An Updated Description of the Strong-Wind Climate of South Africa

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1 INTRODUCTION

Wind constitutes the most critical environmental loading affecting the structural design of the built environment in South Africa. Over the years, several failures of buildings and structures due to wind actions have occurred, some of them resulting in loss of human lives, as well as significant financial losses (Goliger and Retief, 2002). These failures could be attributed to various factors e.g. improper design and/or construction, but also inadequate knowledge of the wind action; more specifically the wind characteristics at low elevations at a regional or local scale affecting the design of specific structures.

The need for updating the environmental input into the process of determining wind loads for structural design was emphasised during the process of revising the South African Loading Code (Goliger 2007). The sparse distribution of climate stations, mainly located in large cities for the present wind maps (Milford 1985a & b) and the subsequent addition of several decades of observations provided the main motivation for a reassessment of the strong-wind climate for the region.

A project was launched to obtain a comprehensive statistical description of the occurrence of high wind speeds for South Africa, which were based mainly on the available reliable wind data measured by the South African Weather Service (SAWS). It was intended that the results should form the basis for wind loading requirements in the future design codes for the built environment.

This paper provides an outline of the process followed to compile the information that should serve as input for the determination of the characteristic wind speed across the country. The main aspects considered here are the physical conditions, the attributes of the strong-wind data, the statistical treatment of the data, the resulting quantile wind speed and the differences between the existing and new wind maps. In an accompanying paper at this conference the results of cluster analysis are presented, through which strong-wind generating mechanisms are characterised (Kruger *et al.*, 2011b).

2 GENERAL CONSIDERATIONS

2.1 *Physical environment*

From the outset it was clear that the climatic diversity of the region would have a significant influence on the results, and therefore the way in which the reassessment needed to be approached. Specifically the occurrence of the two completely different main strong-wind generating mechanisms, namely meso-scale thunderstorms, mainly across the interior and synoptic scale frontal systems across the coastal regions, needed to be accounted for.

Apart from the different strong-wind producing mechanisms, the topography also plays a major role in the magnitude of the strong-winds at the synoptic scale. Major topographical features include the escarpment which divides the country generally between an inland plateau and an elongated region adjacent to the coastline; the Drakensberg mountain range forming a prominent part of the escarpment towards the east; the cape Folded Mountains, particularly its extension to Cape Town and surroundings.

2.2 *Coverage of weather stations*

The present wind maps for South Africa are based on a network of 14 Dines pressure tube anemograph stations (Milford 1985a & b) across a region of $1.2\text{x}10^6$ km^2. Due to the deployment of Automatic Weather Stations (AWS) since 1990, the number of stations has increased to 172, although the recording period is still severely constrained. In spite of the substantial improvement of the network, from about 8 000 annual gust reading in 1985 to 60 000+ in 2007, the following difficulties can be envisaged:

- The limited recording period for the extended AWS network, with a large fraction of the stations recording for less than ten years.
- Continuity between the Dines and AWS records, to obtain an extended recording period, albeit only for a maximum of 14 locations.
- Whether even the extended network provides sufficient coverage to
  - capture the complexity of the strong-wind climate, including topographical effects;
  - fully capture mesoscale thunderstorm events, particularly when considering the small footprint of strong gusts;
  - provide proper coverage of main population and economic centres.
- The quality of the recorded data, with specific reference to strong-wind events, considering standardised requirements of site exposure of the weather stations.

2.3 *Audit and quality control of the available usable climate data*

The wind data could be divided into two distinct periods, the period of the Dines anemograph, and the AWS anemometers. Significant discrepancies were evident between the two periods. It is highly possible that the Dines in most cases overestimated the magnitudes of strong-wind gusts, as shown by Holmes and Henderson (2010) for Australia. The exposure and quality of data from the Dines anemographs are also suspect. Therefore only AWS data were utilised. The extension of the average record period of 26 years of Dines observations with the AWS observations for the 14 important locations could therefore not be done.

The quality assessment of the records included assessments of the record length, homogeneity of the data, the occurrence of spikes, and consideration of the metadata of the observation stations.

2.4 *Exposure of weather stations*

World Meteorological Organization (WMO) standards for the placement of anemometers are followed for the AWS sites, requiring an open level terrain with the measurement taken at 10 m above ground level. An open terrain is defined as the distance to any obstruction being at least 10 times the height of the obstruction. More severe requirements are set for the surrounding surface roughness for the reference site conditions for strong-winds.

