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Clustering of extreme winds in the mixed climate of South Africa

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Abstract. A substantial part of South Africa is subject to more than one strong wind source. The effect of that on extreme winds is that higher quantiles are usually estimated with a mixed strong wind climate estimation method, compared to the traditional Gumbel approach based on a single population. The differences in the estimated quantiles between the two methods depend on the values of the Gumbel distribution parameters for the different strong wind mechanisms involved. Cluster analysis of the distribution parameters provides a characterization of the effect of the relative differences in their values, and therefore the dominance of the different strong wind mechanisms. For gusts, cold fronts tend to dominate over the coastal and high-lying areas, while other mechanisms, especially thunderstorms, are dominant over the lower-lying areas in the interior. For the hourly mean wind speeds cold fronts are dominant in the south-west, south and east of the country. On the West Coast the ridging of the Atlantic Ocean high-pressure system dominate in the south, while the presence of a deep trough or coastal low pressure system is the main strong wind mechanism in the north. In the central interior cold fronts tend to share their influence almost equally with other synoptic-scale mechanisms.

Keywords: cluster analysis; mixed strong wind climate; extreme winds; South Africa.

1. Introduction

By analysing the annual extreme wind gust data from 94 weather stations, which are spatially well distributed over the South African territory, it was possible to develop a climatology of strong wind zones for South Africa (Kruger *et al.* 2010), an update of Goliger and Retief (2002). The strong wind climate of South Africa showed similarities with southern South America (e.g., Argentina) and Australia (Holmes 2002, Oliver *et al.* 2000, Ponte and Riera 2007), exhibiting a mixed strong wind climate for a substantial part of the country. These strong wind zones indicate the geographical extent of six strong-wind producing mechanisms, which were identified by classifying the causes of annual maximum wind gust speeds. Two of the mechanisms, namely thunderstorms and extratropical cyclones (the passage of cold fronts) are dominant, while the other four mechanisms are of a secondary importance. It was shown that in most parts of South Africa the derived strong wind zones overlap, especially for the two dominant strong-wind producing

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mechanisms, i.e., cold fronts and thunderstorms.

If the wind values used to determine the shape of the extreme values distributions are forthcoming from more than one source, the accuracy of the extreme wind speed estimations, and therefore wind design parameters, can be compromised, usually by underestimating the wind speed values for the long return periods (Gomes and Vickery 1978, Milford 1985, Palutikof *et al.* 1999). This is especially true where differentiation is needed between strong winds of thunderstorm and synoptic scale origins (Gomes and Vickery 1978, Twisdale and Vickery 1992). It was therefore recommended in Kruger *et al.* (2010) that the estimations of extreme winds for most locations in South Africa employ methods which take the mixed strong wind climate into account, especially where these estimations are done for the implementation in the design of structures that should have very low probabilities of failure.

This study aims to demonstrate the effect of the mixed strong wind climate on the estimation of quantiles relevant to the built environment in South Africa, and also to characterise the strong wind climate in terms of the relative dominance of the identified strong wind mechanisms.

2. The estimation of extreme winds

In mixed strong wind climates alternative methods to the traditional Gumbel analysis method (Gumbel 1958) for estimating extreme wind speed probabilities from a single population are advised (Palutikof *et al.* 1999). Such methods tend to yield more accurate estimates of annual wind speed maxima for long return periods, greater than 50 years (Gomes and Vickery 1978, Palutikof *et al.* 1999, Twisdale and Vickery 1992). The method first developed by Gomes and Vickery (1978) uses the combined distribution of the strong wind events, determined as the sum of the individual probabilities of exceedances for each of the strong wind mechanisms. The cumulative distribution function is approximated by

$$F(x) \cong 1 - [1 - e^{-s^{-yA}} + 1 - e^{-s^{-yB}} + \cdots] \tag{1}$$

where y_A, y_B etc. are the reduced variates for the data sets related to the different strong wind producing mechanisms (Palutikof *et al.* 1999). The standardized or reduced variate y is given by

$$y = (x - \beta)/\alpha \tag{2}$$

Where α is the scale or dispersion parameter

β is the mode of the Gumbel distribution, and

x is the extreme value.

Eq. (1) was first derived by Gomes and Vickery (1978), by noting that the combined cumulative probability distribution of the absolute annual maximum gust speed V_M is of the form

$$P(V_M < V) = \prod_{q=1}^{Q} P(V_q < V) \tag{3}$$

Where V_M is the absolute annual maximum gust speed

V_q is the annual maximum gust speed for the q^{th} strong-wind producing mechanism

$P(V_M < V)$ and $P(V_q < V)$ are the cumulative probabilities of V_M and V_q , and

Q is the number of significant phenomena.

It follows that for this methodology to be applied, the dispersion and mode parameters need to be determined for all the strong wind producing mechanisms. Firstly, these mechanisms need to be identified, and thereafter the annual maximum wind gust values forthcoming from each strong wind mechanism for each year of record. From the separate datasets for each strong wind mechanism, the distribution parameters, α and β, can be estimated according to the usual ways for the Gumbel method.

To determine an equation that can be used to estimate maximum gust speeds for specific return periods and for a mixed strong wind climate, the following were taken into consideration, derived from Gomes and Vickery (1978): Mathematically

$$1 - (1/R) \approx e^{(-1/R)} \tag{4}$$

Therefore, for a return period of R years, the cumulative probability for a given gust speed V_R can be approximated by

$$P(V_M < V_R) = e^{(-1/R)} \tag{5}$$

Thus,

$$e^{(-1/R)} \prod_{q=1}^{Q} P(V_q - V_R) \tag{6}$$

Therefore, for all strong wind producing mechanisms Gumbel distributed

$$e^{(-1/R)} = \left\{ e^{-s^{-[(V_R - \alpha_1)/\beta_1]}} \right\} * \left\{ e^{-s^{-[(V_R - \alpha_2)/\beta_2]}} \right\} * \cdots \tag{7}$$

where α_l and β_l are the dispersion and the mode parameters of the first strong wind producing mechanism etc. Return period estimations for a specific wind speed in a mixed strong wind climate can be determined with the following equation

$$R = 1/[e^{[(\alpha_1 - V_R)/\beta_1]} + e^{[(\alpha_2 - V_R)/\beta_2]} + \dots] \tag{8}$$

It follows that for this methodology to be applied, the dispersion and mode parameters need to be determined for all the strong wind producing mechanisms. Firstly these mechanisms need to be identified, as well as the annual maximum wind gust values forthcoming from each strong wind mechanism. From the separate datasets for each strong wind mechanism, the distribution parameters are estimated according to the usual ways discussed for the Gumbel method based on a single population.

To illustrate the mixed distribution method, the annual maximum wind gust distribution for Uitenhage, which is located in the south-eastern interior of the country, is discussed. Cold fronts and thunderstorms are the causes of the annual maximum wind gusts, of which the annual maximum values were identified, as presented in Table 1. The most extreme annual maxima are caused by thunderstorm gust fronts. However, cold fronts are the causes of the annual maximum wind gusts in

Table 1. The annual maximum wind gust values produced by the passage of cold fronts and thunderstorms at Uitenhage, for the period 1996-2008

Year	Annual maximum wind gust (m/s)		Annual maximum wind gust (m/s) caused by either a cold front or thunderstorm
	Cold front	Thunderstorm	
1996	30.3	15.9	30.3
1997	22.1	29.5	29.5
1998	22.8	16.3	22.8
1999	25.5	15.9	25.5
2000	25.1	18.5	25.1
2001	23.0	24.7	24.7
2002	-	-	-
2003	-	-	-
2004	26.5	18.2	26.5
2005	23.3	20.8	23.3
2006	27.1	24.3	27.1
2007	26.0	13.4	26.0
2008	24.7	25.8	25.8
Average	25.2	19.8	26.1

eight of the available 11 years of data. The average of the values for cold fronts is 25.2 m/s, which is higher than the average of the values for thunderstorms at 19.8 m/s. However, the value of á is 1.8 for cold fronts and 3.8 for thunderstorms. This relatively large value for α results in a shallower slope in the extreme wind gust distribution graph for thunderstorms, as well as for the mixed climate, as presented in Fig. 1.

