Regional Weather and Climate of South Africa: Gauteng

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1. Introduction

This publication provides a broad overview of the climate and weather of Gauteng Province, the first in a series of regional weather and climate publications for South Africa. The series commences with Gauteng Province as it is the most populous of the nine provinces of South Africa and the main economic hub of the country.

While a thorough needs analysis has been done to explore the possible content to include in the publication, the eventual topics broadly follows those included in the series of SAWS publications that provide overviews of the South African climate, and are mainly divided into a range of common weather parameters. The first of these publications were completed in 2002 on surface winds and covered the whole country. The publications that followed were developed according to the same principle, with the last one, published in 2008, on surface temperature. The above publication series covered their individual topics in detail and it was envisaged in the planning phase that the regional climate publications will at least cover most of the relevant aspects of the climate included in this series. In addition to the above publications a range of additional content that could potentially be included in the new publication was identified from a desktop analysis of international publications. Thereafter the proposed content was arranged into a coherent structure.

Note: References to more information or for some of the information and maps used in this publication can be sourced from the mentioned SAWS publication series. Therefore no specific references to the various publications are made.

In this introductory chapter the factors influencing the weather and climate are presented, how the province is situated in relation to the diverse climate regions of South Africa and the differences in weather experienced on a seasonal basis.

The subsequent chapters provide overviews of the wind, temperature, sunshine and cloudiness, precipitation and finally the impacts of global climate change on the weather and climate of the province.

1.1 Climate controls

The factors controlling the weather and climate at a specific location are mainly the following:

- Latitude, which determines the amount of solar radiation received at the top of the atmosphere at a specific time of the year.
- Position, relative to the distribution of land and sea.
- Topography, for example altitude above sea level.

Other factors, secondary to the above, are:

- The general circulation of the atmosphere.
- Sea-surface temperatures, which can be subdivided into the influence of the currents around the coasts, and the influence from further afield e.g. El Niño/La Niña, which originates in the Pacific Ocean and influences from the central Indian Ocean which is regarded as the major moisture source for South African rainfall.
- The nature of the underlying surface (soil type, moisture content, ground cover etc.).

South Africa falls more or less between 22 to 35ºS and 16 to 33ºE. The amount of direct short-wave solar radiation reaching the top of the atmosphere is mainly dependent on latitude. The amount of solar radiation received on average, decreases with an increase in latitude, although, due to the relative northward and southward orientation of the sun, seasonal variations exist. Because Gauteng Province is situated in the north of the country, this is one of the factors which determines that the province receives generally above average amounts of solar radiation or sunshine if compared with the rest of the country (the other factor is cloudiness, of which the province experiences average amounts compared to the rest of the country).

The distribution of land and sea plays a primary role in the climate of South Africa (and therefore Gauteng) in several ways, namely its position in the Southern Hemisphere, which has a surface comprised of 81 percent water and the position of the country relative to other continents. Due to the relatively large percentage of water covering the surface of the Southern Hemisphere, the climate seems to be more moderate than in the Northern Hemisphere. In the lower latitudes the distribution between land and sea seems to be equal for both hemispheres but land coverage decreases in the Southern Hemisphere as one moves toward the poles, while the opposite hemisphere shows an increase. At the poles the distribution is the opposite as Antarctica is a land mass compared to the area around the North Pole, which comprises the Arctic Ocean, although both regions are covered in ice throughout the year. The positions of the continents relative to each other determine in turn the relative sizes of the oceans in the Southern Hemisphere. These sizes is in the proportion 2: 3: 5 for the South Atlantic, South Indian and South Pacific Oceans respectively. The unequal sizes of the oceans have a bearing on the locations and movements of the tropical and subtropical weather systems.

Regarding the topography, the fact that the region is moderately elevated at a height of generally more than 1000 m above sea level and reaching heights of above 1500 m above sea level over extensive areas, is the most significant influence of the climate of the province. Therefore a continental-type of climate prevails with relatively high summer maximum temperatures and low winter minimum temperatures, often below freezing point.

The distribution of land and sea and the character of the land masses can be considered to be the main cause of the complexity of the atmospheric motions as we know it. The tropics are the main source of atmospheric heat and moisture. The atmospheric pressure fields are the cause of the climate as well as the driving force of the weather from day to day. At the surface there are high pressure cells which are semi-permanent in character. They stay more or less in the same positions with the South Atlantic Anticyclone and the South Indian Anticyclone mostly on either side of the southern African subcontinent. These anticyclones plays the dominant role in the atmospheric circulation and thus the weather and climate of South Africa. Interspersed between the high pressure cells and slightly further north are low pressure areas, while to the south the area of westerly winds prevails.

Figure 1(a and b) and the discussion thereof, from Hurry and van Heerden (1986), consider the features that can usually be expected to be present in the summer circulation as well as the basic movement of air masses over the subcontinent respectively. The following can be seen:

- The westerlies blow well to the south of the continent.
- The Indian Ocean High is situated more eastward. The winds from this high pick up moisture as they move towards the continent, with a subsequent influx of humid air from the east.
- The south-eastern Trades (A) influence the north-eastern part of the region. These winds transport moisture into the subcontinent, curving sometimes from the Northern Province (N) 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 through uplift e.g. from the topography or convection, condensate, with subsequent cloud formation and precipitation.

- The Atlantic High is situated near the west coast, is a source of drier air which moves into the subcontinent from the south-west. The "Moisture boundary" is the area where the moist air from the east and the drier air from the south-west meet.
- Because the air from the Atlantic is cooler and drier, the air from the Indian Ocean tends to move over the Atlantic air, causing uplift and possible precipitation. When the moisture boundary is well to the south, widespread rains are possible.
- If the Atlantic High is further south, winds tend to blow more parallel to the coast and pick up more moisture as it moves along. Rain is then possible over the south-eastern parts.
- Summer heating causes a heat low to develop in the west or north-west of the subcontinent. The south-eastern trades from the Atlantic High 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.
- The north-east 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 ITCZ previously discussed in section 7.
- Usually there is a shallow heat low over the Kalahari desert. This system sometimes influences the direction of the south-eastern trades.
- Coastal lows may either cause cloudy, rainy conditions along the east and south coasts or overcast conditions with fog and mist along the west coast.

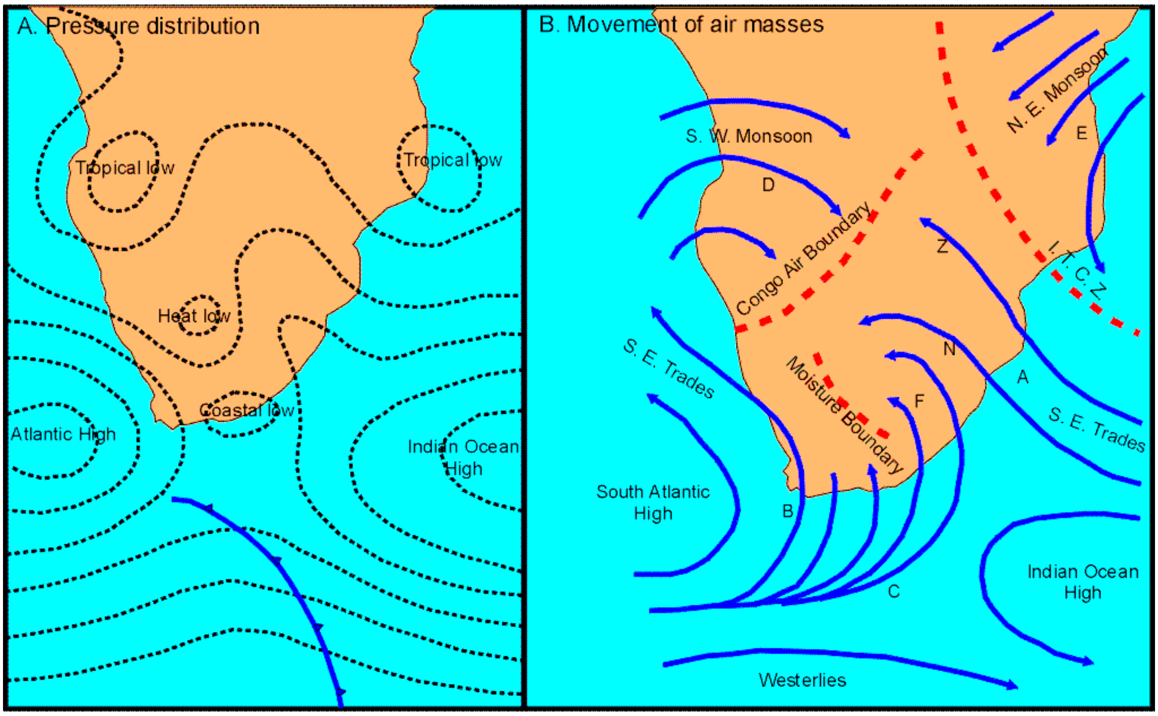


Fig 1. Features in the pressure distribution (a) and basic movement of air masses (b) over southern Africa during summer.

Figure 2(a and b) and the discussion, also from Hurry and Van Heerden (1986), consider the circulation features, as well as the movement of air masses during winter:

- All circulation features are situated more to the north, with the effect that the westerlies influence the weather of the southern part of the subcontinent. Cold fronts, which represents the leading edge of a cold air mass, often move over these areas and may reach areas very far north, but cloudiness and precipitation are normally confined to the southern parts. Snowfalls often occur along the escarpment.

- Absence of heat lows over the interior can cause the Indian and Atlantic highs to be linked over land. Sometimes a separate high pressure cell forms over the interior. These high pressure systems cause subsidence and accompanying clear skies over the interior.
- The south-eastern trade winds (A) still occur, but because the north-east Monsoon is absent, no convergence takes place. The ITCZ as well as the Congo air boundary have moved northwards.

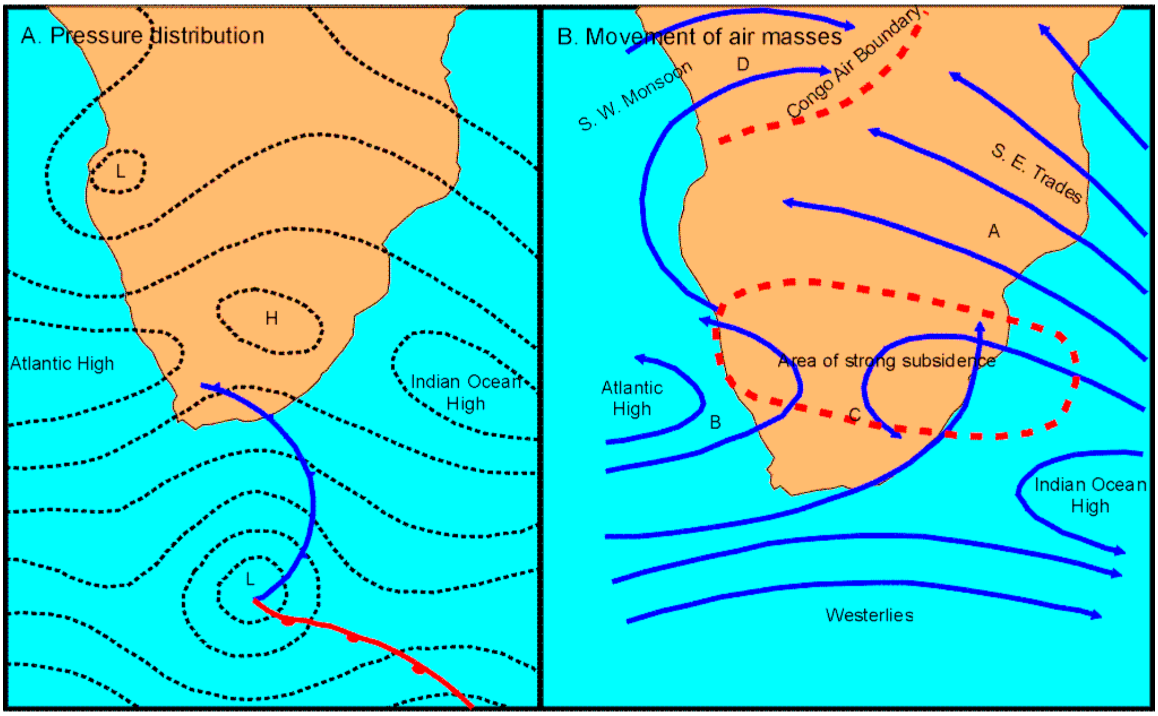


Fig 2. Features in the pressure distribution (a) and basic movement of air masses (b) over southern Africa during winter.

1.2. Climate regions

South Africa can be divided into regions with different climates. The climate controls discussed in section 1.1 and the topography of the region largely determines the delineation of the country into what can be called different climate regimes. The most well-known climate classification system is that of Köppen. According to this system South Africa can be divided into BW: Desert (arid), BS: Steppe (semi-arid), Csa: Winter rain with hot summers, Csb: Winter rain with cool summers, Cwa: Summer rain with hot summers, Cwb: Summer rain with cool summers, Cfa: All-year rain with hot summers and Cfb: All-year rain with cool summers. Through the analysis of long-term climate data it is apparent that Gauteng consists of mainly the Cwa region in the north and Cwb in the south. The C climates are described as mild temperate rainy climates with average temperature of the coldest month below 18 ºC but above –3 ºC. The average temperature of the warmest month is above 10 ºC. For Cw the winter is dry with at least ten times as much rain in the wettest month of summer than in the driest month of winter. Cwa indicates a generally hot summer with average temperature of the warmest month above 22 ºC, while Cwb indicates a cool summer with average temperature of warmest month below 22 ºC.

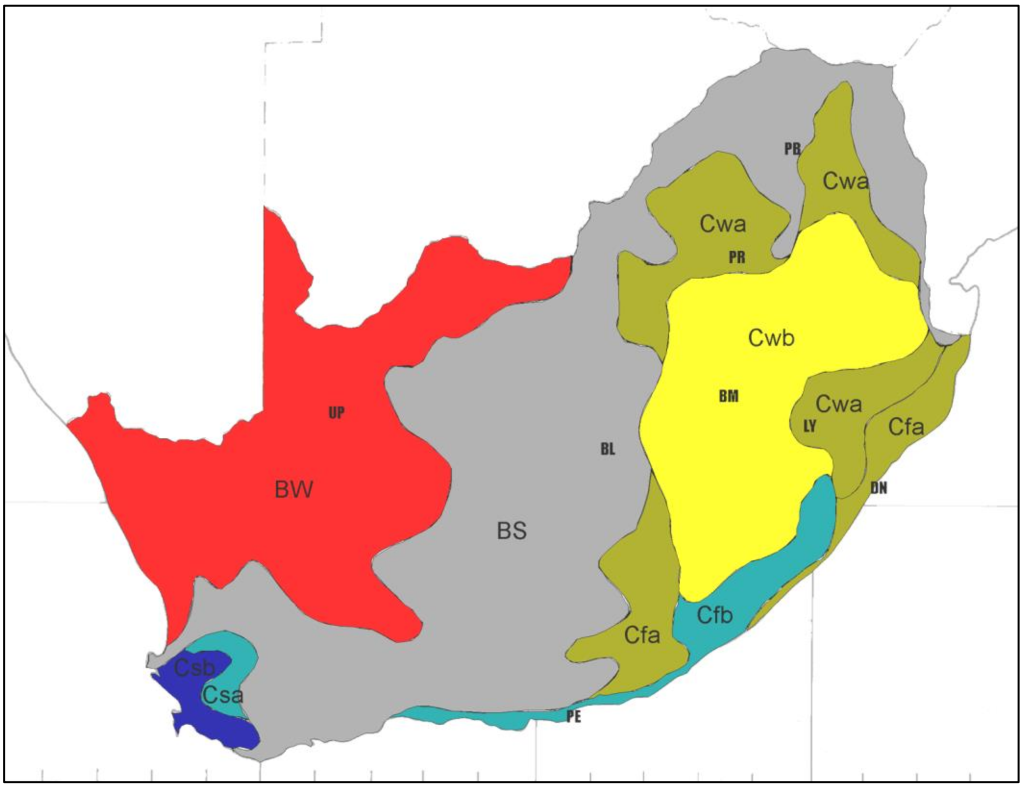


Fig 3. The Köppen Climatic Classification of South Africa: BW: Desert (arid), BS: Steppe (semi-arid), Csa: Winter rain with hot summers, Csb: Winter rain with cool summers, Cwa: Summer rain with hot summers, Cwb: Summer rain with cool summers, Cfa: All-year rain with hot summers, Cfb: All-year rain with cool summers. Gauteng is in the vicinity of PR (Pretoria) at the boundary between Cwa and Cwb.

The Köppen classification is based on five vegetation groups. It can therefore be expected that there should be some relationship between the vegetation biomes in South Africa and the Köppen climate boundaries. Using this relationships, SAWS developed a more detailed system of climate regions. For example, the Cwa and Cwb climates dominating in Gauteng coincides in the province with semi-bushveld and grassland vegetation respectively. Fig 4 presents the vegetation-based climate regions of South Africa. In Table 1 a short summary of the regions relevant to Gauteng (Central Bushveld in the north and Moist Highveld in the central and southern parts), in terms of climatic properties, locality, vegetation and typical agricultural activities is presented.

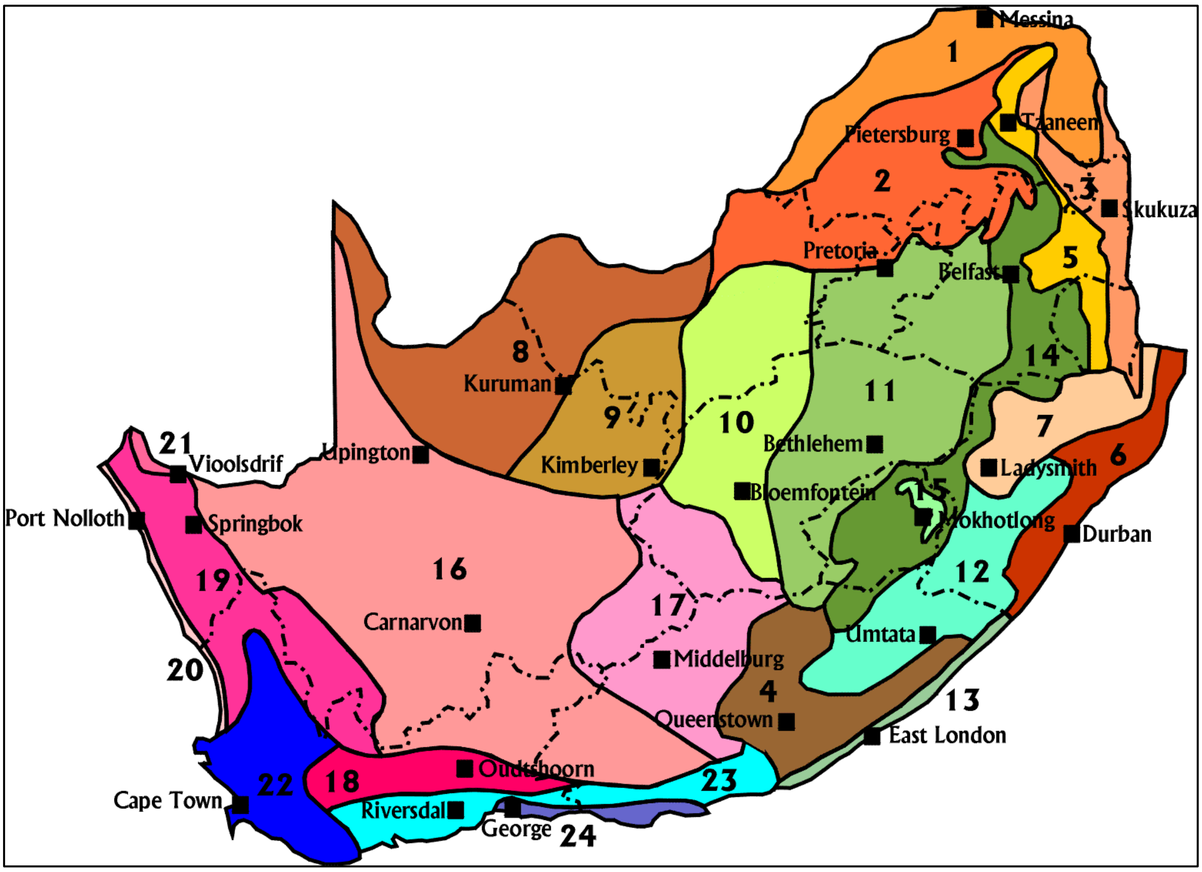


Fig. 4. The Climatic Regions of South Africa: 1. Northern Arid Bushveld 2. Central Bushveld 3. Lowveld Bushveld 4. South-Eastern Thornveld 5. Lowveld Mountain Bushveld 6. Eastern Coastal Bushveld 7. KwaZulu-Natal Central Bushveld 8. Kalahari Bushveld 9. Kalahari Hardveld Bushveld 10. Dry Highveld Grassland 11. Moist Highveld Grassland 12. Eastern Grassland 13. South-Eastern Coast Grassland 14. Eastern Mountain Grassland 15. Alpine Heathland 16. Great and Upper Karoo 17. Eastern Karoo 18. Little Karoo 19. Western Karoo 20. West Coast 21. North-Western Desert 22. Southern Cape Forest 23. South-Western Cape 24. Southern Cape.

Table 1. Vegetation-based climate regions in Gauteng with summaries of climatic properties, locality, vegetation and typical agricultural activity.

Region	Climatic properties	Locality	Vegetation	Agricultural activity
Central Bushveld (north of Gauteng)	Somewhat wetter (500 – 750 mm p.a.) and somewhat cooler than the Northern Bushveld. Frost occurs more often.	Parts of Gauteng, North-West and Northern Province.	Tree species include African Beechwood *Faurea saligna*, Acacia, Buffalo Thorn *Ziziphus mucronata*. Shrublayer is moderately developed with e.g. Sandpaper Raisin *Grewia flavescens*, Peeling Plane *Ochna pulchra* and Blue Guarri *Euclea crispa*. Grasslayer well developed with e.g. Wire Grass *Elionurus muticus*, Turf Grass *Ischaemum afrum*, Fingergrass *Digitaria eriantha* and Common Russet Grass *Loudetia simplex*.	Ecotourism, cattle and game farming, wheat, maize, sunflowers.
Moist Highveld Grassland (south of Gauteng)	Precipitation, ranges from 600 - 800 mm p.a. and has its maximum during Dec and Jan. Frost occurs regularly during the winter months and ranges, from available data, from about 30 days in the Mpumalanga area to about 70 days in the southern Free State. Winds are highly variable but easterly and westerly winds are more prevalent. Closer to the mountain ranges the incidence of frost is probably even higher. Over the higher lying areas snow is not an unusual event.	Parts of Gauteng and Mpumalanga southwards into eastern and south-eastern Free State.	Grass species include Redgrass *Themeda triandra*, Three-awn Rolling Grass *Aristida bipartita*, Fan Lovegrass *Eragrostis plana*, Broom Needlegrass *Triraphis andropogonoides*, Bushveld Turpentinegrass *Cymbopogon plurinodis*. Forbs include Fishbean *Tephrosia semiglabra*, Wild Petunia *Ipomoea obscura*, and Bladderweed *Hibiscus trionum*. Some dense woody thickets e.g. Oldwood *Leucosidea sericea* occur in places in the north.	Maize, Cattle and sheep, crop production, dairy farming, ecotourism.

