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Hazard of extreme wind gusts to buildings in Australia and its sensitivity to climate change

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Abstract: This paper presents a preliminary study on hazard modeling, estimation, and mapping of extreme wind gusts for consideration of buildings and infrastructure in Australia. Buildings and infrastructure provide essential support for the quality of life and are the founding blocks for social and economic development. Typically the design service life of buildings is around 50 years and that of infrastructure is 100 years or beyond; therefore, most existing building stock and infrastructure will be impacted by, and design/construction of new ones needs to consider the potential effect of, climate change.

Achievement of a performance level is typically via the consideration of return period (or average recurrence interval) of the hazard under consideration. Depending on its in-service importance and functionality, a structure such as a low-rise residential construction may need to be designed to withstand a 500-year, and a school building a 1000-year, return period wind speed to ensure an acceptable structural safety level.

To quantify the hazard of extreme gust, daily maximum gust wind speeds recorded up to 2007 at 545 anemometer stations maintained by the Bureau of Meteorology (BOM) were collected. Statistical and probabilistic approaches are used to model the gust wind speeds. Cyclonic gust speeds are modeled by the generalized Pareto distribution. Non-cyclonic wind speeds at sites within 150 km from the coast and affected by cyclones are modeled by the shifted exponential distribution; otherwise, they are modeled by the Weibull distribution of the largest value.

The current provision for design of structures under wind action, AS/NZS 1170.2:2002, was developed based on historical climate data during which no sufficient evidence indicated any trend in wind speeds due to climate change, as stated in its commentary: “the Standard does not attempt to predict the effects of possible future climatic changes, as the evidence for changes in wind speeds is inconclusive.” While the efforts over the last decade for establishing trend changes in severe cyclonic wind intensity and frequency have been inconclusive, preliminary research results suggest that significant alteration in severe cyclonic wind intensity and frequency are possible within the lifetime of existing buildings and infrastructure. As such, sensitivity study conducted at this stage is conducive to gain insight about future gust speed range due to possible frequency and intensity changes of severe cyclonic wind events.

Instead of attempting to give projection for wind gusts under a specified climate scenario as that given in the IPCC greenhouse gas emissions scenarios, this study examines the gust wind hazards under a range of frequency changes: from –50% to +100%, and under a range of intensity changes: from –20% to +20%. Wind gust hazard maps of Australia under current and likely future climate conditions subjected to frequency and intensity changes are produced by the software package ArcGIS 9.2 using kriging and exponential semivariogram for spatial interpolation.

The hazard analysis of this preliminary work is based on the Australian BOM anemometer data only. For improving the accuracy in hazard estimation, the next step of this study will consider: (a) disaggregation of non-cyclonic gusts generated by different mechanisms; e.g. thunderstorms, tornadoes, and synoptic winds; (b) reassessment of mutual independence of the cyclonic gust data included in a superstation according to the homogeneity of physical geography and meteorology; and (c) merger of wind speeds on the best tracks estimated by the Dvorak technique after 1984 at landfall of tropical cyclones to nearby anemometer data.

Keywords: *hazard, extreme wind gust, tropical cyclone, building, infrastructure*

1. INTRODUCTION

This paper presents a preliminary study on hazard modeling, estimation, and mapping of extreme wind gusts for the consideration of vulnerability and design of buildings and infrastructure in Australia. Typically the design service life of buildings is around 50 years and that of infrastructure is 100 years or beyond; therefore, most existing building stock and infrastructure will be impacted by, and design/construction of new ones will need to consider the potential effect of, climate change. However, the current provision for design of structures under wind action, AS/NZS 1170.2 (Standards Australia, 2002), was developed based on historical climate data during which no sufficient evidence indicated any trend in wind speeds due to climate change, as stated in its commentary: "the Standard does not attempt to predict the effects of possible future climatic changes, as the evidence for changes in wind speeds is inconclusive." With the results from climate change research showing that significant changes in wind speeds and frequencies within the lifetime of buildings and infrastructure are possible, this statement now deserves a re-think.

Achievement of a structural performance level is typically via the consideration of return period (or average recurrence interval as often termed in climatology) of the hazard under consideration. Depending on its in-service importance and functionality, construction such as a low-rise residential housing may have 500-year, and school 1000-year, return period defined for its safety performance. While the impacts of wind-induced disasters can be mitigated, the risk cannot be completely eliminated. Therefore, decisions regarding what risks are acceptable need to be made by those involved in managing the impacts. For numerical illustrations, this paper gives hazard estimation for return periods of 500 and 1000 years.