Another interesting example is that for the extreme hourly mean wind speed distribution for Malmesbury. Table 2 presents the maximum hourly mean wind speed values, produced by the passage of cold fronts and the ridging (strong outflow from a high-pressure cell) of the Atlantic

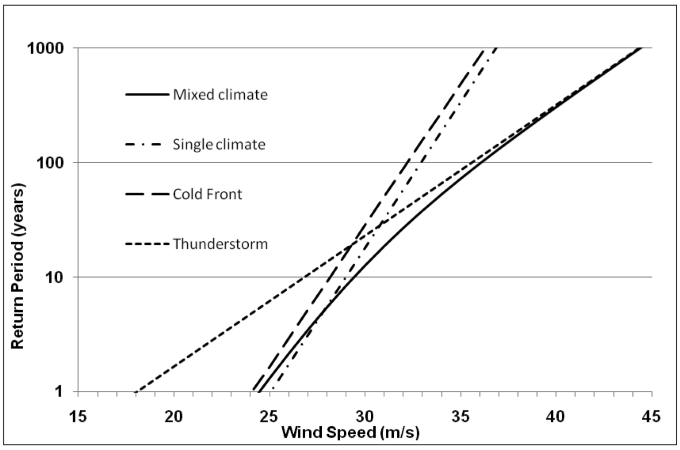

Fig 1 Extreme wind gust distribution for Uitenhage

Table 2. The annual maximum hourly mean wind speed values produced by the passage of cold fronts and ridging of the Atlantic Ocean high-pressure system at Malmesbury, for the period 1992-2008

Year	Annual maximum hourly mean wind speed (m/s)		Annual maximum hourly mean wind speed (m/s) caused by either a cold front or ridging
	Cold front	Ridging	
1992	9.9	9.5	9.9
1993	9.3	11.1	11.1
1994	11.1	10.1	11.1
1995	8.2	9.9	9.9
1996	9.4	9.3	9.4
1997	10.1	10.2	10.2
1998	7.1	9.0	9.0
1999	7.7	9.8	9.8
2000	7.2	9.1	9.1
2001	8.8	9.0	9.0
2002	8.3	9.3	9.3
2003	8.8	9.7	9.7
2004	6.1	8.4	8.4
2005	8.1	6.5	8.1
2006	8.0	7.0	8.0
2007	8.8	6.5	8.8
2008	8.8	9.0	9.0
Average	8.6	9.0	9.4

Ocean high-pressure system, for the period 1992 to 2008. Cold fronts are the causes of the annual maximum hourly mean wind speeds in six of the available 17 years of data, while the ridging of the Atlantic Ocean high-pressure system is the cause for the remaining 11 years. The average of the annual maximum values for the cold fronts is 8.6 m/s, while for the ridging it is 9.0 m/s. The value of α for the cold fronts is 0.9, while for the ridging it is 1.0. Therefore the extreme hourly wind distributions for cold fronts and ridging are very similar. However, the mean of the annual maximum hourly mean wind speeds, regardless of the cause, is 9.4 m/s, with α equal to 0.7. The result is an extreme wind distribution as presented in Fig. 2. The slope of the mixed climate distribution is similar to the distributions for cold fronts and ridging, while the slope for the traditional Gumbel method based on a single population is much steeper, causing a significant underestimation of wind speeds for the longer return periods.

The disaggregated data sets developed in this type of analysis also make it possible to predict extreme wind estimations caused by the different strong wind mechanisms identified. Table 3 presents the estimated wind gust quantiles X_{50}, X_{100} and X_{500} (for 50, 100 and 500 years respectively) for the strong wind mechanisms for Uitenhage.

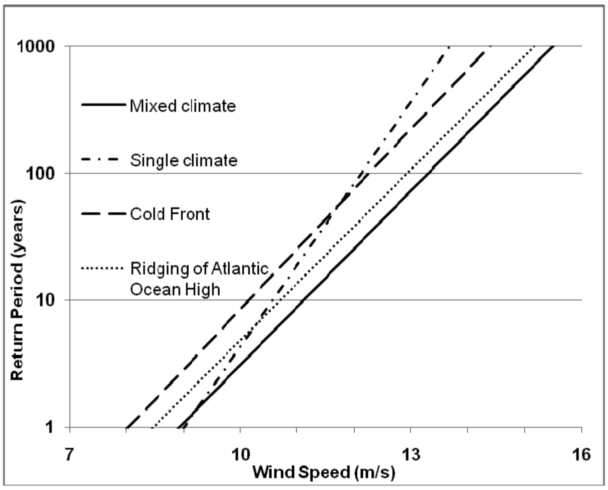

Fig. 2 Annual maximum mean hourly wind speed distribution for Malmesbury

Table 3. Estimations of extreme wind gusts due to cold fronts and thunderstorms for Uitenhage

Strong wind mechanism	X_{50}	X_{100}	X_{500}
Cold front	31.0	32.2	35.0
Thunderstorm	33.0	35.6	41.7

3. Results

From a total of 94 weather stations that were considered, the mixed distribution method could be applied to 65 weather stations for wind gusts, and 50 for hourly mean wind speeds. The full set of results of the differences in quantile values between the mixed distribution method and Gumbel method based on a single population is presented in the Appendix. Maps indicating the positions of the weather stations and provinces of South Africa, which are used as reference in the discussions of the analysis results, are also presented. As can be expected, and also noted by Gomes and Vickery (1978), quantile estimations by the mixed distribution method are usually larger than the estimations by the Gumbel method based on a single population, with the differences increasing with increasing return periods.

For the 1:50 year return period the gust quantile, X_{50} is on average 0.7 m/s larger for the mixed distribution method than the Gumbel method based on a single population, while for the hourly mean wind speeds it is 0.2 m/s larger. For longer return periods the mean differences increase. For X_{100}, the mean differences are 1.0 m/s and 0.3 m/s, while for X_{500} the mean differences are 1.7 m/s and 0.5 m/s respectively.

Where there are large differences between the estimates of the two methods it is usually because the strong wind mechanism that is causing the most extreme wind speeds is under-represented in the sample of annual maximum wind speeds of a weather station. The dispersion, and therefore α, of the annual maximum values of this particular strong wind mechanism is then also always significantly larger than that for the other contributing strong wind mechanism(s).

4. Assessment and integration of extreme wind estimations

To characterise the effect of the mixed strong wind climate on the estimation of quantiles, the spatial distribution of the parameters of the Gumbel distribution, for the various strong wind producing mechanisms, should be assessed. The magnitudes of the differences between quantiles estimated with the mixed distribution method and the Gumbel method based on a single population will depend on the values of the distribution parameters of the various strong wind mechanisms involved.

For each weather station and for each relevant strong wind mechanism, the Gumbel distribution parameters have been estimated; i.e., α, the scale or dispersion parameter, and β, the mode. The value of α is mostly influenced by the variance between the annual extreme values in the sample, while the mode is mostly dependent on the mean. The values of the quantiles estimated by the mixed distribution method are determined by the values of the distribution parameters of each relevant mechanism, and the resulting contributions of these parameters to the mixed distribution in Eq. (1). Many combinations of parameter values exist in the data set used for analysis.

For many weather stations the values of the distribution parameters of one strong wind mechanism are such that the contribution of the particular mechanism tends to dominate the estimation of the quantiles relevant to the built environment, i.e., those of 50 years or longer. As mentioned, such cases usually occur where the dispersion, as expressed by the value of α for the one mechanism is considerably larger than for the other contributing mechanism(s). However, the value of the mode β can also play a significant role.

The identification of zones of similar values of the distribution parameters requires the application of an objective analysis method. Cluster analysis is often used in climatological studies to define regions with similar climatological characteristics. This type of analysis was applied to group weather stations according to similar values of distribution parameters. Of the different cluster analysis techniques, the most widely applied method is the *K*-means method, as it is relatively simple to use and also allows reassignment of observations as the analysis proceeds from one iteration to the next. The *K* refers to the number of groups or clusters, which is specified in advance of the analysis. Various methods exist to determine the optimum number of clusters, of which the most often used is the "rule of thumb"

$$K \approx \sqrt{n/2} \tag{9}$$

developed by Mardia *et al.* (1979), and the "elbow method", first introduced by Thorndike (1953).