1.3 Seasonal weather

Derivative from the climate classification and general observations, Gauteng falls in the summer rainfall region of South Africa, when most of the rainfall is received. While a more detailed analysis of the annual march in the typical and extremes of the most significant climate parameters are provided in the remainder of the publication, a brief overview is provided here.

Summer is the season when the likelihood of rainfall and maximum temperature extremes are the highest. However, a qualification on the last statement is that severe thunderstorms are the most likely in late spring to early summer, when the variation of wind direction with height (vorticity) is the greatest, causing e.g. greater uplift of moist air. Typical maximum temperatures are around the high twenties to low thirties degrees Celsius in the north and mid to high twenties in the south. Minimum temperatures are usually in the mid to high teens of degrees Celsius in the north with lower to middle teens in the south. Seasonal summer rainfall figures usually range from 300 – 350 mm but up to 400 mm in the central and southern parts. However, the interannual rainfall variation for this season is relatively highly, with drought and flood conditions not unusual.

In autumn there is still significant rainfall possible but only about half of the rainfall in summer. The likelihood of fog and low-lying cloud becomes higher. In fact, over higher lying areas, the incidence of fog is highest in mid-autumn. Chilly mornings are possible but incidences of frost are rare.

In winter temperatures around freezing point with accompanying frost occur frequently. The likelihood of rainfall diminishes and most of the time the weather is dominated by quasi-stationary high pressure systems with near-weekly influxes of cold air from the south or east. On most mornings the subsiding air from the high pressure systems cause temperature inversions with the effect that pollution gets trapped in the layer of the atmosphere closest to the ground, i.e. the boundary layer. Because of the widespread use of wood and coal for cooking and heating, air pollution in winter is a serious health hazard in the province

In spring the dates of the first rains of the season vary widely between years and it is not uncommon for the region to remain in the typical winter dry state well into early summer. The first significant thunderstorm activity are often accompanied by strong winds and hail. While a rare occurrence, the likelihood for the formation of tornadoes are greatest in late spring to early summer.

2. Surface Winds

2.1 Annual variation of wind direction and wind speed

The climate controls described in the previous sections has a direct bearing on the general wind field over the region, which is already described in the introductory section. Here the annual variation of the wind direction is illustrated by wind roses for Pretoria and Johannesburg for the period 1991 – 2020 below.

From Figures 5 and 6 it is evident that in general, the wind is stronger in Johannesburg than Pretoria. Also, from a glance of the wind roses there seems to be large differences in terms of the directional wind regime. However, at closer inspection it becomes apparent that there are commonalities in terms of the direction of the stronger winds. In summer, strongest winds are predominantly from the east but a strong north-westerly component is also present in the south. The same situation applies in autumn, where the winds in the south are predominantly north-westerly while in the north a south-easterly component to the strong winds are also present. In winter north-westerly winds still dominate in the south but a southerly component is also present and actually dominates in the north. In spring north to north-westerly dominates in the south and northerly to easterly winds in the north. In summary, it is apparent that the ridging of the Indian Ocean anticyclone from the east has a bigger influence on wind direction throughout the year in the north.

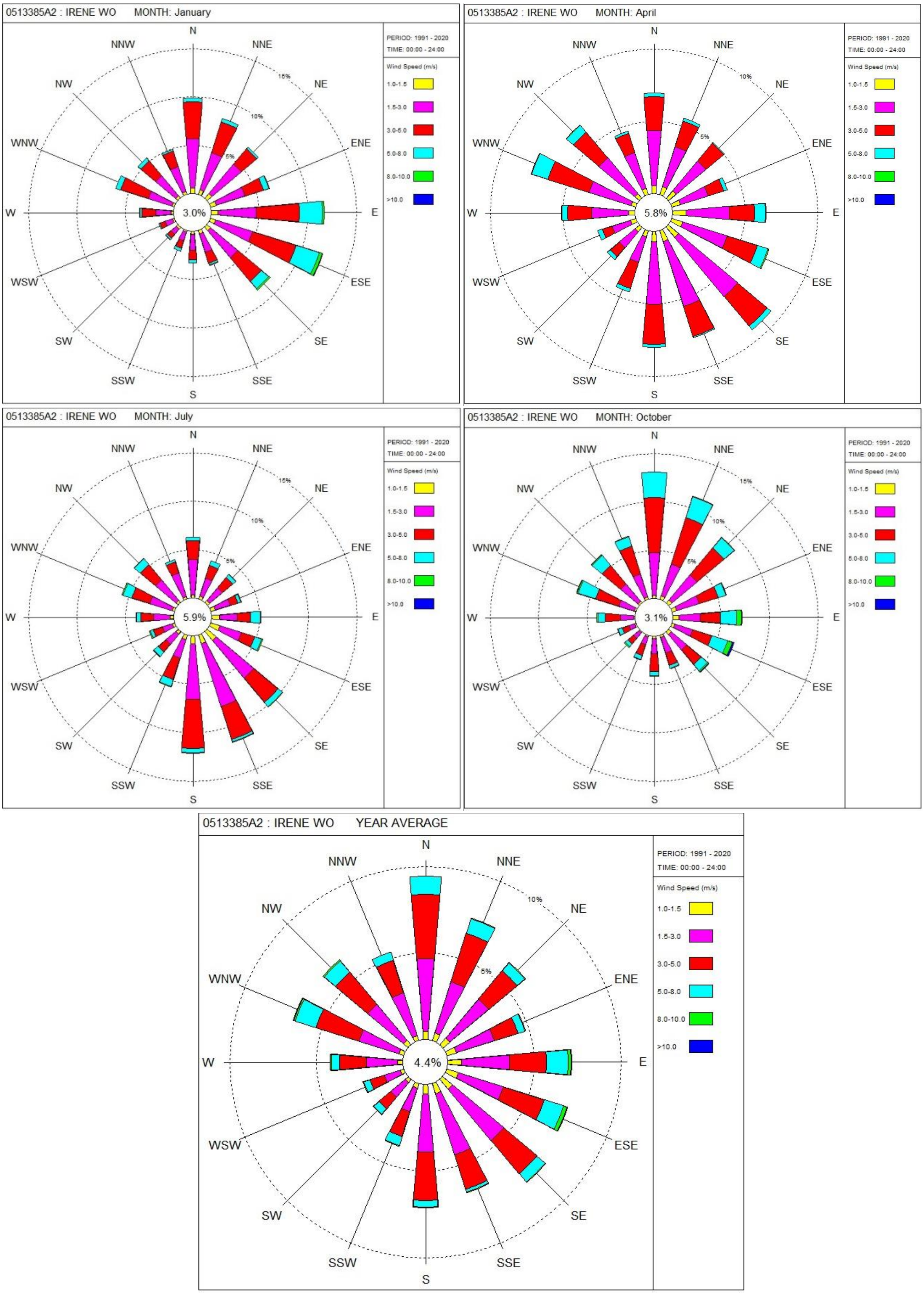


Fig 5. Monthly (Jan, Apr, Jul and Oct) and annual wind roses for Irene Weather Office (1991 – 2020).

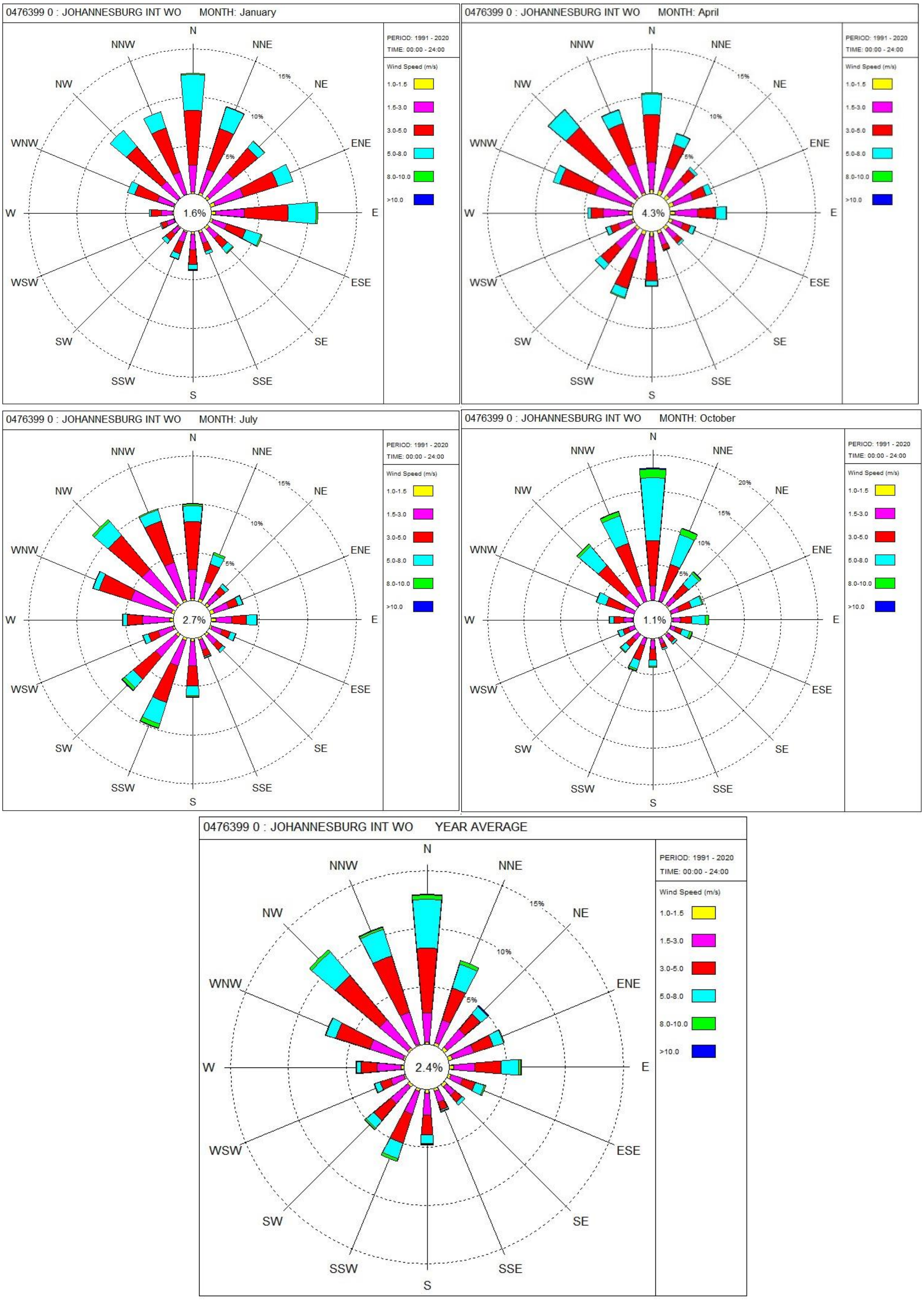


Fig 6. Monthly (Jan, Apr, Jul and Oct) and annual wind roses for OR Tambo International Airport weather station (1991 – 2020).

The high-resolution wind resource map developed by the Wind Atlas for South Africa project (WASA: www.wasaproject.info) shed more light on the spatial variation of the average wind speed in the province. In the north-west winds tend to be lightest while in the south-west the winds are strongest. The mean wind speed tends to follow the topography of the province with the northern parts generally lower than the south. Here it should also be noted that, compared with the rest of South Africa, wind speeds are relatively low and therefore less ideal for wind power generation than the coastal, mountainous and the more southern parts of the country.

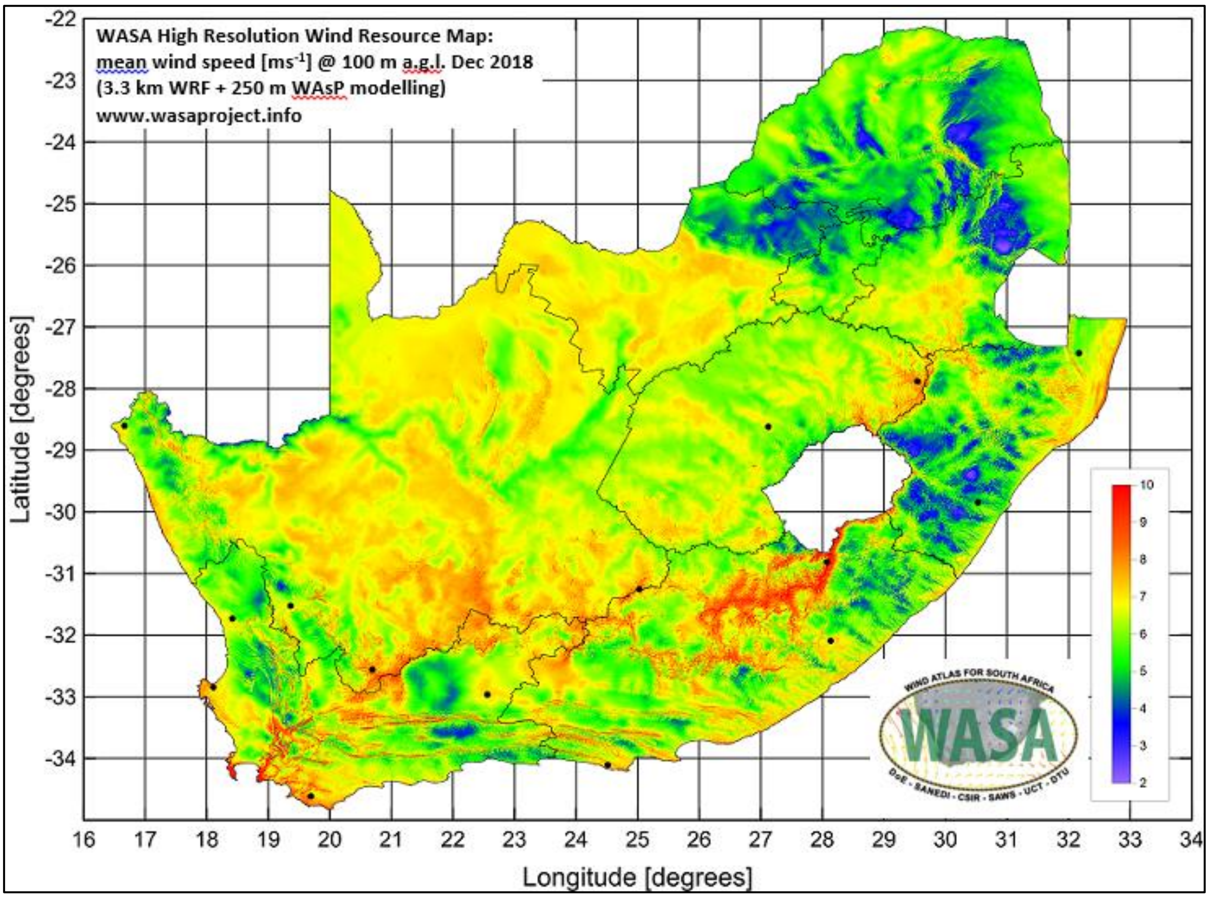


Fig. 7. WASA High Resolution Wind Resource Map. Mean wind speed (m/s) at 100 m above ground (www.wasaproject.info).

Figure 8 presents high resolution images of mean wind speed at 50m height above the surface, topography and land cover. It is clear that the wind speed predominantly reflects the topography with the lower-lying northern parts experiencing calmer conditions than the higher-lying south. While not complete reflected in the wind speed, urbanised areas indicated in yellow in Fig 8(b) should experience lower wind speeds than surrounding areas due to the relatively high surface roughness length. Where the roughness length is in excess of 1 m, i.e. where the surface is at least 15 % built up, the wind speed is slowed down up to a height of at least 10 m above the surface. In highly urbanised areas such as central business districts the effect of buildings is significantly more.

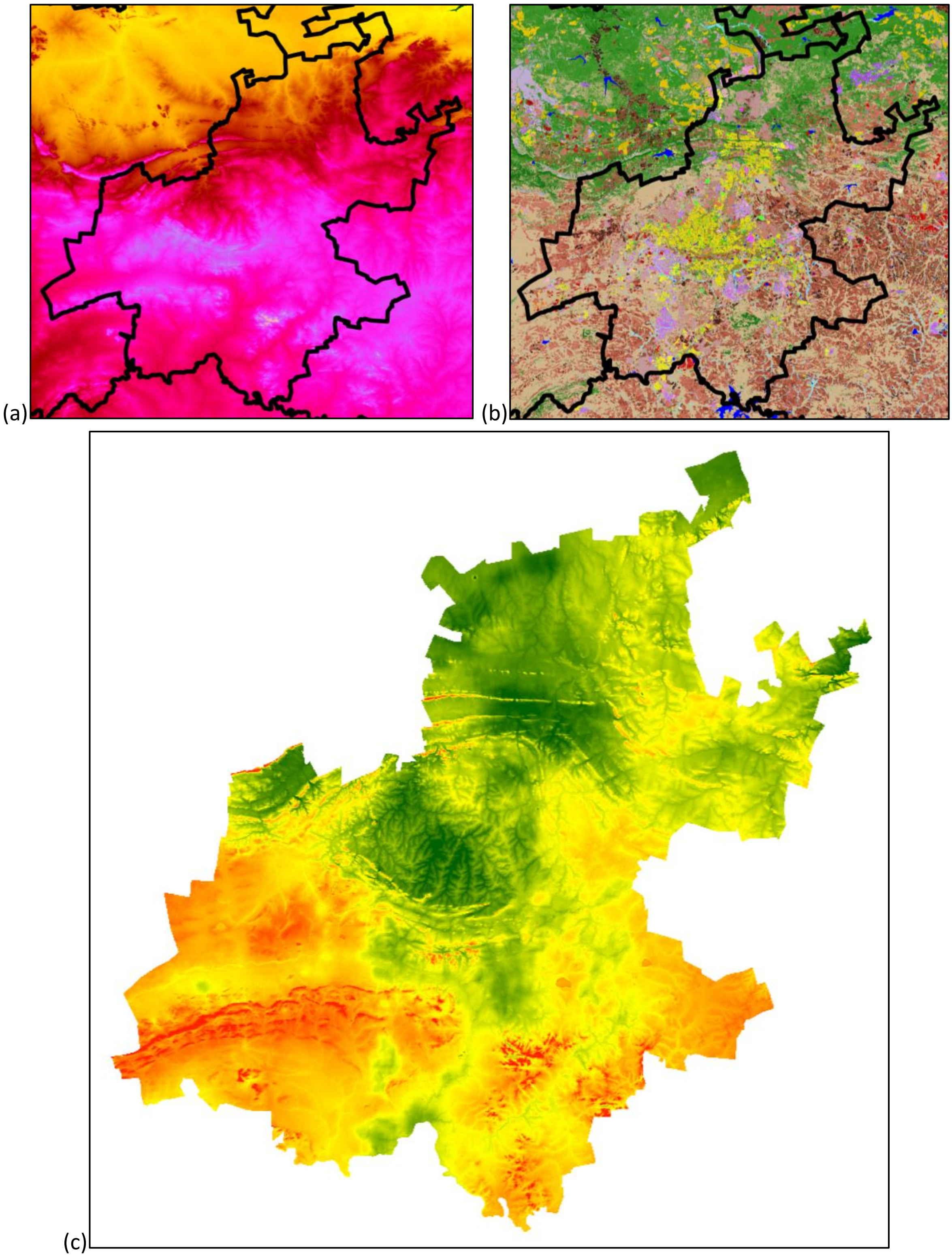


Fig. 8. (a) Topography of Gauteng Province. Yellow to brown areas present lower-lying areas while pink to light blue higher-lying areas (b) Land cover with the urban metropolitan areas of Tshwane and Johannesburg in the north and south (in yellow) respectively (c) WASA High Resolution Wind Resource Map for Gauteng Province. Mean wind speed (m/s) at 50 m above ground with lower wind speeds in green (< 3 m/s) and higher wind speeds in red (> 7 m/s) (www.wasaproject.info).

2.2 Annual variation of wind speed

The mean wind speed varies on an annual basis. A minimum is experienced in autumn with a maximum in spring, as can be seen from the wind roses in the previous section for April and October respectively. Figure 9 presents the average monthly wind speed for Irene and OR Tambo International Airport weather offices. For both Irene and OR Tambo the minimum is in May and the maximum in October.

The most probable explanation for the relatively strong winds in spring is that from a planetary (or at least hemispheric) perspective as summer approaches in the Southern Hemisphere and the more direct rays of the sun begin warming the mid-latitudes, the associated mid-latitude high pressure belt (part of the Hadley cell circulation) starts to "assert itself" and become more spatially dominant. Consequently this high pressure belt starts to take up or occupy a more southerly latitudinal band (as opposed to its more northerly latitudinal band during winter). This process of re-arranging of pressure systems inevitably results in a fair amount, or at least "a higher frequency" of windiness, which generally settles down in early summer. So, in summary, the subtropical high pressure systems start to become more dominant over the northern parts of the region and together with the prevailing cold fronts still affecting the country from the south it follows that due to a relatively large pressure difference between the low- and high-pressure systems the winds tend to be stronger.

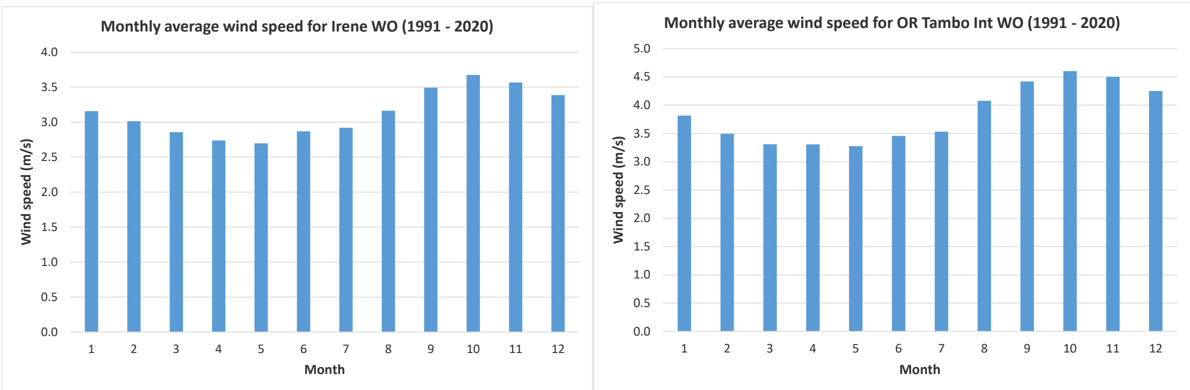


Fig. 9. Monthly average wind speed over the period 1991 – 2020 for Irene and OR Tambo International Weather Offices as indicated.