A survey was therefore conducted to confirm the location of the weather stations and to establish the exposure of the site. The survey was of a desktop nature, using predominantly Google Earth information, with limited verification by local weather offices. Based on a set of criteria, the AWS sites were assessed in terms of conforming to Terrain Category II (TC-II) with a roughness length of 0.05 m.

- Due to unacceptable surrounding topography or obstructions, 16 stations had to be rejected outright from the initially selected 94 stations, i.e. 76 remaining.
- No exposure corrections for hourly mean wind speed was necessary for only 6 locations. The Exposure Correction Factor (ECF) due to improper terrain categories were estimated for 22.5° sectors for the remaining locations. The ECF is applied to convert the observed wind speed from the corresponding direction to the wind speed for TC-II.
- For observations of gusts from synoptic mechanisms, adjustments were made for 41 sites, whilst no adjustments were applied for thunderstorm gusts, in accordance with ISO 4354:2009.

3 DATA EXTRACTION AND ANALYSIS

For a region with a mixed strong-wind climate, a dual dataset needs to be extracted from the records, consisting of both the strong-wind observation and the associated generating mechanism. Although the two components of the dataset are closely interrelated, it is useful to consider the wind generating mechanisms from a climatic perspective and the strong-wind records from the angle of statistical analysis.

3.1 *Strong-wind climatology data*

The strong-wind climate view of the region evolved through the various stages: The nominal treatment of strong-wind mechanisms in the present design wind speed maps for South Africa was clarified to some extent by Goliger and Retief (2002) by providing an indication of the regional contribution of the main strong-wind mechanisms. A reassessment of climatic conditions related to strong-wind occurrence in South Africa was updated by considering the regional distribution of prevailing macroclimatic conditions, with emphasis on seasonal changes and the differentiation between synoptic and meso-scale conditions (Kruger *et al.*, 2010). A quantitative assessment of the strong-wind climate is presented subsequently by Kruger *et al.* (2011a & b).

3.2 *Measured strong-wind data*

Since 1995 the SAWS archives high resolution weather measurements from AWS in 5-minute intervals, serving as the main source of data for the investigation. The data tables included the strongest 2-3 second wind gust, with direction and time for each 5-minute interval; hourly mean wind speed and direction. Sources of annual maximum wind gusts were identified with the following procedure:

- The 2-3 second wind gust values were identified for each year of the time series.
- The 5-minute time series of the climatic data, of which the variables are the maximum wind gust, mean wind speed, mean wind direction, surface temperature, rainfall, relative humidity and surface pressure, were plotted for those days that the annual maximum gusts occurred, to enable the identification of the causes of extreme winds.
- Evidence of the prevailing weather systems, identified from synoptic charts published in the SAWS Daily Weather Bulletin, were used to confirm the strong-wind producing mechanism.

Strong-wind observations extracted from the SAWS climate databank consist of extreme value observations, selecting the maximum wind speed for a given period (year) or over a given threshold within such period. The following strong-wind observations were extracted for further analysis, as discussed below:

- Annual maximum 2-3 second wind gust and hourly mean values, with the associated strong-wind mechanism for each case;
- For stations where there is evidence of mixed strong-wind mechanisms, the annual maximum gust and hourly mean values for *each* strong-wind mechanism;
- Peak-Over-Threshold (POT) wind speed at selected threshold values for the reigning strong-wind mechanism at a station. The independence of events is based on the probable causes of the recorded strong wind values. For meso-scale mechanisms, i.e. thunderstorms, a separation period of one day were deemed sufficient to ensure independence, while for synoptic-scale mechanisms a period of two days were applied.

It is therefore evident that the compilation of the strong-wind dataset required extensive interrogation of the SAWS climate databank. The result is a much richer set of information consisting of wind speed and the associated generating mechanism, which is essential input in assessing strong-winds in a mixed climate.

3.3 *Extreme value statistical analysis methods*

The objective of the statistical analysis is to derive probability models for strong-winds which could serve as environmental input for reliability based design procedures for wind loads on structures. Two issues need consideration when selecting the appropriate extreme value statistical analysis:

- The short observation periods, an epistemic matter that would be improved when the available records are extended with time;
- The mixed strong-wind conditions pervasive over large parts of the country, a matter that can be classified as aleatoric; the implications of the limited record length obviously also applies to the mixed climate analysis.

