Strong wind climatic zones in South Africa

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Abstract. In this paper South Africa is divided into strong wind climate zones, which indicate the main sources of annual maximum wind gusts. By the analysis of wind gust data of 94 weather stations, which had continuous climate time series of 10 years or longer, six sources, or strong-wind producing mechanisms, could be identified and zoned accordingly. The two primary causes of strong wind gusts are thunderstorm activity and extratropical low pressure systems, which are associated with the passage of cold fronts over the southern African subcontinent. Over the eastern and central interior of South Africa annual maximum wind gusts are usually caused by thunderstorm gust fronts during summer, while in the western and southern interior extratropical cyclones play the most dominant role. Along the coast and adjacent interior annual extreme gusts are usually caused by extratropical cyclones. Four secondary sources of strong winds are the ridging of the quasi-stationary Atlantic and Indian Ocean high pressure systems over the subcontinent, surface troughs to the west in the interior with strong ridging from the east, convergence from the interior towards isolated low pressure systems or deep coastal low pressure systems, and deep surface troughs on the West Coast.

Keywords: strong winds; wind climate; climate zones; South Africa.

1. Introduction

1.1. Background

The Institute of Structural Engineering at Stellenbosch University and the Council for Scientific and Industrial Research (CSIR) are currently involved in the process of developing a set of new generation building design codes for South Africa. The wind climatic information, which is currently incorporated in the design specifications, is based on the statistical analysis of medium/long-term records from a very limited number of wind recording stations, mainly located in large cities (Milford 1985). In view of the size, as well as the climatological diversity of South Africa, this information cannot be deemed to be adequate. This issue, as well as its impact on the design of built-environment, has been raised by Goliger (2005). Therefore, the incorporation of comprehensive and updated information on wind climate is essential, and of great relevance to the construction industry. The South African Weather Service (SAWS), together with the above-mentioned institutions,

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are in the process of determining a comprehensive statistical description of strong wind speeds and directions for South Africa, which will be based mainly on the available data measured by the SAWS. These analyses will form the basis for wind loading requirements in future design codes for the built environment.

The aim of this study is the zoning of the area of interest, in this case South Africa, into geographical regions that indicate the most likely sources of strong winds, particularly the annual maxima of 2-3 second wind gusts. The awareness of different sources or mechanisms of extreme winds is recommended in the subsequent statistical analysis of high wind speeds, as it is an important factor in the selection or development of the most appropriate extreme value distributions to be fitted to the wind data. In mixed strong wind climates, alternative approaches to the traditional Gumbel analysis method to estimate extreme wind speed probabilities are advised. These are based on the premise that data produced by different phenomena should be analysed separately, and then combined into a distribution of mutually exclusive events (Palutikof, *et al.* 1999). Such methods then tend to yield more accurate estimates of annual wind speed maxima, especially for long return periods greater than 50 years. This is usually due to the increased variance of the data of the extremes related to the mechanism of the strongest wind speeds, if compared to the data of annual maxima (Gomes and Vickery 1978; Palutikof, *et al.* 1999; Twisdale and Vickery 1992).

In the past South Africa has been classified into climatic zones by various authors and applying different criteria (Schulze 1947, 1965; Jackson 1951; Kruger 2004). All of these climate regionalisations used the rainfall data as the primary factor in the delineation of the regions. Other climatological factors, such as temperature and humidity, were also considered in some cases. None of the already developed climatic regions consider the prevailing winds as an explicit factor in the delineation of different zones.

The only attempt to divide South Africa into strong wind regions was undertaken by Goliger and Retief (2002), who identified geographic zones where various types of strong wind events are likely to be dominant. The recorded lightning activity, specific documented extreme weather events, the "Lemon Technique" (which serves as an aid to weather forecasters), as well as the knowledge of the relevant SAWS experts were used as the input information. However, no wind climate statistics were taken into account, and the zones, which were identified, were referred to as the "first approximations", based on the limited information utilised in the investigation. Fig. 1 presents the spatial extent of two strong wind types from Goliger and Retief (2002), which they regard as those

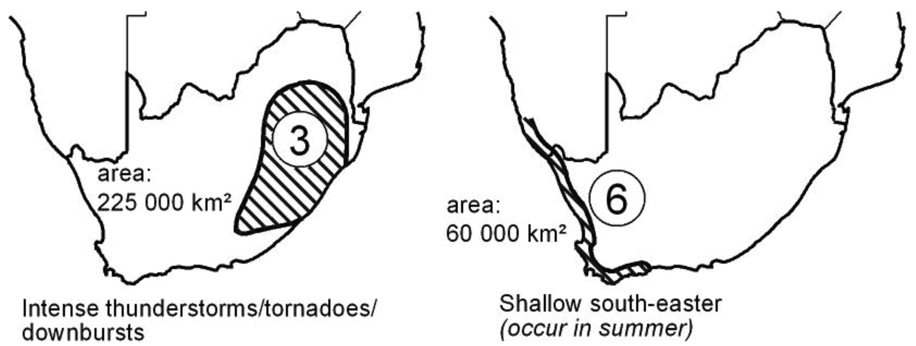

Fig. 1 The spatial extent of two strong wind types, from Goliger and Retief (2002), which they regard as the types that cause the most damage and adverse wind conditions in South Africa

types that cause the most damage and adverse wind conditions in South Africa.

A map of the strong wind climatic zones can be described as a basic diagram indicating the spheres of influence of specific weather systems that are likely to cause strong winds. Therefore, some resemblances between a general climate region and a wind climate region can be found as mean precipitation, temperature, humidity and other climate variables are also, to a large degree, determined by the prevailing weather systems. In this study the emphasis is on the weather systems which have the potential to cause very strong or extreme winds in a specific location, i.e., those climatic formations that are the usual causes of annual maximum wind gusts. In essence, we define a strong wind climatic zone in this study as a geographical area which indicates a type of weather system that has the potential to be the cause of an annual maximum wind gust.

One should keep in mind that regional climatic boundaries are usually indefinite, except where they coincide with prominent physical features, such as mountain ranges, which then should be regarded as zones where the climates sometimes change rapidly from the type shown on the one side to that on the other (Jackson 1951). Therefore, a measure of subjectivity and uncertainty will usually be present in the process of delineation of climatic zones.

1.2. Prevailing macroclimatic conditions

As part of the introduction to the study, background is given here on the prevailing weather systems during different times of the year, with emphasis on the synoptic conditions which are conducive to the development of strong winds. The seasonal differences in the circulation features of the atmosphere, near the surface of southern Africa and the surrounding oceans, are mainly the result of the northward displacement of the subtropical high pressure belt by almost five degrees latitude from summer to winter. Usually these lower-level anticyclones on land are interrupted once to twice per week by cold-front troughs (Taljaard 1995). Therefore, the influences of the subtropical high-pressure belt and the mid-latitude westerlies with associated fronts vary significantly during the course of the year over the subcontinent.

