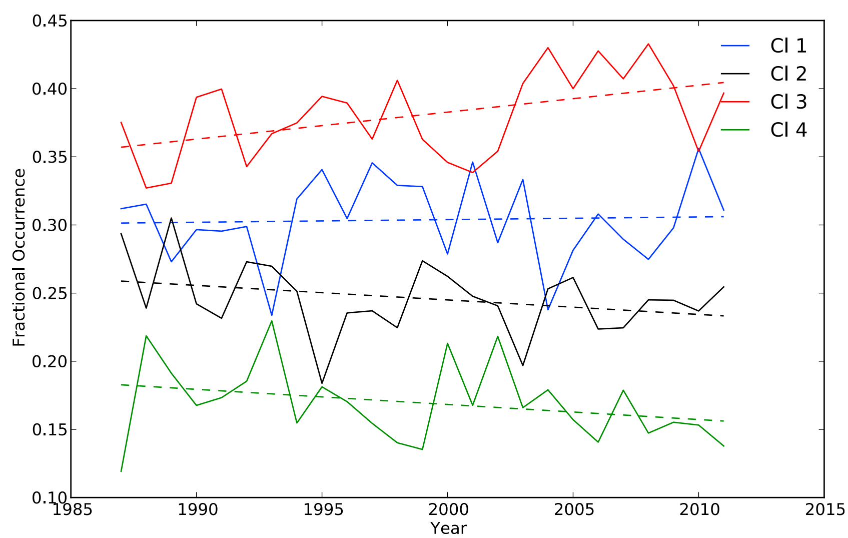


**Figure 2.** Trend in the occurrence of clusters from 1987 to 2011.

wind speed. The correlations between the monthly mean winds in the MAC soundings and the monthly SAM index show moderate correlation coefficients, typically between 0.4 to 0.5. The winds at the surface are also highly correlated to the upper level winds. These correlations are well represented in the ERA data set. Cluster analysis reveals there is a potential shift to more frequent strong north westerly winds at the surface and 500 hPa, associated with low surface pressure in the vicinity of Macquarie Island. The discrepancy in the wind trends represents a potentially important bias for climate studies over the Southern Ocean, where the generation of sea-spray by surface wind has an influence on the overall albedo, representing an important climate feedback as identified by *Korhonen et al.* [2010].

[22] **Acknowledgments.** This research has been supported by Monash University. Sounding data provided by the University of Wyoming. The authors wish to thank the reviewers, in particular Professor Alexander Babanin for insightful discussions and helpful reviews.

[23] The Editor wishes to thank Alexander Babanin and an anonymous reviewer for assisting in the evaluation of this paper.

## References

Anderberg, M. R. (1973), *Cluster Analysis for Applications*, 359 pp., Elsevier, New York.

Arblaster, J. M., and G. A. Meehl (2005), Contributions of external forcings to Southern Annular Mode trends, *J. Clim.*, *19*, 2896–2905.

Korhonen, H., K. S. Carslaw, P. M. Forster, S. Mikkonen, N. D. Gordon, and H. Kokkola (2010), Aerosol climate feedback due to decadal increases in Southern Hemisphere wind speeds, *Geophys. Res. Lett.*, *37*, L02805, doi:10.1029/2009GL041320.

Marshall, G. J. (2003), Trends in Southern Annular Mode from observations and reanalyses, *J. Clim.*, *16*, 4134–4143.

McNally, A. P., P. D. Watts, J. A. Smith, R. Engelen, G. A. Kelly, J. N. Thepaut, and M. Matricardi (2006), The assimilation of AIRS radiance data at ECMWF, *Q. J. R. Meteorol. Soc.*, *132*, 935–957, doi:10.1256/qj.04.171.

Pope, M., C. Jacob, and M. J. Reeder (2009), Regimes of north Australian wet season, *J. Clim.*, *22*, 6699–6715, doi:10.1175/2009JCLI3057.1

Rossow, W. B., G. Tselioudis, A. Polak, and C. Jakob (2005), Tropical climate described as a distribution of weather states indicated by distinct mesoscale cloud property mixtures, *Geophys. Res. Lett.*, *32*, L21812, doi:10.1029/2005GL024584.

Tokinga, H., and S. Xie (2011), Wave- and Anemometer-Based Sea Surface Wind (WASWind) for climate change analysis, *J. Clim.*, *24*, 267–285.

Trenberth, K. E., and J. T. Fasullo (2010), Simulation of present-day and twenty-first-century energy budgets of the southern oceans, *J. Clim.*, *23*, 440–454, doi:10.1175/2009JCLI3152.1.

Young, I. R. (1999), Seasonal variability of the global ocean wind and wave climate, *Int. J. Climatol.*, *19*, 931–950.

Young, I. R., S. Zieger, and A. V. Babanin (2011), Global trends in wind speed and wave height, *Science*, *332*, 451–455.