The algorithm usually begins with a random partition of the n data vectors into the pre-specified number of groups, and proceeds as follows:

1. Compute the vector means, i.e., $\overline{x}_k$, k = 1…K; for each cluster;
2. Calculate the Euclidian distances between the current data vector x_i and each of the K $\overline{x}_k$'s;
3. If necessary the x_i is reassigned to the group whose mean is closest;
4. Repeat for all x_i, i = 1...n. Return to step 1.

The algorithm is iterated until a full cycle through all the data vectors produces no reassignments (Wilks 2006).

For the analysis of the distribution parameters of single climates, i.e., one strong wind mechanism at a time, cluster analysis could only be performed on thunderstorms and cold fronts in a meaningful manner, mostly due to the spatially limited footprint of the other secondary strong wind mechanisms. For the single climate analyses the data from weather stations with mixed strong wind climates were also utilised. Regarding the combination of strong wind mechanisms, thunderstorms and cold fronts, as well as combinations of these two dominant mechanisms with the other secondary mechanisms, could be analysed.

4.1 Thunderstorm gusts

Fig. 3 presents the results of cluster analysis on the distribution parameters of the thunderstorm gusts. Three clusters could be resolved, of which the number of weather stations, ranges and standard deviations of the values of the distribution parameters are presented in Table 4. One should note that the zones presented in Fig. 3 and subsequent cluster analyses only indicate same strong wind characteristics for the weather stations depicted. Examples where one could erroneously interpolate or extrapolate the results are the Western Cape, due to complex topography, and Lesotho, mainly due to the absence of data.

The average value of α ranges from 2.4 to 4.1 for each cluster, with the region of highest α covering the larger part of the Eastern Cape province, south-western KwaZulu-Natal and the central Free State provinces, into the North-West province. The average values of β show a general increase from 21.3 to 24.6, from north-east to south-west. In Table 4 it is noticeable that the ranges of the average distribution parameters are comparable, except for the cluster covering the south-east

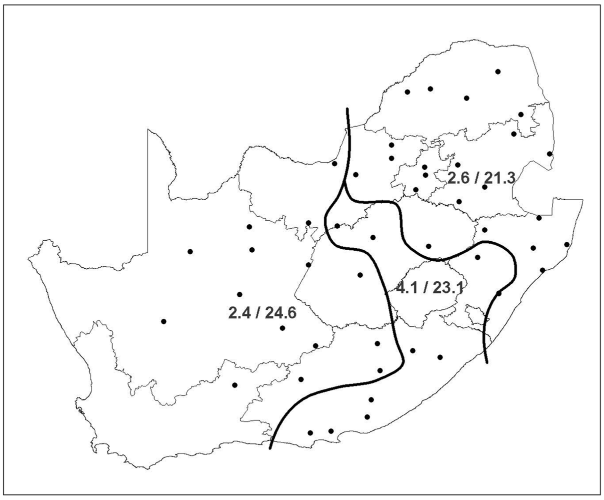

Fig. 3 Thunderstorm gust clusters, with distribution parameters $\bar{\alpha}/\bar{\beta}$ for each cluster

Table 4. Ranges and standard deviations of estimated values of distribution parameters for weather stations in clusters presented in Fig. 3

Cluster $\bar{\alpha}/\bar{\beta}$	Number of stations	α		β	
		Range	σ	Range	σ
2.4 / 24.6	15	2.0-3.5	0.5	16.6-25.9	2.1
4.1 / 23.1	10	3.8-5.1	0.5	17.5-26.6	2.9
2.6 / 21.3	23	1.7-3.6	0.5	20.6-30.0	2.1

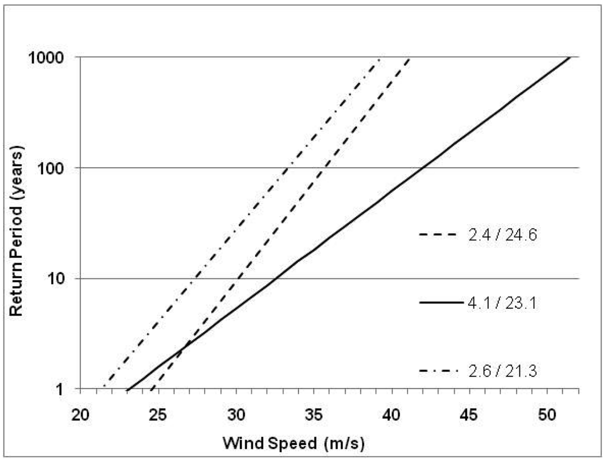

Fig. 4. Annual maximum wind gust distributions for the clusters presented in – Fig. 3

of the country. The high α value is reflected in the relatively bigger range of values of β, which in turn reflects the high interannual variability of the annual maximum gust values in the region.

The region of highest α coincides with the areas of highest quantile values in the east of the country. This illustrates the significant role that the interannual variability of the annual maximum gusts from thunderstorms plays in the estimation of high gust quantiles in the east. Fig. 4 graphically illustrates the effect of the different mean distribution parameters, particularly α, on the estimation of the quantiles, in which it can be seen that the regions with similar α show almost the same slope, while the slope for the higher α value presents a much flatter slope with a consequent rapid increase of quantile values with return period.

4.2 Cold front gusts and hourly mean wind speeds

High hourly mean and gust quantiles in the west of the country are mostly due to the frequent occurrence of strong cold fronts, but also the interaction of these fronts with the topography. As cold fronts produce strong winds on the synoptic scale, the relative strength of the winds will also be determined by the height above sea level (Ballio *et al.* 1999). However, apart from the topography, the winds from the cold fronts also tend to be stronger closer to the coastline.

The zoning of similar distribution parameters of wind gusts produced by cold fronts were not satisfactorily resolved by the cluster analysis. The reasons for this seem to be the complex topography, as well as the spatial variability of the gust factor. It is believed that a denser network of weather stations could have produced a result that is spatially more coherent.

For the hourly mean wind speeds, four spatially coherent zones of similar distribution parameters could be resolved, which are presented in Fig. 5. The number of stations and ranges of the values of the distribution parameters for each cluster are presented in Table 5. The numbers of stations in each cluster are a function of the spatial distribution of the weather stations influenced by cold fronts, as well as the relative sizes of the zones; e.g., the zone in the south has the smallest number of stations as it mainly covers only the coastal region in the south and parts of the adjacent interior. The ranges and standard deviations of α are comparable between clusters. However, the zones in the south exhibit higher ranges and standard deviations of β, which indicates the relatively high

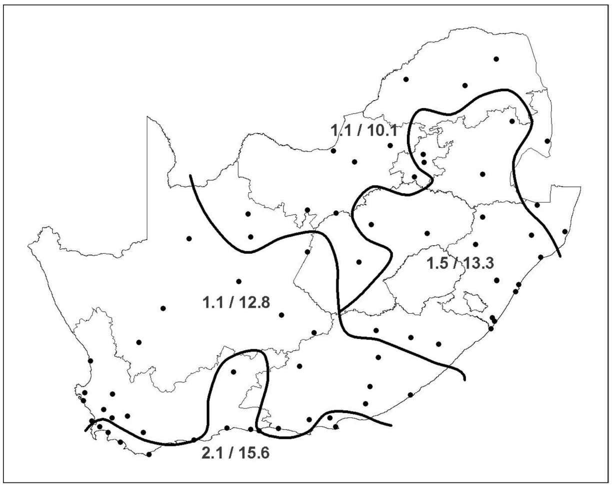

Fig. 5 Cold front hourly mean wind speed clusters with distribution parameters $\bar{\alpha}/\bar{\beta}$ for each cluster

Table 5. Ranges and standard deviations of estimated values of distribution parameters for weather stations in clusters presented in Fig. 5

Cluster $\bar{\alpha}/\bar{\beta}$	Number of stations	α Range	α σ	β Range	β σ
2.1 / 15.6	11	1.5-2.8	0.4	12.0-18.9	2.3
1.1 / 12.8	22	0.7-1.6	0.3	8.8-18.6	2.1
1.1 / 10.1	15	0.6-1.8	0.3	7.0-11.9	1.3
1.5 / 13.3	19	0.8-2.4	0.4	10.6-15.2	1.3

spatial variability of β values between stations in the south and west of the country, probably a reflection of the complex topography of the region.