The differences in the circulation features between the seasons, and hence the likelihood of strong winds due to particular circulation features, can be summarised with reference to Hurry and Van Heerden (1987), who gave a detailed overview of the seasonal differences in the atmospheric circulation over southern Africa. From the pressure distribution and basic movement of air masses, the following are noted with regards to the general synoptic circulation pattern in summer time, referring to Fig. 2: The “westerlies”, a band of strong westerly winds surrounding the globe in which extratropical low pressure systems develop, is situated well to the south of the continent. This implies that strong winds forthcoming from extratropical cyclones and their associated cold fronts will mostly be limited to the southern parts of the subcontinent. The Indian Ocean high pressure system is situated more eastward, with frequent strong ridging over the subcontinent, where “ridging” refers to usually strong wind flow spiralling out from a high pressure system. The associated south-eastern Trades (A) influence the north-eastern part of the region. These winds can be strong, curving sometimes from Limpopo Province (L) into the Free State (F), or moving over far northern areas, such as Zimbabwe and Zambia (Z).

The moist air transported into the subcontinent can condense through uplift, e.g., from the topography or convection, with subsequent cloud formation and precipitation, often from thunderstorms which can produce strong wind gusts. The Atlantic high pressure system, which is situated near the west coast, is a source of drier air which moves into the subcontinent from the

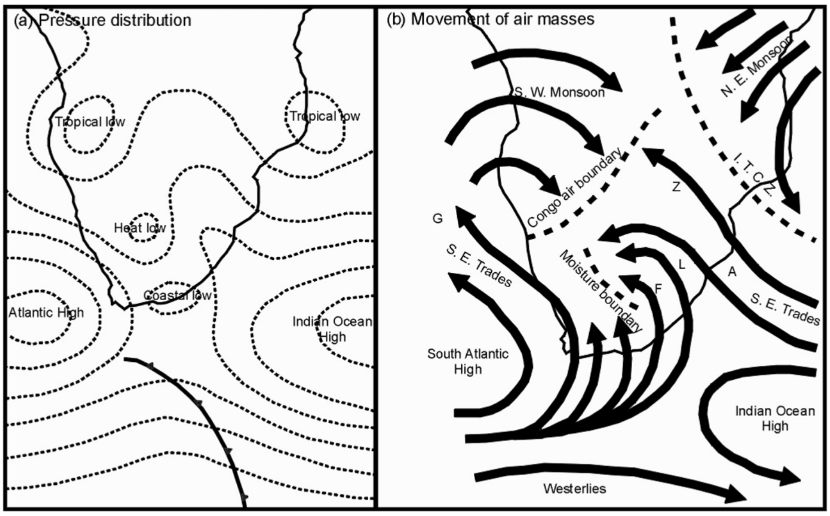

Fig. 2 Features of the pressure distribution (a) and basic movement of air masses (b) over southern Africa during summer (after Hurry and Van Heerden 1987)

Fig. 3 An example of the growth of a tree in the Cape Peninsula in a north-westerly direction, due to persistent strong south-easterly winds

southwest and southeast. The south-easterly wind blows mostly over the Cape Peninsula and is locally known as the “Cape Doctor”, due to its removal of pollutants in the air and possibly also because of the associated unpleasant dryness and gustiness. This wind can be quite persistent, as shown by an example in Fig. 3, of the growth in a north-westerly direction of some trees in this region.

The “moisture boundary” is the area where the moist air from the east and the drier air from the southwest meet. The air from the Indian Ocean tends to move over the Atlantic air, causing uplift and possible thunderstorms. When the moisture boundary is well to the south, widespread thunderstorms are possible. Summer heating causes a heat low to develop in the west or northwest of the subcontinent. The south-eastern Trades from the Atlantic high pressure system (G) sometimes curve around this low, and change to the south-western Monsoon winds. Where these winds meet the south-eastern Trades the air masses converge to form the Congo air boundary, where thunderstorms are likely to develop. The north-eastern Trades from the north-eastern Monsoon system cross the equator, and where they meet the south-eastern Trades, convergence takes place. This convergence area determines the position of the Intertropical Convergence Zone (ITCZ) where heavy rainfall with associated thunderstorms frequently occurs. Usually there is a shallow heat low over the Kalahari Desert, which sometimes influences the direction of the south-eastern Trades.

Therefore, in conclusion to the above discussion, gust fronts from thunderstorm activity are frequent over most of the country in summer, but less so in the southern and western parts. The heating of the earth's surface acts as a trigger for the development of thunderstorms, but additional factors play a role, such as orographic uplift, frontal uplift, and large-scale convergence ahead of a trough (an elongated area of relatively low atmospheric pressure) or east of a low-pressure cell. In addition, line storms can form parallel to trough lines and are associated with strong wind gusts ahead, typically referred to as "line squalls".

From the basic pressure distribution and movement of air masses for winter, presented in Fig. 4, it is observed that all circulation features are situated more to the north than in summer. The south-eastern trade winds still occur, but because the north-eastern Monsoon is absent, no convergence takes place. The ITCZ, as well as the Congo air boundary, move northwards and therefore the likelihood of thunderstorms to occur is diminished.

The "westerlies" influence the weather of the southern and central parts of the subcontinent to a large degree. Therefore, cold fronts, with associated strong winds, often move over these areas and may reach far to the north. Strong winds and gusts during winter are usually caused by strong cold fronts, moving mostly over the southern half of South Africa, and also by the ridging of the high pressure systems behind the fronts. During this time of the year, gale force winds are frequently

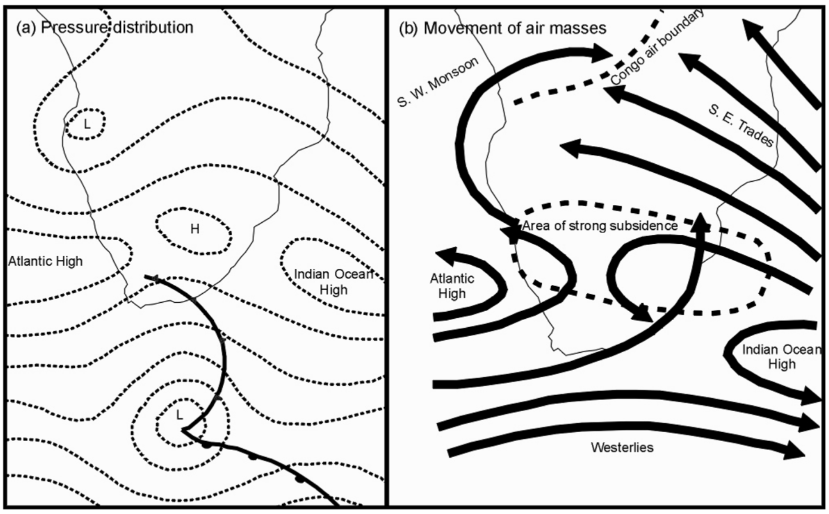

Fig. 4 Features of the pressure distribution (a) and basic movement of air masses (b) over southern Africa during winter (after Hurry and Van Heerden 1987)

experienced over the Cape Peninsula, as well as the southern and south-eastern coasts.

