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Statistical comparison of coincident wind gust measurements from Dines and cup anemometers

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Abstract

Peak gust wind speed observations collected over more than 70 years by the Australian Bureau of Meteorology (BoM) are utilised by Standards Australia (Australia/New Zealand Wind Actions Standard) and the Building Code of Australia (BCA) to minimise natural hazard risk to people and buildings. In the mid-1980's BoM commenced a program to replace the aging pressure tube Dines anemometers with cup anemometers. During the anemometer replacement procedure, many localities had more than one type of anemometer operating, recording extreme events. Systematic differences between instrument measurements during this overlap period raised serious concerns about the utility of the peak gust wind speed database. This study utilises statistical extreme value distribution analysis and compares estimates of the 500-year return-period (RP) peak gust wind exceedance level derived from coincident wind gust measurements from Dines and cup anemometers. The data on the extreme gust wind speeds for 7 sites (coincident measurement period of 89 years) were considered, allowing an assessment of bias for gust wind speeds between 45 and 60 m/s.

Introduction

Australian building codes through the Australia/New Zealand Wind Actions Standard (AS/NZS 1170.2 2011) as well as the wind engineering community in general rely to a significant extent on the peak gust wind speed observations collected over more than 70 years by the Australian Bureau of Meteorology (BoM). The current wind loading code and the performance of our infrastructure (residential, commercial, industrial and critical infrastructure) with regards to wind hazard, is based primarily on the Dines anemometer interpretation of the peak gust wind speed. In the mid-1980's BoM commenced a program to replace the aging pressure tube Dines anemometer with the Synchrotac and Almos cup anemometers. During the anemometer replacement procedure, many localities had more than one type of anemometer operating, recording extreme events. The passage of Cyclone Vance through Exmouth in 1999 saw Dines and Almos anemometers, separated by 25 metres, recording peak gusts of 144 and 122 knots respectively (Reardon et al, 1999). A weak cyclone that passed through Townsville in April 2000 recorded a peak gust of 70 knots on the Dines and 59 knots on the Almos anemometer (Reardon, 2000). These systematic differences raised serious concerns about the utility of the peak gust wind speed database.

Installation of Dines anemometers at Australian sites commenced in the 1930's. The Dines anemometers were factory calibrated under steady state conditions (mean wind speeds); their response to transient wind conditions (gusts) was not determined. In practice, a calibration-extrapolation technique was utilised for wind speeds measured outside the calibration wind speed range (i.e. extension of calibration curve). Once installed, the Dines anemometer could not be calibrated due to its large size which incorporated either a 6 or 10 metre long tube, depending on the type of installation. Station intercomparisons were conducted on an ad-hoc basis (mean wind conditions), however it was difficult to undertake this comparison at exactly the same location and height as the head of the Dines anemometer. The Australian (BoM) anemometer replacement program, which replaced the pressure-tube Dines instruments (paper chart recording) with cup anemometers (digital recording), had the potential to drastically change the characteristics of observed wind speed. It was well known that the Dines had a high minimum start-up speed (i.e. minimum speed before the instrument registers a reading) whilst the cup anemometers suffered from overspeeding (i.e. cups keep rotating even though wind has dropped resulting in higher readings than the actual wind speed; Gorman 2004). For this reason there was initially a concern that the cup anemometers may read higher than the Dines anemometer during extreme wind conditions. At the time, the anemometer calibration equipment (wind tunnel) was not able to accurately characterise the transient (gust) response of the cup anemometers. For high (extreme) wind speeds measured by cup anemometers, extrapolation of the wind tunnel calibration continued to be employed.