Estimation of extreme wind speeds are carried out by probabilistic and statistical analysis of historical data. For this purpose, the maximum daily gusts recorded by the BOM at 545 weather stations around Australia were used to derive the probability models of the gust wind hazard. The earliest recorded data of these stations were started at ten stations in 1939. Collectively, these stations represent 7263 station-years of data.

The wind gusts in the BOM data records are separated into cyclonic and non-cyclonic wind gusts. In the following, probabilistic modeling of cyclonic and non-cyclonic wind gusts are described in Sections 2 and 3, respectively. Based on statistical independence, Section 4 presents the method of combining cyclonic and non-cyclonic gust hazards. Section 5 investigates the sensitivity of wind gust hazard to possible climate change. Gust wind hazard maps are given and comparisons to the AS/NZS 1170.2 specifications are made.

2. MODELLING OF CYCLONIC GUST SPEED

The daily gust wind speeds recorded at weather stations within 500 km radius of a cyclone track on the same day are regarded as being generated by the cyclonic wind (Dorman, 1984). In total, 220 stations are identified as having experienced cyclonic winds. Merger of the BOM best track data with the anemometer data will be considered in future work.

Typically tropical cyclones do not occur every year at a given location, therefore the annual maxima method is not directly applicable for extreme wind speed modeling. In contrast, the generalized Pareto distribution (GPD) uses only the peak speeds over threshold provided that the peaks are statistically independent. The GPD is thus used to model the extreme wind speed generated by tropical cyclones. The GPD is expressed by

$$F_Y(y) = 1 - \left(1 - k_p\, y/\sigma_p\right)^{1/k_p} \tag{1}$$

where y is the excess over a threshold, σ_p and k_p are the scale and the shape parameters, respectively, of the distribution. The estimation of the GPD model parameters for the locations having cyclonic wind speeds recorded is based on the 'superstation' approach (e.g. Dorman, 1984).

A useful characteristic of the GPD is that, if $k_p > -1$, the threshold $u > u_p$, where u_p is the lowest threshold chosen, and $\sigma_p - uk_p > 0$, the mean value of the excess $Y - u$, given $Y > u$, is a linear function of $u - u_p$,

$$E(Y - u \mid Y > u) = \frac{\sigma_p}{1 + k_p} - \frac{k_p}{1 + k_p}\left(u - u_p\right) \tag{2}$$

In this study, a peaks-over-threshold analysis was performed for each 'superstation' by choosing a lowest threshold and then increasing thresholds by 1 m/s intervals. A minimum of ten exceedances of a threshold was specified for inclusion in the mean exceedance plot. If the slope of the mean exceedance plot was negative, a shape parameter of zero was used; i.e. $k_p = 0$, and σ_p is taken as the mean exceedance over all thresholds (Holmes 2002; Beirlant et al. 2004).

For determination of the wind speed, v_R, at a return period, *R*, the rate of exceedance, λ (times/year), of the lowest threshold, u_p, is required. If we equate the mean crossing rate of the level v_R to $1/R$, i.e., $\lambda\left[1-k_p\left(v_R-u_p\right)/\sigma_p\right]^{1/k_p}=1/R$, then after rearranging we have

$$v_R = \begin{cases} u_p + \sigma_p\left[1-(\lambda R)^{-k_p}\right]/k_p, & \text{when } k_p \neq 0; \\ u_p + \sigma_p \ln(\lambda R), & \text{when } k_p = 0. \end{cases} \tag{3}$$

When $k_p > 0$ and $R \to \infty$, $v_R \to u_p + \sigma_p/k_p$, meaning that the predicted extreme wind speeds have a limiting value at high return periods. When $k_p \le 0$, v_R is unbounded from above.

3. MODELLING OF NON-CYCLONIC GUST SPEED

For modeling of non-cyclonic gust speeds, because the BOM data consist of daily gust maxima, the extreme value theory is appropriate for this purpose. To avoid large sampling errors, only the sites with recorded data longer than 10 years are considered in the analysis. As a result, 122 sites having at least 10 years daily gust data are used in non-cyclonic gust speed modeling.