When the Atlantic high pressure system moves more eastwards and stays strong, gale force winds can spread to the KwaZulu-Natal coast as far north as the Mozambique Channel. When the Atlantic high pressure system is situated south of the country, with the associated isobars lying almost parallel latitudinally, strong south-easterly to easterly winds can be experienced along the west coast.

2. Data and methods

2.1. Selection of data

Long-term wind data, the primary input information of this study, was obtained from the SAWS climate databank, which contains most climate records measured in South Africa. A total of 94 automatic weather stations (AWSs) were selected for the analysis, a list of which is presented in the appendix, together with a map of their positions. AWSs measure the weather continuously, and record the measured climate data values at 5-minute intervals. These values are then archived in the SAWS climate databank. The time series, which were selected, had to fulfil the following requirements in terms of the lengths of the record as well as the completeness and the data quality:

· The time series of daily maximum wind gust data should have been at least 10 years long to ensure that a reliable estimation of all possible sources of annual maximum wind gusts could be obtained.

· Each year, of the utilised time series, should contain at least 90% data, taking into consideration which times of the year the annual maximum wind gusts are most likely to occur. As an example, over the interior, where it is expected that annual maximum wind gusts are usually caused by thunderstorm activity, all spring, summer and autumn months had to be complete for a specific year of the data to be utilised for further analyses.

· Time series of wind gust speeds were checked for possible data inhomogeneities by visual inspection of the plots. Any years that indicated abrupt discontinuities in the time series were omitted from further analyses, as these were indicative of either instrument malfunction, calibration errors or problems in the transfer of the data.

· The daily time series, on days that the annual maximum wind gusts were recorded, were plotted to check for possible electronic spikes in the data, which occur from time to time in the data sets forthcoming from automatic weather stations.

It is only since 1995 that the SAWS archives weather measurements in 5-minute intervals. These high resolution data measurements and averaging times are necessary to identify the causes of strong wind gusts with a high confidence. Therefore, for the purpose of this study, data before 1995 could not be considered in most cases. Where data before 1995 was considered, there was sufficient evidence that the occurrence of the particular extreme wind was due to a synoptic scale mechanism.

2.2. Analysis of data

After ensuring that only the near-complete and quality data sets were to be utilised, the different sources of annual maximum wind gust values were identified as follows: the annual maximum 2-3 second wind gust values were identified for each year of the time series. Then 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. An example of such a plot, generated through the SAWS quality control system, is presented in Fig. 5, which shows the 5-minute time series from Cape Town Weather Office for 15 July 2008. On this day the annual maximum wind gust speed of 25,0 m/s for 2008 was recorded at 17:25 South African Standard Time (SAST). From the time series it is apparent that the wind gust was caused by the passage of a cold front, *inter alia* evidenced by north-westerly winds, a significant decrease in temperature, and the onset of rainfall between 17:00 and 18:00 SAST. Evidence of prevailing weather systems, identified from synoptic charts published in the SAWS Daily Weather Bulletin (South African Weather Service 1993-2008), were used to confirm the strong-wind producing mechanisms identified from the plots of the 5-minute time series. The synoptic chart for southern Africa for 15 July 2008 at 14:00 SAST is presented in Fig. 6, from which one can see that a cold front was approaching the south-western Cape from the west.

The above procedure was sufficient to identify all sources of wind gusts which were caused by synoptic scale phenomena, such as cold fronts, ridging of high pressure systems and convergence towards troughs or isolated low pressure systems. However, evidence of meso-scale phenomena, such as thunderstorms, cannot be easily gained from synoptic charts. Therefore, where it was suspected that a particular wind gust was caused by, e.g., a thunderstorm; mostly evidence from the 5-minute time series plots was used for the purpose of identification. An example of a typical 5-minute time series plot which shows evidence of a strong wind gust caused by thunderstorm activity is presented in Fig. 7. The plot, for 27 December 2004, shows the annual maximum wind gust at

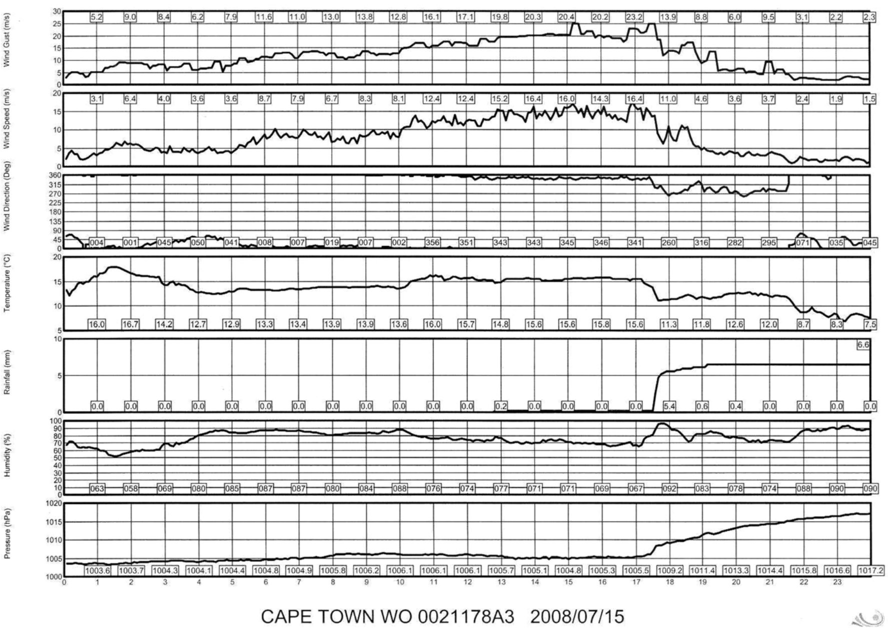

Fig. 5 Plots of the 5-minute time series recorded at Cape Town Weather Office for 15 July 2008 for, from top to bottom: maximum wind gust, mean wind speed, mean wind direction, surface temperature, rainfall, relative humidity and surface pressure. The numbers at the foot of each graph represent the values recorded on the hour