2.3 Strong winds of short duration

In the interior of the country, especially in the north, strong wind gusts (strong winds with a duration of a few seconds) are most often caused by convective activity, particularly thunderstorms. This is in contrast with the southern and south-western parts where strong wind gusts are mostly caused by synoptic-scale mechanisms, especially cold fronts. The highest verified wind gust ever recorded at Irene Weather Office was most probably on 30 December 2017 when a gust of 31,9 m/s occurred at 19:00 in the evening (see Fig. 10). For wind gusts caused by thunderstorms there are usually tell-tale signs from other weather parameters to verify that a strong gust occurred. These are e.g. a change in wind direction, onset of rain just after the thunderstorm gust front, as well as sudden changes in pressure (increase) and temperature (decrease). In-depth research in wind gusts in South Africa indicated a conservative estimate for Gauteng Province to experience a wind gust of 36 m/s every 50 years (Kruger et al., 2017).

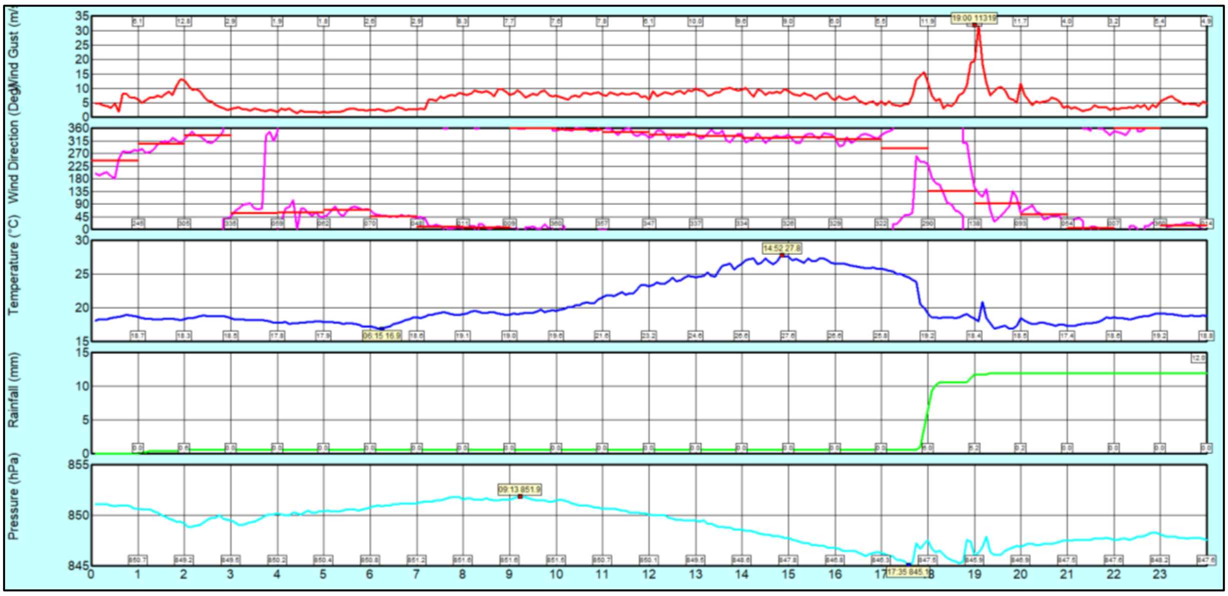


Fig. 10. 5-minute measurements of wind gust (m/s), wind direction (degrees), surface temperature (°C), rainfall (mm) and surface pressure (hPa) at Irene Weather Office on 30 December 2017.

Infrequent meteorological events in South Africa, such as the occurrence of tornadoes, tropical cyclones and downbursts, are important to consider when estimating the likelihood of extreme winds (Kruger, 2011). For Gauteng in particular, the most relevant of these events are tornadoes, of which a sizeable number were documented through the years. At a particular location, where the wind may have been measured over even a long period of time, the likelihood may exist for tornadoes to occur, although not yet measured. It is only due to the small probability and/or limited spatial extent of these events, that their related extreme magnitude winds have never been recorded at the particular location. Furthermore, the associated winds are so strong that it is typically not possible to measure them directly.

The information about the spatial distribution, frequency and strength of tornadoes can only be inferred from a statistical analysis of the related wind damage reports (Goliger et al., 1997). Tornadoes occur in regions where thunderstorms are able to develop an organised internal structure of sufficient strength. The wind strengths of specific tornado events are based mainly on engineering estimation or the calculation of the wind force necessary to inflict various degrees of damage and/or the overturning or transporting of various other objects. The only comprehensive study on the spatial distribution and probabilities of tornado-strength winds in South Africa were done by Goliger et al. (1997). The probabilities of tornadoes to occur inferred from documented cases reflect the distribution of the prevailing or dominant strong wind mechanisms in the country, but also the likelihood of severe thunderstorms and to a large extent the population distribution in South Africa. Due to the latter Gauteng is indicated as one of the hot spots for tornadoes to occur in South Africa, but this feature of the tornado probability map presented in Fig. 11 is most probably due to the relatively better reporting of tornadic events.

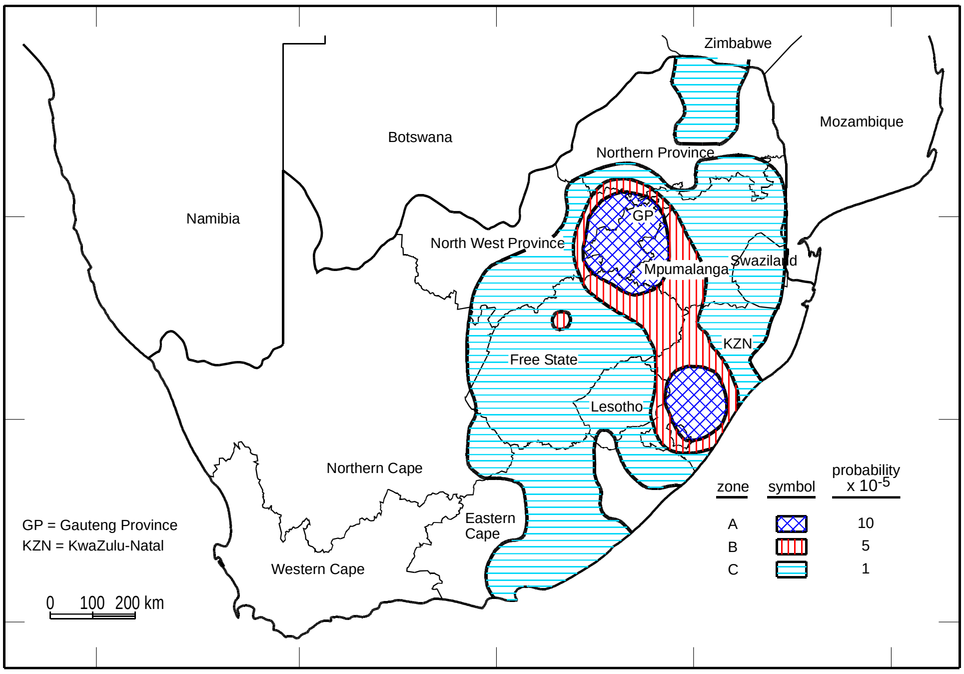


Fig. 11. Mean rate of occurrence of tornadoes per annum, excluding tornadoes of low intensity F0.

SAWS collects media reports of significant weather events on a routine basis and publish the information in the CAELUM bulletin since 1991 (CAELUM, 1991 and updates thereof), which is updated on a routine basis. While it is not possible for all significant weather events to be reported on in the media, the CAELUM however provides a sufficient database of notable significant weather occurrences in South Africa over a period of hundreds of years. Tornado events are reported 242 times in the publication since 1905, of which 38 were in Gauteng. The latest tornado reports in Gauteng over the last 30 years are listed in Table 2, but this can however not be regarded as an exhaustive list of tornado occurrences in the province.

Table 2. Tornado events in Gauteng reported in the print media since 1991 (CAELUM, 1991 and updates thereof).

YEAR	MONTH	DAY	PLACE/LOCATION	ADDITIONAL INFORMATION
1993	10	25	FLORIDA	
1994	4	21	PRETORIA	
1995	12	22	JOHANNESBURG	
1998	12	15	KLIP RIVER	400 HOUSES DESTROYED
2000	4	16	JOHANNESBURG	
2011	10	2	DUDUZA, NIGEL	1 KILLED
2014	11	24	SOWETO	
2016	7	25	KRUGERSDORP	
2016	7	26	PHUMULANI MALL	
2016	7	26	TEMBISA	100 SHACKS AND 20 HOUSES DAMAGED
2016	7	26	WINNIE MANDELA, GAUTENG	200 HOUSEHOLDS, ABOUT 400 PEOPLE AFFECTED
2016	11	14	ENNERDALE	ABOUT 53 HOUSES DAMAGED, 1 INJURED
2017	12	11	MID-VAAL, GAUTENG	50 PEOPLE SUSTAINED INJURIES
2017	10	9	RUIMSIG	DAMAGE RATED AS EF2 (ENHANCED FUJITA SCALE)
2017	12	30	SOWETO	F1 TORNADO, TWO PEOPLE DIED

2.4 Diurnal variation of wind speed

While the wind varies seasonally, there is also substantial variation on a daily basis. Usually there is a stilling of the wind at night and increase in wind speed in the morning, reaching a maximum in the late morning and afternoon hours. This is due to solar heating of the surface, convective activity and in the rainy months around summer the formation of thunderstorms with associated strong winds. Figure 12 presents the hourly average wind speed for summer and winter at OR Tambo International Airport. Apparent is the generally lower wind speeds in winter, except during mid-day. Also, the wind is markedly stronger outside the midday hours during summer. This feature of the wind is probably due to more surface heating in summer that is sustained into the night and early morning hours.

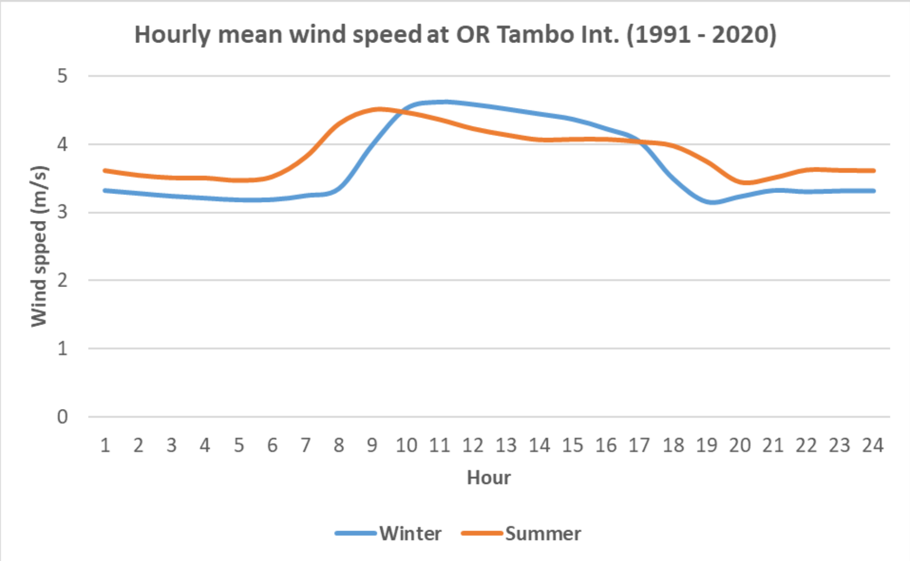


Fig. 12. Hourly mean wind speeds for winter and summer at OR Tambo Int. Airport (1991 – 2020).

3. Surface Temperature

3.1 Mean seasonal and monthly temperature

The average surface temperature is governed by the general circulation patterns and topography, amongst others. The mean seasonal temperature, as well as minimum and maximum temperature, is presented in map format in Figures 13 to 24. From the maps it can be seen that the northern parts of the province generally experience higher temperatures than the south. This feature of surface temperature is related to the topography, where lower (higher) elevations experience higher (lower) temperatures. However, it should be noted that at the local- or micro-scale lower elevations, e.g. valleys, generally experience lower temperatures at night and in the early morning, due to colder, denser air accumulating in lower-lying areas. The maps mostly presents one isohyet, with temperatures varying within one degree on either side of the line of equal mean temperature, unless otherwise indicated.

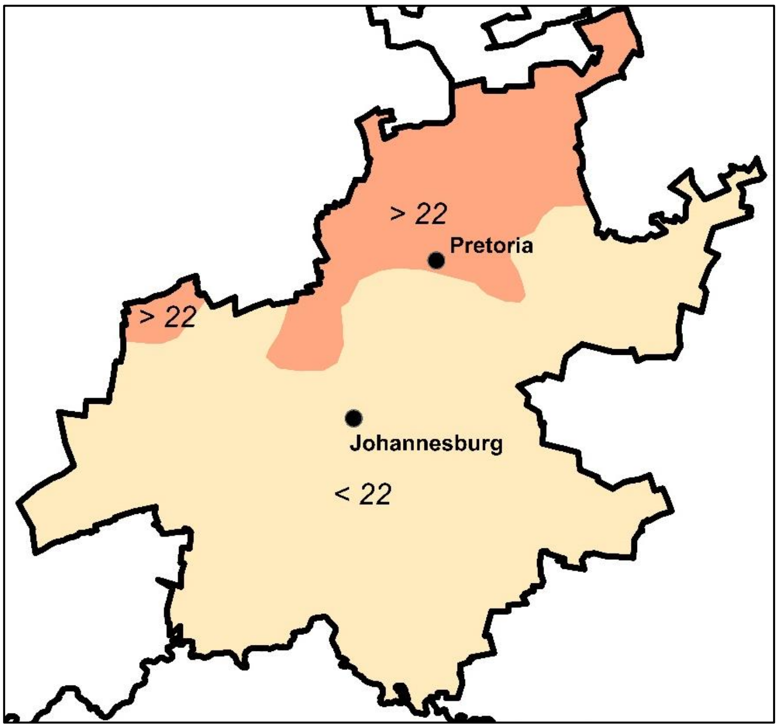


Fig. 13. Mean summer (DJF) temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

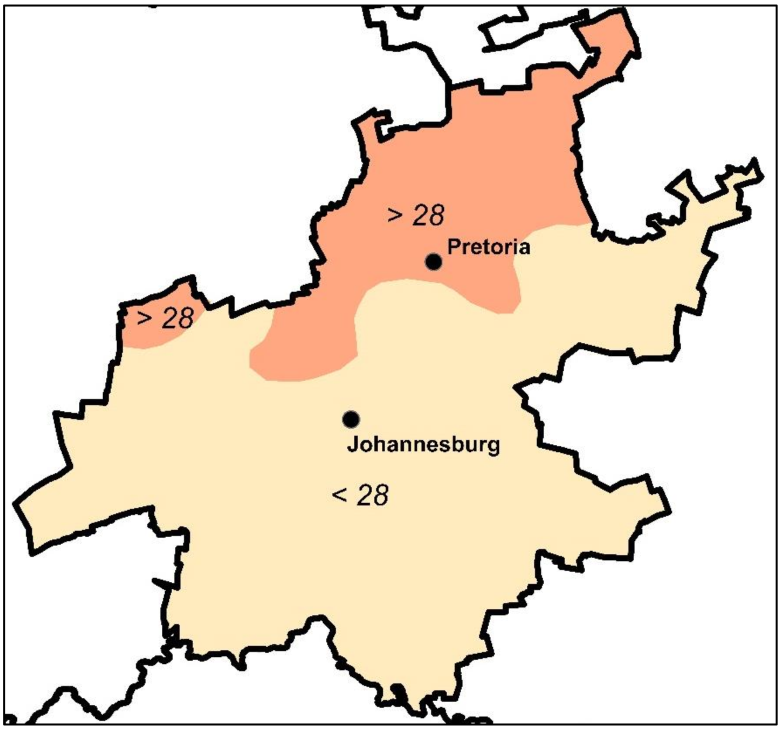


Fig. 14. Mean summer (DJF) maximum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

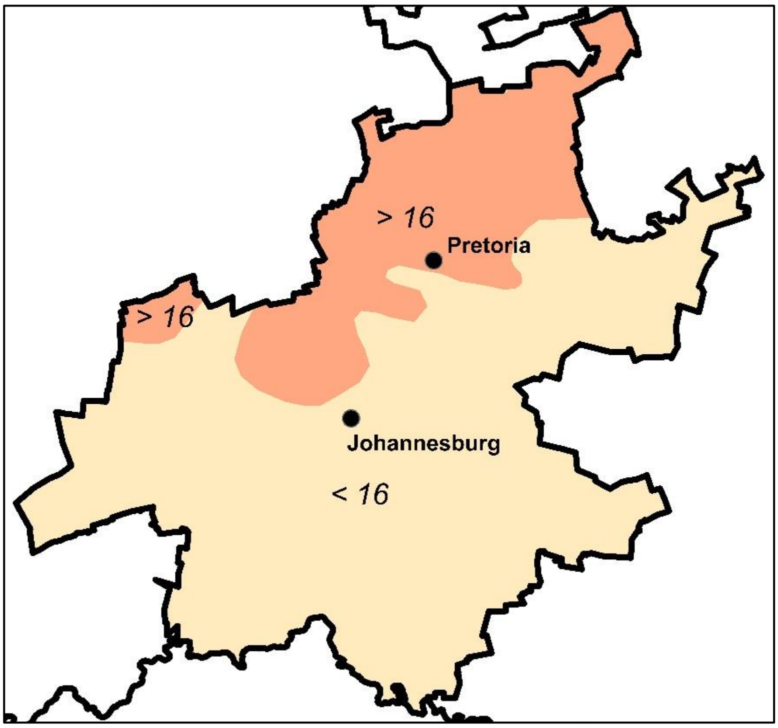


Fig. 15. Mean summer (DJF) minimum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

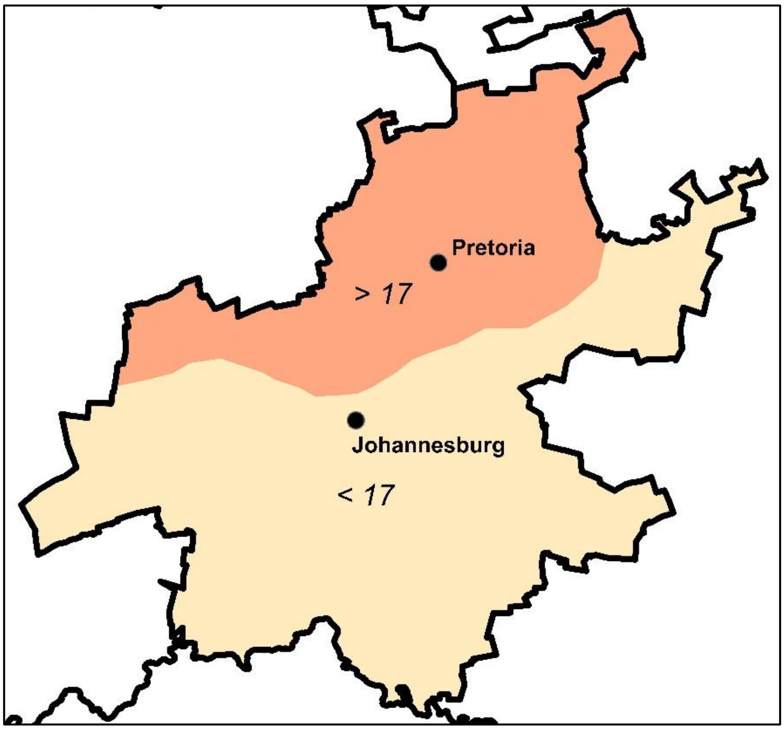


Fig. 16. Mean autumn (MAM) temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

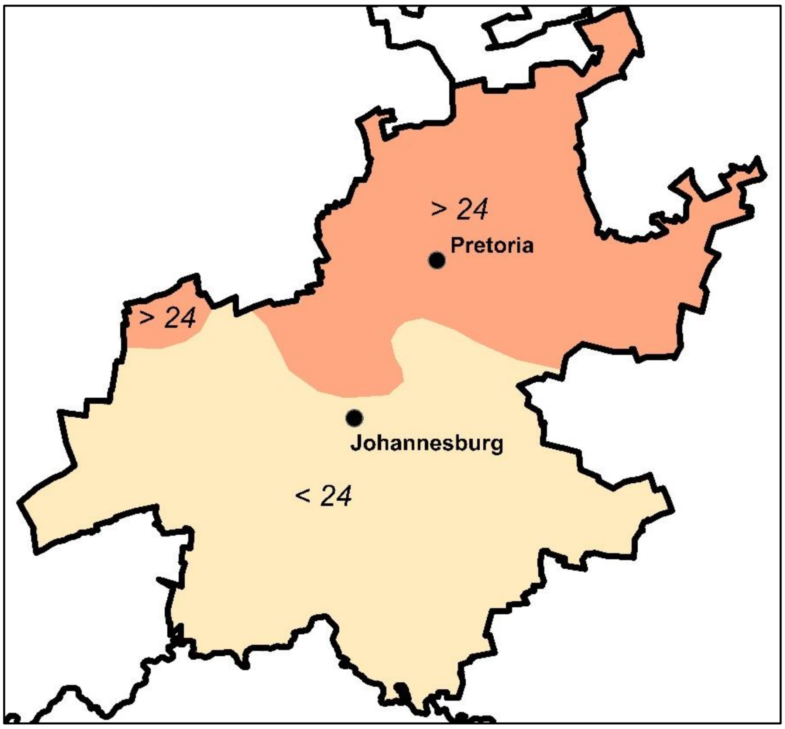


Fig. 17. Mean autumn (MAM) maximum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

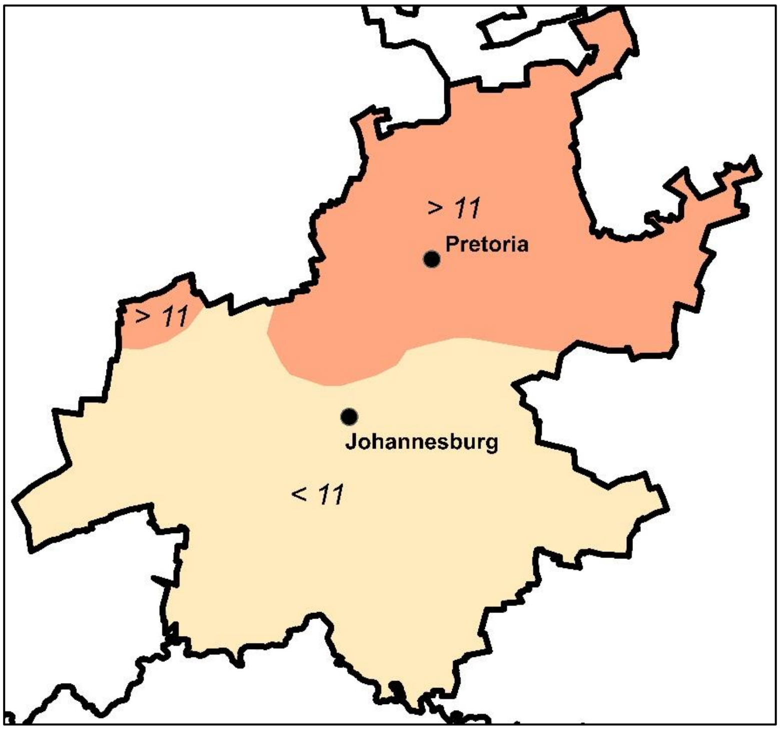


Fig. 18. Mean autumn (MAM) minimum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