The basic extreme value method considered is the Generalized Extreme Value (GEV) method (Jenkinson, 1955), given as Equation [1] for the case where the shape parameter $\kappa \neq 0$ and as Equation [2] for the special case, the Gumbel distribution, for $\kappa = 0$. For mixed distributions, treatment is based on Equation [3] (Gomes & Vickery, 1978):

$$F(x) = e^{-(1-\kappa y)^{1/\kappa}} \qquad \kappa \neq 0 \qquad [1]$$

$$F(x) = e^{-e^{(-y)}} \qquad [2]$$

$$y = (x-\beta)/\alpha$$

α *scale or dispersion parameter*

β *mode of extreme value* x

$$F(x) = 1 - [(1 - e^{-e^{(-y_A)}}) + (1 - e^{-e^{(-y_B)}}) + \ldots] \qquad [3]$$

For time series shorter than 20 years, it is preferable that analysis methods such as the Peak-Over-Threshold (POT) method is used (Palutikof *et al.*, 1999), but in a mixed strong-wind climate, a mixed climate approach should be adopted. The Generalised Pareto Distribution (GPD) is fitted to the data series, as given by Equation [4], which simplifies to the Exponential distribution (EXP) for $\kappa = 0$, given by Equation [5].

$$F(x) = 1 - [1 - (\kappa / \alpha)(x - \xi)]^{1/\kappa} \qquad [4]$$

ξ *selected threshold*

$$F(x) = 1 - e^{-[(x-\xi)/\alpha]} \qquad [5]$$

4 GENERATION OF STRONG-WIND INFORMATION

The comprehensive process of generating probability models for strong-winds and maps to present quantile wind speed values, based on the SAWS climate database and extreme value models described above, consist of the following steps:

- Identification of wind generating mechanisms which define the strong-wind climate of the region (section 4.1);
- Data selection (section 4.2);
- Compilation of extreme wind records (annual maximum, POT) values; for gust and hourly means; for all the relevant strong wind mechanism from the set of thunderstorm and five synoptic conditions; corrected for the 22.5° sector exposure conditions at the site; for all 76 qualifying AWS stations which conformed to the requirements that were set, mainly based on site exposure conditions (section 4.3);
- Selection of the appropriate distribution for the respective case: Provision for mixed strong-wind sources; treatment of short observation periods; for gust and hourly mean values respectively (section 4.4);
- Mapping of gust and hourly mean quantile values; including selection of appropriate and corrected values; method of interpolation for elevation (section 4.4);
- Assessment; including comparison with existing maps (section 4.4).

4.1 *Identification of causes of strong-winds and relationships between mechanisms*

Six different causes, or strong-wind mechanisms, were responsible for the strongest winds recorded in South Africa (Kruger *et al.*, 2010). One mechanism is on the mesoscale, the thunderstorms, while the others are on the synoptic scale. However, thunderstorms and cold fronts can be considered to be the primary causes.

The relationships between mechanisms provide new insight in the characteristics of strong-winds in the country (Kruger *et al.*, 2011a). A discussion of the regional characterisation of the strong-wind mechanisms is presented in an accompanying paper (Kruger *et al.*, 2011b).

4.2 *Selected weather stations*

Only 94 out of the 172 AWS stations qualify for the initial selection, mostly on the basis of a record length of at least 10 years (see section 2.4). Ultimately only 76 stations with a mean record length of 14 years (including 6 with 10 years and 8 with 16 years of records) conformed to the quality requirements that were set, mainly based on site exposure conditions. A reasonable geographic coverage of the country was obtained, reflecting to some degree also the population and development densities.

4.3 *Compilation of strong-wind data*

An important finding of the quality assessment of the wind records was that for various reasons the original dataset from the Dines network did not qualify for use in the analysis. The implication is that only data from the AWS network, which was deployed starting from the early 1990's, could be considered.