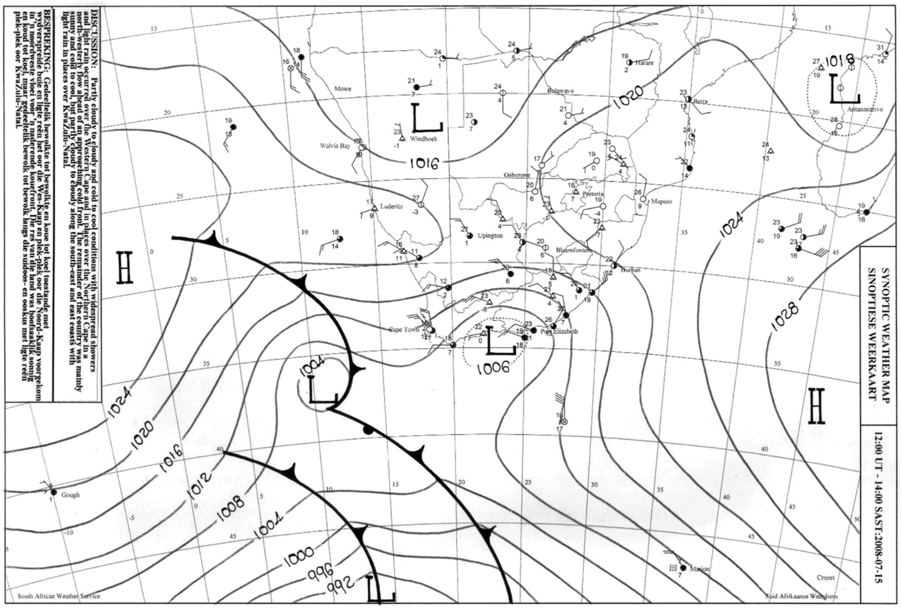

Fig. 6 Synoptic chart for southern Africa for 15 July 2008 at 14:00 SAST (South African Weather Service 1993-2008)

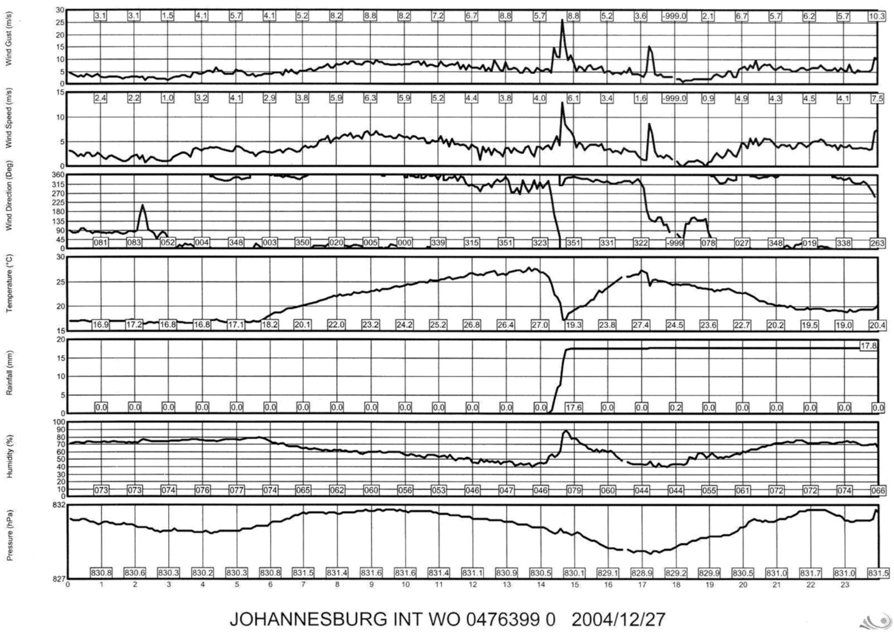

Fig. 7 Plots of the 5-minute time series measured at Johannesburg Weather Office for 27 December 2004 for, from top to bottom: maximum wind gust, mean wind speed, mean wind direction, surface temperature, rainfall, relative humidity and surface pressure. The numbers at the foot of each graph represent the values recorded on the hour

14:40 SAST in Johannesburg, when a wind speed of 26,3 m/s was recorded. The strongest winds forthcoming from thunderstorms are usually caused by the “gust front”, the leading edge of the downdraft of cold air from the thunderstorm cloud. These gust fronts are associated with strong wind gusts, sharp drops in temperature, and usually but not always increases in humidity and onsets of rain. In many cases a slight increase in air pressure can also be recognised. All of these signs can be observed in Fig. 7. In cases in which the evidence of gust fronts was not as clear as in this typical example, evidence was sought from synoptic charts, to ascertain whether surface pressure patterns were conducive to the development of thunderstorms, such as a well-developed surface trough to the immediate west. In addition, manned weather offices do reports of observed weather. These reports are stored on the SAWS climate database and were interrogated for any evidence of thunderstorms on the day that the annual maximum gust occurred.

However, the possibility exists that on some occasions thunderstorms are imbedded in cold fronts, which makes it impossible to ascertain whether the wind gust under investigation was mainly caused by the cold front or thunderstorms. In these cases cold fronts were assumed as being the primary strong-wind producing mechanism. One should also note that, in cases where thunderstorms are embedded in the frontal zones, the wind profiles are usually similar to the wind profiles of passages of cold fronts without imbedded thunderstorms. Due to these similar wind profiles, there should then not be any significant implications for the analysis, of the winds so grouped.

Eventually all causes of annual maximum wind gusts were listed for each weather station. Some examples are presented in Table 1, in which the values, as well as the causes, of each annual

Table 1. Annual maximum wind gusts speeds (m/s) recorded at Cape Town (a), Grahamstown (b), De Aar (c), and Johannesburg (d) and their causes, for the available years for the period 1993 – 2008 (CF: Cold Front, R: Ridging, R/T: Ridging from the east with a deep trough to the west, TS: Thunderstorm).

Year	(a) Cape Town		(b) Grahamstown		(c) De Aar		(d) Johannesburg	
	Wind Gust (m/s)	Cause	Wind Gust (m/s)	Cause	Wind Gust (m/s)	Cause	Wind Gust (m/s)	Cause
1993	30.5	CF	-	-	-	-	-	-
1994	35.5	CF	-	-	32.4	TS	21.0	CF
1995	28.5	CF	22.4	CF	32.1	TS	26.5	TS
1996	33.4	CF	27.6	CF	29.3	R/T	23.0	TS
1997	35.5	CF	19.7	CF	29.7	R/T	26.5	TS
1998	26.2	R	28.7	TS	33.0	TS	24.0	TS
1999	25.2	R	24.7	CF	30.7	TS	19.5	CF
2000	23.6	CF	22.3	CF	35.7	TS	22.5	TS
2001	28.9	CF	21.2	CF	34.7	TS	22.1	TS
2002	25.2	CF	28.7	CF	31.6	TS	23.2	TS
2003	26.2	CF	28.6	TS	30.8	TS	23.0	TS
2004	21.6	R	22.7	CF	31.8	TS	26.3	TS
2005	25.2	CF	22.3	TS	29.8	TS	29.4	TS
2006	23.7	CF	26.9	CF	29.4	TS	23.1	TS
2007	28.8	CF	22.9	CF	40.2	TS	-	-
2008	25.0	CF	24.4	CF	32.0	TS	34.1	TS