It is observed from processing the recorded data that for locations along the coast lines significantly affected by tropical cyclones; i.e., a location within 150 km of the coastline in cyclone-affected area, the probability distribution of non-cyclonic winds, *V*, may be modeled by the shifted exponential distribution as follows,

$$F_V(v) = 1 - e^{-\frac{v-v_e}{\sigma_e}} \tag{4}$$

where v is the wind speed (m/s), v_e (m/s) and σ_e (m/s) are the location and the scale parameters, respectively, of the distribution. With a shifted exponential distribution, the gust speed v_R associated with a given return period *R* (years) can be determined by

$$v_R = v_e + \sigma_e \ln R \tag{5}$$

For locations not affected by tropical cyclones or 150 km away from the coast, the non-cyclonic gust speeds are modeled by the Weibull distribution of the largest value,

$$F_V(v) = e^{-\left(\frac{v_w - v}{\sigma_w}\right)^{1/k_w}} \tag{6}$$

where v (m/s) is the wind speed, v_w (m/s), σ_w (m/s), and k_w are the location, scale, and shape parameters, respectively, of the distribution. With a Weibull distribution of the largest value, the gust speed v_R associated with a given return period *R* (years) can be determined by

$$v_R = v_w - \sigma_w\left\{\ln\left[R/(R-1)\right]\right\}^{k_w} \tag{7}$$

4. COMBINATION OF CYCLONIC AND NON-CYCLONIC WIND HAZARDS

The previous two sections presented the probabilistic modeling of extreme wind speeds induced by cyclonic and non-cyclonic wind events. This section presents the method of computing the gust speed associated with a given return period for locations subjected to both cyclonic and non-cyclonic wind hazards.

Let the combined return period of a gust speed be *R* and the corresponding return periods due to cyclonic and non-cyclonic events be R_C and R_N, respectively. If the gust speeds generated by cyclonic and non-cyclonic events are statistically independent, then the following relationship holds,

$$1 - 1/R = \left(1 - 1/R_C\right)\left(1 - 1/R_N\right) \tag{8}$$

When non-cyclonic wind speeds are modeled by the shifted exponential distribution, Eqs. (3), (5), and (8) are needed to solve for the wind speed v_R associated with a combined return period *R*; when non-cyclonic wind speeds are modeled by the Weibull distribution of the largest value, then Eqs. (3), (7), and (8) are needed.

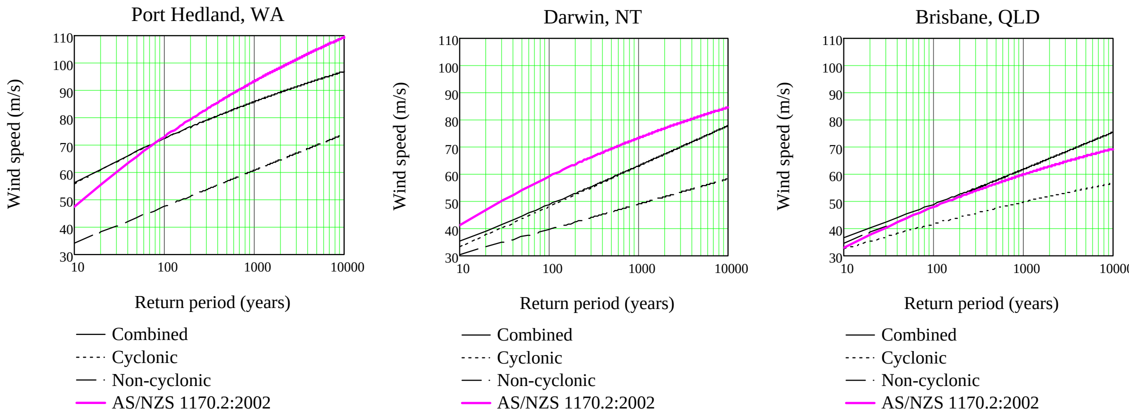


Figure 1. Wind gust vs. return period for Port Hedland, WA, Darwin, NT, and Brisbane, QLD.

As illustrative examples, Figure 1 shows the wind gust versus return period determined by the models presented in this paper. Also plotted in pink curves are the design wind speeds specified in the Standard. It shows that the Standard specifications are adequate for practical design purposes for Port Hedland and Darwin, but may not so for Brisbane.