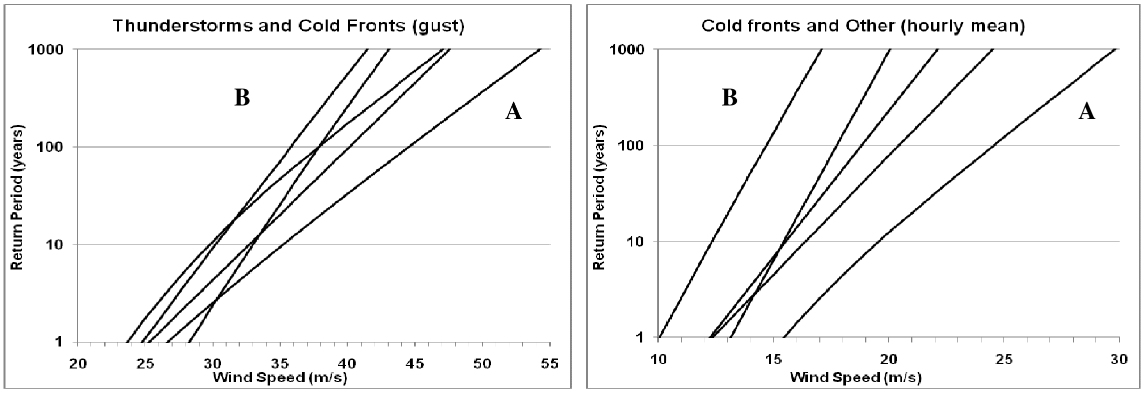
Extreme value data extracted from the SAWS climate data archives for the 76 qualifying stations include annual maximum values for gust and hourly mean wind speed; for each of the strong-wind mechanism occurring at the station; POT values, including establishing optimal threshold values. For the final analysis, the exposure corrected value of the observation is determined.

4.4 *Development of probabilistic parameters for purposes of design standards*

Within the context of the two complications of the aleatoric effect of a mixed climate and the epistemic effect of short recording periods, a primary consideration was whether to include provision for the skewness of the distribution or not. In practical terms the choice is between a Gumbel and EXP model when the shape parameter is taken as $\kappa = 0$, or where its value is also extracted when the data is fitted to the GEV or GPD for annual or POT maxima respectively.

Following an extensive assessment, it was concluded that the general case (GEV, GPD) is particularly sensitive to the data input from short recording periods. Gumbel and EXP models were therefore selected for the analysis. Although this approach is not conservative for the case of $\kappa < 0$, the general cases lead to unrealistic wind speed for long return period quantiles; the estimated quantiles are not consistent with regional trends but only apply to a limited number of stations. However, in order to provide a degree of conservatism in the strong-wind models, the parameters of the Gumbel and EXP distributions were adjusted to represent the mean and standard deviation at the upper 75% confidence level.

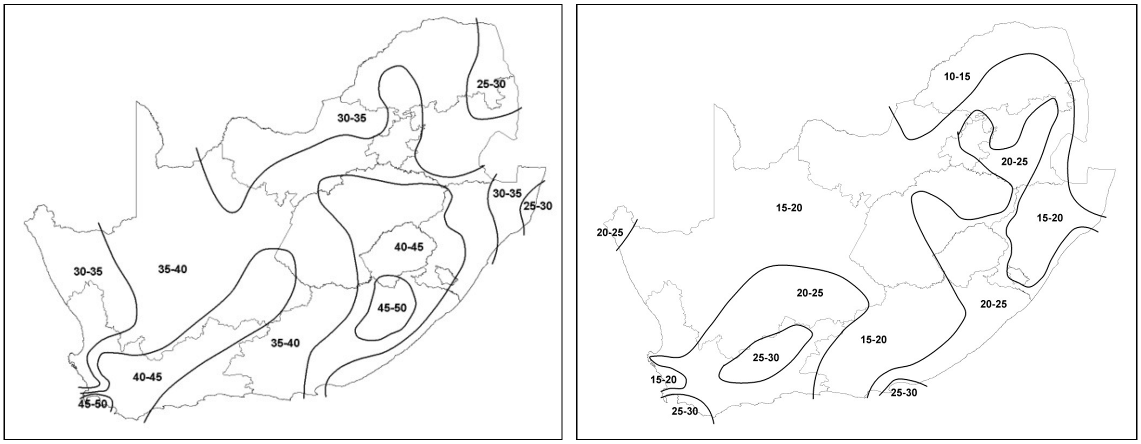
The mean mixed climate distributions for regions determined through cluster analysis for gust wind and hourly mean wind is shown in Figure 1. For gusts (Figure 1(a)), significantly higher quantile wind speeds (Line A) are obtained for a narrow inland region running parallel to the south-eastern coastline, then for a central-east region (Line B), with an extended region of intermediate values in between. For hourly mean quantile wind speeds (Figure 1(b)), the highest values (Line A) are obtained for a narrow region along the south-western coastline, with a progressive decrease towards the north with the lowest values in the northern and north-eastern region (Line B).