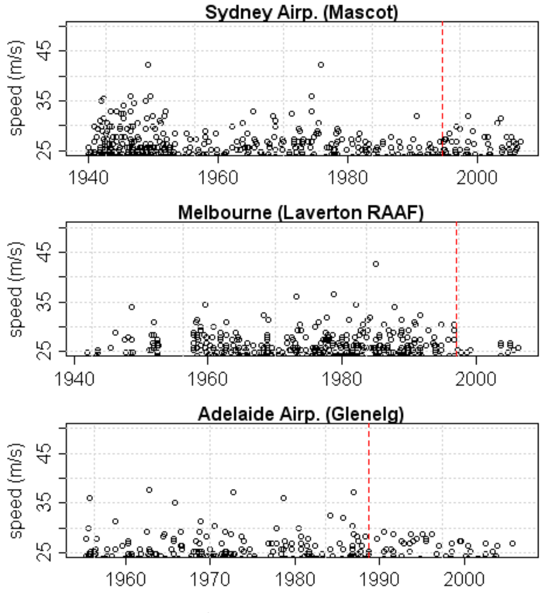

Figure 1. Time-series plots of the daily maximum gust wind speed (above a threshold of 25 m/s) for the Sydney, Melbourne and Adelaide (airport) meteorological observing station. The broken vertical line indicates the replacement of the Dines anemometer with a 3-cup anemometer.

Figure 1 shows time-series plots of the daily maximum gust wind speed (above a threshold of 25 m/s) for the Sydney, Melbourne and Adelaide meteorological observing stations. Visual inspection indicates that the early part of the record (Dines anemometer) contains a greater number and also higher amplitude extreme events compared to the later part of the record (replacement anemometer). Other stations considered within the Australian region show similar time-series characteristics.

A number of intercomparisons involving Dines and cup anemometers have been undertaken over the last 50 years or so, most primarily concerned with the differences in the mean wind speed; see for example (Smith, 1981). Logue (1986) compared both mean and gust wind speeds measured using a Dines co-located with a standard cup anemometer at the Irish Meteorological Service's Galway observing site (during the year of 1984). Overall the mean wind speeds from the two instruments compared well. However, the cup anemometer significantly underestimated the gust wind speeds when compared to those obtained using the Dines. The cup anemometer used by Logue (1986) was similar in design to the Bureau of Meteorology (i.e. heavy construction). An earlier paper by the authors (Cechet and Sanabria, 2010) considered time-series analysis of Australian region anemometer observations (no overlap of observed record). This is overviewed in the discussion section.

Methodology

Results presented here were generated using a statistical model of severe winds developed by Geoscience Australia (Sanabria and Cechet, 2007). Although statistical models have limitations, they are useful for the assessment of potential severe winds at discrete points in a region and are fundamental for the calculation of hazard from records of observational gust wind speed datasets. Statistical methods are extensively utilised in the current Australian wind loadings standard (AS/NZS 1170.2, 2011), with 500-year return period hazard utilised as the design wind speed for the majority of buildings.

The main limitation of statistical models is their dependency on the quality of the observational data utilised. One of the issues affecting the quality is the small size of the datasets available for analysis; the largest dataset used in this study has only 60 years of data whilst it is required to predict the 500 year return period for gust wind hazard. The ability to calculate reliable confidence intervals for the results is also an issue of further research. The core of the statistical model is the calculation of return periods for extreme gust speeds. This is carried out by fitting an extreme value distribution to the given gust wind speed dataset. Extreme value distributions are asymptotic functions that allow modellers to extrapolate limited data samples to maximum possible values. The theory behind extreme value distributions is similar to the Central Limit Theorem (CLT); both infer the limiting distribution of independent, identically distributed (iid) random variables. According to the CLT, the mean value of a sample of iid random variables converges to a standard normal distribution. Similarly if the maxima of a large number of iid random variables converge to a distribution, this distribution has to be a member of the Extreme Value Distributions (Jagger and Elsner, 2006).

Although the extreme value distribution theory has been derived considering a set of infinite data samples, it is regarded as good approximations to the behaviour of limited data. There are two basic types of functions to fit extreme values: Generalised Extreme Value distributions (GEV) and the Generalised Pareto Distribution (GPD). Sanabria and Cechet (2007) modelled a number of gust wind speed datasets using both GEV and GPD methods. The results produced by the GEV distributions were considered too poor for wind hazard applications, so for this study we have focused on the application of the GPD method.

A number of techniques to fit extreme value distributions to the given data have been developed. Palutikoff et al., (1999) and Seguro and Lambert (2000) reported that for geophysical data the maximum likelihood method (mle) provides the most effective technique for fitting data. The authors have tested seven techniques (not presented here) with similar results, and so the ‘mle’ technique was adopted here.