4.1. Gust Wind Hazard under Current Climate Conditions

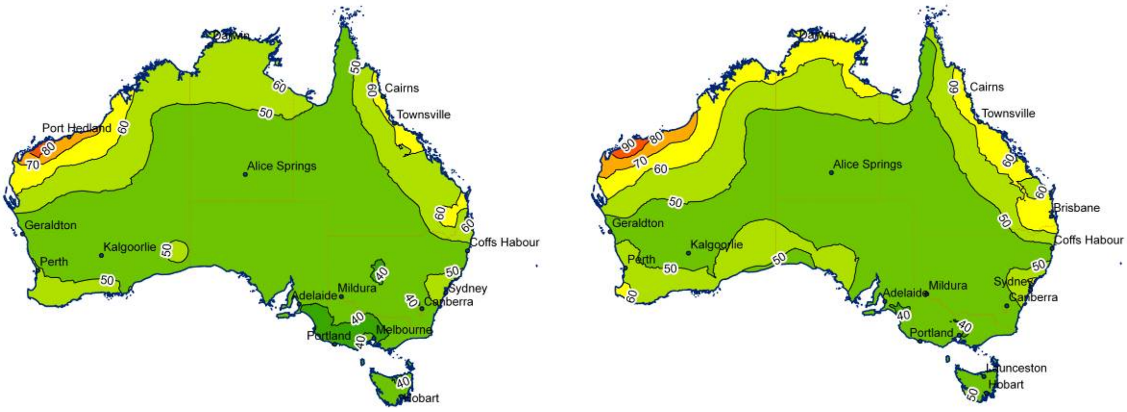
Following the combination procedure presented above, the hazard considering both cyclonic and non-cyclonic wind events can be estimated for locations at which the probability models of the individual wind-induced mechanisms were identified. Thus the extreme wind hazard under current climate conditions in Australia is mapped, as shown in Figure 2, for 500 and 1000 years of return periods. The hazard maps are produced by the software package ArcGIS 9.2 using kriging and exponential semivariogram for spatial interpolation (Smith et al. 2007).

5. SENSITIVITY OF GUST SPEEDS TO CLIMATE CHANGE

Though computing technology has been undergoing rapid advances, prediction of future wind speed changes with current state of computer power remains a difficult task and thus a subject of active research. While definite trend changes in severe cyclonic wind intensity and frequency have not yet established, preliminary research results suggest that significant alteration in cyclonic wind intensity and frequency are possible within the lifetime of existing buildings and infrastructure. Therefore, sensitivity study conducted at this stage is conducive to gain insight about future gust speed range due to possible frequency and intensity changes of severe wind events.

Difficulties in accurate projection of tropical cyclone severity mainly reside in the sources of uncertainty inherent in perceived climate change. For example, the likely future climate-forcing scenario, errors in modeled tropical cyclone climatology, and regional climate patterns such as the El-Nino Southern Oscillation, each of them contributes to the difficulty of precise projection. Furthermore, high year-to-year and decade-to-decade variations in occurrences in the Australian region add another dimension of complexity. Observational records in this region to date span about fifty years since the use of satellite tracking, which is yet too short to establish a definitive trend of changes.

For consideration of gust speed changes under non-cyclonic wind intensity changes, because the A1FI scenario is considered as of high emissions among the IPCC scenarios (CSIRO 2007), this study investigates the projected extreme wind speed changes under the A1FI scenario using the extreme and mean wind speed percentage change relationship published by CSIRO (2007). Because the mean wind speed percentage changes by the year 2050 is uncertain, the 10th, 50th, and 90th percentile values are considered (CSIRO 2007). Figure 3 shows the 1000-year return period hazard maps under (a) the 10th-percentile wind speed percentage change, and (d) the 90th-percentile wind speed percentage change. Though not shown here, the projected 50th-percentile wind speed percentage change does not differ much from that under current climate condition. On the other hand, when under the 10th and 90th percentile wind speed percentage changes, as comparing Figure 2 to Figure 3, the differences become notable in non-cyclonic dominated regions, but remain limited in