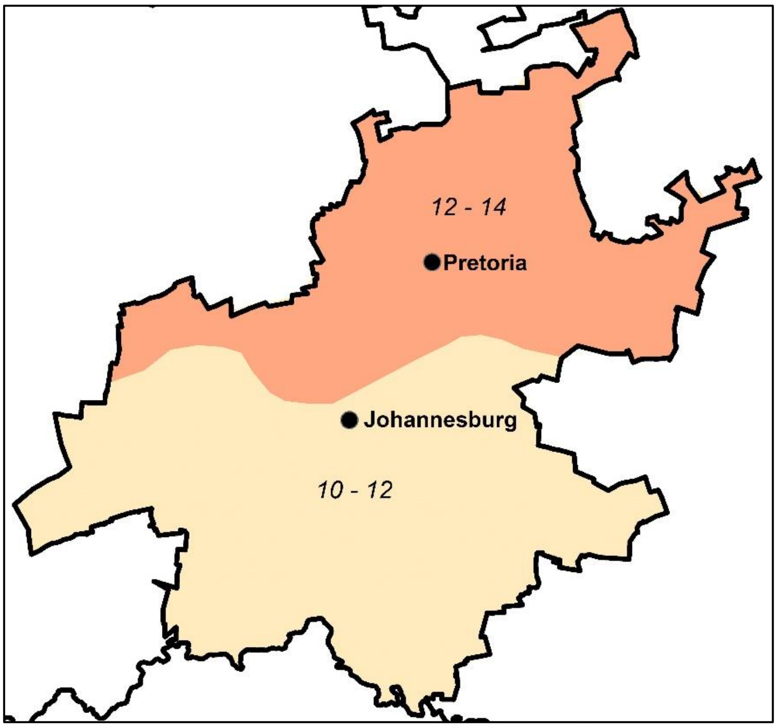


Fig. 19. Mean winter (JJA) temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

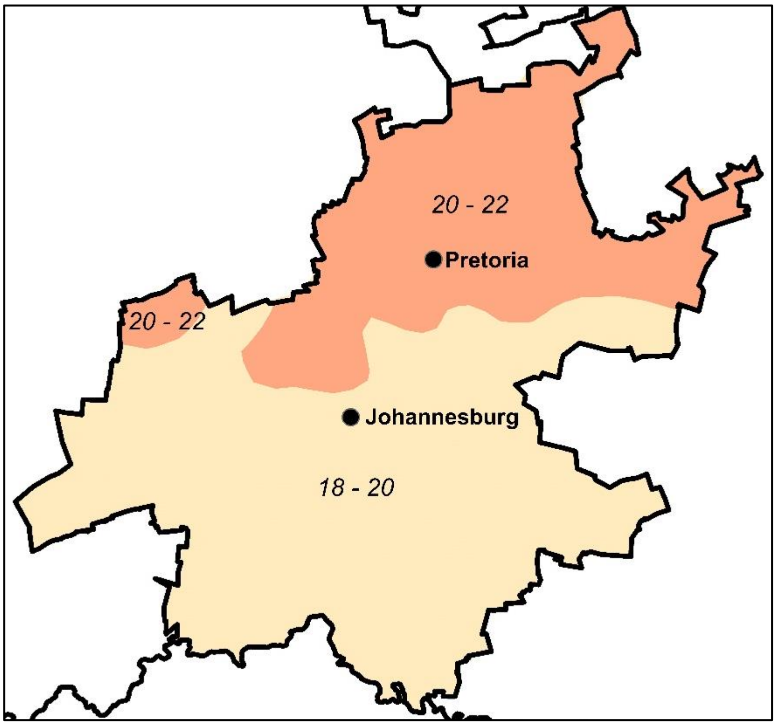


Fig. 20. Mean winter (JJA) maximum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

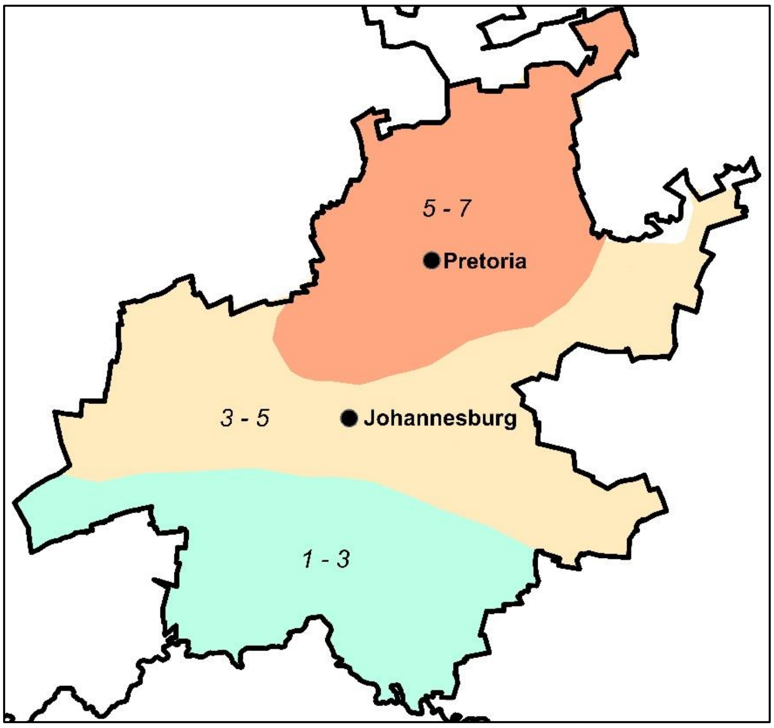


Fig. 21. Mean winter (JJA) minimum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

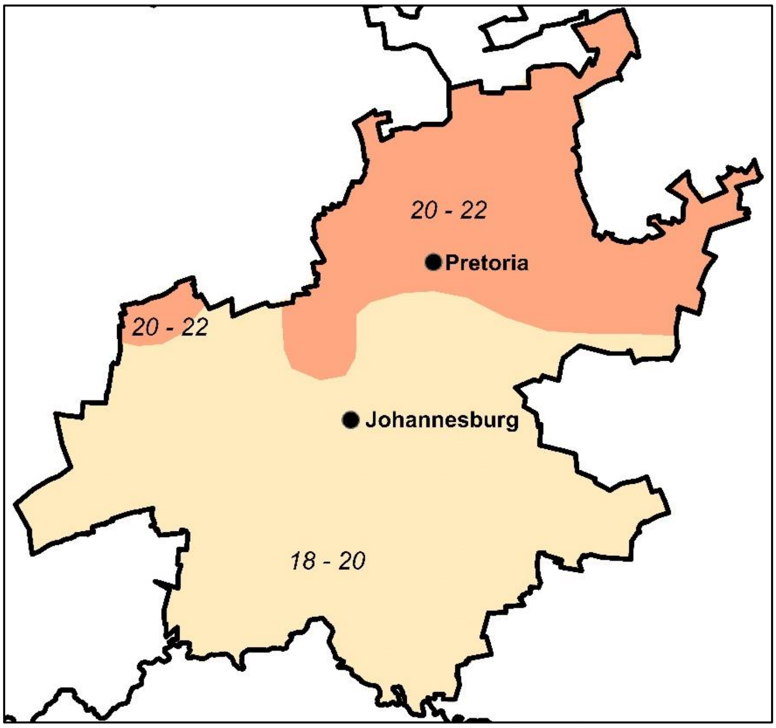


Fig. 22. Mean spring (SON) temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

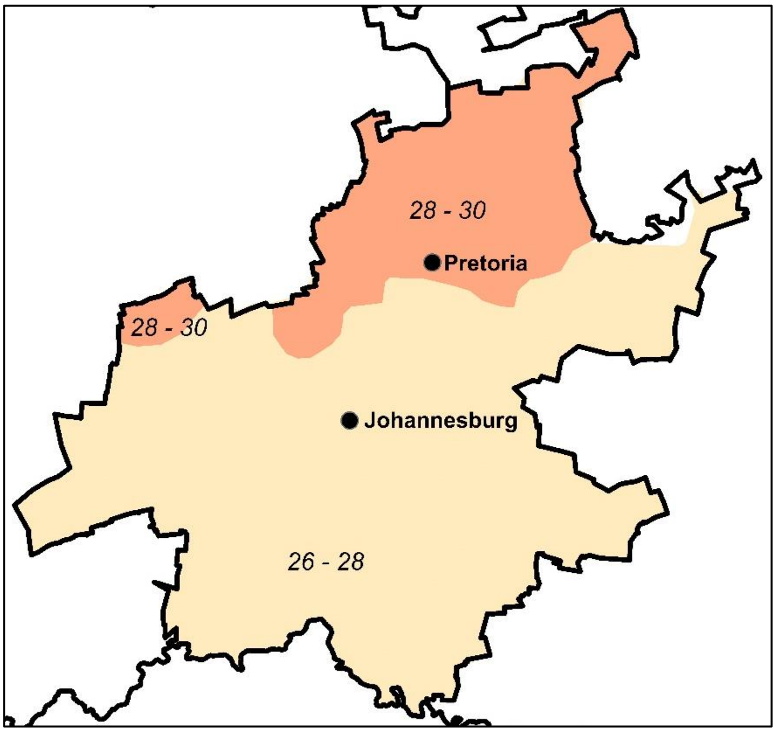


Fig. 23. Mean spring (SON) maximum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

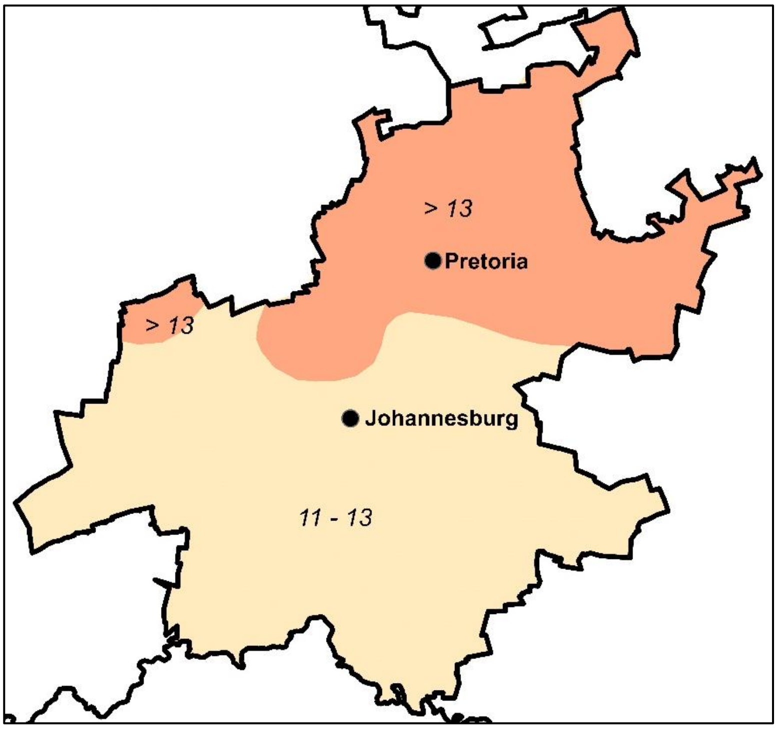


Fig. 24. Mean spring (SON) minimum temperature (°C) over Gauteng, based on topography and data over the period 1991 – 2020.

Figures 25 and 26 present graphs of monthly means and extremes of the maximum and minimum temperature for Irene and OR Tambo Weather Offices respectively. These graphs reiterates the general observation that the north is hotter than the south.

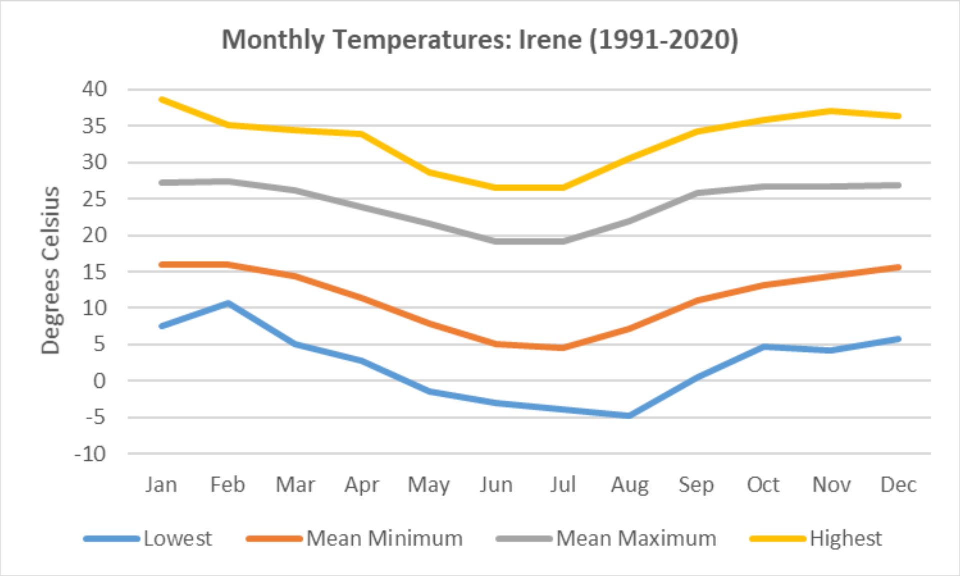


Fig. 25. Monthly means and extremes of the maximum and minimum temperature for Irene Weather Office (1991 – 2020).

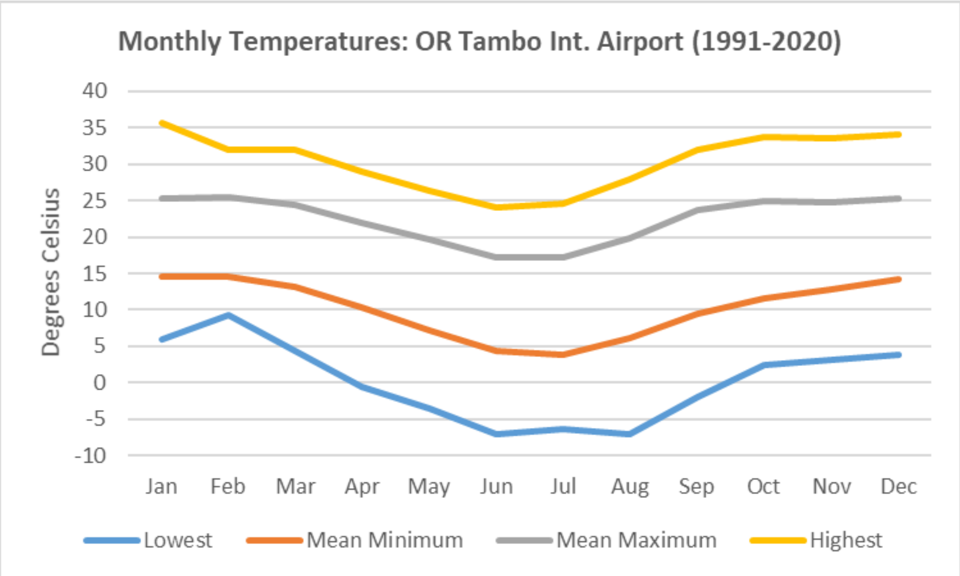


Fig. 26. Monthly means and extremes of the maximum and minimum temperature for OR Tambo Weather Office (1991 – 2020).

3.2 Extreme temperatures

Hot extreme temperatures tend to occur in the summer months. With climate change, specifically global warming, affecting surface temperatures, it is more likely for record temperatures to have occurred in the recent past. An analysis of annual mean temperatures indicate that 2016 was one of the hottest years on record globally. It was also during this year that most stations that are operational recorded their highest temperatures. On 7 January 2016 a substantial number of long-term weather stations recorded their highest temperatures ever. These stations include Vereeniging (38,8°C), Zuurbekom (38,6°C), OR Tambo International (35,6°C), Lanseria (38,3°C), UNISA in Pretoria (42,7°C), Irene (38,7°C) and University of Pretoria (39,5°C). One can assume that the temperature measured at UNISA in Pretoria is the highest ever recorded by and official weather station in Gauteng. Figure 27 presents the 5-minute graph of the surface temperature on 7 January 2016 at the Pretoria UNISA automatic weather station.

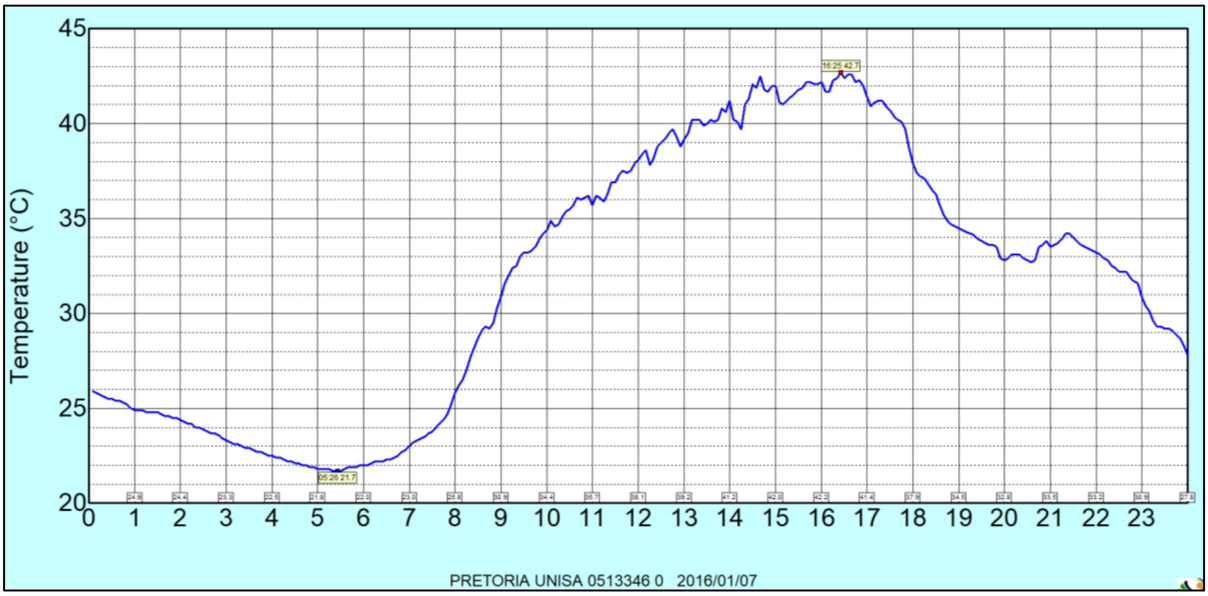


Fig. 27. 5-Minute graph of surface temperature measured on 7 January 2016 at Pretoria UNISA automatic weather station.

Figure 28 presents the synoptic conditions in the afternoon of 7 January 2016, the hottest day on record in Gauteng. A cold front was situated along the south-east coast of the sub-continent and with a high pressure system ridging behind it, as well as a surface trough over the northern interior, partly cloudy to cloudy and cool to warm and hot conditions with showers and thundershowers as well as light rain occurred over KwaZulu-Natal and in places over Gauteng, Mpumalanga, Limpopo and the Western and Eastern Cape Provinces. However, it was also very hot to extremely hot in places over Gauteng, Mpumalanga, Limpopo, North-West, Free State and KwaZulu-Natal Provinces.

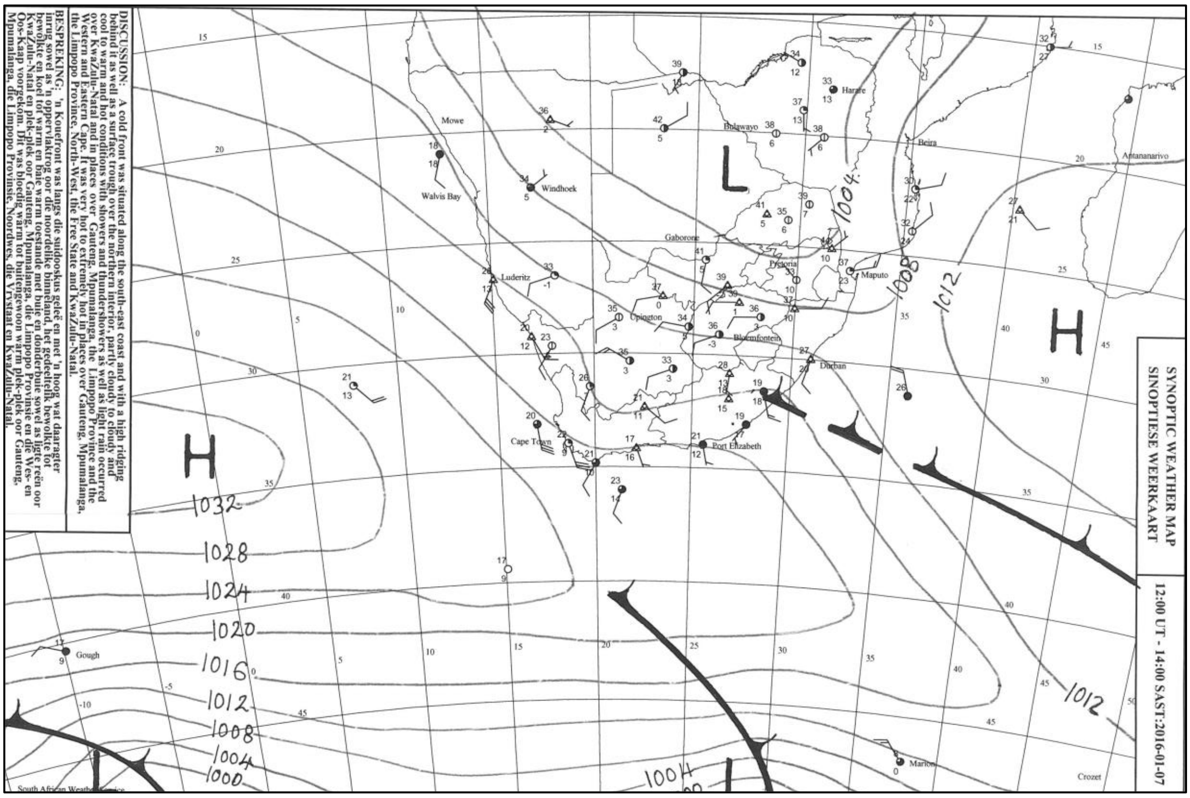


Fig. 28. Synoptic conditions in the afternoon of 7 January 2016, the hottest day on record in Gauteng.