The Generalised Pareto Distribution (GPD) defines a family of extreme value distributions. The GPD utilises all values of a dataset exceeding a given threshold. It has certain advantages over the Generalised Extreme Value Distributions (GEV); first it uses significantly more data than the GEV; secondly by setting the threshold high enough, the data will be better distributed in time, so it is likely that the observations are independent from each other, one of the conditions of extreme value distributions (Coles, 2001). The GPD is defined by the expression:

$$H(y) = 1 - (1 + \xi * y/\check{s})^{-1/\xi} \quad (1)$$

defined in $y : y > 0$ and $(1 + \xi * y/\check{s}) > 0$
where: $\check{s} = \sigma + \xi * (u - \mu)$

$\check{s}$ = GPD scale parameter;
σ = scale parameter of GEV
ξ = GEV shape parameter
u = threshold value
μ = GEV location parameter

Note that μ and ξ are also the parameters of the GEV, i.e. if the original data can be fitted with a GEV distribution, values above the threshold can be fitted with a GPD.

Threshold Selection

One of the issues found in fitting a GPD to given wind speed datasets is the selection of the appropriate threshold value ‘u’. High threshold values result in the selection of only a few data points, most likely not enough for a good fitting of the distribution. Low values result in too many samples which are most likely not independent from each other. Return period calculation using GPD distributions are very sensitive to the threshold selection. Although there are methods to help modellers select the appropriate threshold for a given dataset they are mostly visual, subjective techniques, prone to producing inaccurate results and inappropriate for large scale applications. In these studies the computer-based, automatic algorithm discussed in Sanabria and Cechet (2007) was used.

Confidence Interval - determination

Calculation of return periods of wind gusts should be considered incomplete if a confidence interval (CI) for the results is not presented. A confidence interval shows the range of values in which the true value of the return period lies for a given probability. The confidence interval depends on the size and structure of the dataset, particularly the variance-covariance matrix which measures the spread of the samples around their mean. In this study we are interested in finding confidence intervals with 95% probability, in other words, we want to find the return period of wind speeds with the interval in which the true value of the return period can be found in 95% of cases. There are two basic algorithms for calculation of the confidence intervals of results produced by extreme value distributions: the `Delta' method and the `Profile Likelihood' method. Both methods have been implemented in the R environment by Gilleland and Katz (2005a) based on Coles (2001). Applying the methods to temperature data, Gilleland and Katz found out that the Profile-likelihood method gives better results because it considers the asymmetry of the data (Gilleland and Katz 2005b). Since wind speed data is highly asymmetric the Profile-likelihood method has been used in this study.

Results

Coincident gust wind speed measurements at 7 northern Australian observing stations were analysed to determine the magnitude of the direct bias. Only Dines “high-speed range” anemometers (0-200 knots) were considered for observing stations where extreme wind gusts are dominated by thunderstorm and tropical cyclone events. The stations examined were Cairns, Townsville, Brisbane, Darwin, Gove, Broome and Learmonth. Cup anemometer data was available in digital form (maximum gust wind speed for each 30 minute interval) whereas the maximum gust wind speed for the Dines anemometer record was scaled directly off the chart record by recording the maximum peak each 30 minute period. A threshold of 15 m/s over the 30 minute period for the cup anemometer was selected so that only thunderstorm and tropical cyclone events were considered (i.e. no synoptic wind events were considered; gusts were independent events). All results are reported in detail in Cechet and Sanabria (2011).

Coincident probability distributions (PDF's) of the gust wind speed (Dines & cup anemometer; 15 m/s threshold) for the seven sites considered display some interesting characteristics:

- PDF's are broader for the Dines instrument (all cases) indicating an elevated level of noise compared with the cup anemometer. This noise may be partly made up of random error (instruments not coincident in position; separated by between 25m and 100m) and also instrument error (issues such as the Dines float resonance and the Dines wind vane not parallel to gust direction as well as others such as the Dines float level not being maintained at the correct position). This confirms both theoretical and laboratory testing (CTS, 2011) which indicated that the Dines instrument was more "noisy" compared to cup anemometers. In addition, the magnitude of the bias appears to be a function of wind speed.
- Focusing on the peak of the PDF's, there appears to be some systematic bias between Dines and cup anemometers for some of the observing stations. The PDF peak appears slightly low for the Dines at Darwin compared to the cup anemometer and too high for Learmonth and Townsville. Agreement is excellent for Cairns.