The results for the hourly mean wind speed indicate a general decrease in the mean value of α from south to north, which reflects the relative strength of the cold fronts as they move over the subcontinent. The zone in the east of the country, with a high mean value of α of 1.5, coincides with those annual maximum wind speeds that were mostly the result of strong flow caused by deep coastal low pressure systems (closed circulation of relatively low pressure, occurring ahead of the passage of a cold front) to the east, in conjunction with cold fronts approaching from the west. The zone in the south of the country shows the highest mean value of α of 2.1. This region will not only experience the highest annual hourly mean wind speeds from cold fronts, but also the highest interannual variability, both contributing to the estimation of relatively high quantiles.

Fig. 6 illustrates the effect of the different mean distribution parameters of the clusters on the estimation of the quantiles. In the south the combination of high α and β values leads to a relatively rapid increase of quantile values with increase in the return period, i.e., a visibly less steep slope.

4.3 Combination of thunderstorms and cold front gusts

Cluster analysis was performed on combinations of distribution parameters of different strong

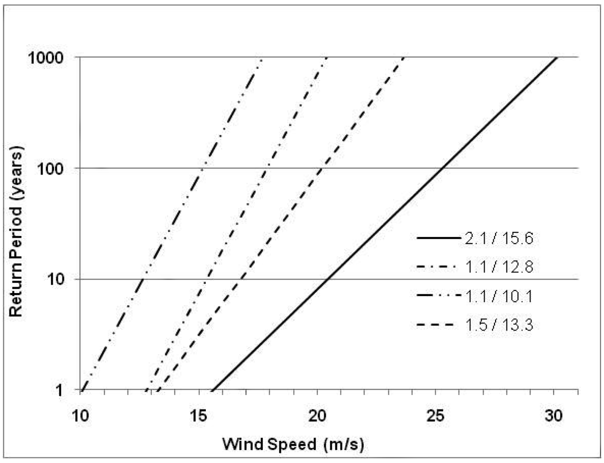

Fig. 6 Hourly mean wind speed distributions for the clusters presented in Fig. 5

wind mechanisms, to investigate the relative dominance of the particular mechanisms on the estimation of quantiles at different return periods. Fig. 7 presents the cluster analysis performed on the distribution parameters of the gusts at weather stations where the annual maxima are caused by both the two dominant strong wind mechanisms, i.e., thunderstorms and cold fronts.

The number of stations and ranges of the values of the distribution parameters for each cluster are presented in Table 6. For all five clusters the mean value of α is higher for thunderstorms, which indicate larger interannual variability of the maximum gusts from thunderstorms compared to cold fronts. This is especially true for the clusters in the east and south-east of the country, where thunderstorms tend to dominate the estimation of quantiles at longer return periods, e.g., the weather station of Uitenhage described in section 2. The clusters toward the north indicate less dominance from thunderstorms for those weather stations where thunderstorms and cold fronts are the main sources of a mixed strong wind climate. Also notable are two of the clusters in the south which

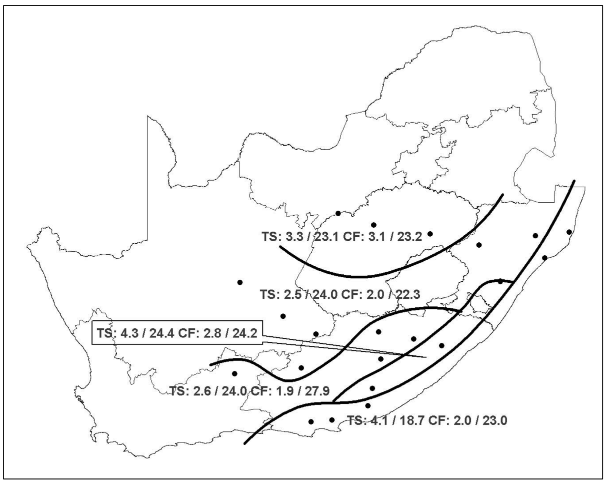

Fig. 7 Combined thunderstorm (TS) and cold front (CF) gust clusters with distribution parameters TS: $\bar{\alpha}/\bar{\beta}$ CF: $\bar{\alpha}/\bar{\beta}$

Table 6. Ranges and standard deviations of estimated values of distribution parameters for weather stations in clusters presented in Fig. 7

Cluster TS: $\overline{\alpha}/\overline{\beta}$; CF: $\overline{\alpha}/\overline{\beta}$	Total	Thunderstorm				Cold Front			
		α		β		α		β	
		Range	σ	Range	σ	Range	σ	Range	σ
4.1 / 18.7; 2.0 / 23.0	4	3.0-5.1	0.8	16.6-21.5	1.9	1.8-2.3	0.2	21.6-24.1	0.9
4.3 / 24.4; 2.8 / 24.2	3	3.1-4.9	0.7	20.1-29.2	2.3	2.6-3.1	0.2	21.4-26.8	2.0
2.6 / 24.0; 1.9 / 27.9	5	1.7- 3.9	0.9	20.6-26.6	2.4	1.5-2.0	0.3	25.7-31.5	2.1
2.5 / 24.0; 2.0 / 22.3	7	2.0-3.5	0.5	19.4-30.0	3.0	1.6-2.5	0.3	19.9-24.6	1.7
3.3 / 23.1; 3.1 / 23.2	3	2.3-4.1	0.7	22.3-24.8	1.2	2.8-3.4	0.2	20.5-24.7	1.9

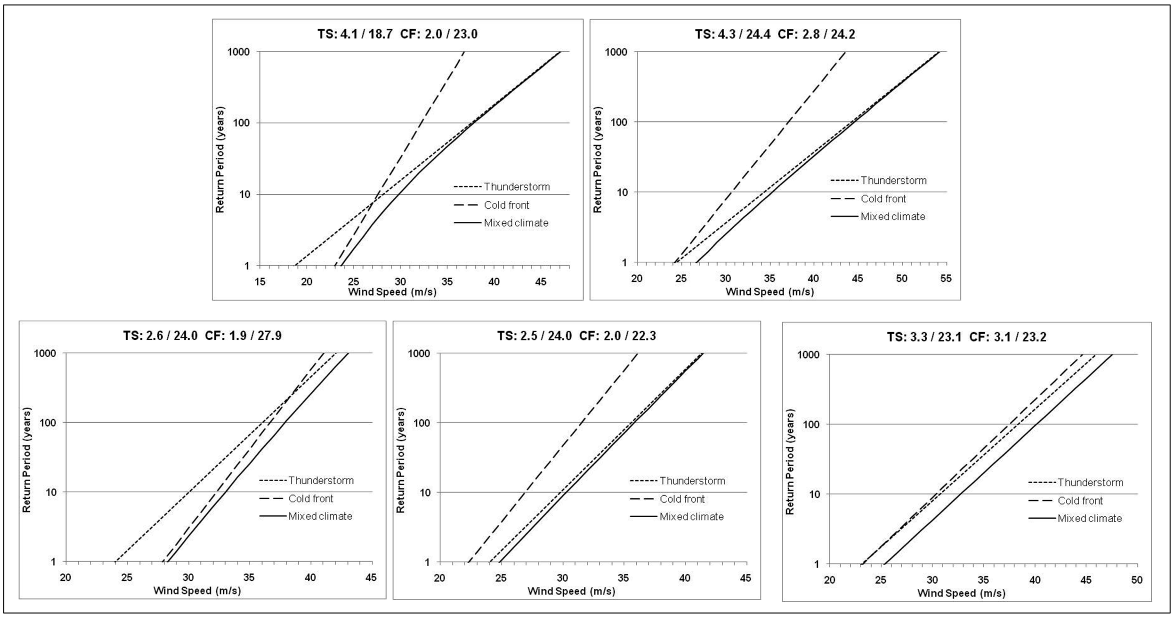

Fig. 8 Annual maximum gust distributions for the clusters presented in Fig. 7

show the mean β value for cold fronts to be higher than for thunderstorms. The effect of this is for cold fronts to dominate the estimations of quantiles at shorter return periods, but eventually the thunderstorms will still dominate at the longer return periods.