As previously mentioned, global warming has increased the likelihood of hot extremes to occur, but also a decrease in the likelihood of cold extremes. The dates and values of the record lowest minimum temperatures measured at various weather stations in Gauteng are largely dependent on the periods over which the stations were operational. In the more distant past the lowest minimum temperature measured in Gauteng seems to have been on 27 June 1933, where both the long-term weather stations in Zuurbekom (southern Gauteng) and University of Pretoria (northern Gauteng) recorded their lowest minimum temperatures, of -13,1°C and -7,0°C respectively. The month of June 1964 seems to be one of the coldest months on record, with several weather stations, of which most have closed since then, recording record low temperatures. Examples of these are 25 June 1964 (Onderstepoort: -9,0°C, Roodeplaat: -6,7°C) and 27 June 1964 (Lynnwood Ridge: -5.3°C). However, one should note that it is almost impossible to verify values at old stations which were not manned by SAWS staff. A critical study of the dates of record low temperatures show that almost all of these low temperatures were recorded during winter soon after the passage of a cold front over the subcontinent. Recently, on 7 June 2014, very low temperatures were recorded over Gauteng, with the weather station at Wonderboom Airport recording a minimum temperature of -4,6°C which is very unusual for the northern parts of Gauteng. Figure 29 presented the synoptic conditions on 6 June 2014 when the Atlantic Ocean high-pressure system ridged in over the country behind a cold front situated to the east of South Africa. Very cold conditions spread across the country, with an extremely cold morning on 7 June 2014.

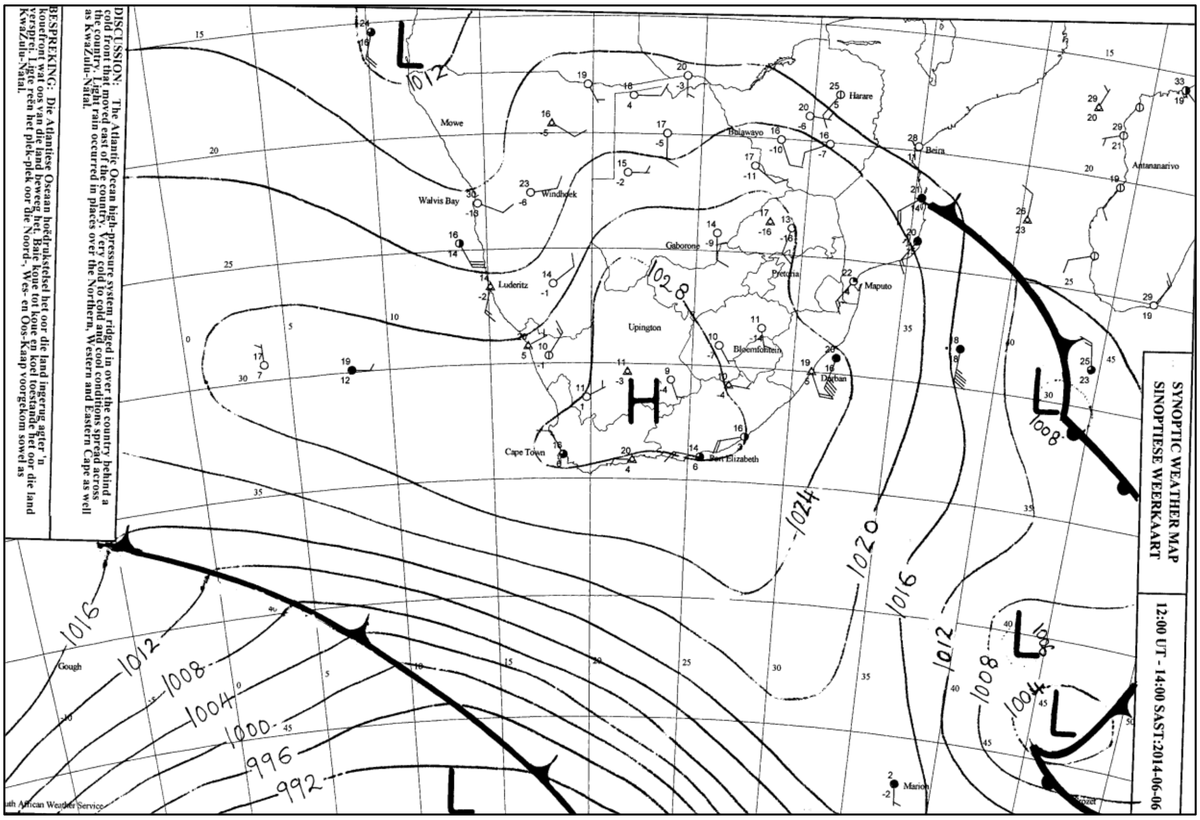


Fig. 29. Synoptic conditions on the afternoon of 6 June 2014. Unusually low minimum temperatures were recorded the following morning in Gauteng and other parts in the interior of South Africa.

3.3 Temperature frequencies

Tables of temperature frequencies allow for the examination of typical expected temperatures at specific hours of the day on a monthly and yearly basis, and also the likelihood of e.g. extreme high and low temperatures. Tables 3 and 4 present the frequency tables for Irene and OR Tambo respectively. These tables can be done on request for any station and time period, e.g. month or season.

Table 3. Frequencies (%) of surface temperature (screen) in specified ranges of 5°C at specified times at Irene Weather Office (1991-2020).

Hour	Frequencies (%) of surface temperature (screen) in specified ranges of 5°C at specified times (1991-2020)									
	-5-0	**0-5**	**5-10**	**10-15**	**15-20**	**20-25**	**25-30**	**30-35**	**35-40**	**40-45**
00	0.1	5.7	19.8	30.4	39.9	4.1	0.0	0.0	0.0	0.0
01	0.1	6.8	21.2	31.5	37.8	2.6	0.0	0.0	0.0	0.0
02	0.2	7.9	22.1	32.2	35.6	1.9	0.0	0.0	0.0	0.0
03	0.2	9.2	22.8	33.1	33.3	1.3	0.0	0.0	0.0	0.0
04	0.3	10.2	23.1	31.8	33.1	1.4	0.0	0.0	0.0	0.0
05	0.3	10.6	20.7	25.5	37.2	5.5	0.1	0.0	0.0	0.0
06	0.0	4.5	16.3	23.8	36.4	18.5	0.7	0.0	0.0	0.0
07	0.0	2.7	5.6	22.4	34.0	31.7	3.6	0.0	0.0	0.0
08	0.0	2.4	1.9	13.8	32.8	38.3	10.6	0.2	0.0	0.0
09	0.0	2.4	0.8	8.8	28.4	40.3	18.4	0.9	0.0	0.0
10	0.0	2.4	0.5	5.8	24.3	38.7	26.2	2.2	0.0	0.0
11	0.0	2.4	0.3	4.1	21.0	36.7	31.2	4.2	0.0	0.0
12	0.0	2.1	0.3	3.1	19.0	36.1	33.8	5.8	0.1	0.0
13	0.0	2.3	0.2	3.1	18.9	35.5	33.2	6.7	0.1	0.0
14	0.0	2.3	0.3	3.6	21.1	35.5	31.1	6.0	0.1	0.0
15	0.0	2.3	0.6	6.3	27.2	33.1	26.5	3.9	0.0	0.0
16	0.0	2.3	1.6	15.3	30.7	31.3	17.7	1.2	0.0	0.0
17	0.0	2.4	3.1	20.6	33.5	32.7	7.5	0.2	0.0	0.0
18	0.0	2.1	4.9	23.6	37.4	29.0	3.2	0.1	0.0	0.0
19	0.0	2.6	7.2	25.8	39.2	23.7	1.5	0.0	0.0	0.0
20	0.0	2.9	10.3	26.8	41.1	18.3	0.6	0.0	0.0	0.0
21	0.0	3.5	13.1	27.5	42.0	13.6	0.3	0.0	0.0	0.0
22	0.0	4.0	16.0	28.1	42.5	9.2	0.2	0.0	0.0	0.0
23	0.1	4.9	18.1	29.2	41.5	6.1	0.1	0.0	0.0	0.0
AVG	0.1	4.2	9.6	19.8	32.8	21.9	10.3	1.3	0.0	0.0

Table 4. Frequencies (%) of surface temperature (screen) in specified ranges of 5°C at specified times at OR Tambo International (1993-2020).

Hour	Frequencies (%) of surface temperature (screen) in specified ranges of 5°C at specified times (1993-2020)									
	-5-0	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45
00	0.4	6.8	20.9	38.2	31.2	2.4	0.0	0.0	0.0	0.0
01	0.6	7.9	21.9	39.1	29.1	1.5	0.0	0.0	0.0	0.0
02	0.9	8.8	22.6	40.5	26.2	0.9	0.0	0.0	0.0	0.0
03	1.1	8.7	23.9	41.3	24.4	0.6	0.0	0.0	0.0	0.0
04	1.3	9.2	23.7	39.8	25.1	0.9	0.0	0.0	0.0	0.0
05	1.2	8.4	21.4	31.9	33.8	3.3	0.0	0.0	0.0	0.0
06	0.2	4.3	15.7	29.4	39.9	10.3	0.2	0.0	0.0	0.0
07	0.0	1.9	9.3	26.1	39.4	22.2	1.1	0.0	0.0	0.0
08	0.0	1.1	4.8	20.9	36.5	32.9	3.7	0.0	0.0	0.0
09	0.0	0.8	2.5	15.5	34.1	38.3	8.7	0.1	0.0	0.0
10	0.0	0.7	1.4	11.5	31.8	40.2	14.1	0.3	0.0	0.0
11	0.0	0.7	1.0	8.8	29.6	40.4	18.9	0.6	0.0	0.0
12	0.0	0.7	0.7	7.4	28.9	39.3	21.9	1.2	0.0	0.0
13	0.0	0.6	0.7	7.1	29.6	38.1	22.5	1.3	0.0	0.0
14	0.0	0.7	0.9	8.3	31.3	37.3	20.6	1.0	0.0	0.0
15	0.0	0.7	1.5	13.4	33.1	34.3	16.4	0.5	0.0	0.0
16	0.0	0.9	4.3	21.0	32.5	31.6	9.5	0.2	0.0	0.0
17	0.0	1.3	6.6	24.4	36.6	27.2	3.8	0.0	0.0	0.0
18	0.0	1.6	8.3	27.0	39.2	22.2	1.8	0.0	0.0	0.0
19	0.0	2.1	10.4	28.9	40.1	17.5	0.9	0.0	0.0	0.0
20	0.1	2.9	13.3	30.5	40.4	12.3	0.4	0.0	0.0	0.0
21	0.1	3.7	15.4	32.9	39.1	8.5	0.2	0.0	0.0	0.0
22	0.2	4.8	17.5	34.4	37.0	5.9	0.1	0.0	0.0	0.0
23	0.3	5.9	19.2	36.2	34.7	3.6	0.0	0.0	0.0	0.0
AVG	0.3	3.6	11.2	25.6	33.5	19.7	6.0	0.2	0.0	0.0

3.4 Apparent temperature

Apparent, sensible or effective temperature refers to the temperature at which motionless saturated air would induce, in a sedentary worker wearing ordinary indoor clothing, the same sensation of comfort as that induced by the actual conditions of temperature, humidity, and air movement (American Meteorological Society Glossary of Meteorology, http://amsglossary.allenpress.com/glossary/). By a combination of air temperature and humidity in summer, and air temperature and wind speed in winter, the apparent temperature which a person would feel can be determined for conditions with specific humidity and wind speed values respectively. Measures of apparent temperature are used to indicate whether weather conditions are expected to be or become hazardous to human health. Similar indexes have been developed in the agricultural sector to measure the effect of the weather conditions on the productivity and well-being of livestock, but will not be discussed here.

Temperature-humidity index

The temperature-humidity index, also known as the discomfort index, is a guide to determine human comfort levels in summer. The higher this combination between temperature and humidity, the more difficult it is for the body to cool itself. If you work outdoors it is critical that you remain aware of the heat index and take the appropriate precautions. Table 5 provides a guideline used by the South African Weather Service (as adopted from the United States Weather Service) when warnings should be issued to the public. Depending on data availability, different equations are used to calculate index values, of which the most often used values are presented in Table 6.

Table 5. Hazardous values of the temperature humidity index and likely effects on the human body.

Heat Index	Effects on the human body
55 or above	Heat stroke highly likely
40 to 54	Heat stroke likely with prolonged exposure
32 to 39	Heat stroke possible with prolonged exposure

Table 6. The temperature-humidity index or discomfort index. Values of 55 or above are indicated in red, 40 to 54 indicated in orange and 32 to 39 indicated in yellow.

		Relative Humidity (%)													
		35	40	45	50	55	60	65	70	75	80	85	90	95	100
Air Temperature (°C)	44														
	42	50	54												
	40	46	48	51	55										
	38	41	43	46	49	52	55								
	36	38	39	41	43	46	48	51	54						
	34	34	35	37	38	40	42	44	47	49	52	55			
	32	31	32	33	34	36	37	39	40	42	44	47	49	51	54
	30	29	30	30	31	32	33	34	35	36	38	39	41	42	44
	28	27	28	28	28	29	29	30	31	31	32	33	34	35	36
	26	26	26	26	27	27	27	27	27	27	28	28	28	28	28

Heat waves

A heat wave is most often defined as a period of abnormally and uncomfortably hot and humid weather, lasting for three days or longer. To determine the existence of a heat wave, the temperature-humidity index can therefore be useful. The average number of heat waves per year is zero in southern Gauteng, but with OR Tambo International experiencing a maximum of four days with days when heat stroke are possible in 2003. In the northern parts, due to generally higher temperatures, heat waves are more likely. The weather station at UNISA recorded its highest number of days with heat strokes possible at 74 in 2000, with an average of 13 per year during the last decade. It should however be noted that most years experienced zero days when heat strokes are possible.

If heat waves are defined as a period of at least three days when the daily maximum temperature is at least five degree higher than the average of the hottest month, Pretoria has about an average of 10 days per year which can contribute to a heat wave (maximum temperature 35°C or higher), while for Johannesburg it is about four days per year (maximum temperature 32°C or higher). However, these extreme temperatures tend to cluster together with the effect that during anomalously hot summers the likelihood of heat waves are higher than the number of extremely hot days suggests. In 2015, considered to be one of the hottest years on record, Pretoria UNISA had 117 and OR Tambo eight extremely hot days. As a consequence OR Tambo had only one or two heatwaves (depending on how it is defined), while UNISA experienced a relatively large number, with the longest stretching over 14 days.

Wind chill index

The wind-chill index gives an indication of the apparent temperature under low temperature and windy conditions, usually in the winter months. Several equations exist to calculate this index, with consequent small differences of index values for specific temperature and wind speed values. Table 7 presents values of the wind-chill index as used by the South African Weather Service, adopted from the United States and Canadian Weather Services. Wind-chill index values are only applicable to temperatures of 10°C or below. Dangerous index values are usually considered to be -29°C or lower, when frostbite to the face is likely within half an hour or less. However, even index values as high as 0°C can prove to be dangerous to humans and animals that are in ill health or do not have adequate protection or shelter.

Fortunately, low temperatures in winter in Gauteng are not often accompanied by high wind speeds. The wind tends to be mostly calm in the early morning when the lowest temperatures are experienced. Notwithstanding, Johannesburg experiences on average more than 100 hours per year when the index value falls below 0°C. In Pretoria it is much less with about 35 hours per year when it is dangerous for humans and animals without adequate shelter.

Table 7. The wind-chill index.

		Wind Speed (km/h)									
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Air Temperature (°C)	**10**	9	7	7	6	6	5	5	4	4	4
	8	6	5	4	3	3	2	2	2	1	1
	6	4	2	1	1	0	0	-1	-1	-2	-2
	4	1	0	-1	-2	-3	-3	-4	-4	-4	-5
	2	-1	-3	-4	-5	-5	-6	-6	-7	-7	-8
	0	-3	-5	-6	-7	-8	-9	-9	-10	-10	-11
	-2	-6	-8	-9	-10	-11	-12	-12	-13	-13	-14
	-4	-8	-10	-12	-13	-14	-14	-15	-15	-16	-16
	-6	-10	-13	-14	-15	-16	-17	-18	-18	-19	-19
	-8	-13	-15	-17	-18	-19	-20	-21	-21	-22	-22
	-10	-15	-18	-19	-21	-22	-23	-23	-24	-25	-25

3.5 Frost

Frost can be defined as a deposit of small white ice crystals formed on the ground or other surfaces when the temperature falls below freezing. It follows then that if a surface is chilled below the dew point of the surrounding humid air, and the surface itself is colder than freezing, ice will form on it. Depending on the locality, the prevalence of frost are quite variable and depend on the locality and wind speed. In the winter, valleys, where colder air tends to accumulate, are more susceptible to frost than higher lying areas close by.

Due to relatively lower temperatures, frost are more likely in the southern than northern parts of Gauteng. However, frost is not uncommon in the north. Temperatures are usually measured at 1 – 2 m above ground level and if this temperature falls below 2°C frost becomes likely, dependent on air moisture and wind speed, which should be almost calm. Johannesburg has on average about 30 days per year when frost is likely, but this number has diminished over the last decade to an average of about 15 per year. While the normal for Pretoria over the last 30 years was about 16 days per year, we experienced only five days on average over the last decade when frost was possible.

4. Sunshine and Cloudiness

4.1 Introduction

Gauteng receives a relative high amount of sunshine, compared to the rest of the world. The province receives just more than 70% of the maximum possible sunshine, which equates to an annual average of more than 8 hours of sunshine per day. In comparison the western interior receives more than 80% and the east coast mostly below 55%. Therefore Gauteng receives close to the average amount of sunshine in South Africa as a whole. Figure 30 presents an approximation of the daily average sunshine duration, expressed as a percentage of the maximum possible duration.

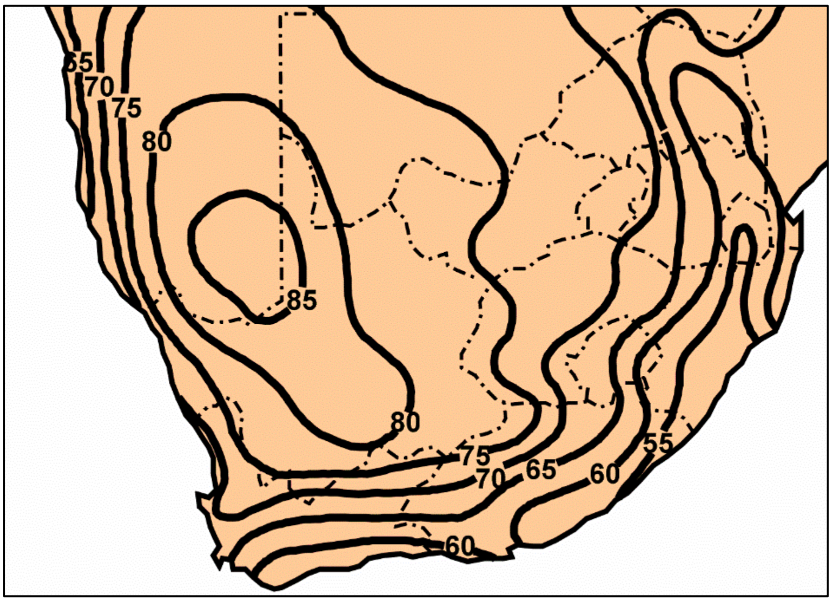
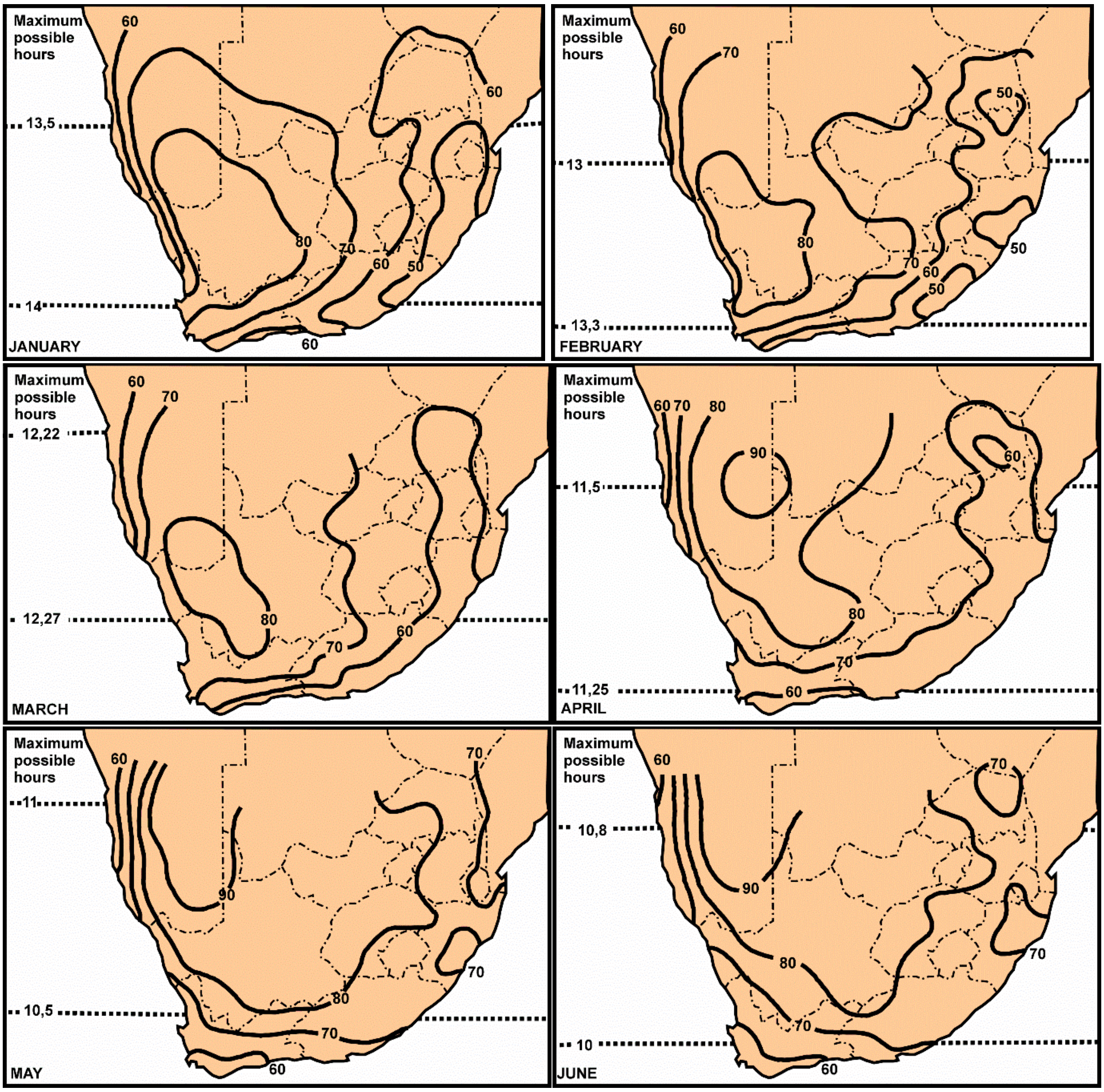


Fig. 30. Approximation of the daily average sunshine duration in South Africa, expressed as a percentage of the maximum possible duration.

