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Australian Tropical Cyclone Wind Hazard: Analysis of AWS Observations

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Abstract

Estimates of extreme wind hazard are used by a wide range of industries and regulatory bodies to ensure public, business and fiscal safety. From a wind engineering perspective, a primary use of this data is to define design wind speeds for the calculation of wind loads on structures. In cyclonic regions, simulation models are often used to estimate wind hazard, but to ensure their veracity these models must be validated with an extreme value analysis of observed data. This paper presents such an analysis for Automatic Weather Stations (AWS) around the Australian coastline. It concludes that the estimation of wind hazard with extreme value analyses alone is highly variable depending on the specific technique (Gumbel, Peaks over Threshold, Method of Independent Storms) chosen to analyse available data. Therefore, discretion should be used when validating results of simulation models or estimating exceedance probabilities for a given wind speed to ensure the uncertainty in these results are adequately considered.

Introduction

Extreme wind gusts, such as those caused by tropical cyclones, have the potential to generate significant damage to both property and people. An understanding of the likelihood and magnitude of these events, defined as the wind hazard (Holmes, 2015), is necessary for safe engineering design. Wind hazard calculations underpin the wind loading codes and standards used by civil engineers to design structures, but also have uses in other fields: for example, the insurance industry and government planning (Harper, 1999).

Two main methods exist for estimating wind hazard. The first, *observation-based extreme value analysis*, is widely used to estimate wind hazard around the world (e.g. Holmes & Moriarty, 1999; Rajabi & Modarres, 2008; Castellani et al, 2015). This technique involves fitting theoretical probability distributions to historic wind speed observations at a given location (Palutikof et al, 1999). Through these distributions, data can be extrapolated to estimate wind speeds for a range of exceedance probabilities well beyond the observation period of that site. The second method, *simulation models*, are becoming increasingly common in areas that suffer from short data records, such as cyclonic regions. These models take into account a broad range of data, and use a series of stochastic and/or probabilistic tools to generate long records of synthetic gust events. Standard statistical techniques are then applied to these data to estimate site- or region-specific wind hazard.

Observation-based extreme value analyses are not typically relied upon solely for the estimation of site-specific wind hazard in cyclonic regions. Harper (1999) and Holmes (2015) suggest that data records are not sufficiently long because of event occurrence rates and relatively short observation periods. Despite this, a thorough analysis of available observations has great value in that it can be used to assess and validate the efficacy of stochastic estimates of gust exceedance probability, such as those generated through simulation models, e.g. Georgiou (1985), Harper (1999) and Harper et al (2012). It is also of interest to conduct a detailed analysis of these gust observations to see what information is contained in these records and how well differing probability distributions fit to these data, despite their short duration. Comparison studies such as these have shown that extreme wind speed estimates can vary significantly depending on the approach used (An & Pandey, 2005; Holmes & Moriarty, 1999). Therefore, this study aims to investigate the variability in wind hazard estimation for observation sites around the tropical cyclone prone coastline of Australia using different extreme value analysis techniques. The Gumbel (GM), Peaks over Threshold method (PoT), and Method of Independent Storms (MIS) techniques are explored, with estimated 50- and 1000-year return period wind gusts for each method compared with the regional wind speed specified in AS/NZS1170.2 for each particular site.

Methodology

Site selection

Maximum daily wind gust data for all Automatic Weather Station (AWS) sites around Australia were obtained from the Australian Government Bureau of Meteorology (BoM). These data were reduced by considering only those mainland sites within 200 km of the coastline above the latitude of 30°S. Station data were then inspected, and any calendar year with less than 80% of days registering a valid wind gust were removed. Stations with greater than 30 years of valid observations were then retained for analysis. Figure 1 shows the distribution of analysis sites used in this study, with greater detail on record period and observed number of tropical cyclones listed in Table 1. Stations in cyclonic (C, D) and non-cyclonic (B) regions of AS/NZS1170.2 (Australian Standards, 2011) were identified for analysis.