maximum wind gust recorded at Cape Town in the Cape Peninsula, Grahamstown in the south-eastern interior, De Aar in the central interior, and Johannesburg in the northern interior, are shown. The main causes of the annual maximum wind gusts in Cape Town are the passage of cold fronts (13 out of 16 years, or 81%), and the ridging of the Atlantic Ocean High pressure systems, i.e., strong south-easterly winds (three out of 16 years, or 19%); contrary to a general belief that most strong winds in Cape Town are south-easterly. At Grahamstown the main cause of annual maximum wind gusts are cold fronts (11 out of 14 years, or 79%) and thunderstorms (three out of 14 years, or 21%). At De Aar the main cause of annual maximum wind gusts are thunderstorms (13 out of 15 years, or 87%) with, as a secondary cause, a synoptic situation which is characterized by ridging from the east with a deep surface trough to the west (two out of 15 years, or 13%). In Johannesburg most of the annual maximum wind gusts are caused by thunderstorms (12 out of 14 years, or 86%) with, as a secondary cause, the passage of cold fronts (two out of 14 years, or 14%). The determinations of the causes of annual maximum wind gusts, as well as corresponding percentages of years of occurrence, were done for all weather stations utilised in the study, with results as presented in the appendix.

2.3. Infrequent meteorological events

It is feasible that a specific site, where the wind has been measured over a long period of time, is situated in an area where it is possible for extreme but infrequent meteorological events, such as tornadoes, downbursts or tropical cyclones, to occur. Due to the limited spatial extent of some of these events, it is most likely that the related extreme magnitude winds affecting small areas have never been recorded. Furthermore, in the case of tornadoes winds are so strong that it is impossible to measure them directly, and information about their spatial distribution, frequency and strength can therefore only be inferred from a statistical analysis of the related wind damage reports. The detailed description and information on occurrences of these events, as well as their effects on the design wind speed, were done by Goliger, *et al.* (1997).

A total of seven cyclones affected the eastern parts of South Africa in a 43-year period, from 1962 to 2005 (South African Weather Service 2005). One should note, however, that no weather station in South Africa has ever recorded extreme wind speeds which were caused directly by a tropical cyclone. Thus we conclude, with the limited information available, that there is a risk of hurricane-strength winds to occur over the eastern coastal belt of South Africa, due to the landfall of tropical cyclones, mostly forthcoming from the Mozambique Channel.

No detailed analysis can be undertaken to accurately determine the likelihood of downbursts and micro bursts to occur, and their frequency in South Africa is unknown. Because they are typically associated with the intense thunderstorms it is sufficient to accept that they develop over the eastern parts of South Africa, and similarly to tornadoes, are also more likely to occur in the particular regions identified by Goliger, *et al.* (1997).

3. Results and discussion

The climatological analysis of the measured wind data produced six sources of annual maximum wind gust values. The fractions of annual maximum wind gusts caused by these sources are presented in the maps in Fig. 8(a-c), for each station utilised in the study (see the appendix for full

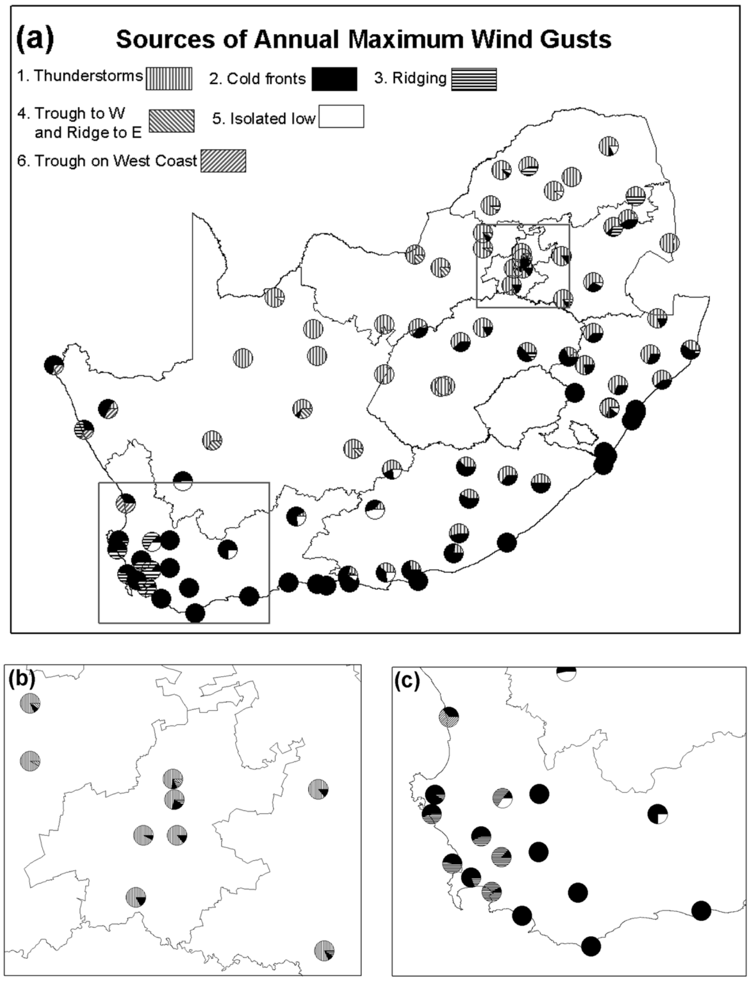

Fig. 8 Fractions of annual maximum wind gusts caused by six identified sources, for each station utilised in the study (a). The blocks indicate the positions of the enlargements for Gauteng province in the north (b) and Western Cape Province in the south-west (c)

list of results). For most weather stations more than one source of annual extreme wind gusts were found. Therefore, the different strong wind zones that were derived from this information overlap. These zones are depicted on separate maps, which are presented in Fig. 9(a-f). Following are the descriptions of these sources, ordered in approximate level of dominance:

1. Thunderstorms:

   Most annual maximum wind gusts in the interior are caused by thunderstorm activity during the summer months. This is especially true in the central interior where annual maximum wind gusts at many weather stations were solely caused by thunderstorms (10% of the total number of stations). The strongest gusts from thunderstorms are usually recorded during the passages of "gust fronts" over the weather station, which in turn usually precedes the first rainfall from the thunderstorm cell. Fig. 9(a) presents the area in the interior where annual maximum gust speeds can occur due to thunderstorms.