The annual march of average daily sunshine duration closely follows the seasonal variation in rainfall and therefore to a large extent cloudiness. An approximation of the average percentage of possible sunshine per month is presented in Figure 31. The following can clearly be seen from the maps, with special emphasis on Gauteng:

- Almost the whole country receives more than 70% of the possible sunshine during the winter months, except for the south-western Cape and a small part of the KwaZulu-Natal coastal area. From May to August Gauteng usually receives more than 80% of possible sunshine.
- With the exception of the south-western Cape, which receives most rainfall in the winter months, the percentage of possible sunshine largely reflects the rainfall distribution over South Africa. The months of minimum sunshine in Gauteng are from November to March, when just over 60% of possible sunshine is received. These months largely coincide with the summer rainfall season.



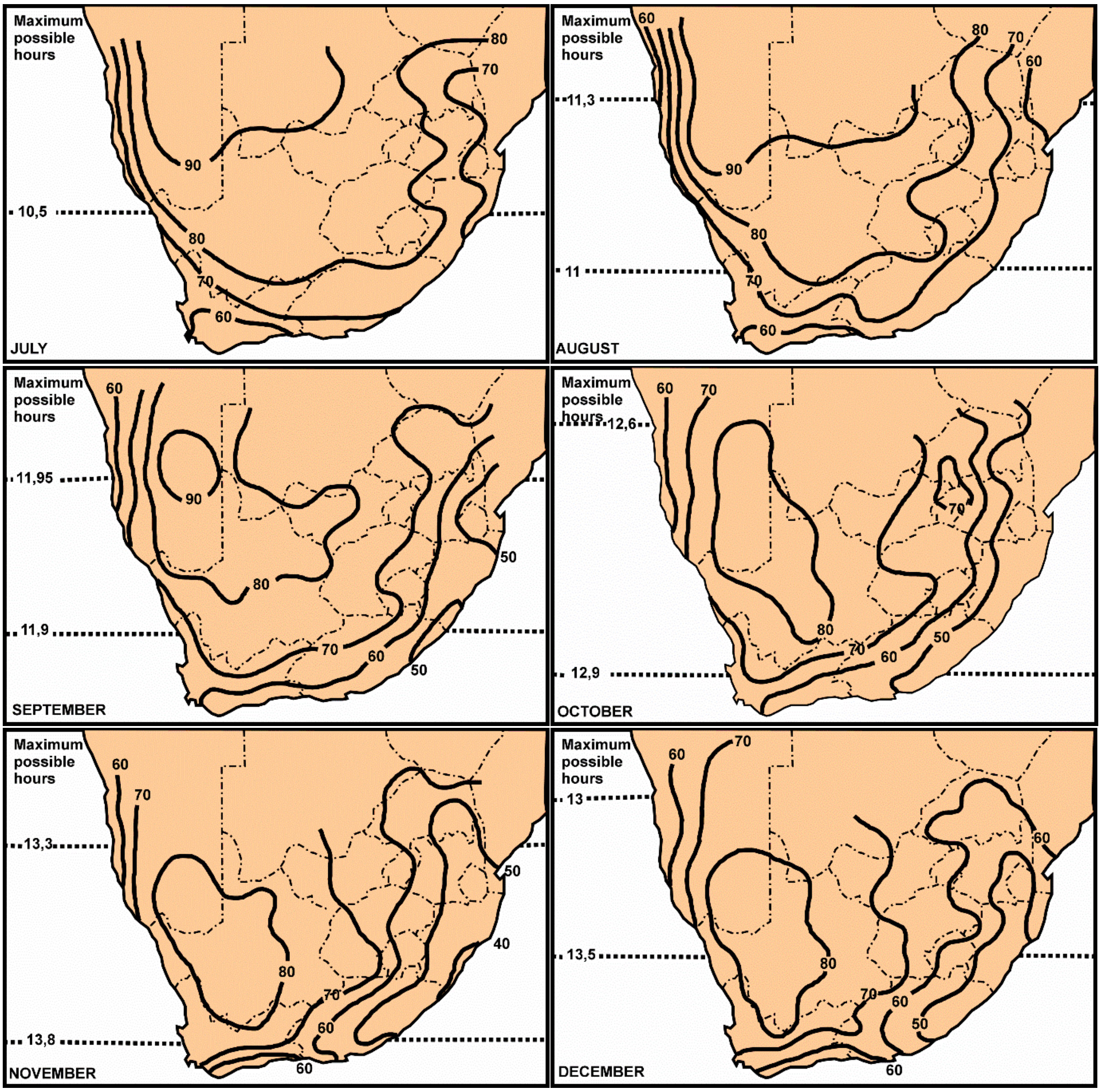


Fig. 31. Approximation of average percentage of possible sunshine per month. The figures on the left indicate the maximum possible hours per day.

4.2 Frequencies of days with sunshine within certain limits

In respect of sunshine duration or cloudiness, days are often described as overcast, cloudy, sunny or fine. To assist in the discussion of the frequency of days within certain limits of sunshine duration or cloudiness, we define the following:

- Overcast day: no sunshine or total cloud cover for the total duration of daylight time
- Cloudy day: up to 10% of the possible sunshine received during a particular day
- Sunny day: at least 50% of the possible sunshine duration
- Fine day: at least 90% of the possible sunshine duration.

On an annual basis, Gauteng experiences fewer than 10 overcast days, in the region of 20 cloudy days, just over 300 sunny days and more than 150 fine days, with the last mentioned mostly occurring in the winter and early spring.

To illustrate how the number of cloudy and overcast days varies throughout the year, Figure 32 presents the average monthly frequencies of cloudy days for Gauteng, averaged from all available data from 1991 to 2020. As can be expected, maximum occurrence occur during the months of maximum average rainfall in summer, which is also linked to the amount of rainfall received.

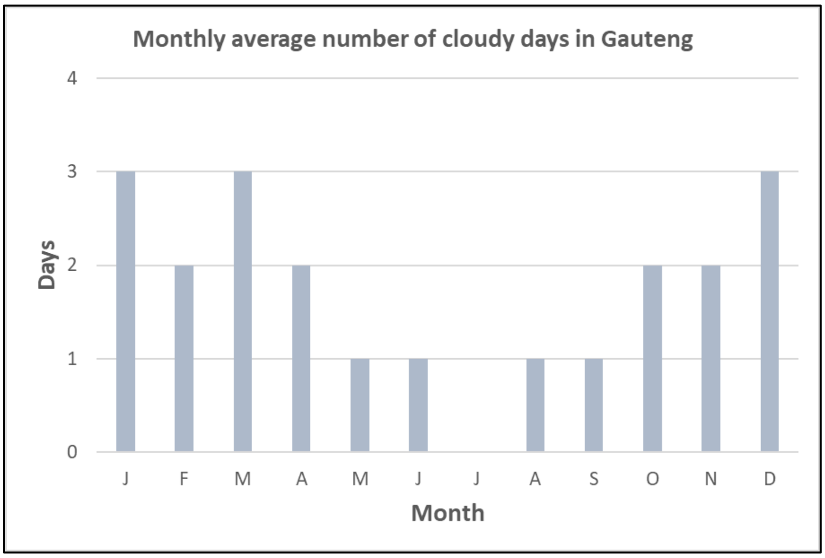


Fig. 32. Average number of cloudy days in Gauteng per month (1991 – 2020).

Figure 33 presents the average number of fine days in the province. The interior, which includes Gauteng, experiences most of its fine days during the dry winter season and the least in early autumn, when influxes of moist air from the east with resultant low cloud are frequent.

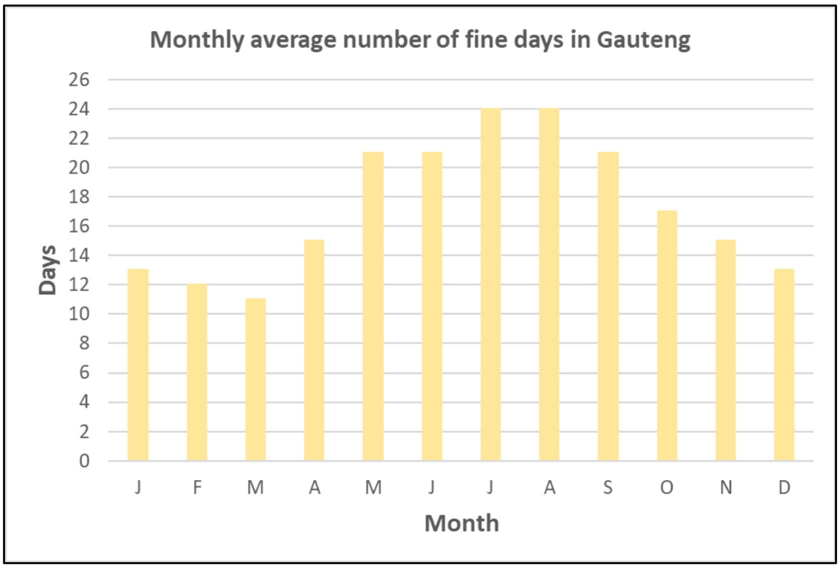


Fig. 33. Average number of fine days in Gauteng per month (1991 – 2020).

4.3 Different types of clouds and their frequencies of occurrence.

The different types of cloud present influence the incoming solar radiation in different ways. Particular cloud types are also an indication of occurrence of the type of weather and precipitation that can be associated with them. Clouds can be broadly categorized in three classes, namely:

Low clouds, for example Cumulus, Stratus and Stratocumulus. These clouds can be as low as ground level, e.g. Stratus in the form of fog, but can reach heights of more than 10 km as is the case with well-developed Cumulonimbus thunderclouds. Low clouds are usually relatively thick and are able to reflect most solar radiation incident upon it into space. However, with loose Cumulus or Stratocumulus cloud, a high percentage of diffuse radiation is caused by reflection, reducing the blanketing effect of the clouds. Cumulus clouds are convective and usually develop during late morning or afternoon in summer. The preconditions for them to develop are sufficient surface heating, enough moisture and an unstable air mass. This will cause moist air to rise and reach its condensation point at a specific level. After sufficient development, Cumulonimbus thunder clouds may develop.

Stratus may form due to advection of moisture laden air over a surface, or forced to a higher level, colder than its condensation point, usually during the early morning. The clouds formed often dissipate when the sun’s heat evaporates the water droplets of the clouds. When moist air experiences some form of convection or upliftment, but here is a stable layer of air at a relatively low level above it, Stratocumulus may form when condensation occurs, but convective action will be limited. The clouds will then form as rolls or waves. Sometimes there are gaps in the cloud layer through which the sun can shine. Low cloud are more important because they are the clouds that produce most precipitation and in some cases like Stratus, have an effect on visibility.

Middle clouds, for example Altocumulus and Altostratus. Especially Altocumulus clouds can also be quite thick and can thus reflect most of the solar radiation back into space. Their height range from about two to five km, but in the case of Nimbostratus can be at almost ground level due to extensive precipitation which lowers the base of the cloud.

High clouds, for example Cirrus, Cirrocumulus and Cirrostratus. These clouds can occur in very thin layers which enable a large portion of incoming solar radiation through, but also give rise to a substantial amount of diffuse radiation. High clouds usually occur at a height of about 10 km.

As low cloud is the only cloud category for which the amount can be assessed accurately from the surface, and is also most indicative of prevailing weather conditions, a more detailed analysis of types of low cloud occurring in Gauteng during different seasons and times of observation should be useful. Table 8 presents the percentage contribution of three broad categories of low cloud, namely Cumulus-types, Stratocumulus-types and Stratus-types at 08:00, 14:00 and 20:00 during the four seasons and for the year. There is also a category for both Cumulus and Stratocumulus, as it happens frequently that Cumulus may develop from Stratocumulus with sufficient surface heating and that Stratocumulus can form with the dissipation of Cumulus. Cumulonimbus is categorised separately as these clouds are associated with thunderstorms and associated severe weather. It is clear that in Gauteng Cumulus dominates in the afternoon and evening, but not during the morning when there is still not enough surface heating for the development of convective clouds. A high presence of Stratocumulus is observed in the morning, and in autumn fog (Stratus) occurs relatively frequent due to the advection of moist air from the east.

Table 8. Average percentages (1991 – 2020) of skies with no low cloud, predominantly Cumulonimbus (Cb), Cumulus (Cu), Cumulus and Stratocumulus (Sc) combined, Stratocumulus and Stratus (St) at OR Tambo International Weather Office at specific observation times per season as indicated.

Season	Hour	No low cloud (%)	Predominantly:				
			Cb (%)	Cu (%)	Cu and Sc (%)	Sc (%)	St (%)
Summer	08:00	42	3	6	1	25	24
	14:00	5	19	63	1	11	2
	20:00	48	31	7	3	8	3
Autumn	08:00	66	1	2	0	11	19
	14:00	27	8	52	2	10	1
	20:00	77	9	3	1	7	2
Winter	08:00	83	0	1	0	5	10
	14:00	72	0	18	1	8	0
	20:00	93	1	1	1	4	0
Spring	08:00	66	2	3	0	13	16
	14:00	33	10	46	1	9	1
	20:00	71	17	3	2	5	3

4.4 Solar energy

With the drive from fossil fuels to renewable energy sources, it is primarily wind and solar energy that have both become increasingly important for our future energy needs. Gauteng's position in the north of South Africa makes the local exploitation of wind for energy generation restricted, compared to the relatively windy south. However, solar energy is a very viable source of energy in the province. Solar energy resource information is widely available, particularly in atlas format. Developers and users of solar energy are mostly interested in the direct normal irradiation, global horizontal irradiation and resultant power potential. Atlases with this information are readily available from the Global Solar Atlas web portal (https://globalsolaratlas.info/), endorsed by the World Bank, and presented in Figures 34 to 36 respectively.

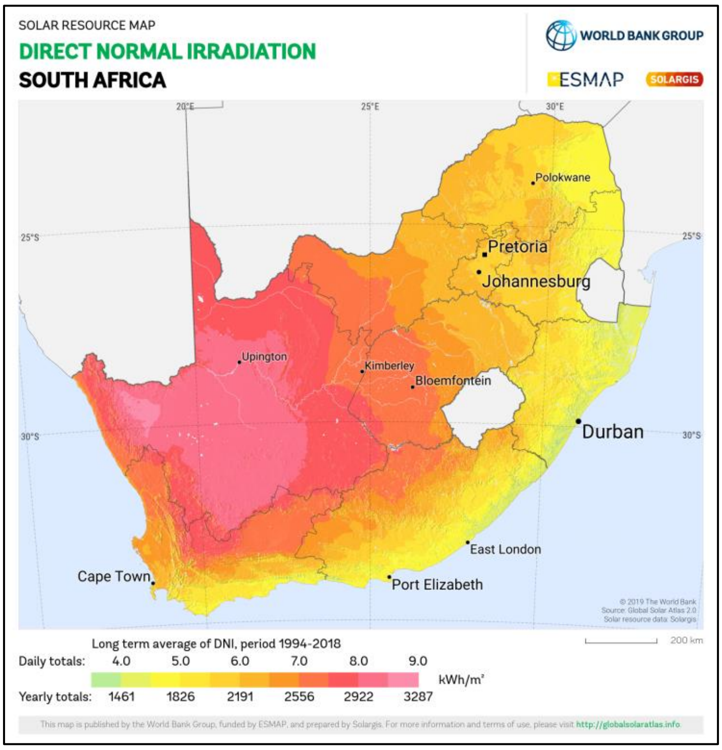


Fig. 34. Direct normal irradiation per year (1994 – 2018) (https://globalsolaratlas.info/).

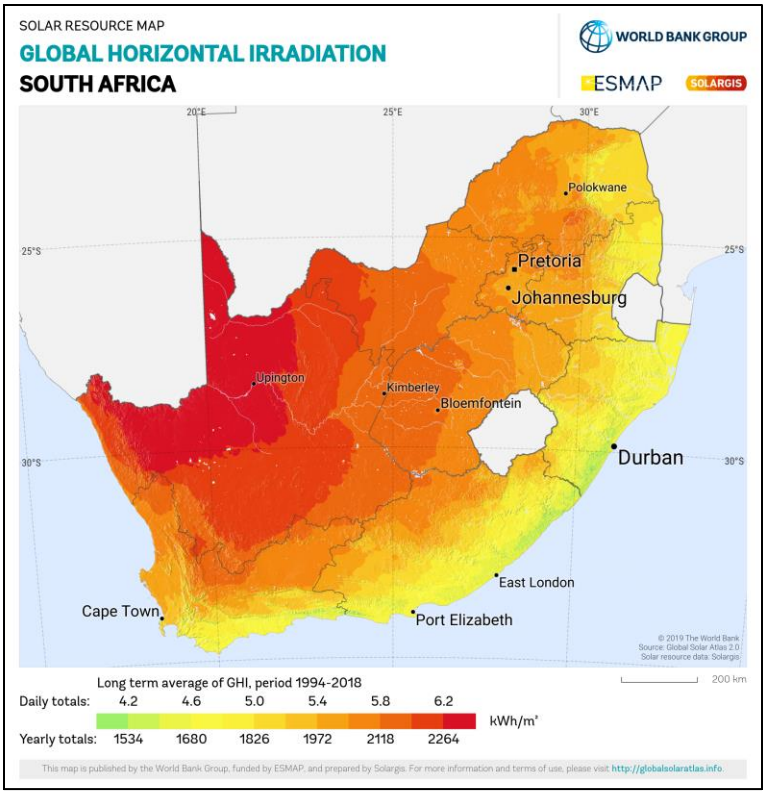


Fig. 35. Average global horizontal irradiation per year (1994 – 2018) (https://globalsolaratlas.info/).

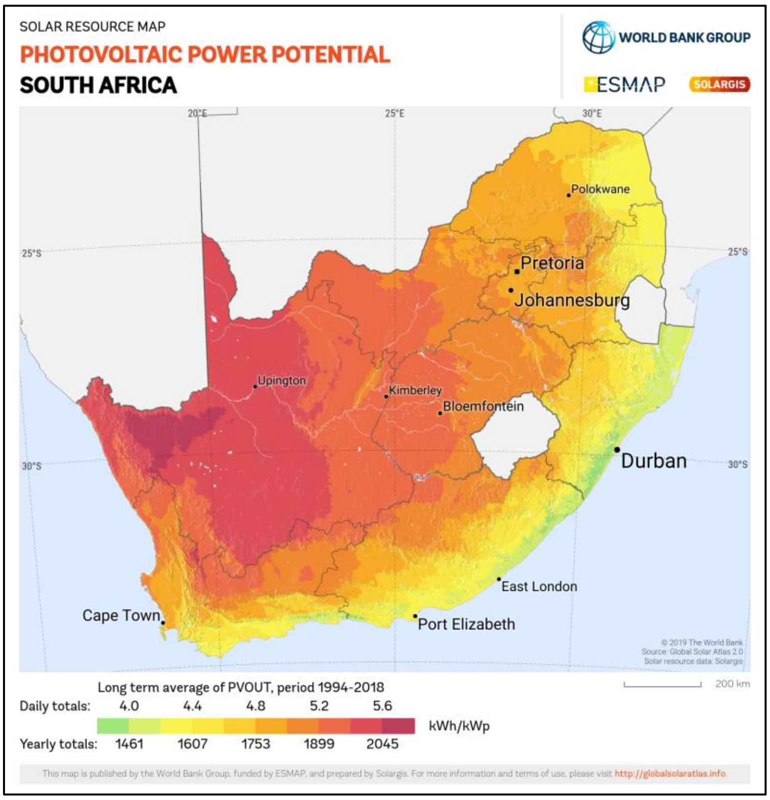


Fig. 36. Average photovoltaic power potential per year (1994 – 2018) (https://globalsolaratlas.info/).

5. Precipitation

5.1 Introduction

The annual and seasonal distribution of rainfall are presented in Figures 37 to 41. As mentioned before, Gauteng falls within the summer rainfall region of South Africa. Therefore summer is the season which receives most rainfall, followed by spring and autumn. In winter rainfall is negligibly small, although isolated cases of significant rainfall were recorded in the past.

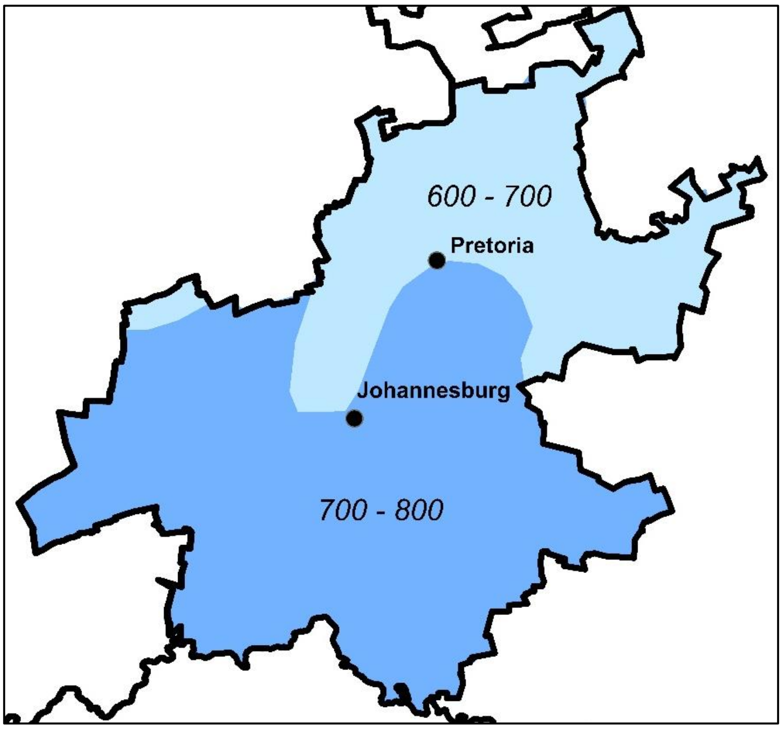


Fig. 37. Mean annual rainfall (mm) based on topography and data over the period 1991 – 2020.

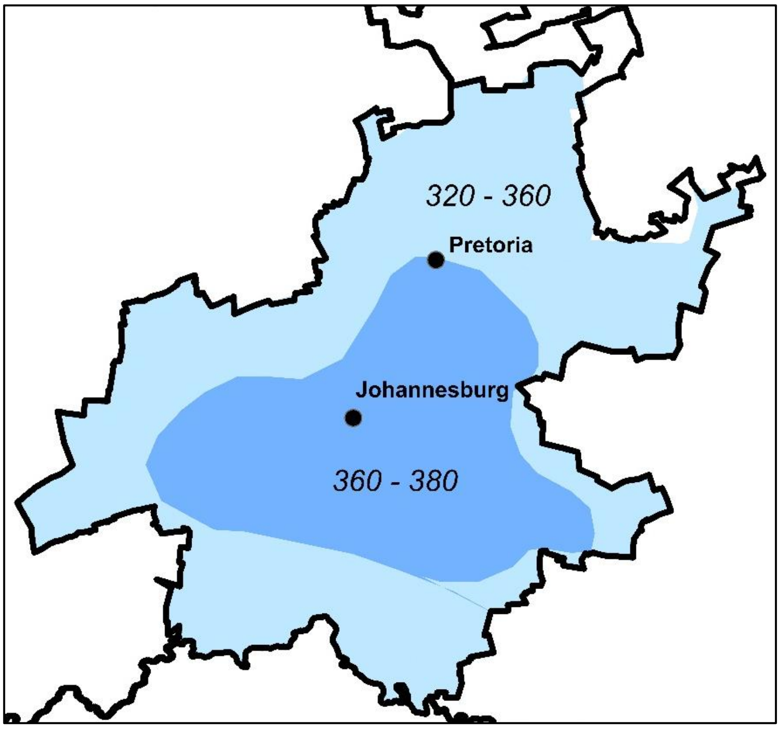


Fig. 38. Mean summer (DJF) rainfall (mm) based on topography and data over the period 1991 – 2020.