Fig. 8 illustrates the effect of the different mean distribution parameters of the clusters on the estimation of the quantiles. For most clusters the estimations of relevant quantiles are almost solely determined by thunderstorms, except in the north where the mean distribution parameters of thunderstorms and cold fronts are comparable, and a region in the south that are prone to relatively strong gusts from cold fronts.

4.4. Thunderstorms or cold fronts combined with other strong wind mechanisms

4.4.1. Wind gusts

Similar analysis to that performed in the previous section was done for combinations of cold fronts or thunderstorms with other strong wind mechanisms. For the wind gusts only three stations had a combination of thunderstorms and other mechanisms present, excluding cold fronts: one station in the western interior where isolated lows played a secondary role in the mixed distribution, and two stations in the north-east where the ridging of the Indian Ocean high-pressure system played the secondary role.

There were 15 weather stations, mostly situated in the west and south of the country, where the cold front gusts were combined with another mechanism, thunderstorms excluded. Three clusters could be resolved, as presented in Fig. 9. The numbers of stations, and ranges and standard deviations of the values of the distribution parameters for each cluster, are presented in Table 7. Because of the limited number of weather stations that were analysed, the numbers of stations in each cluster were small, with only three stations grouped in a cluster in the south-west of the country. This particular cluster also has the highest mean value in α for cold fronts, indicating a relatively larger range in annual maximum wind gusts compared to the other clusters. This is probably a reflection of the complex topography of the particular region. On the other hand the climatic diversity of the region where the cluster in the east is situated is reflected by its relatively large range in the β values, as well as a high mean value for α.

The analysis shows that where cold fronts are combined with other mechanisms excluding

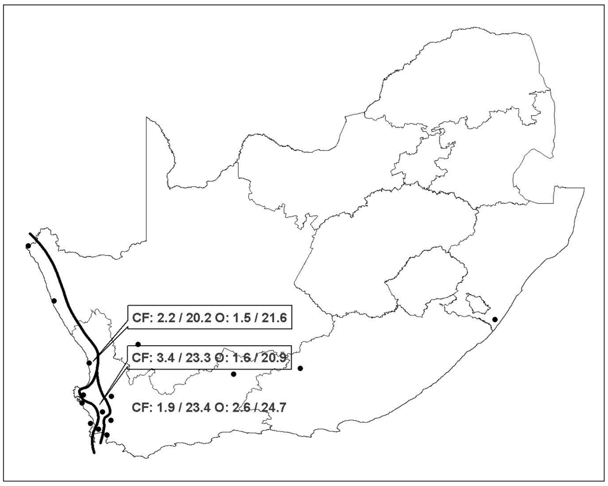

Fig. 9 Combined cold front (CF) and other mechanism (O) gust clusters with distribution parameters CF: $\bar{\alpha}/\bar{\beta}$ and O: $\bar{\alpha}/\bar{\beta}$

Table 7. Ranges and standard deviations of estimated values of distribution parameters for weather stations in the clusters presented in Fig. 9

Cluster CF: $\bar{\alpha}/\bar{\beta}$; O: $\bar{\alpha}/\bar{\beta}$	Total	Cold Front				Other			
		α		β		α		β	
		Range	σ	Range	σ	Range	σ	Range	σ
2.2 / 20.2; 1.5 / 21.6	6	1.4-2.6	0.4	18.5-22.0	1.1	1.1-1.7	0.2	19.8-23.5	1.2
3.4 / 23.3; 1.6 / 20.9	3	2.7-3.8	0.5	21.2-25.1	1.6	1.1-1.9	0.4	19.1-22.8	1.5
1.9 / 23.4; 2.6 / 24.7	6	1.7- 2.3	0.2	17.4-29.2	3.9	1.9-3.7	0.7	22.5-27.4	1.6

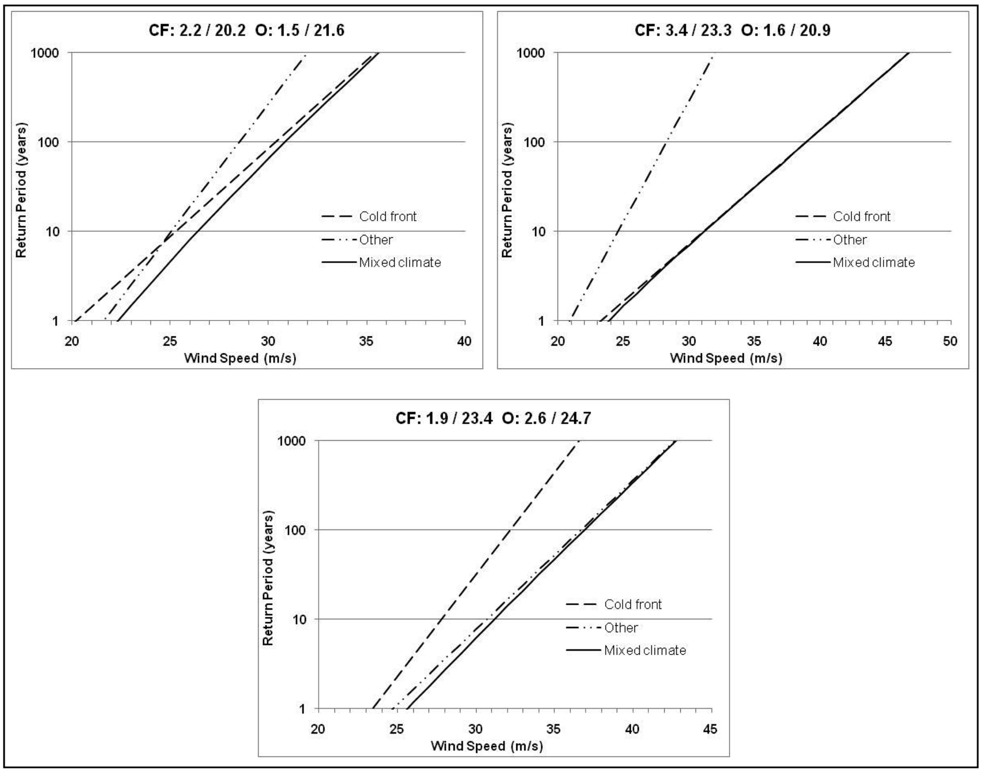

Fig. 10. Annual maximum gust distributions for the clusters presented in Fig. 9

thunderstorms, cold fronts tend to dominate the estimation of quantiles for longer return periods in the west and south-west. However, from the eastern side of the south-western Cape and further to the east, other synoptic-scale mechanisms tend to dominate, particularly the ridging of the Atlantic Ocean high-pressure system in the west, and elsewhere the convergence towards isolated low-pressure systems close to the coast.

Fig. 10 illustrates the effect of the different mean distribution parameters of the clusters on the estimation of the quantiles. For two clusters and relevant return periods, cold fronts tend to dominate the estimation of quantiles, except for the cluster in the east.

4.4.2. Hourly mean wind speed

For the hourly mean wind speeds there were 34 weather stations where cold fronts were combined with other synoptic-scale mechanisms. From the distribution parameters of these stations five clusters could be resolved, which are presented in Fig. 11. The numbers of stations, and ranges and standard deviations of the distribution parameter values for each cluster, are presented in Table 8. The numbers of stations in each cluster are comparatively small, except for the cluster mostly covering the central and western interior, which covers a much larger area compared to the other. The mean value of α for cold fronts for the cluster in the south-west is much larger than for the other clusters, while the range and standard deviation of the β values for other mechanisms in this cluster is also much larger than elsewhere. This would indicate a tendency in the south for other mechanisms to dominate at shorter return periods, but cold fronts at the longer return periods.