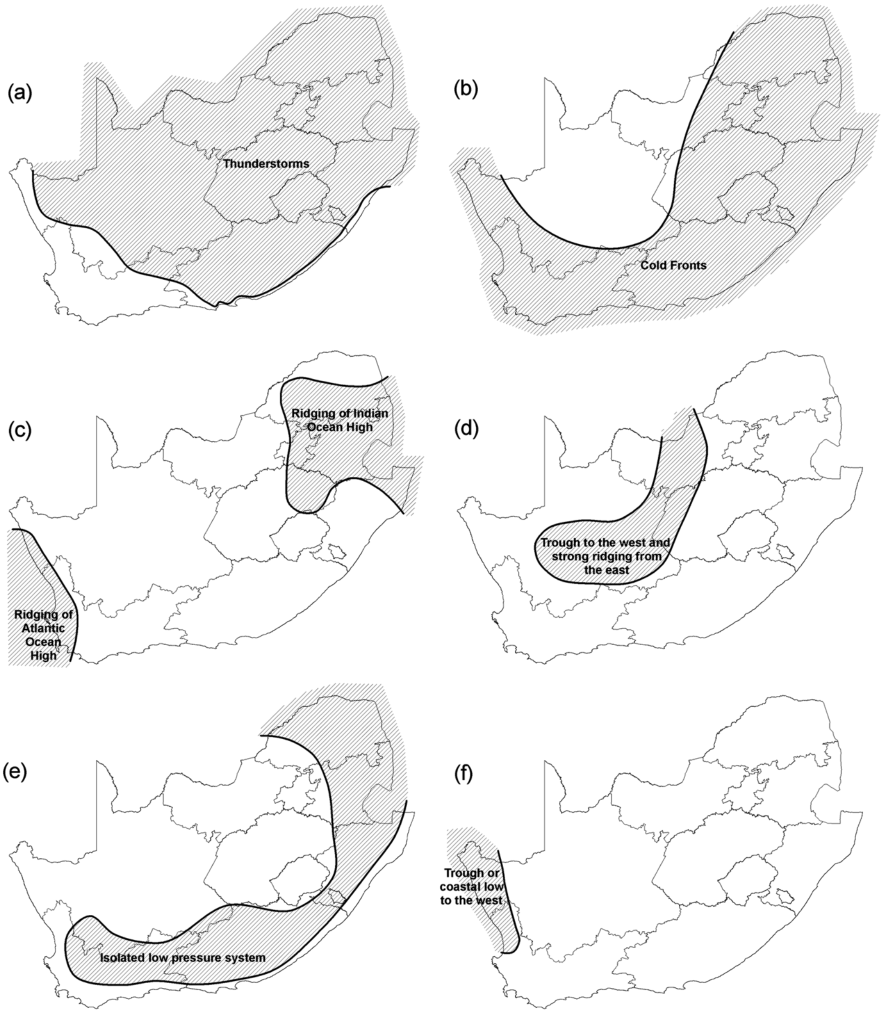

Fig. 9 Zones with extreme winds possible as a result of thunderstorms (a), cold fronts (b), ridging of the Atlantic or Indian Ocean high pressure systems (c), a surface trough to the west and strong ridging from the east (d), convergence towards isolated low pressure systems or deep coastal low pressure systems on the coast (e), and a deep surface trough to the west on the West Coast (f). Shading which extends over South Africa's borders indicates that the influence of the particular mechanism probably extend beyond the border or coastline

2. Cold fronts:
   Most annual maximum gusts along the coastline and adjacent interior are caused by the passage of cold fronts. It should be noted that along the western and southern coasts strongest winds mostly occur in the vicinity of the actual front. However, along the south-eastern and eastern coasts the winds are usually strongest just behind the coastal low pressure system preceding the front. Finally, in the central to northern interior strong wind gusts usually occur well east of the actual fronts, which move in from the west, and are also associated with deep coastal low pressure systems on the south-eastern and eastern coasts. This results in a strong flow of the air

towards the east. It is also along the coast and adjacent interior where the annual maximum wind gusts of many stations were caused by only cold fronts (19% of the total). The spatial extent of the annual maximum wind gusts, occurring as a result of the extratropical cyclones, i.e., the passage of cold fronts, is presented in Fig. 9(b).

3. Ridging of the quasi-stationary Atlantic and Indian Ocean high pressure systems over the subcontinent:
   The annual maximum wind gusts caused by the ridging of the Atlantic Ocean high pressure system are evident along the western and south-western Cape coasts and adjacent interior. This ridging is strongest during the summer months, and as previously mentioned, the associated wind in the south-western Cape is locally known as the “Cape Doctor”. Ridging in the eastern interior is associated with either the Atlantic Ocean high pressure system ridging around the coast from west to east behind a cold front, or the Indian Ocean high pressure system to the east of the subcontinent. Fig. 9(c) presents the areas experiencing extreme winds as a result of the ridging of the Atlantic Ocean and Indian Ocean high pressure systems.
4. A synoptic situation in the central interior, characterised by a deep surface trough which is situated to the west, and ridging of the Atlantic or Indian Ocean high pressure systems from the east:
   Some annual maximum wind gusts in the central and western interior occur just east of deep surface troughs, usually together with strong ridging by the Indian Ocean high pressure system from the east. These synoptic conditions are usually conducive to the development of thunderstorms due to convergence. However, sometimes the necessary moisture is not available so that the only effect is the occurrence of strong, gusty and dry winds. Fig. 9(d) presents the area in the southern to central interior where extreme wind gusts due to these conditions are likely to occur.
5. Strong isolated low pressure systems, also including unusually strong coastal low pressure systems:
   Often synoptic situations occur when strong isolated low pressure systems develop, usually along the coast but also sometimes in the interior. Occurrences of the annual maximum wind gusts due to the convergence around isolated low pressure systems, as well as around very deep coastal low pressure systems ahead of a cold front (where the strong low pressure system is considered to be the overwhelming cause of the strong winds occurring), were grouped together. A significant fraction of annual maximum wind gusts at some weather stations in the south-western and southern interior are caused by these weather systems, but other cases were also identified for weather stations along the escarpment towards the north. Therefore, while isolated low pressure systems tend to be the cause of a sizeable number of annual maximum wind gusts in the south, these systems can also cause extreme winds elsewhere, of which the area is presented in Fig. 9(e). Notable from Fig. 9(e) is that the area close to the coast under the influence of isolated low pressure systems does not include the coastline itself. This is because strong winds, which are caused by these systems, occur due to a strong horizontal pressure gradient towards the low pressure system. Such isolated low pressure systems are most often situated very close or on the coastline itself.
6. A synoptic situation on the west coast and adjacent interior, characterised by a coastal low, but sometimes a deep surface trough, developing ahead of the passage of a cold front:
   Along the west coast and adjacent interior, annual maximum wind gusts are sometimes caused by convergence towards a deep trough to the west, which is associated with the occurrence or development of a coastal low pressure system ahead of the passage of a cold front. Fig. 9(f) presents the area that can experience extreme wind conditions while under the influence of these synoptic conditions.