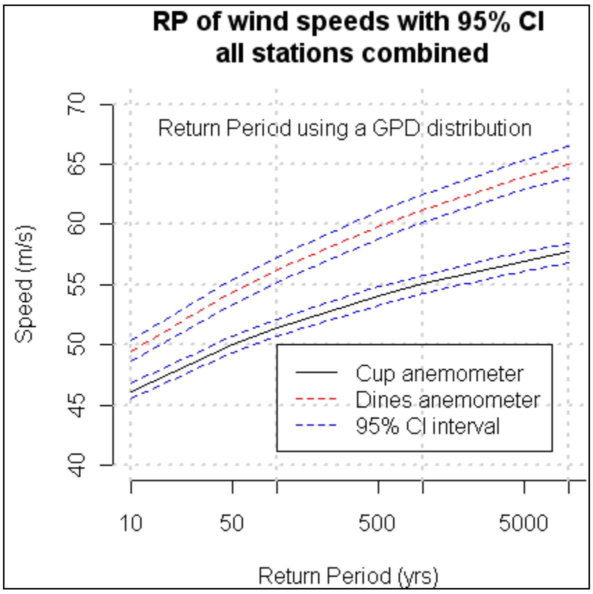

Figure 2. Return period plots of coincident maximum gust wind speed (above a threshold of 15 m/s for 30 minute time sections) for the combined 7 northern Australian observing stations over a total coincident measurement period of 89 years. 95% confidence limits for the GPD fit to the Dines anemometer observations are also provided.

Time-series plots of the bias between the Dines and cup anemometer measurements show no time dependent relationships. The bias is uni-directional for some extreme cases where the cup anemometer recorded an event that the Dines either captures to a much lesser extent or misses altogether. The size of thunderstorm gust fronts can cause significant differences in wind speed over 10's to 100's of metres.

The data on the extreme gust wind speeds for the 7 sites were combined into one dataset and extreme value statistical theory (GPD's) were used to investigate the return period exceedence levels for the combined dataset. Figure 2 shows the return period plots of coincident maximum gust wind speed (above a threshold of 15 m/s for 30 minute time sections) for the combined 7 northern Australian observing stations obtained over a total coincident measurement period of 89 years. 95% confidence limits for the GPD fit to the Dines extreme gust wind observations are also shown.

Table 1 details the percentage bias between the cup anemometer and Dines return period estimates (including the 95% confidence limits regarding the fitting of the extreme value distribution to the Dines gust observations). The observed data allows us to consider gust wind speeds between 45 and 60 m/s. When considering gust wind speeds at about 45 m/s, the Dines anemometer has a tendency to read about 5 to 10% higher than the cup anemometer (considering coincident data at 30 minute intervals); this increases to about 12 to 17% higher at gust wind speeds around 60 m/s. These systematic differences are consistent with those reported by Reardon et al (1999) and Reardon (2000), and confirm concerns about the consistency of the peak gust wind speed observational database which underpins the Australian wind loading standard (AS/NZS 1170.2, 2010).

Cup anemometer gust wind speed	Dines anemometer gust wind speed	Dines; Lower 95% confidence limit	Dines; Upper 95% confidence limit
45 m/s	+7 %	+5 %	+9 %
50 m/s	+9%	+7 %	+11 %
55 m/s	+11 %	+9 %	+13.5 %
60 m/s	+14 %	+12 %	+17 %
65 m/s	N/A	N/A	N/A

Table 1. Percentage difference (return period gust wind speed) between the Dines anemometer and cup anemometers over a range of wind speeds, considering coincident extreme wind gust measurements at 7 observing sites over a total coincident measurement period of 89 years. The asymptotic nature of the GPD fit to the observations does not allow a comparison for gust wind speeds above 60 m/s.