(a) Return period = 500 years (b) Return period = 1000 years

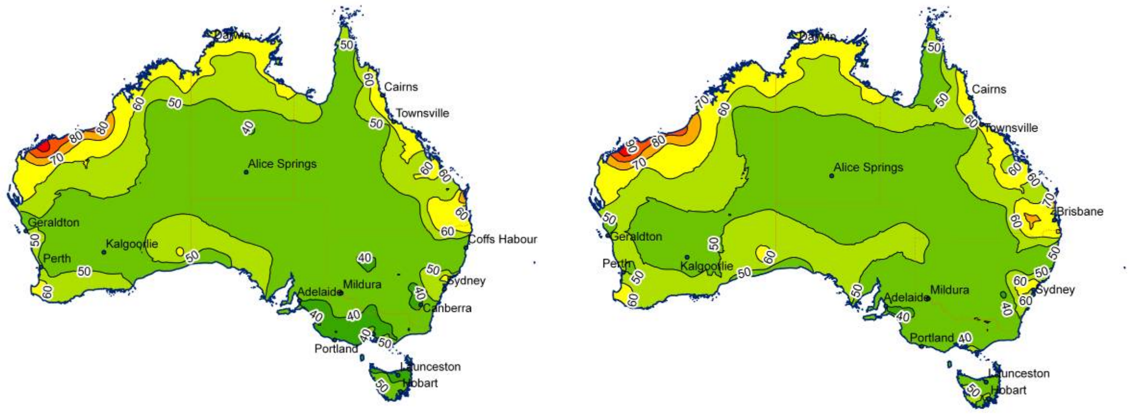
Figure 2. Combined hazard of cyclonic and non-cyclonic gust wind speeds under current climate conditions.

cyclonic dominated regions.

For the frequency changes in severe cyclonic winds, studies on global trend give projected increases ranging from 10% (Klotzbach 2006) to 100% (Webster et al. 2005). For studies specific to the Australian region, the only work concerning the coast off Western Australia (Abbs et al. 2006) predicts a frequency decrease in that area. For the coast off Queensland, the projected frequency increase ranges from 22% (Leslie et al 2007) to 56% (Walsh et al. 2004). Such a wide range of predicted frequency increases indicates that the physics-based climate models currently in use still have difficulty in modeling wind fields with satisfactory accuracy. Consequently, no definite trends in frequency or intensity changes under a future climate scenario have been identified, not to mention the magnitude of changes. Instead of attempting to give projection for wind gusts under a specified climate scenario, this study examines the gust wind hazards under a range of frequency changes: from –50% to +50%.

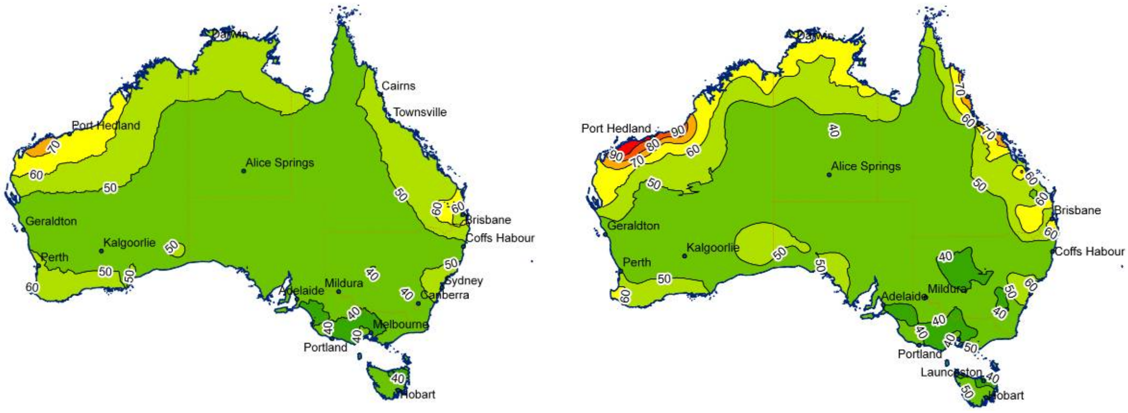
So far no published researches have given quantitative trends for the future intensity changes in extreme cyclonic winds in the Australian region. Kossin et al. (2007) stated that over a 23-year period (1983 – 2005) worldwide, no upward trends in hurricane intensity over that period were found in any basin except the Atlantic. Therefore, this study chooses to examine intensity changes ranging from –20% to +20%.

Figure 4 compares the 500-year return period hazard maps under (a) current climate condition; (b) –20% intensity and –50% frequency changes; and (c) +20% intensity and +50% frequency changes in cyclonic winds. It shows that the northwest coast around Port Hedland, WA, the northern part of Northern Territory, and the northeast coast along Cairns and Townsville, QLD are the most sensitive regions to the cyclonic intensity and frequency changes.



(a) 10%-tile mean speed change (b) 90%-tile mean speed change

Figure 3. The 1000-year return period hazard maps under (a) 50th-percentile and (b) 90th-percentile mean wind speed percentage changes.



(a) –20% intensity & –50% frequency (b) +20% intensity & +50% frequency

Figure 4. The 500-year return period hazard maps under (a) –20% intensity and –50% frequency and (b) +20% intensity and +50% frequency changes in cyclonic winds.