It is only the first two dominant strong-wind producing mechanisms (thunderstorms and extratropical cyclones) which are, for many weather stations, the sole causes of annual maximum wind gusts. The weather stations where thunderstorms and extratropical cyclones are respectively the only causes of annual extreme wind gusts make up 23% of the total number of stations. For 52% of the stations the only causes of strong winds are either thunderstorms, extratropical cyclones, or both. At the remaining 48% of stations the other four strong-wind producing mechanisms also play a role, which are for most of these weather stations of a secondary nature. The percentage of weather stations where three or more mechanisms are the causes of strong winds is 23%.

The secondary strong-wind producing mechanisms are associated with synoptic scale processes, often of a frontal origin. Together with winds directly attributed to the passages of cold fronts, these strong winds are usually more persistent in nature due to the relatively slow changes of synoptic-scale flow patterns. This is in contrast to strong winds produced by thunderstorms, which in many cases may last only a few minutes. Therefore, for some applications e.g. the statistical modelling for wind load predictions, a broad differentiation can be made between strong winds attributed to thunderstorms, and strong winds caused by the remainder of the mechanisms. In this regard the specific methodologies applied in the application of mixed distributions are important, where in some cases broad groupings into only synoptic and non-synoptic origins are recommended.

4. Conclusions

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 the climatology of strong wind zones for South Africa. The strong wind climate of South Africa appears to show similarities with southern South America (e.g. Argentina, Ponte and Riera 2007) and Australia (Holmes 2002; Oliver, *et al.* 2000). Six strong-wind producing mechanisms were identified by classifying the causes of annual maximum wind gust speeds. Two of those mechanisms, namely thunderstorms and extratropical cyclones (the passage of cold fronts) are dominant, while the other four mechanisms are of a secondary importance.

The geographic distribution of strong wind climates was established, and is in general agreement with the strong wind zones developed by Goliger and Retief (2002). As examples, Fig. 1 (zone 6) and Fig. 9(c) show strong overlapping between the regions that indicate strong south-easterlies and ridging, which refer to the same strong-wind mechanism. Fig. 1 (zone 3) indicates the zone for the intense thunderstorms, which is almost covered by the area depicted in Fig. 9(a), except for the coastal region. This is due to the fact, which was referred to in the analysis section, that thunderstorms that occur over the coastal parts are usually embedded in cold fronts, and therefore reveal a similar wind profile.

It is shown that in most parts of South Africa the derived strong wind zones overlap. This is especially true for the two dominant strong-wind producing mechanisms, i.e., the extratropical cyclones and thunderstorms. Where these two mechanisms dominate in a particular region, strong winds produced by extratropical cyclones usually occur during the winter months, while strong winds from thunderstorms occur during the summer season. There are only two regions in South Africa where the annual maximum wind gusts are associated with only one type of strong-wind producing mechanism, while the other mechanisms are of a secondary nature. For the south-western, southern, south-eastern and eastern coasts as well as their immediate adjacent interior, the annual maximum gusts are only caused by extratropical cyclones. On the other hand, parts of the central and far northern interior are dominated exclusively by thunderstorms.

When considering the entire country, some of these secondary mechanisms still tend to dominate regionally. Examples of these are the south-easterly winds in the south-western Cape, caused by the ridging of the Atlantic Ocean high pressure system, and the strong winds produced by deep troughs or strong coastal lows on the West Coast, where their influences dominate over isolated areas.

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, if the wind values used to determine the shape of the extreme values distributions are forthcoming from more than one source (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 is therefore recommended 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 design of structures that should have very low probabilities of failure.

Also, the footprints of the different strong wind producing mechanisms differ. In the case of strong winds produced by thunderstorms, the footprints of areas subject to strong or extreme winds tend to be much smaller than for example cold fronts, of which the footprint can be hundreds of kilometres. These larger footprints have ramifications for the risk analysis of structures such as transmission line networks which cover a sizable area.

References

Goliger, A.M., Milford, R.V., Adam, B.F. and Edwards, M. (1997), *Inkanyamba: tornadoes in South Africa*, Joint Publication of the CSIR and SAWB, Pretoria.

Goliger, A.M. and Retief, J.V. (2002), "Identification of zones of strong wind events in South Africa", *J. Wind Eng. Ind. Aerod.*, **90**, 1227-1235.

Goliger, A.M. (2005), "South African wind climate and its implications on the design of large stadia for the 2010 Fifa soccer event", *Proc. of the 6th Asia-Pacific Conf. on Wind Engineering (APCWE VI)*, Seoul, Korea, September 2005.

Gomes, L. and Vickery, B.J. (1978), "Extreme Wind Speeds in Mixed Wind Climates", *J. Ind. Aerod.*, **2**, 331-344.

Holmes, J.D. (2002), "A re-analysis of recorded extreme wind speeds in Region A", *Aust. J. Struct. Eng.*, **4**, 29-40.

Hurry, L. and Van Heerden, J. (1987), *Southern Africa's Weather Patterns. A guide to the interpretation of synoptic maps*, Via Afrika Ltd., Goodwood, Cape Town, South Africa.

Jackson, S.P. (1951), "Climates of Southern Africa", *S. Afr. Geogr. J.*, **33**, 17-37.

Kruger, A.C. (2004), *Climate of South Africa. Climate Regions. WS45*, South African Weather Service, Pretoria, South Africa.

Milford, R.V. (1985), *Extreme value analysis of South African gust speed data*, Unpublished Internal Report 85/4, Structural and Geotechnical Engineering Division, National Building Research Institute, CSIR, Pretoria, South Africa.

Oliver, S.J., Moriarty, W.W. and Holmes, J.D. (2000), "A risk model for design of transmission line systems against thunderstorm downburst winds", *Eng. Struct.*, **22**, 1173-1179.

Palutikof, J.P., Brabson, B.B., Lister, D.H. and Adcock, S.T. (1999), "A review of methods to calculate extreme wind speeds", *Meteorol. Appl.*, **6**, 119-132.

Ponte, J. and Riera, J.D. (2007), "Wind velocity field during thunderstorms", *Wind Struct.*, **10**, 287-300.

Schulze, B.R. (1947), “The climates of South Africa according to the classifications of Köppen and Thornthwaite”, *S. Afr. Geogr. J.*, **29**, 32-42.

Schulze, B.R. (1965), *Climate of South Africa. Part 8. General Survey, WB 28*, South African Weather Bureau, Pretoria, South Africa.

South African Weather Service (1993-2008), *Daily Weather Bulletin*, South African Weather Service, Pretoria, South Africa.

South African Weather Service (2005), *CAELUM*, South African Weather Service, Pretoria, South Africa.

Taljaard, J.J. (1995), *Technical Report No 30 - Atmospheric Circulation Systems, Synoptic Climatology and Weather Phenomena of South Africa - Part 4: Surface Pressure and Wind Phenomena in South Africa*, South African Weather Bureau, Pretoria, South Africa.