(a) (b)

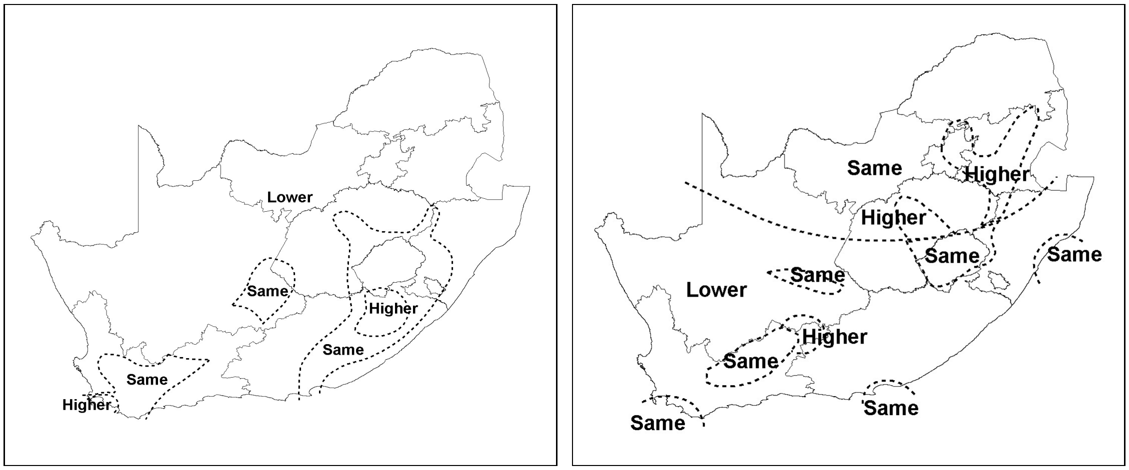
Figure 1. Mixed distribution curves of combinations of thunderstorms, cold fronts and other mechanisms for (a) gust and (b) hourly mean wind.

Figure 2 presents the final 50-year quantile maps derived from the analyses, which took the height above sea level, but not the complex topography, into consideration in the interpolation procedures applied. The maps in Figure 3 indicate the relative differences between the updated maps and those used in the current South African loading code (Milford, 1985a & b).



(a) (b)

Figure 2. Updated 50-year quantiles for (a) gust and (b) hourly mean wind.



(a) (b)

Figure 3. Relative differences between the updated 50-year wind speed quantiles, and those used in the current South African Loading Code for (a) gust wind (b) hourly mean.

5 CONCLUSIONS

Data from the extended AWS network made it possible to obtain a substantially revised view of the strong-wind climate of South Africa. Quantitative models of the influence of the diverse sources of strong-winds, consisting of meso-scale thunderstorms and synoptic scale cold front and other mechanisms, including provision for mixed climate zones, could be resolved. The improved geographical coverage and the incorporation of wind generating mechanisms contribute to the improvements achieved through the revision.

The quality of the results were mostly compromised by the short periods of data records, the density of available weather stations in especially the regions prone to thunderstorms, and to a lesser degree the extent of subjectivity in the spatial interpolation of results. The inconsistent exposure of the wind recording instrumentation was analysed and corrected by introducing a set of relevant factors. Various statistical techniques were applied to compensate for this deficiency and to provide a degree of conservatism to the predictions. Considering the recent rapid expansion of the AWS observation network in South Africa, significant improvements can be made to this analysis if updated in the short to medium term, by extending the methodology as presented here.

The main steps that were taken have the characteristics of a system, in the sense that they are interrelated, and therefore require iterative development. These include the compilation and quality assessment of data, including the exposure conditions of the AWS for strong-wind records; identification and classification of strong-wind generating mechanisms; statistical analysis methodologies; extreme wind data analysis, including selection of the proper probability models; geographical interpolation and mapping. All these analyses were implemented in terms of the environmental input parameters needed for wind load design procedures.

This research, in essence, highlights the challenges and shortcomings inherent in the statistical analysis of observed climate data. In the various aspects of the work the importance of the critical evaluation of the climate data, measuring environment, statistical techniques and the spatial interpolation of results are demonstrated and discussed. The findings emphasise the importance of reliable, high-quality climate data in climatological analyses relevant to the built environment.

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