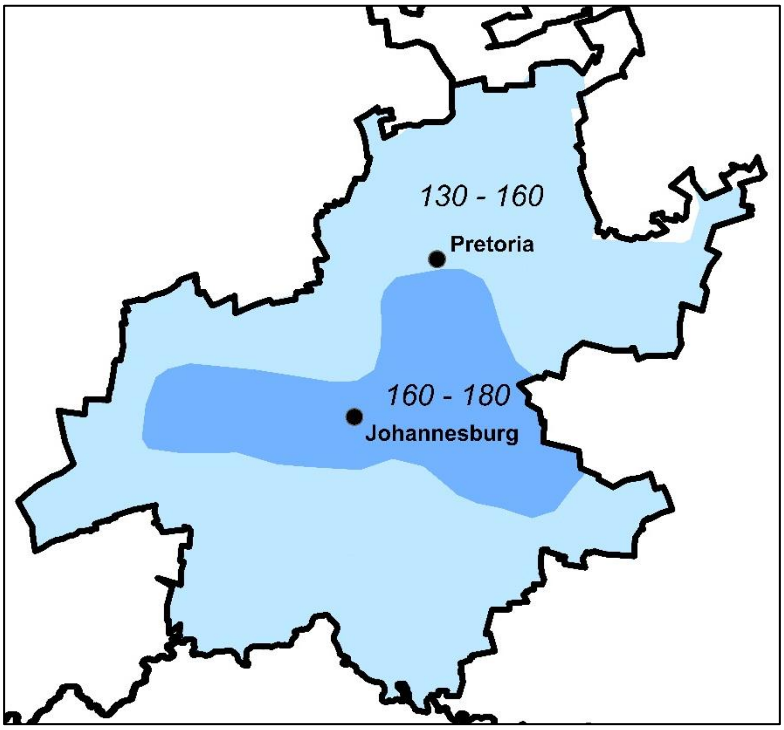


Fig. 39. Mean autumn (MAM) rainfall (mm) based on topography and data over the period 1991 – 2020.

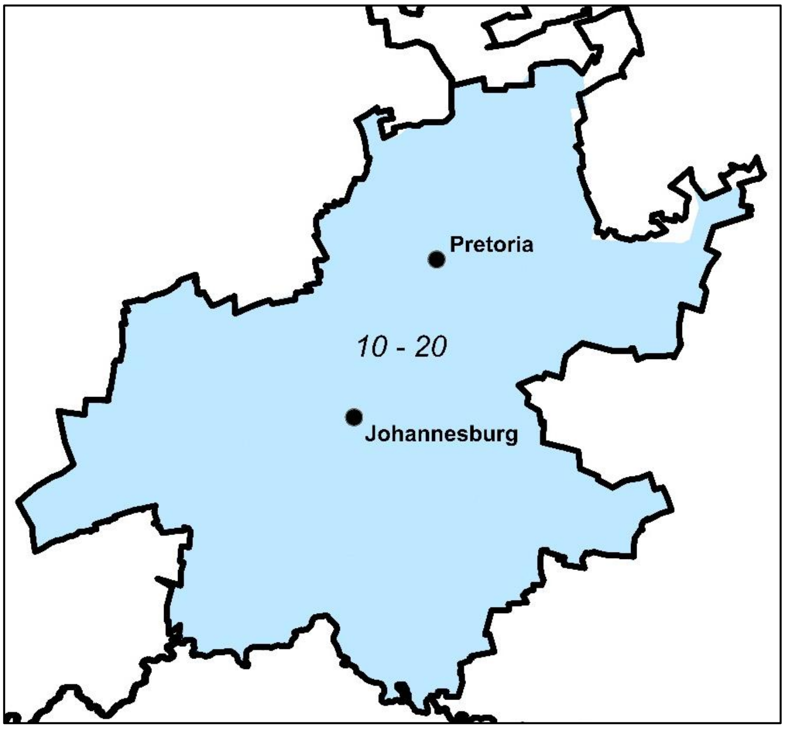


Fig. 40. Mean winter (JJA) rainfall (mm) based on topography and data over the period 1991 – 2020.

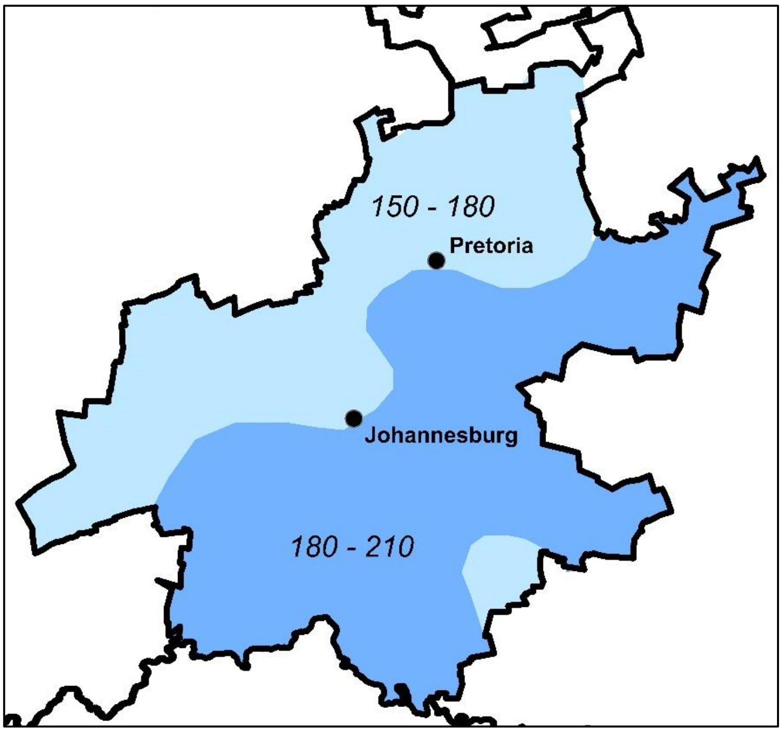


Fig. 41. Mean spring (SON) rainfall (mm) based on topography and data over the period 1991 – 2020.

5.2 Dry and wet seasons/years

Is there cyclical behaviour in seasonal rainfall? This is a question that is still often raised and some decades ago a clear near-decadal cycle in rainfall in most of the summer-rainfall region of South Arica could be observed, with alternation between a series of drier and wetter periods. However, more recently this decadal-scale behaviour of the rainfall largely diminished. Figures 42 and 43 present the time series of the 12-month SPI (Standardised Precipitation Index) and SPEI (Standardised Precipitation and Evaporation Index) of the rainfall at OR Tambo International Airport. The SPI is the most widely used drought index and can be calculated over any period (in this case 12 months to consider the rainfall over a calendar year) and only uses monthly rainfall data as input. The SPEI is a refinement of the SPI and also takes the surface temperature into account. Figure 6 clearly shows in the early part of the record that intermittent decades of drier and wetter decades can be discerned. The 1950s were mostly wet, the 1960s dry, the 1970s mostly wet and the 1980s dry. However, the late 1980s was relatively wet and was followed by the very dry early 1990s with the 1991/2 drought one of the worst on record.

Interesting to note is the difference in trend between the SPI and SPEI. In the case of SPI no significant trend is detected but there is a significant negative trend in the SPEI over the analysis period. Because the SPEI, in contrast with the SPI, takes surface temperature (and therefore evaporation) into account, the gradual warming due to climate change seems to exacerbate the intensity of droughts over the long term.

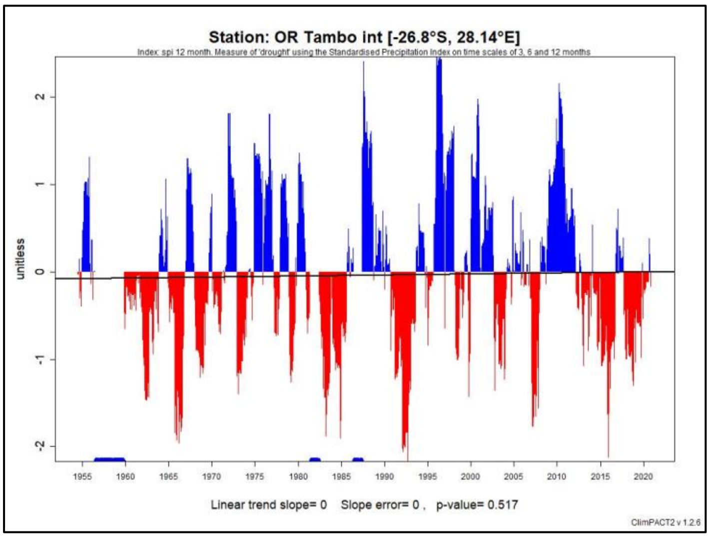


Fig. 42. 12-month SPI for OR Tambo International Airport (1953 – Jan 2021).

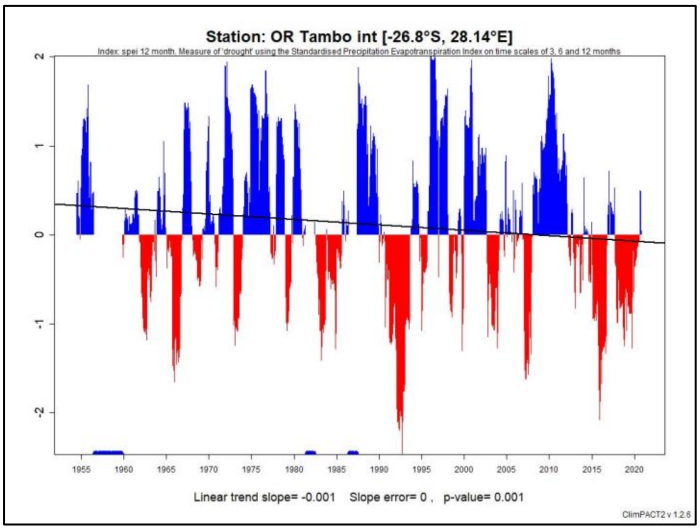


Fig. 43. 12-month SPEI for OR Tambo International Airport (1953 – Jan 2021).

The accuracy and subsequent usefulness of seasonal rainfall forecasts are largely based on the identification of teleconnection patterns between synoptic conditions conducive to rainfall and the variation of SST anomalies over large areas of the ocean. A teleconnection can be defined as an effect or correlation between the conditions of physical entities over very large distances. In the case of the summer rainfall region of South Africa it has been established as early as the 1980s that SST anomalies in the equatorial Pacific Ocean has a significant influence on the local rainfall. If the equatorial Pacific Ocean is anomalously warm (El Niño)/cold (La Niña) local conditions tend to be drier/wetter than normal. It should be noted that while this correlation is strong it does not mean that all El Niño seasons are dry and La Niña seasons wet, and also does not apply over the whole summer-rainfall region of South Africa. A simple analysis of the possible correlation between Niño3.4 SSTs and seasonal rainfall for OR Tambo International shows that over Gauteng in particular, such a simple correlation does not exist but the relationship can be pronounced when only recognised El Niño and La Niña seasons are considered (see Figure 44). In the next section on detected climate change it will be further investigated whether there is a systematic long-term trend in the seasonal rainfall, i.e. analysing whether it has become progressively wetter or drier in the province.

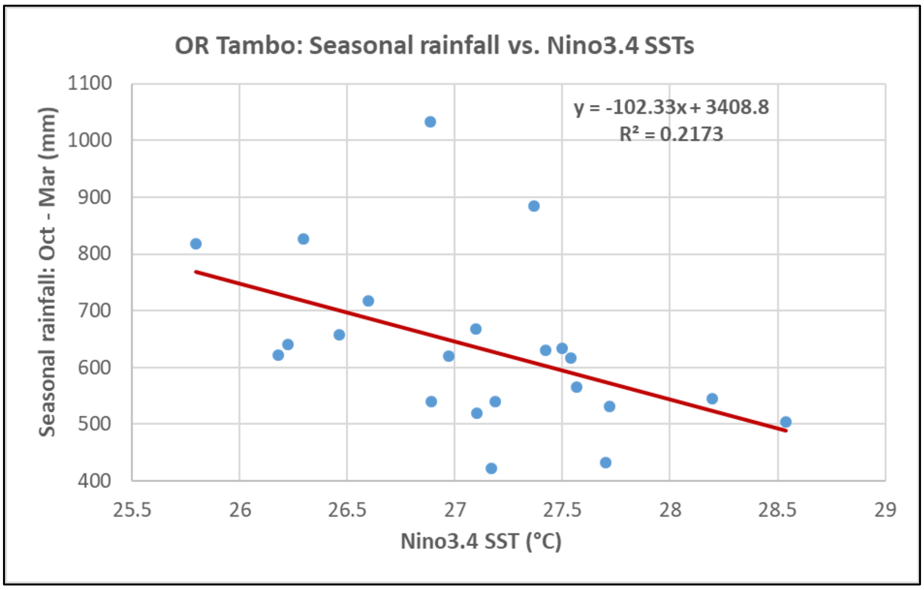


Fig. 44. Nino3.4 SST vs. seasonal rainfall at OR Tambo International (1991/92 – 2019/20). The red line indicates a statistically significant correlation at the 5% level *(Neutral years, i.e. neither La Nina nor El Nino are excluded).*

5.3 Daily rainfall

Table 9 presents the monthly average total of rain days per month and per year for OR Tambo International Airport and Irene Weather Office. These figures are representative for most of the province, but with a somewhat higher figure for especially rain days in summer in the south compared to the north.

Table 9. Average number of rain days (>= 1mm) per month and year (1991 – 2020).

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
OR Tambo Int.	11	9	8	5	2	1	0	1	2	7	11	13	69
Irene WO	11	9	8	5	2	1	0	1	2	6	10	12	65

In addition to the number of rainy days it is of interest to various users of climate information to know the number of days with rainfall above specific thresholds. Table 10 presents the average number of days with rainfall equal or more than 5 mm, 10 mm, 15 mm, 20 mm and 30 mm for OR Tambo International and Irene Weather Offices. Here the differences between the two locations are more noteworthy than the average number of rainy days in Table 9. There is an average of 43 days with rainfall equal or more than 5 mm at OR Tambo, compared to a markedly lower 37 days at Irene.

Table 10. Average number of days with rain >= 5mm, 10 mm, 15 mm, 20 mm and 30 mm, per month and year (1991 – 2020).

Rainfall amount (mm)	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
OR Tambo International													
>=5	8	6	5	3	1	0	0	0	1	4	7	8	43
>=10	5	4	3	1	1	0	0	0	0	3	4	5	26

>=15	3	2	2	1	0	0	0	0	0	1	2	3	17
>=20	2	2	2	1	0	0	0	0	0	1	1	2	11
>=30	1	1	1	0	0	0	0	0	0	0	1	1	5
Irene Weather Office													
>=5	7	5	4	2	1	0	0	0	1	3	6	7	37
>=10	4	3	3	1	1	0	0	0	0	2	3	4	23
>=15	3	2	2	1	0	0	0	0	0	1	2	3	15
>=20	2	2	1	1	0	0	0	0	0	1	1	2	10
>=30	1	1	1	0	0	0	0	0	0	0	0	1	4

The likelihood of extreme rainfall is of interest to planning and emergency sectors, such as the built environment and disaster management. Climate extremes can be described as those events with a probability of occurrence only over multiple years. If a daily rainfall amount of 50 mm or more is considered to be substantial enough for the possibility of flooding, the return period or likelihood of such an event can be estimated. For OR Tambo the likelihood of recording 50 mm or more is about once a year while for 75 mm the likelihood or return period is about once every 6 years. For Irene the likelihood for 50 mm is about the same but extreme rainfall of 75 mm or higher is more likely, with a 4-year return period. Return periods and likelihoods of occurrence can be calculated for any rainfall amount, but is dependent on the availability of reliable long-term measurements. Here it should also be noted that it is generally assumed that due to climate change the likelihood of extreme rainfall events have increased and will do so in future.

5.4 Hourly rainfall

The probability of rainfall occurring during specific hours are presented on a seasonal basis for OR Tambo International Airport and Irene Weather Office in Figures 45 and 46 respectively. As can be expected for the province, the probability for rainfall is greatest in summer and smallest in winter, regardless of the hour of day. For the rainfall seasons when the rainfall probability is greatest there is a substantial bias of probability towards the late afternoon and early evening hours. This is due to the convective nature of most of the rainfall where the probability of rainfall coincides with the time of typical thunderstorm development in summer, which is in the late afternoon after sufficient surface heating over the course of the day. It should be noted that with conducive atmospheric conditions, i.e. sufficient moisture and instability, thunderstorms can develop and be sustained during any time of the day.

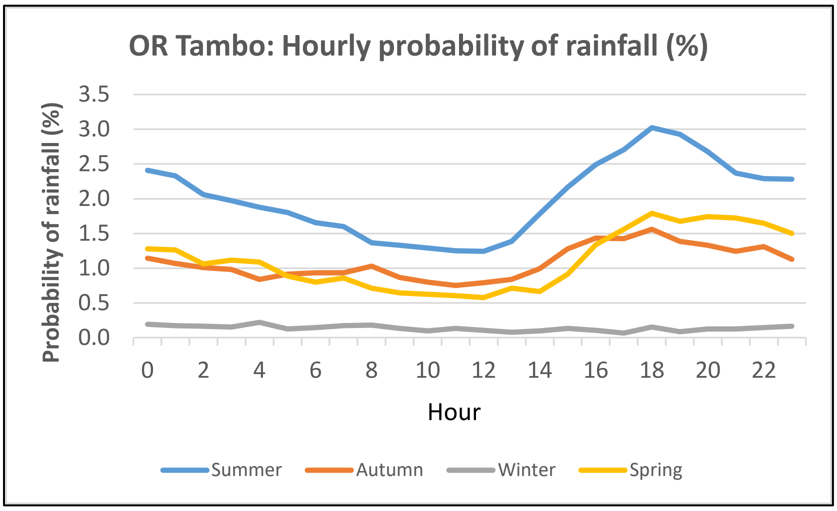


Fig. 45. Probability of rainfall (%) during specific hours at OR Tambo International Airport (1991 – 2020).

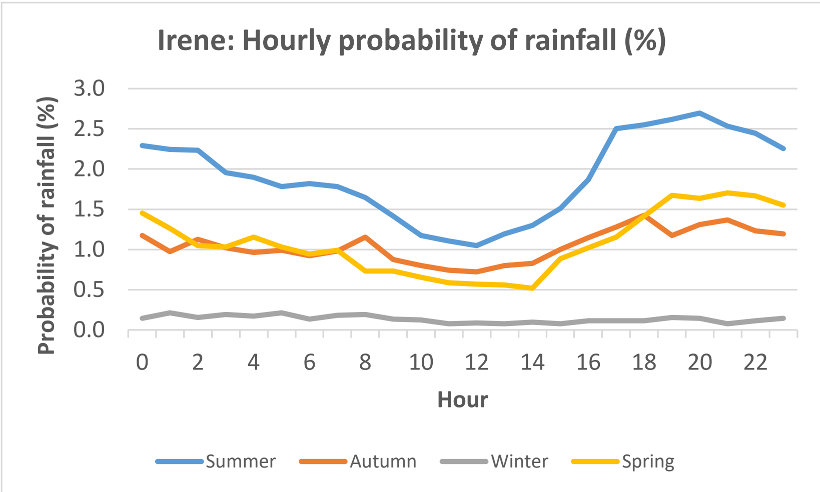


Fig. 46. Probability of rainfall (%) during specific hours at Irene Weather Office (1991 – 2020).

5.5 Sub-hourly rainfall intensity

Flood are usually caused by persistent rainfall of various intensity over a prolonged period or a lot of rainfall over a short period of time. In Gauteng floods are usually caused by the latter. The automatic weather station technology that SAWS utilise is able to provide the rainfall amounts to a frequency of five minutes. Table 11 presents, for OR Tambo International and Irene Weather Office, the frequency with which the rainfall exceeded 5 mm, 10 mm and 15 mm within a five minute period over the 1991 – 2020 period. These statistics, as well as return periods of hourly and sub-hourly rainfall figures, can be calculated for any period over any interval which a user might require, but is dependent on a sufficiently long measurement period.

Table 11. Frequencies of five minute intervals with rain >= 1mm, 5 mm, 10 mm and 20 mm (1991 – 2020).

	Rainfall amount (mm) more than:			
Weather station	**>= 1**	**>= 5**	**>= 10**	**>= 15**
OR Tambo	3100	180	5	1
Irene	3182	199	14	0

5.6 Heavy precipitation and thunderstorms

In addition to meteorological measurements, visual observations are also done at weather offices. From these observations the frequencies of particular weather types can be analysed. Table 12 and 13 present the frequencies of heavy precipitation (including from thunderstorms) at OR Tambo International Airport and Irene Weather Office over the period 1991 – 2020, at the main synoptic times of 08:00, 14:00 and 20:00 SAST. From the observations of heavy precipitation it is clear that heavy precipitation is most likely in the summer months in the afternoon. However, there is also a likelihood of heavy precipitation in the mornings, especially in the mid-summer months. This type of weather is almost non-existent in late autumn and winter.

Table 12. Frequency of heavy precipitation (including from thunderstorms) at OR Tambo International Airport over the period 1991 – 2020, at the main synoptic times of 08:00, 14:00 and 20:00 SAST.

Month/Time (SAST)	08:00	14:00	20:00
J	0	4	2
F	6	3	1
M	4	5	1
A	0	2	1
M	0	0	1
J	0	0	0
J	0	0	0
A	0	0	0
S	2	0	0
O	5	1	1
N	2	4	7
D	4	5	5

Table 13. Frequency of heavy precipitation (including from thunderstorms) at Irene Weather Office over the period 1991 – 2020, at the main synoptic times of 08:00, 14:00 and 20:00 SAST.

Month/Time (SAST)	08:00	14:00	20:00
J	4	5	7
F	5	3	5
M	4	5	1
A	1	0	2
M	4	1	2
J	0	1	0
J	0	0	0
A	0	0	0
S	1	0	0
O	1	0	6
N	0	5	8
D	4	0	3

Tables 14 and 15 present the frequencies of all thunderstorms at the same offices, including those that are observed from a distance. Apparent is that thunderstorms are most likely in the evening in summer. The likelihood for thunderstorms to occur diminish to almost zero in winter. Interestingly there is a greater likelihood for thunderstorms in the morning than in the early to mid-afternoon. Frequently in the summer months convective weather can last throughout the night from the afternoon of the previous day.