Site	**Station Name**	**AS1170.2 Region**	**Years of Data (*T*)**	**Number of cyclones (300km radius)**
1	Geraldton Airport	B	57	15
2	Carnarvon Airport	D	60	31
3	Learmonth	D	35	27
4	Onslow Airport	D	43	45
5	Mardie	D	30	32
6	Port Hedland	D	59	61
7	Broome	C	67	56
8	Darwin Airport	C	53	29
9	Thursday Island MO	B	34	12
10	Cairns Aero	C	71	27
11	Townsville Aero	C	71	20
12	Mackay MO	C	44	26
13	Rockhampton Aero	C	75	19
14	Gladstone Radar	C	37	14
15	Brisbane Aero	B	61	11

Table 1. BoM stations used in the analysis.

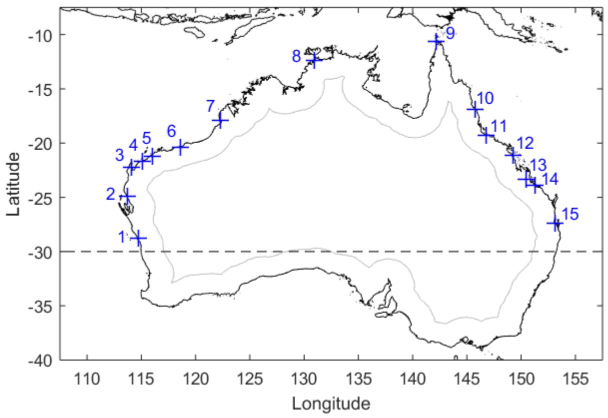

Figure 1. Locations of BoM observation stations used in the analysis. The grey line shows the 200km buffer used to select stations. Numbers correspond with the sites shown in Table 1.

Standardisation of wind gust data

All wind gust data were standardised to a common exposure (flat, open, 10 m elevation) and gust averaging period (3-seconds), as per World Meteorological Organisation (WMO) guidelines (WMO, 2008). To do this, terrain and topography in all directions surrounding each observation station were inspected using Google Earth. If these did not match the desired specification, wind speed records were adjusted using the terrain/height or topographic multipliers found in AS/NZS1170.2. While this approach is reasonable when sites are located on upwind slopes, uncertainty around its application to sites located in the lee or valley of topographic features should be noted.

Over the observation period of many BoM stations, wind gust data were recorded using a combination of Dines and 3-cup Synchrotac anemometers. These anemometers have different effective moving averaging periods: i.e., 0.2 seconds for Dines anemometers, and 3 seconds for 3-cup Synchrotac anemometers (Ginger, 2011). Correction factors derived by Holmes & Ginger (2012) were applied to wind gusts recorded by Dines anemometers to convert them to equivalent 3 second gusts. This conversion reduces gusts by approximately 12 - 15%.

Selection of cyclone wind gust data

Wind gusts recorded during cyclones were selected by creating a list of ‘cyclone days’ for each site. This was done using cyclone track data from the International Best Track Archive for Climate Stewardship (IBTrACS) cyclone database (National Oceanic and Atmospheric Administration, 2014). A day was considered a ‘cyclone day’ when a cyclone track was recorded within a 300 km radius of the station. The maximum daily wind gust recorded on ‘cyclone days’ was extracted to create a list of wind gusts from cyclones for each site. To ensure independence of the data, cyclone serial numbers were compared and only the maximum daily gust for each cyclone retained in the list. Left censorship of the data at 17 ms^{-1} was performed to ensure only extreme values were included in the analysis (Harper et al, 2012; Holmes & Moriarty, 1999).

The choice of a fixed cyclone radius for selecting data to be analysed is based on the approach of Cook et al (2003). While a more event-specific selection process would be preferred, it is only since the early 2000s that the BoM has systematically recorded metrics for cyclone size in their database. Figure 2 shows the radii of maximum winds, radii of gale force winds (34 knots) and radii of outer closed isobar for the 17 cyclones in the database with each of these metrics recorded. These data show that a radius of 200-300 km serves as an upper bound to the radii to gale force winds, but the storm to storm value varies greatly. The choice of a single threshold distance for inclusion (300 km), as used here, is believed acceptable when coupled with the left-censorship of data, as this will automatically exclude low wind gust values within this region not associated with the cyclone. The threshold radius used here is less than the 500 km used by Cook et al (2003).