Twisdale, L.A. and Vickery, P.J. (1992), “Research on Thunderstorm Wind Design Parameters”, *J. Wind Eng. Ind. Aerod.*, **41-44**, 545-556.

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Appendix

List of stations utilised in the study in order of SAWS station number. Columns with captions TS to LP indicate percentages of annual maximum wind gusts caused by the six identified sources (TS: thunderstorms, CF: Cold fronts, R: Ridging, T: Trough to the west with strong ridging from the east, TW: Trough on the West Coast, LP: Isolated low pressure systems). The geographical coordinates are presented in decimal degrees.

Station Number	Station Name	Latitude (ºS)	Longitude (ºE)	TS	CF	R	T	TW	LP
0003108	STRUISBAAI	34.80	20.06		100				
0005609	STRAND	34.14	18.85		8	92			
0006386	HERMANUS	34.43	19.22		100				
0007699	TYGERHOEK	34.15	19.90		100				
0010682	STILBAAI	34.37	21.40		100				
0012661	GEORGE WO	34.02	22.38		100				
0014123	KNYSNA	34.06	23.09		100				
0014545	PLETTENBERGBAAI	34.09	23.33		100				
0015692	TSITSIKAMMA	34.03	23.91		100				
0020618	ROBBENEILAND	33.80	18.37		47	53			
0021178	CAPE TOWN WO	33.97	18.60		81	19			
0021823	PAARL	33.72	18.97		13	87			
0022729	WORCESTER-AWS	33.66	19.42		100				
0031650	JOUBERTINA AWS	33.84	23.86	20	70				10
0033556	PATENSIE	33.77	24.82	38	38				24
0034763	UITENHAGE	33.71	25.44	27	73				
0035209	PORT ELIZABETH	33.98	25.61		100				
0040192	GEELBEK	33.20	18.12		55	45			
0041388	MALMESBURY	33.47	18.72		57	43			
0041841	PORTERVILLE	33.01	18.98		13	53			34
0045642	LAINGSBURG	33.20	20.87		75				25
0056917	GRAHAMSTOWN	33.29	26.50	21	79				
0059572	EAST LONDON WO	33.03	27.83		100				
0061298	LANGEBAANWEG	32.97	18.16		91	9			
0063807	EXCELSIOR CERES	32.96	19.43		100				
0078227	FORT BEAUFORT	32.79	26.63	55	45				
0083572	LAMBERTSBAAI	32.03	18.33		36			64	
0092081	BEAUFORT-WES	32.36	22.58	8	69				23
0096072	GRAAFF - REINET	32.19	24.54	15	38				47
0123685	QUEENSTOWN	31.92	26.88	42	58				

Station Number	Station Name	Latitude (ºS)	Longitude (ºE)	TS	CF	R	T	TW	LP
0127272	UMTATA WO	31.53	28.67	50	50				
0134479	CALVINIA WO	31.48	19.76		53				47
0144791	NOUPOORT	31.19	24.97	57	21				22
0148517	JAMESTOWN	31.12	26.81	38	62				
0150620	ELLIOT	31.34	27.85	64	36				
0155394	PORT EDWARD	31.07	30.23		100				
0169880	DE AAR WO	30.67	24.00	86			14		
0182465	PADDOCK	30.75	30.26	7	80				13
0182591	MARGATE	30.85	30.33		100				
0184491	KOINGNAAS	30.20	17.29		27	40		33	
0190868	BRANDVLEI	30.47	20.48	67			33		
0214700	SPRINGBOK WO	29.67	17.89	15	54			31	
0224400	PRIESKA	29.67	22.73	62	8		30		
0239698	PIETERMARITZBURG	29.63	30.40	69	23				8
0239699	ORIBI AIRPORT	29.65	30.40	78	11				11
0240808	DURBAN WO	29.97	30.95		100				
0241072	MT EDGECOMBE	29.70	31.05		100				
0241076	VIRGINIA	29.77	31.05		100				
0261307	BLOEMFONTEIN	29.12	26.18	100					
0261516	BLOEMFONTEIN WO	29.10	26.30	100					
0268016	GAINTS CASTLE	29.27	29.52		100				
0270155	GREYTOWN	29.08	30.60	69	31				
0274034	ALEXANDERBAAI	28.57	16.54		72			28	
0290468	KIMBERLEY WO	28.80	24.77	100					
0300454	LADYSMITH	28.57	29.77	77	23				
0304357	MTUNZINI	28.95	31.70	62	38				
0317475	UPINGTON WO	28.41	21.26	100					
0321110	POSTMASBURG	28.35	23.09	100					
0331585	BETHLEHEM WO	28.25	28.33	38	46	16			
0333682	VAN REENEN	28.37	29.38	33	67				
0337738	ULUNDI	28.30	31.42	70	30				
0339732	CHARTERS CREEK	28.20	32.42	40	50	10			
0356880	KATHU	27.67	23.01	100					
0360453	TAUNG	27.55	24.77	100					
0362189	BLOEMHOF	27.65	25.62	64	36				
0364300	WELKOM	27.99	26.67	62	38				
0365398	KROONSTAD	27.63	27.23	83	17				

Station Number	Station Name	Latitude (°S)	Longitude (°E)	TS	CF	R	T	TW	LP
0370856	NEWCASTLE	27.77	29.98	64	36				
0410175	PONGOLA	27.41	31.59	80	20				
0427083	VAN ZYLSRUS	26.88	22.05	92					8
0438784	VEREENIGING	26.57	27.95	83	17				
0441416	STANDERTON	26.93	29.23	82	9	9			
0472278	LICHTENBURG	26.13	26.17	77			23		
0475879	JHB BOT TUINE	26.15	28.00	92	8				
0476399	JOHANNESBURG	26.15	28.23	86	14				
0479870	ERMELO WO	26.50	29.98	64	29				7
0508047	MAFIKENG WO	25.81	25.54	75			25		
0511399	RUSTENBURG	25.65	27.23	92			8		
0513346	PRETORIA UNISA	25.77	28.20	73	9	9	9		
0513385	IRENE WO	25.91	28.21	71	21	8			
0515320	WITBANK	25.84	29.19	86	14				
0520691	KOMATIDRAAI	25.52	31.90	100					
0548375	PILANESBERG	25.26	27.23	82	9		9		
0554816	LYDENBURG	25.11	30.48	62	9	29			
0587725	THABAZIMBI	24.58	27.42	90		10			
0594626	GRASKOP AWS	24.93	30.85	60	40				
0633882	POTGIETERSRUS	24.21	29.01	90					10
0638081	HOEDSPRUIT	24.35	31.05	50		50			
0674341	ELLISRAS	23.68	27.70	86	7				7
0675666	MARKEN	23.60	28.38	58		42			
0677802	PIETERSBURG WO	23.87	29.45	100					
0723664	THOHOYANDOU WO	23.09	30.38	75	8				17