Table 14. Frequency of thunderstorms (including from a distance) at OR Tambo International Airport over the period 1991 – 2020, at the main synoptic times of 08:00, 14:00 and 20:00 SAST.

Month/Time (SAST)	08:00	14:00	20:00
J	88	66	205
F	68	47	152
M	76	58	155
A	27	24	69
M	14	9	14
J	9	3	5
J	2	0	5
A	15	3	14
S	26	6	35
O	97	32	153
N	84	57	193
D	108	49	264

Table 15. Frequency of thunderstorms (including from a distance) at Irene Weather Office over the period 1991 – 2020, at the main synoptic times of 08:00, 14:00 and 20:00 SAST.

Month/Time (SAST)	08:00	14:00	20:00
J	69	46	202
F	54	35	155
M	49	39	130
A	30	17	68
M	15	6	13
J	6	0	9
J	2	0	1
A	10	0	13
S	26	1	28
O	63	23	138
N	77	34	169
D	99	31	215

5.7 Hail

It is a challenge to accurately estimate the likelihood of hail to occur. This is because hail originate from very strong thunderstorms and is usually reported as such. For example, if a weather observer observes a strong thunderstorm with strong winds and heavy precipitation which includes hail, a single code is given for the present weather. Indirect measurements with satellite and radar can provide an estimate of the likelihood for hail, but these statistics are often overestimated because a cloud formation with a high likelihood of producing hail does not inevitably produce hail in a specific area. Notwithstanding, we know that the province has a high likelihood of strong thunderstorms in late spring and early summer, which is also the time of year when most hailstorms are observed. However, there is a significant likelihood of hail to occur during all of spring and summer, less in autumn and basically none in winter. Previous estimates are between three and five hail days in Gauteng but this can vary substantially on a yearly basis. The months with highest frequencies are usually in early summer (November and December).

6. Climate change

6.1 Introduction

Due to the increase in so-called greenhouse gases (i.e. gases that are able to absorb heat) since the Industrial Revolution, of which carbon dioxide is the most important, the atmosphere has been gradually warming over a long period of time. The increase in atmospheric warming can be traced back for centuries and has increased over the last 100 years by about 1°C. This warming of the atmosphere obviously cause warmer surface temperatures in general but also changes other atmospheric properties, e.g. changes in the general circulation, likelihood of the development of tropical cyclones, climate extremes amongst others. The change in the global climate is expected to accelerate and there are already clear signals that this is already happening.

6.2 Trends in the average climate

The simplest way to establish whether the climate has changed or is changing is by the measurement of the mean climate (e.g. annual) over a number of decades. The clearest signal of climate change is the gradual warming and this can be seen in most long-term temperature records across the world. For Gauteng the most reliable long-term record is that at OR Tambo International Airport and is presented in Figure 47. It is noticeable that since 2002 all the years had average surface temperatures higher than the 1981 – 2020 long-term average. Since 1955 the warming trend is about 0,19°C per decade. The hottest year was 2015 with 2019 a close second, when the annual average temperature was more than 1,5°C above the long-term average.

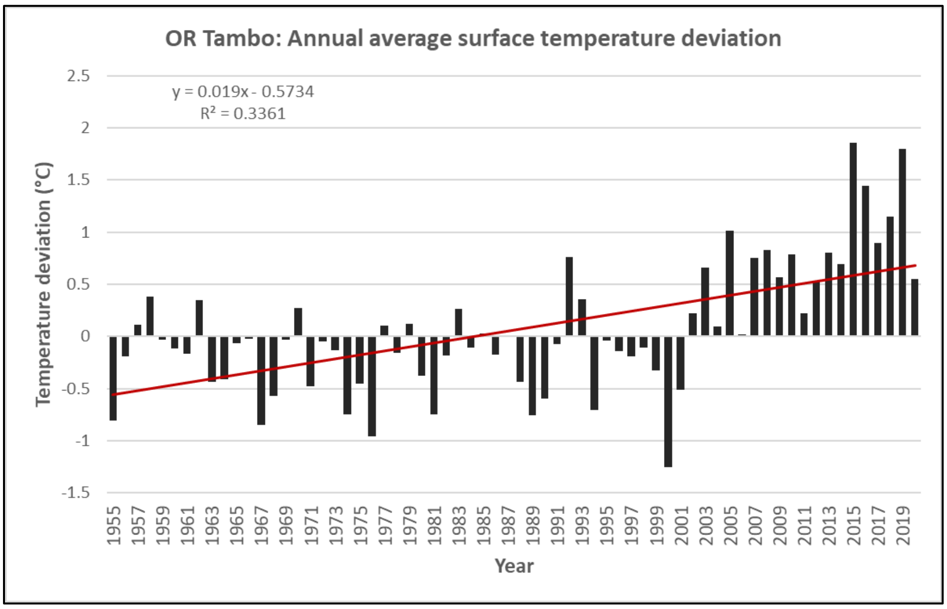


Fig. 47. Annual average surface temperature deviation at OR Tambo International Airport for the period 1955 to 2020 (base period: 1981 – 2010).

While there is general warming across most of the globe the trends in rainfall is more complicated, with some regions experiencing a wetter climate while others are drying. South Africa is no exception with the far northern parts and south-western Cape showing signals of drying and the remainder of the country showing mostly no significant trend. Based on monthly district rainfall statistics, Figure

48 presents the annual percentage of normal rainfall for Gauteng since 1921. The red line represents the linear trend and it is clear that there is no significant change in the annual totals of rainfall received over the last century.

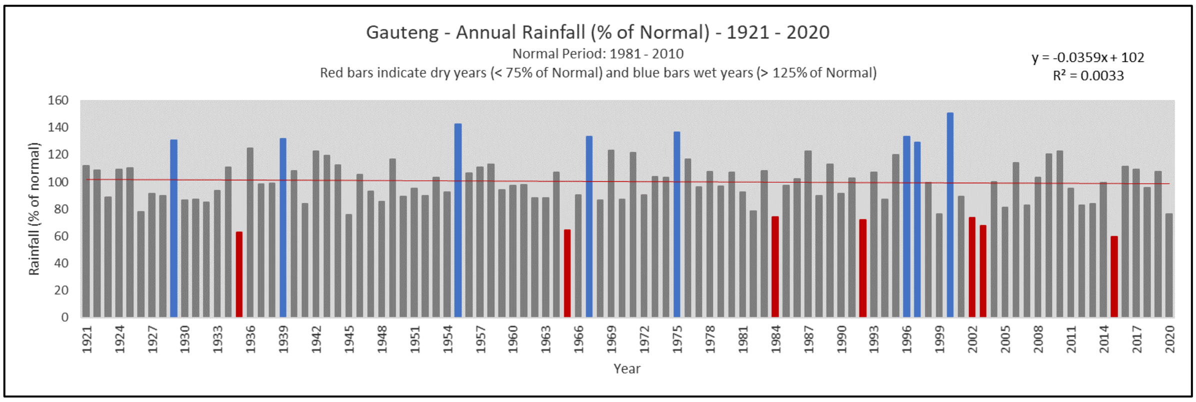


Fig. 48. Annual rainfall (% of normal) for Gauteng province over the period 1921 – 2020. The base period is 1981- 2010 and red bars indicate dry years (< 75% of normal) and blue bars wet years (>75% of normal). The red line indicates the linear trend.

6.3 Trends in extreme climate

While trends in the long-term averages can be discerned from the analysis of climate data sets, the effects of climate change will mostly be felt in the changes in the frequencies of weather and climate extremes. To establish a uniform manner of analysis globally, The World Meteorological Organization established the Expert Team on Climate Change Detection and Indices (ETCCDI) which developed a set of 27 core indices which is used globally to detect trends in relevant climate extremes. The South African Weather Service (SAWS) use these indices to analyse historical trends in rainfall and temperature extremes in South Africa and update the trends on an annual basis.

As can be expected with temperature, hot extremes have increased and cold extremes decreased. The number of hot days and nights increased and cold days and nights decreased. The length of longest warm spell per year has also increased at most places while the longest cold spells per year decreased in length. These observations also apply to Gauteng.

Trends in rainfall extremes are spatially more variable. The average amount of rainfall on a rainy day has increased over most of the interior, including Gauteng (see Figure 49). While a figure of 0,2 to 0,4 mm/decade does not seem like a lot, the upward trend over the province is still significant. Figure 50 presents the trend in the highest daily rainfall per year. Here also it is clear that Gauteng falls within a broad region where the rainfall has become more extreme with an increase of 10 – 20 mm per decade over that last century.

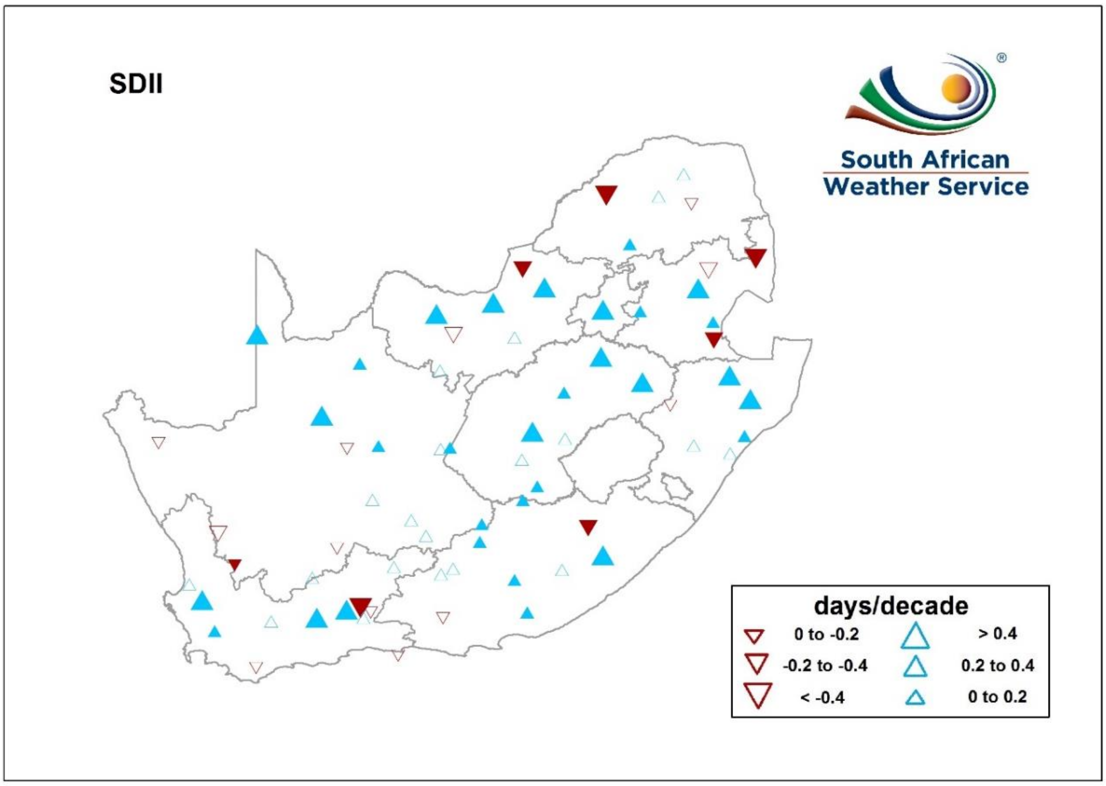


Fig. 49. Trends in SDII, the simple daily rainfall intensity index, for the period 1921–2019. Shaded symbols indicate statistical significance at the 5% level.

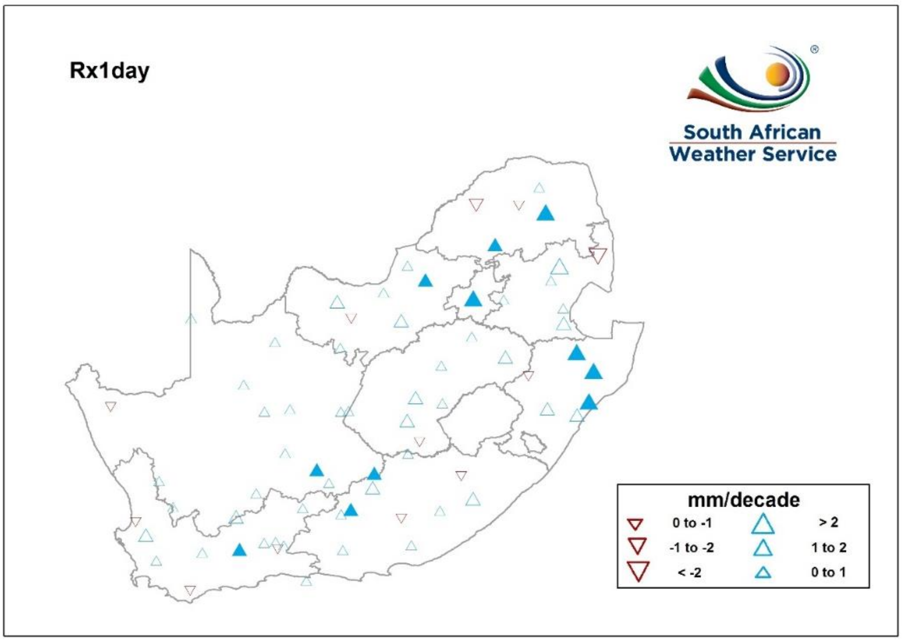


Fig. 50. Trends in rx1day, the annual maximum 1-day precipitation, for the period 1921–2019. Shaded symbols indicate statistical significance at the 5% level.

6.4 Significant weather events

An assessment of the frequencies of specific weather events (e.g. large hail or floods) over a long period of time can only be done through an analysis of media reports. As mentioned before in the section on tornadoes, SAWS produces a publication the CAELUM which provides a geocoded list of significant weather events which were reported in South Africa from 1647. It should be noted that such reports are highly dependent on demographics and population density, where a relatively high population density and the presence of the print media and other documenters makes the documentation of a significant weather events more probable. Also, the amount of damage and/or loss of life that a significant weather event causes also influences its coverage in the media. Nonetheless the above shortcomings it is of importance to analyse these reports to assess the most prevalent events and whether a trend in these events can be discerned. In Gauteng most significant weather reports are on floods, hail and strong wind and their related impacts. Figures 51 to 53 presents the annual number of reports on floods, hail and strong wind respectively, over the period 1961 - 2020. For all these types of events increasing trends are noticeable. These trends can be ascribed to an increase in population density (and therefore more people are affected and also report events), as well as a probable increase in severe weather events, e.g. stronger thunderstorms. The last-mentioned hypothesis can be linked to the results presented in the previous section, which indicates an intensification in rainfall events over the province.

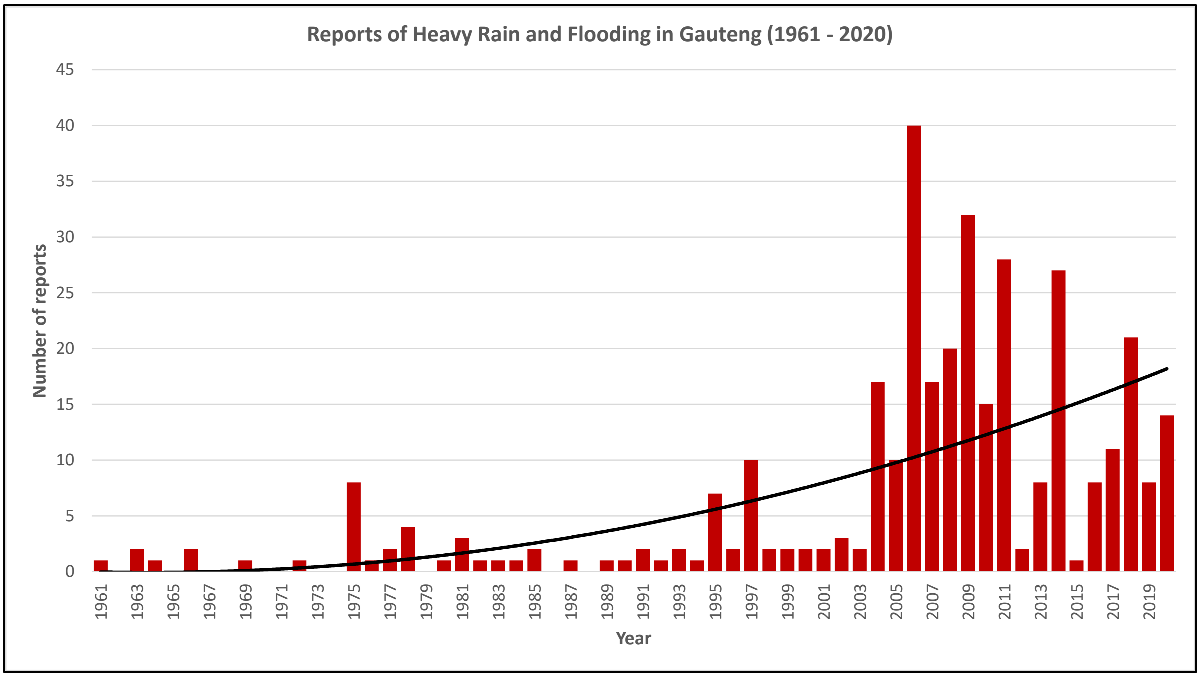


Fig. 51. Annual number of reports on heavy rain and flooding in Gauteng province over the period 1961 – 2020.

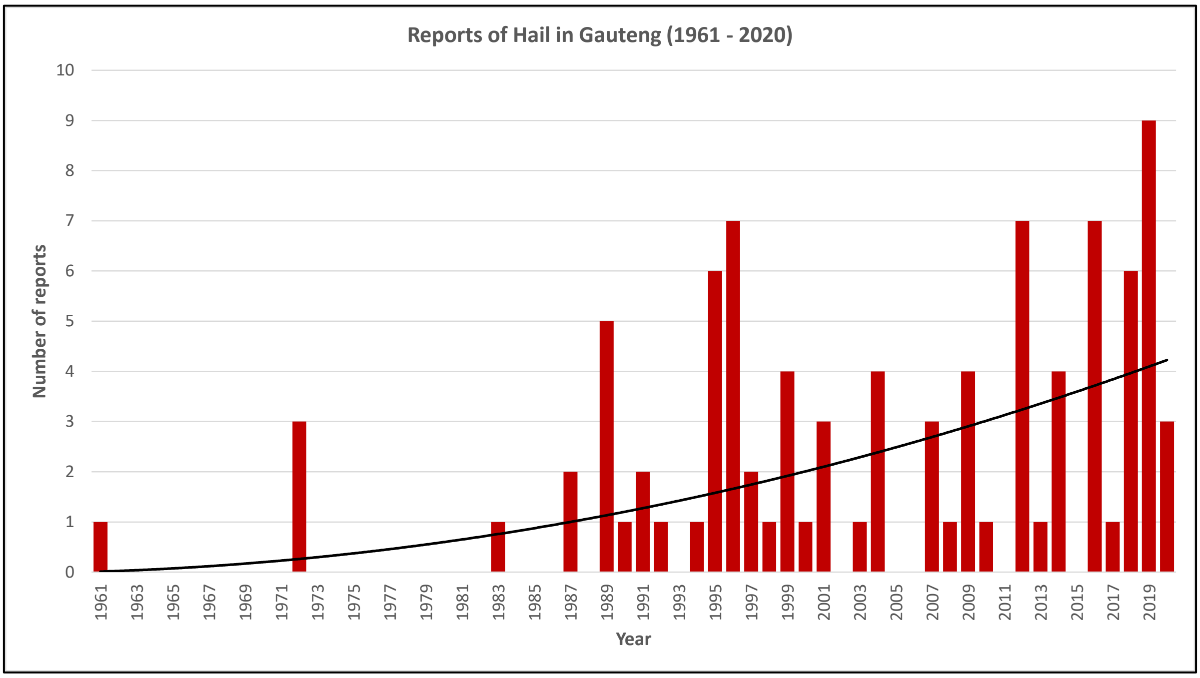


Fig. 52. Annual number of reports of hail in Gauteng province over the period 1961 – 2020.

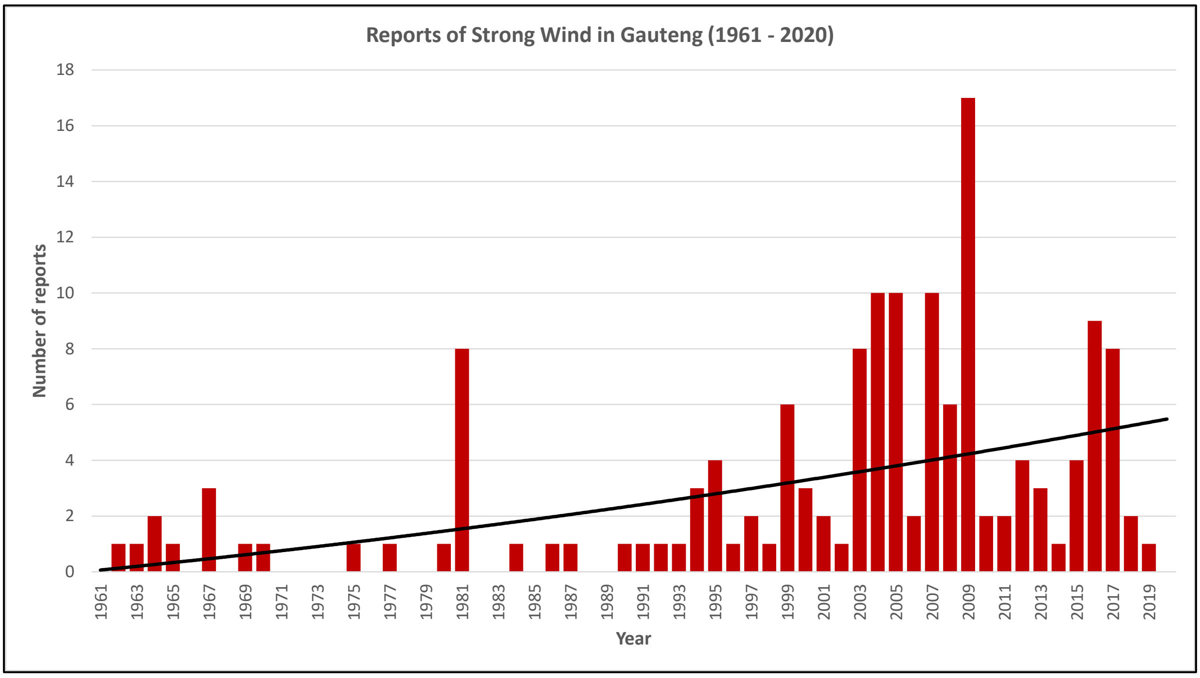


Fig. 53. Annual number of reports on strong winds in Gauteng province over the period 1961 – 2020.

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