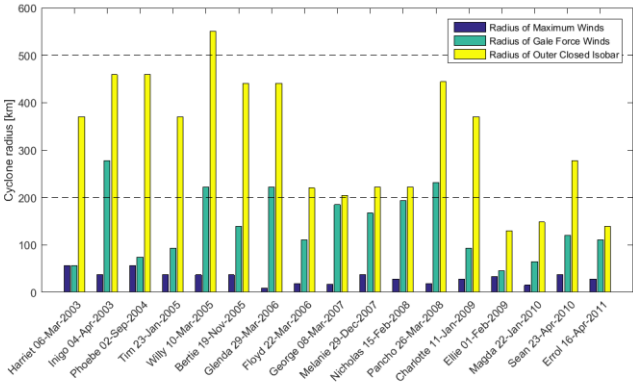

Figure 2. Radii of maximum winds, gale force winds and outer closed isobar for 17 observed Australian cyclones since 2003 in the IBTrACS database.

Extreme value analysis

Three extreme value analyses were performed on the data: the Gumbel method (GM), the Peaks over Threshold method (PoT) and the Method of Independent Storms (MIS). Descriptions of these methods can be found in Palutikof et al. (1999), An & Pandey (2005) and Holmes (2015).

The GM was performed using a traditional annual maxima approach using the maximum cyclone generated wind gust in any calendar year. The MIS applied in this study was modified from that presented in Palutikof et al. (1999) to account for the fact that a continuous wind record was not used. This meant the original up-crossing and down-crossing approach was not required. The maxima of independent storms were simply taken as the maximum value from each cyclone. Data were then fit with a Type 1 Extreme Value distribution (i.e. Gumbel). Return intervals were scaled by an average rate of cyclones per year, *r*, based on the number of cyclones recorded in total over the recording period, *n*, and the number of years of data, *T* (Harper et al, 2012):

$$r = \frac{n}{T} \tag{1}$$

A fit was also made using the Generalised Extreme Value distribution (GEV), where the MATLAB GEV maximum likelihood estimator was used to calculate the distribution parameters that best fit the observational data.

The PoT method was applied as described in Palutikof et al. (1999). Fitting of the Generalised Pareto Distribution (GPD) was done using the MATLAB GPD maximum likelihood estimator for each of the method parameters. A threshold of 20 m/s was chosen and implemented for all sites, approximately aligning with the threshold suggested by Holmes (2002). This threshold was chosen to be larger than the left truncation value of 17 m/s applied to the original data record, while also optimising the length of data available. Thresholds of 18 and 19 m/s were also tested, which showed that decreasing this threshold did not significantly affect the results at most sites.