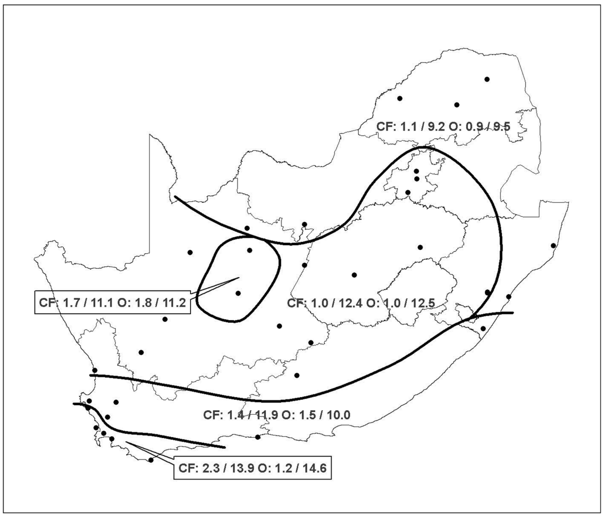

Fig. 11 Combined cold front (CF) and other mechanisms (O) hourly mean wind speed clusters with distribution parameters CF: $\overline{\alpha}/\overline{\beta}$ and O: $\overline{\alpha}/\overline{\beta}$

Table 8. Ranges and standard deviations of estimated values of distribution parameters for weather stations in clusters presented in Fig. 11

Cluster CF: $\overline{\alpha}/\overline{\beta}$; O: $\overline{\alpha}/\overline{\beta}$	Total	Cold Front				Other			
		α		β		α		β	
		Range	σ	Range	σ	Range	σ	Range	σ
2.3 / 13.9; 1.2 / 14.6	5	2.0-2.8	0.3	13.2-15.6	1.0	0.5-1.9	0.5	12.7-16.8	1.7
1.4 / 11.9; 1.5 / 10.0	5	1.0-1.6	0.2	10.6-14.2	1.4	1.1-2.2	0.4	9.1-10.8	0.7
1.0 / 12.4; 1.0 / 12.5	15	0.8-1.3	0.2	10.1-15.9	1.4	0.5-1.6	0.3	10.8-15.4	1.2
1.7 / 11.1; 1.8 / 11.2	2	1.3-2.0	0.4	10.6-11.5	0.5	1.7-1.9	0.1	11.2-11.2	0.0
1.1 / 9.2; 0.9 / 9.5	7	0.6-1.6	0.3	7.0-10.0	0.9	0.5-1.2	0.2	7.0-11.0	1.1

While the distribution parameters for the cluster in the south suggest that cold fronts tend to dominate the quantile estimations over relevant time scales (indicated by the relatively high mean value of α), the other clusters show the distribution parameters of the cold fronts and other mechanisms to be comparable, so that no mechanism will totally dominate the other. Fig. 12 illustrates the effect of the different mean distribution parameters of the clusters on the estimation of the quantiles, where it can be seen that it is only in the south-west of the country where cold fronts totally dominate the estimations of quantiles at relevant time scales.

4.5 Combinations of secondary strong wind mechanisms

For wind gusts there are no weather stations with mixed strong wind climates that exclude both thunderstorms and cold fronts. For hourly mean wind speeds there are only two weather stations that exclude cold fronts, both situated in the extreme west of the country. For these stations the hourly mean wind speed quantiles, for longer return periods, are dominated by the ridging of the Atlantic Ocean high-pressure system at the one station, while a trough (an elongated area of

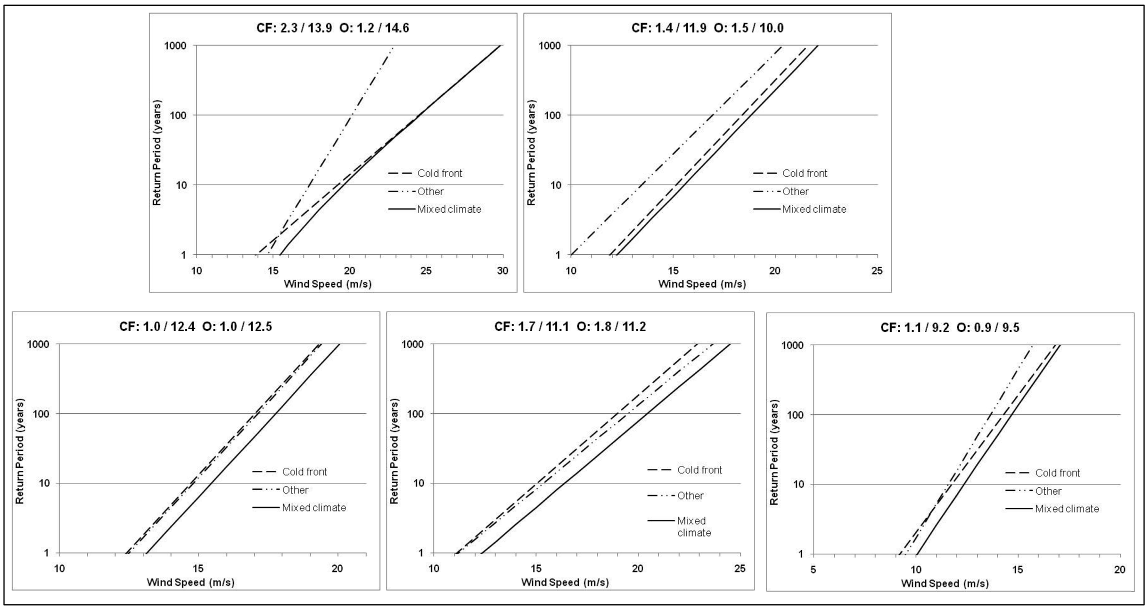

Fig. 12 Hourly mean wind speed distributions for the clusters presented in Fig. 11

relatively low pressure) or coastal low-pressure system situated on the West Coast dominates the other.

5. Summary

In Kruger *et al.* (2010) South Africa was zoned into geographical regions that indicate the most likely sources of strong winds, particularly the annual maxima of the 2-3 second wind gusts. The aim of the current paper was to identify and characterise strong wind climate regions from the results of the analyses in section 4, and, in the case of the wind gusts, to compare the results with that of Kruger *et al.* (2010).

5.1 Wind gusts

It was shown that the relatively high gust quantiles in parts of the east and south-east of the country are mainly due to the high interannual variability of the annual maximum wind gusts from thunderstorms (section 4.1). This feature of the strong wind climate also plays a role in the estimation of the gust quantiles in a mixed strong wind climate with thunderstorms and cold fronts (section 4.3). For a large part of the south-east of the country thunderstorms tend to dominate the estimation of relevant quantiles, but with their dominance generally decreasing in a north-westerly direction (Figs. 3 and 4).

Regarding wind gusts from cold fronts, cluster analysis could not satisfactorily resolve spatially coherent zones of weather stations with similar distribution parameters.

Considering the combination of cold fronts and thunderstorms, thunderstorms dominate cold fronts in the south-east, with their influence decreasing in a north-westerly direction (section 4.3).

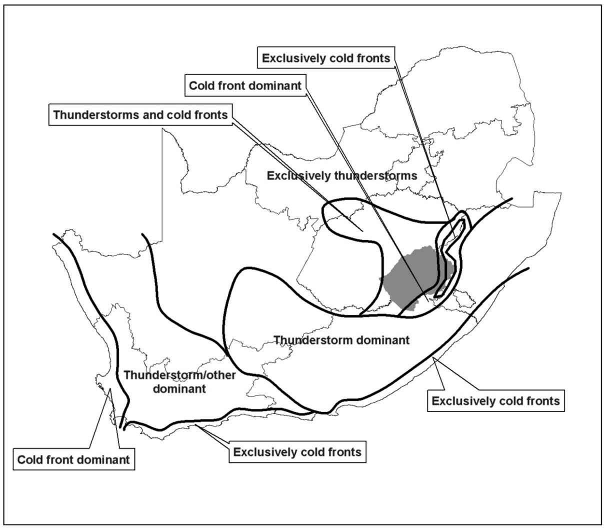

Fig. 13 Relative contribution of the different strong wind mechanisms for wind gusts

For the combination of cold fronts and other mechanisms, the dominance of cold fronts in the extreme west and south-west is indicated, while other mechanisms, such as ridging and isolated low pressure systems play a larger role towards the east (section 4.4.1).