Discussion

An earlier paper on this work by Cechet and Sanabria (2010) considered time-series analysis of Australian region anemometer observations (no overlap of observed record). They evaluated both the daily maximum gust and 3PM mean wind speed 500-year return period (500RP) exceedance levels of gust wind speeds for the 31 wind observing stations selected (within AS/NZS 1170.2 Region A). For the cup anemometer 500RP exceedance level gust wind speed estimates, there are 17 observing stations where the cup anemometer estimates fell below the lower 95% confidence interval (95CI) for the Dines segment of the observing record. For 24 of the 31 observing stations the cup anemometer estimate fell below the corresponding Dines segment estimate. Considering the 3PM mean wind speeds, there were 18 observing stations where the cup anemometer estimate fell below the lower 95CI for the Dines segment of the observing record. The statistical analysis utilising extreme value distributions (EVD's) resulted in more than half of the observing stations considered (later part of the time-series record) having both 500-year RP gust wind speed (17 of 31) and 3PM mean wind speed (18 of 31) exceedance level estimates being in the lower tail of the distribution for the early part of the observing record (period prior to equipment upgrade from Dines to cup anemometer).

For this study coincident measurements of gust wind speed at 7 northern Australian observing stations were analysed to determine the magnitude of the direct bias. Coincident probability distributions (PDF's) of the gust wind speed (Dines & cup anemometer; 15 m/s threshold) for the seven sites considered display some interesting characteristics. Focusing on the peak of the PDF's, there appears to be some systematic bias for some of the observing stations. The peak of the PDF appears slightly low for Darwin and too high for Learmonth and Townsville. Agreement is excellent for Cairns. PDF's are broader for the Dines instrument indicating either an elevated level of noise compared to the cup anemometer, or possible damping of the cup anemometer response compared to the Dines anemometer. This difference may be due to a number of issues such as:

(i) random error (instruments not coincident in position; separated by 25-100m);
(ii) instrument error (issues such as the Dines float resonance and the Dines wind vane not being parallel to gust direction as well as others such as the Dines float level not being maintained at the correct position);
(iii) the 3-second moving average filter applied to the 1-second wind speed measurements which forms the gust recorded by the BoM instrumentation.

Digital recording of meteorological data became prevalent in the 1990's. With regards to gust wind speed measurements, BoM implemented a 3-second averaged gust wind speed in the mid-1990's on a recommendation from World Meteorological Organisation (Beljaars, 1987). In practice applying a 3-second moving average to the sampled signal (one measurement each second) will filter out anything with a period of less than around 6.8 seconds, which more than doubles the effective wavelength of the measured gust wind speeds. Clearly not even a true 3-second gust is fully captured by the current filtering, and this is not consistent with the gust length scales relevant for a typical residential structure. Miller (2007) examined the response of the combination of a Munro MK IV anemometer with a chart recorder as used in the UK Meteorological Office until the mid-1970's. He found that this combination gives an effective gust duration approaching 1 second at high wind speeds (considered suitable for informing design wind speeds). Discussions with the BoM are continuing with regards to understanding the impact of this filtering on the consistency of the long-term record. It may be prudent to review the use of the 3-second moving average for gust wind speed observations (including an experimental study) in order to assess the significance of this issue.

Conclusions

Coincident gust wind speed measurements at 7 northern Australian observing stations were analysed to determine whether a bias existed between the early part of the gust wind speed record (measurements obtained using pressure-tube Dines anemometers) and the later part of the record (measurements obtained using 3-cup anemometers). In general, the time-series plots of the bias between the Dines and cup anemometer measurements show no time dependent relationships. The data on the extreme gust wind speeds for 7 sites (coincident measurement period of 89 years) were considered, allowing an assessment of bias for gust wind speeds between 45 and 60 m/s. For gust wind speeds of about 45 m/s, the Dines anemometer has a tendency to read about 5 to 10% higher than the cup anemometer; this increases to about 12 to 17% higher at gust wind speeds around 60 m/s. These systematic differences are consistent with those reported by Reardon et al (1999) and Reardon (2000). These results confirm the earlier concerns of Cechet and Sanabria (2010), and also confirm concerns about the consistency of the peak gust wind speed observational database which underpins the Australian wind loading standard (AS/NZS 1170.2, 2011).

Acknowledgments

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