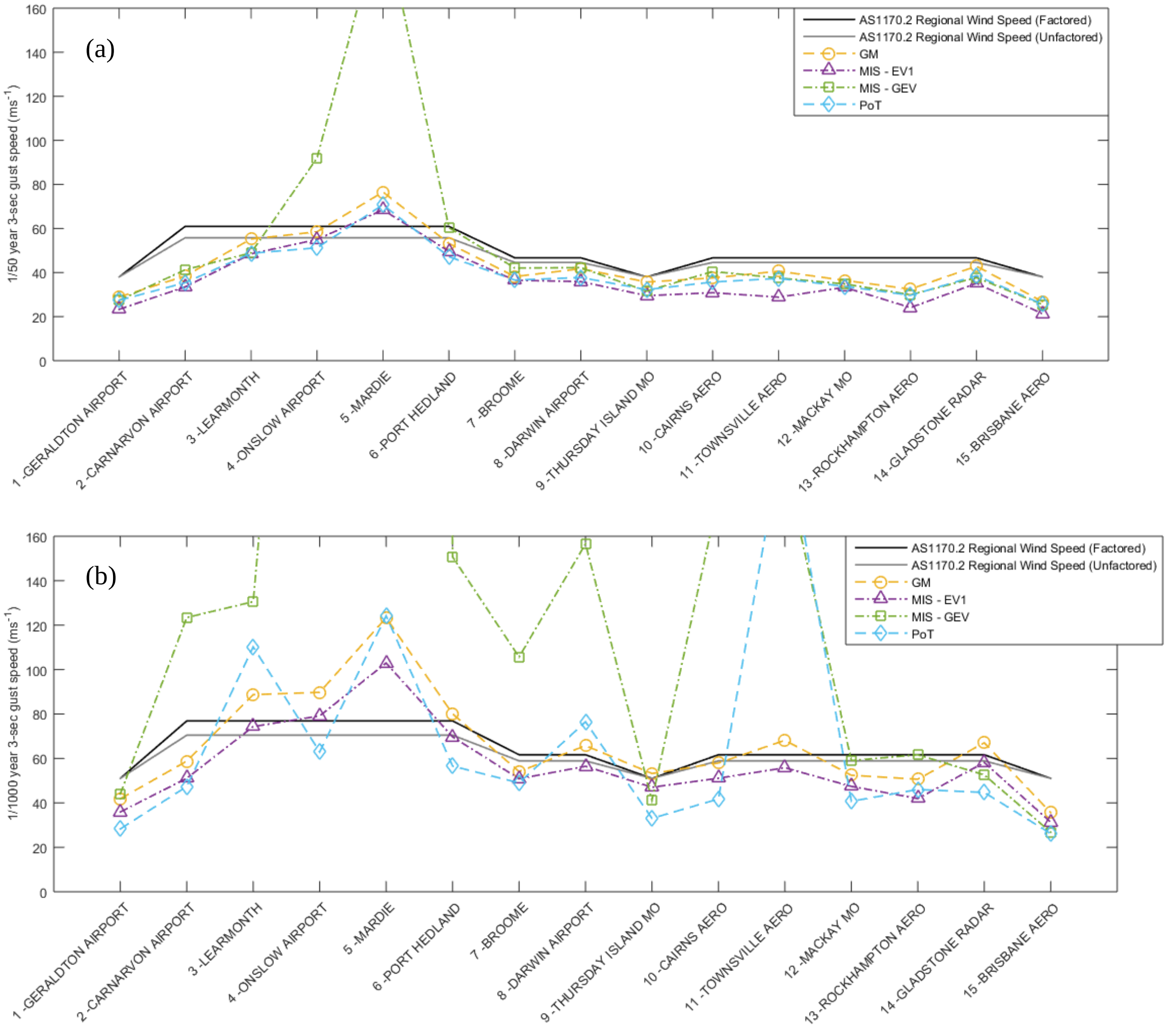

Figure 3. (a) 50- and (b) 1000-year return period 3-sec gust wind speed estimates using the, Gumbel (GM); Method of Independent Storms (MIS) with an Extreme Value Type 1 distribution (MIS – EV1) and data-driven Generalised Extreme Value distribution (MIS – GEV); and Peaks over Threshold (PoT) extreme value analysis techniques. Also shown is the Regional Wind Speed specified in AS/NZS1170.2, factored using F_C and F_D, and unfactored, for each site.