These results for gusts can be summarised on a map as presented in Fig. 13, which provides a broad characterisation of the relative dominance of the different strong wind mechanisms affecting the statistical estimations of relevant quantiles. Lesotho has been blocked out in the map due to lack of information. Over the coastal and higher-lying areas cold fronts tend to dominate. This is probably due to the relationship between the strength of synoptic-scale winds and elevation (Ballio *et al.* 1999). Over the lower-lying areas, even in the south, other mechanisms, especially thunderstorms, dominate the cold fronts. Towards the north the strengths of cold fronts decrease, to such a degree that in most of the northern and north-western interior the annual maximum gusts originate exclusively from thunderstorms.

Fig. 13 can be deemed to be more informative and substantiated for some uses than those developed in Kruger *et al.* (2010), which do not provide information on the relative contributions and dominance of the different strong wind mechanisms where they overlap.

5.2 Hourly mean wind speed

Thunderstorms are not considered to be a strong wind mechanism for time-scales longer than a few seconds, due to the very short duration of strong winds from thunderstorms - usually in the form of gust fronts. Therefore a map of the relative dominance of the strong wind mechanisms in the estimation of quantiles on the hourly scale only take synoptic scale mechanisms into consideration.

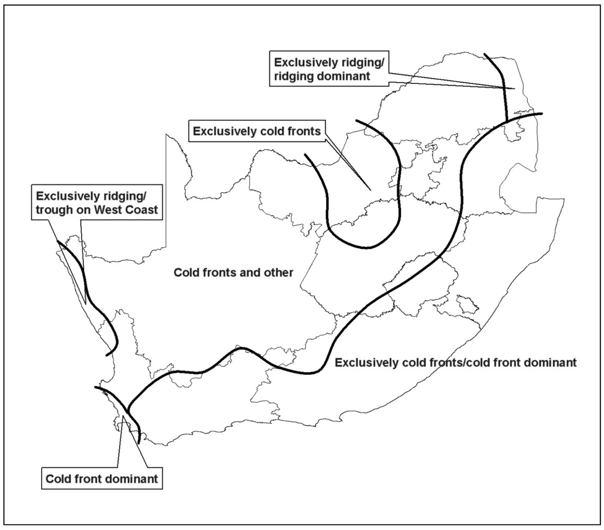

Fig. 14 Relative contribution of the different strong wind mechanisms for hourly mean wind speeds

Fig. 14 presents a map which indicates the relative dominance of the strong wind mechanisms for the hourly mean wind speeds. In the south-west, cold fronts are dominant, with the ridging of the Atlantic Ocean high-pressure system as a secondary mechanism. Towards the north, along the West Coast, annual maximum hourly mean wind speeds are exclusively caused by ridging in the south, or the presence of a deep trough or coastal low pressure system more to the north. In the south and east of the country the vast majority of weather stations show annual maximum wind speeds exclusively caused by cold fronts. However, for a small number of stations other mechanisms also play a role, such as ridging or isolated low pressure systems close to the coast. In the region situated mostly in the interior of the country, indicated by "Cold fronts and other, the cold fronts share their influence with other mechanisms. In the west it is mostly deep surface troughs, while in the north-east it tends to be the ridging of the Indian Ocean high-pressure system. An area covering most of the North-West province falls outside the influence areas of these two mechanisms, with the effect that all annual maximum hourly mean wind speeds are caused by cold fronts only. In the Lowveld, in the far north-east, ridging of the Indian Ocean high-pressure system tends to dominate due to the diminished strength of the cold fronts which move over this region from time to time, but also the relative proximity of the quasi-stationary Indian Ocean high-pressure cell.

6. Conclusions

The assessment of the characteristics of extreme winds in South Africa confirms the necessity to consider the mixed strong wind climate of the region. It is therefore essential not simply to treat annual extreme values of either annual maximum gust or hourly wind speed statistically from the records, but to establish the contributing wind generation mechanism in order to be able to assess the combined effects of different mechanisms. This approach is essential, not only for proper prediction of extreme winds with a long return period, but also to characterise the strong wind climate in terms of the geographic distribution of the mechanisms, particularly the complex combined effects. The following specific conclusions can be derived from the assessment:

• The general observation that the treatment of the combined effects of different strong wind generating mechanisms, where these conditions do apply, leads to the prediction of higher fractile wind speeds than when this differentiation is not applied, is comprehensively confirmed by this investigation.

• The expected complex strong wind climate for South Africa is confirmed by the assessment. The level of complexity is much higher than simply representing the two main mechanisms of cold fronts and thunderstorms and a region of overlap, as the result not only of the relative contribution of each mechanism, but also whether such dominance is driven by a higher degree of dispersion of annual maximum values or systematically stronger winds, as represented by the Gumbel parameter α and β respectively.

• As expected, thunderstorm gusts play a dominant role across the central parts of the regions, particularly for long return period wind speed. However, the strongest winds are obtained for an extended region following the south eastern coastline (Fig. 7) and extending to the south eastern part of the central inland (Fig. 3). Thunderstorm gusts are significantly less severe across the north eastern and western parts of the country.

• The contribution of cold front gusts is nevertheless significant across a wide band parallel to the south and south-eastern coastline, and penetrates surprisingly far into the interior (Figs. 7 and 13). As expected cold fronts dominate all along the coastline, although domination further inland is limited (Fig. 13).

• Even for hourly mean annual extreme winds for which synoptic mechanisms apply across the country, differentiation into cold fronts and other mechanisms have an influence on the predictions (Figs. 11 and 12). Although the resulting climatic characteristics are substantially less complicated than for gusts, significant regional variation can be identified (Figs. 5, 11 and 14).

Interpretation of strong wind records in terms of the contributing mechanisms is essential for predicting appropriate wind speeds for the design of structures and infrastructure. Representation of the results as an interpretation of the strong wind climate of South Africa by using cluster analysis provides an appreciation of the complexity of the climate, which should assist in practical applications, such as deriving design wind speed maps and identifying specific areas of concern and regions where improvement of the assessment is required. Relating the strong wind climatic regions to other associated information such as the general climate or topography should assist in providing a phenomenological basis to the results, and improve the understanding of the results of the assessment.

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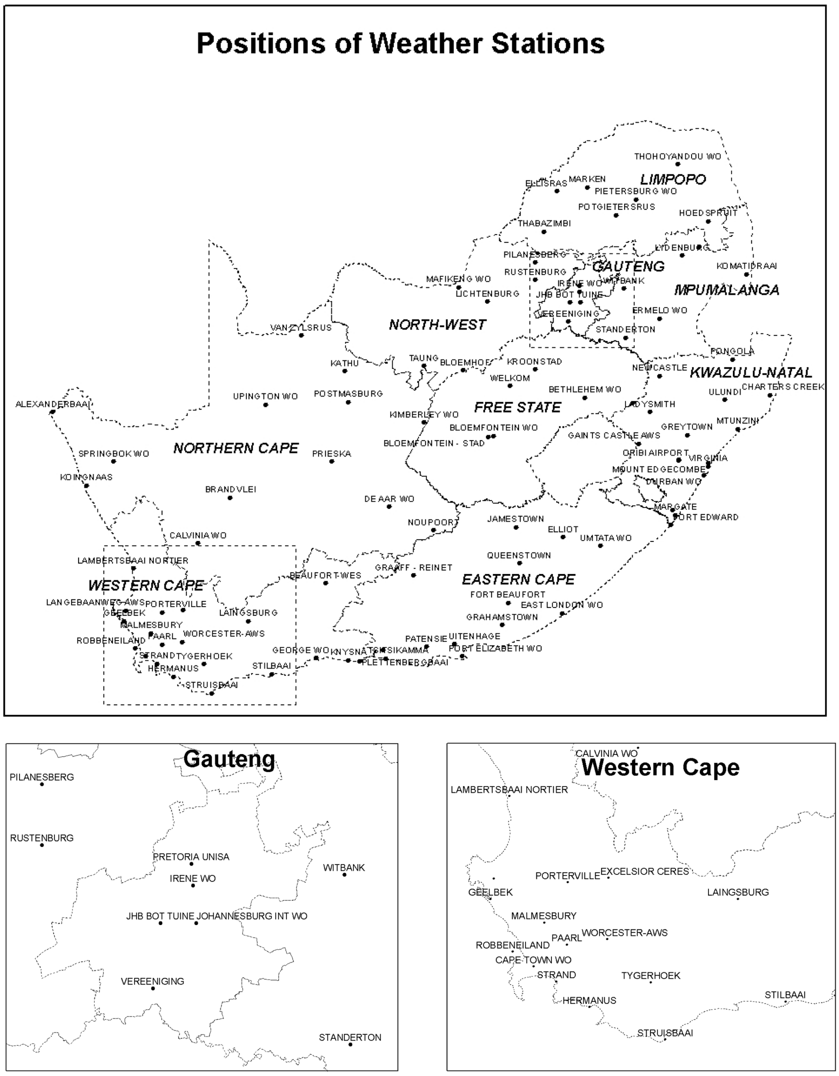
Appendix

Differences between the estimates for the quantiles X_T by the mixed distribution method and Gumbel method based on a single population, for weather stations with a mixed strong wind climate. Stations are listed according to station numbers, arranged in rows from west to east, and then from south to north.