6. DISCUSSION AND CONCLUSIONS

This paper presents a preliminary study on estimating the hazard to the Australian continent under extreme wind speeds by analyzing the wind gust data recorded by the Australian Bureau of Meteorology. Statistical and probabilistic approaches are used to model the wind gust speeds. Cyclonic gust speeds are modeled by the generalized Pareto distribution. Non-cyclonic wind speeds at sites within 150 km from the coast and affected by cyclones are modeled by the shifted exponential distribution; otherwise, they are modeled by the Weibull distribution of the largest value. Maps of wind gust hazard in Australia subject to cyclonic and non-cyclonic winds under current climate condition are produced and compared to the AS/NZS 1170.2 specifications. The following are observed:

- The design wind speeds specified in the Standard may be inadequate for Region A, in which non-cyclonic winds dominate, except the island state of Tasmania, the areas in the Cape York Peninsula in north Queensland, and the areas from inland Alice Springs, NT, extending to Melbourne, VIC.
- When considering combined hazard of cyclonic and non-cyclonic winds, the Standard specifications for Region D are adequate. When considering combined hazard of cyclonic and non-cyclonic winds, the Standard specifications for Brisbane, QLD, Sydney, NSW, and Perth, WA, may be inadequate. The gust wind hazards around the areas of these three state capitals are dominated by non-cyclonic wind gusts.

While climate researchers have been unable to give definite projection for small-scale systems such as tropical cyclones and thunderstorms, they are relatively confident about large-scale systems like synoptic winds. This study investigates the effect of the projected wind speed change of large-scale systems by the year 2050 under the IPCC A1FI emissions scenario using the extreme and mean wind speed percentage change relationship published by CSIRO (2007). The analysis results of this study show that the 50th-percentile changes in non-cyclonic wind speeds have negligible effect on the gust wind hazard almost everywhere in the Australian continent. The uncertainty (e.g. ranging from the 10th to the 90th percentile changes) also has negligible effect on the gust wind hazard in cyclone-dominated regions; nonetheless, such uncertainty has notable effect on the gust wind hazard in regions dominated by non-cyclonic wind. For this reason, the uncertainty of non-cyclonic gust speed changes in non-cyclonic locations needs to be considered for design of buildings and infrastructure.

While the efforts over the last decade for establishing trend changes in severe cyclonic wind intensity and frequency have been inconclusive, preliminary research results suggest that significant alteration in severe cyclonic wind intensity and frequency are possible. This study examines the gust wind hazards under a range of cyclonic frequency changes: from –50% to +50%; and a range of cyclonic intensity changes: from –20% to +20%. The analysis results show that the northwest coast around Port Hedland, WA, the northern part of Northern Territory, and the northeast coast along Cairns and Townsville, QLD are the most sensitive regions to the cyclonic intensity and frequency changes; therefore, future wind gust hazard at cyclone-dominated locations depends notably on the percentages of change in frequency and intensity of cyclonic winds.

Considering that the wind gust hazard in many locations in Australia is somewhat sensitive to the frequency and intensity changes of severe wind events, climate change research related to extreme wind gusts, both cyclonic and non-cyclonic, is important for reducing epistemic uncertainty of future climate conditions and is thus a key factor for more accurate projection of gust wind hazard.

The regions where the design specifications may be inadequate under current or likely future climate conditions represent many of the most densely inhabited areas of Australia (Sydney, Brisbane, northeast Queensland, and Perth). An extension of the design Standard AS/NZS 1170.2:2002 to explicitly address potential future climate scenarios is recommended.

Also, with the aid of expanding climatological records, the increasing public awareness, and active research efforts on the physics and modeling of climate change, it is sensible to re-evaluate the extreme wind hazard in the Australian region regularly, e.g. every 3 to 5 years, so as to take advantages of rapidly improving information and knowledge advances.

The hazard analysis of this preliminary work is based on the Australian BOM anemometer data only. For improving the accuracy in hazard estimation, the next step of this study will consider: (a) disaggregation of non-cyclonic gusts generated by different mechanisms; e.g. thunderstorms, tornadoes, and synoptic winds; (b) reassessment of mutual independence of the cyclonic gust data included in a superstation according to the homogeneity of physical geography and meteorology; and (c) merger of wind speeds on the best tracks estimated by the Dvorak technique after 1984 at landfall of tropical cyclones to nearby anemometer data.

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