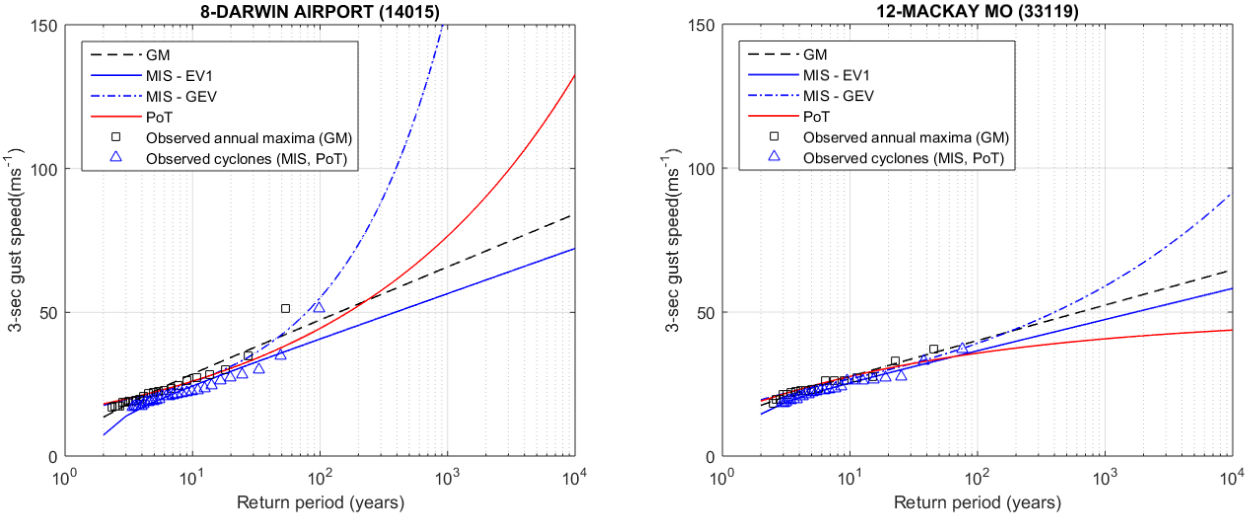

Figure 4. Examples of site wind hazard plots for Darwin (left) and Mackay (right).

Results

Figure 3 shows the 50 year and 1000 year return interval gust wind speed estimates for each site. The regional wind speeds specified by AS/NZS1170.2:2011 for design are also shown with and without the specified uncertainty factors, F_C and F_D, where required.

For the 50-year return period, all methods except for the MIS-GEV yield similar results, which are less than those prescribed in AS/NZS1170.2 for all sites except Mardie. MIS-GEV results produce the highest wind speed estimates for 1000-year return periods at most sites, and for 50-year return periods at sites 4 and 5 (Onslow Airport and Mardie). This occurs because a Type 2 EV distribution is almost exclusively chosen as the optimal fit for each record. This is exemplified in Figure 4 for the case of Darwin, where a small number of very strong events (one in this case, Cyclone Tracy) influence the distribution shape factor. While not always as extreme as Darwin, the large difference between 50- and 1000-year gusts estimated by the MIS-GEV for most sites shows that this is the preferred distribution shape when the data itself is allowed to dictate the distribution. This observation is not entirely new. In a study of non-cyclonic AWS sites in Australia, Holmes (2002) found several that favoured a Type 2 distribution. Rather than being purely a reflection of the true data trend, it is believed that the choice of a Type 2 distribution is a symptom of short duration records. The presence of any event significantly greater than the majority of other events will almost ensure this type of distribution is selected. While this approach clearly generates unphysical wind speed estimates for return periods beyond the observation record, it, by definition, provides the best fit for return periods less than the observation period.

Figure 4 also shows the fitted distributions for the Mackay AWS where again the Type 2 distribution was selected by the GEV fitting procedure. However, unlike Darwin there are no extraordinary events in the Mackay data record, so the distribution shape factor is low. As such, each distribution collapses more closely than for Darwin and the spread in 1000-year gust wind speed estimates is low. Interestingly though, while the GEV does display a Type 2 fit, the PoT, which utilises a GPD fitting method, asymptotes to a Type 3. This highlights that even for the same data sample, different asymptotic behaviour can be predicted based on the fitting method chosen.

When comparing analysis results with the equivalent return period gust wind speed specification in AS/NZS1170.2 (Figure 3), it is seen that based on GM, MIS-EV1 and POT analysis the standard is conservative at the 50-year level for most sites. Exceedance at Mardie and Onslow are, however, noted for this return period. Significantly more exceedances occur at the 1000-year level, with the greatest magnitude of exceedance again occurring in the Western Australia region. As expected from the preceding discussion, MIS-GEV results generate the greatest exceedances, but each technique generates them at multiple locations. The MIS-GE1 has the least exceedances and generally generates lower wind speed estimates than the standard GM method.

Conclusions

Results of this study show that estimated tropical cyclone wind hazard around the Australian coastline can vary greatly when obtained through different extreme value analyses. Variability between technique estimates systematically increases as the return period extends beyond the length of observational records. When the GEV distribution is not constrained to a given type, a Type 2 profile is generally found to be optimal. This distribution, however, results in an unrealistic estimate of wind gust speeds at long return periods and is deemed by many authors (e.g. Holmes, 2002) to be unphysical. These results highlight the variable nature of estimating extreme wind speeds for long return periods based on short observation records. Different analyses can lead to vastly different results, and therefore multiple estimation techniques should be adopted and results viewed in a context of uncertainty.

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