Sation numer	Station name	Annual maxium wind gust (m/s)			Annual maxium hourly wind gust (m/s)		
		X_{50}	X_{100}	X_{500}	X_{50}	X_{100}	X_{500}
0003108	STRUISBAAI				0.3	0.3	0.8
0005609	STRAND	0.2	0.3	0.4	0.4	0.5	0.8
0006386	HERMANUS				0.1	0.2	0.1
0014545	PLETTENBERGBAAI				0.5	0.6	1.0
0020618	ROBBENEILAND	1.3	1.7	2.8	0.3	0.4	0.7
0021178	CAPE TOWN WO	0.4	0.5	0.7	0.4	0.5	0.6
0021823	PAARL	1.0	1.4	1.9			
0031650	JOUBERTINA	2.1	2.8	4.7	0.7	0.9	1.3
0033556	PATENSIE	4.5	5.5	7.9	0.2	0.4	0.7
0034763	UITENHAGE	2.1	3.1	6.3			
0040192	GEELBEK	0.4	0.6	0.9	0.2	0.3	0.4
0041388	MALMESBURY	0.4	0.5	0.6	0.9	1.2	1.6
0041841	PORTERVILLE	0.0	0.2	0.4	0.6	0.9	1.6
0045642	LAINGSBURG	1.2	1.5	2.4			
0056917	GRAHAMSTOWN	1.8	2.7	4.8			
0061298	LANGEBAANWEG	–0.1	0.1	0.3	0.4	0.4	0.7

0063807	EXCELSIOR CERES				0.1	0.2	0.4
0078227	FORT BEAUFORT	0.8	1.3	2.3			
0083572	LAMBERTSBAAI	1.1	1.3	1.9	0.0	0.1	0.1
0092081	BEAUFORT-WES	0.2	0.3	0.3			
0096072	GRAAFF - REINET	0.7	0.9	1.6	0.3	0.4	0.7
0123685	QUEENSTOWN	1.2	1.5	2.2			
0127272	UMTATA WO	1.4	1.8	2.7			
0134479	CALVINIA WO	0.0	0.1	0.0	0.6	0.7	1.2
0144791	NOUPOORT	0.6	0.7	1.1	–0.6	–0.4	0.1
0148517	JAMESTOWN	2.0	2.4	3.4			
0150620	ELLIOT	3.0	3.9	6.3			
0169880	DE AAR WO	1.5	1.8	2.8	0.1	0.1	0.3
0182465	PADDOCK	–0.3	0.0	0.9	–0.2	–0.2	–0.3
0184491	KOINGNAAS	1.0	1.3	2.0	0.6	0.9	1.6
0190868	BRANDVLEI	3.1	4.0	6.0	0.0	–0.1	0.0
0214700	SPRINGBOK WO	1.3	1.8	3.1	0.1	0.1	0.2
0224400	PRIESKA	0.1	0.1	0.1	0.7	0.7	0.8
0239698	PIETERMARITZBURG	1.6	1.8	2.2	0.0	0.0	0.0
0239699	ORIBI AIRPORT	0.4	0.6	0.9	–0.1	–0.1	–0.1
0241072	MT EDGECOMBE				0.2	0.2	0.3
0241076	VIRGINIA				0.3	0.3	0.5
0261307	BLOEMFONTEIN				0.1	0.2	0.3
0261516	BLOEMFONTEIN WO				0.2	0.2	0.2
0270155	GREYTOWN	1.1	1.4	2.2			
0274034	ALEXANDERBAAI	0.9	1.3	2.8			
0290468	KIMBERLEY WO				0.1	0.1	0.2
0300454	LADYSMITH	–0.1	–0.1	0.0			
0304357	MTUNZINI	2.5	3.3	5.2			
0317475	UPINGTON WO				0.4	0.6	0.9
0321110	POSTMASBURG				0.4	0.5	0.8
0331585	BETHLEHEM WO	1.5	2.0	2.8	0.0	0.0	0.0
0333682	VAN REENEN	0.7	1.1	2.2			
0337738	ULUNDI	0.6	0.8	1.3			
0339732	CHARTERS CREEK	0.6	1.0	2.2	–0.1	0.0	0.1
0356880	KATHU				–0.1	–0.1	–0.3
0360453	TAUNG				0.2	0.1	0.1
0362189	BLOEMHOF	–0.7	–0.8	–0.9			
0364300	WELKOM	0.0	0.0	0.0	0.0	0.1	0.3

0365398	KROONSTAD	0.1	0.3	0.6	0.7	1.0	1.4
0370856	NEWCASTLE	–0.4	–0.3	–0.3			
0410175	PONGOLA	0.3	0.5	0.8			
0427083	VAN ZYLSRUS	0.0	0.0	0.0	0.3	0.3	0.5
0438784	VEREENIGING	0.0	0.0	0.0	0.4	0.5	0.7
0441416	STANDERTON	–0.1	0.1	0.5	0.0	0.1	0.0
0472278	LICHTENBURG	–0.5	–0.5	–0.5			
0475879	JHB BOT TUINE	0.2	0.2	0.4	–0.1	–0.2	–0.2
0476399	JOHANNESBURG	0.6	0.9	1.2	0.4	0.4	0.6
0479870	ERMELO WO	–0.1	–0.1	0.1			
0508047	MAFIKENG WO	–0.1	0.0	0.2			
0511399	RUSTENBURG	0.5	0.7	1.0			
0513346	PRETORIA UNISA	–0.3	–0.4	–0.5			
0513385	IRENE WO	0.4	0.5	0.8	0.5	0.6	0.8
0515320	WITBANK	0.3	0.4	0.7			
0548375	PILANESBERG	0.3	0.3	0.7			
0554816	LYDENBURG	1.5	1.9	2.9	0.1	0.0	0.2
0587725	THABAZIMBI	0.1	0.1	0.2	0.2	0.3	0.5
0594626	GRASKOP	–1.5	–1.2	–0.8			
0633882	POTGIETERSRUS	0.0	0.1	0.2	0.2	0.2	0.2
0638081	HOEDSPRUIT	1.0	1.6	3.1			
0674341	ELLISRAS	0.1	0.2	0.2	0.4	0.5	0.6
0675666	MARKEN	1.1	1.7	2.8			
0677802	PIETERSBURG WO				0.1	0.2	0.4
0723664	THOHOYANDOU WO	1.1	1.6	2.4	0.8	0.9	1.3


Positions of Weather Stations
LIMPOPO
GAUTENG
MPUMALANGA
NORTH-WEST
KWAZULU-NATAL
FREE STATE
NORTHERN CAPE
EASTERN CAPE
WESTERN CAPE
Gauteng
PILANESBERG
RUSTENBURG
PRETORIA UNISA
IRENE WO
WITBANK
JHB BOT TUINE
JOHANNESBURG INT WO
VEREENIGING
STANDERTON
CALVINIA WO
Western Cape
LAMBERTSBAAI NORTIER
PORTERVILLE
EXCELSIOR CERES
GEELBEK
LAINGSBURG
MALMESBURY
WORCESTER-AWS
PAARL
ROBBENEILAND
CAPE TOWN WO
STRAND
TYGERHOEK
STILBAAI
HERMANUS
STRUISBAAI