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Statistical classification of South African seasonal divisions on the basis of daily temperature data

Across South Africa, a wide range of activities is influenced by differences in seasonality. In a South African context, there is little consensus on the timing of seasonal boundaries. Inconsistency exists through the use of ad-hoc approaches to define seasonal boundaries across South Africa. In this paper, we present one of the very first uniform statistical classifications of South African seasonal divisions on the basis of daily temperature data. Daily maximum and minimum temperature data were obtained from 35 selected South African Weather Service meteorological stations that had sufficiently complete data sets and homogeneous time series, spanning the period 1980–2015. An Euclidean cluster analysis was performed using Ward's D method. We found that the majority of the stations can be classified into four distinct seasons, with the remaining 12 stations' data best classified into three seasons, using T_{avg} as the classifier. The statistically classified seasonal brackets include summer (October/November/December/January/February/March), early autumn (April) and late autumn (May), winter (June/July/August), and spring (September). Exploring the boundaries of seasons, the start of summer and end of winter months follow a southwest to northeastwards spatial pattern across the country. Summers start later and winters end later in the southwestern parts of the country, whereas in the northeast, summers start earlier and winters end earlier.

Significance:

- The findings contribute to the common knowledge of seasonality in South Africa.
- New seasonal divisions in South Africa are proposed.

Introduction

Seasonal differences in climate, day length, and plant activity form the primary environmental control on a wide range of activities. These activities include economic and agricultural practices[1], which are affected by the length and timing of growing seasons[2,3], the related timing of sowing and harvest, and the necessity for irrigation and fertilisation. Climatic seasons also influence resource management and energy demand[4], tourism[5], social and economic planning[6], hydrology[1] and health[7]. The capacity to accurately determine the start and end of seasons is thus of critical importance. However, in the South African context, there is little consensus as to distinct seasonal boundaries. This lack of consensus is unusual. For most parts of the northern hemisphere[8,9] – including Italy[10], USA[11], China[12], Poland[13] and Finland[14] – seasonal boundaries are well established and clearly communicated.

South Africa is classified as a semi-arid country[15] which is situated in the mid-latitudes and subtropics[16,17]. The South African climate is influenced by major synoptic systems, including the semi-permanent subtropical high-pressure systems[16] and the variability of the Inter-Tropical Convergence Zone (ITCZ)[18-20]. The resultant continental anticyclones, ridging anticyclones, westerly waves, tropical easterly waves, and cut-off lows[16,21,22], produce a pronounced climatic seasonality across the country[20]. However, there is little consensus on the timing of seasons in South Africa, and approaches in defining seasonal boundaries often vary on the basis of the application (Table 1).[18] The South African Weather Service (SAWS) even highlights that there is no official designation and definitions of seasons.[23]

The most basic classifications commonly used are astronomical, meteorological and phenological divisions.[23] Astronomical summer is defined as the period from the summer solstice to the vernal equinox. By this classification, autumn is defined to conclude at the winter solstice, and winter spans the winter solstice to the spring equinox.[23,24] It is well known that the earth–sun geometry affects the seasons; however, there is no direct link between astronomical seasons and mean weather variations.[24,25] Meteorological classification refers to the subdivision of four equal-length periods of 3 months each, mostly and commonly used in the temperate latitudes.[23] In South Africa, the meteorological classification of temperature seasonality is the most widely used (Table 1).[2,26-29] Most agroclimatological studies use the conventional break of 3 months but may extend it to the farming season of the specific regions that are under investigation and use two distinct seasons, summer and winter (Table 1).[30] Climate modelling projections and analyses of influences of climatic factors studies often use six run-on seasons that coincide with synoptic circulations, with the latter coinciding with epidemiological seasons of heightened disease-risk.[31] Some climatologists classify seasons on an ad-hoc basis that is appropriate to specific regions, with classifications such as hot season, cold season, post-rainy season and growing season, with no direct relationship with calendar months. These seasons are defined for convenience and to suit the data output rather than to drive sensible analytical processes.[25-27] Phenological studies can also be used to define annual seasonality, and to reveal shifts in the timing of these events[32], as phenological shifts are often directly related to changes in local air temperatures[33].

Classification of South African seasons based on rainfall patterns is similarly complicated due to the variety of rainfall regimes, and thus likewise no standard definition has been adopted[18], and discrepancies exist between the seasonal brackets of rainfall and temperature-related classifications[34]. The differences are further complicated by the influence of distance from large water bodies, and the variation in heat from the Indian and Atlantic Oceans.[24]

Here we present one of the first statistical classifications of South African seasonal divisions on the basis of daily temperature data for 35 weather stations spanning the country. We argue that this method represents a more standardised and objective approach to the classification of seasons, particularly in a region that spans the subtropics and mid-latitudes.

Study region

South Africa is located within the latitudes 22–35°S and longitudes 17–33°E, and is bordered by the Atlantic Ocean in the west and southwest and the Indian Ocean to the south and southeast. It shares political boundaries with Mozambique, Zimbabwe, Botswana, Namibia and Eswatini (Swaziland), and encloses Lesotho (Figure 1).[35] The climate of South Africa, in particular temperature, is governed by the complex interaction between the subtropical location, the altitude of the interior plateau, the position of the subcontinent with respect to the major atmospheric circulation features, and the oceans on all sides except the north.[19,20,36] The subcontinent lies within the subtropics, with rainfall dominated by convective storms in the north and mid-latitude cyclones to the south.[16,37] The influence of the tropical and temperate pressure regimes, and the intra-annual migration of the inter-tropical convergence zone (ITCZ) results in pronounced seasonal differences in rainfall and temperature patterns over South Africa.[19] The ITCZ shifts with the monthly and seasonal changes of the sun's maximum insolation and the location of dominant atmospheric high- and low-pressure systems.[19,37] The high-pressure systems sit over the southern tip of the subcontinent in summer, and over the interior during winter. These high-pressure systems are interrupted by mid-latitude cyclones.[38] The influences of the subtropical high-pressure belt, and the mid-latitude westerlies with associated fronts vary significantly inter- and intra-annually over the subcontinent.[38] These interactions between tropical and temperate disturbance have significant consequences for the weather of the subcontinent.[16] The orography of South Africa influences the temperature distribution over the country such that the escarpment forms a climatic division between the high plateau and the low-lying coastal regions in the east and southeast (Figure 1).[19] The southern and eastern escarpments are the regions with the lowest temperatures, due to the decrease in temperature with altitude.[39,40] The oceans surrounding South Africa influence the temperatures experienced along the coastal areas.[39,40] The Indian Ocean, on the east, is warmed by the western boundary Agulhas Current, while the Atlantic, on the west coast, is cooled by the eastern boundary Benguela Current (Figure 1).[19,39] All these factors result in a broad east–west temperature gradient, with the Northern Cape experienceeing the lowest rainfall and highest temperatures in the country.[39,40]

Table 1: Published temperature seasonality classifications for South Africa

Publication	Research topic	Seasonal temperature brackets	Seasonal temperature brackets approach
Karl et al., 1993[26]	Daily maximum and minimum temperatures	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Three-month mean
Klopper et al., 1998[27]	Seasonal maximum temperature predictability in South Africa	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Climatological austral seasons
Craig et al., 2004[31]	Malaria case data in KwaZulu-Natal	Nov/Dec/Jan/Feb/Mar (summer) Mar/Apr/May/Jun (autumn) Jun/Jul/Aug (winter) Aug/Sep/Oct/Nov (spring)	Defined approach
Kruger and Shongwe, 2004[28]	Temperature trend in South Africa	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Subdivided into four seasons
Benhin, 2006[30]	Climate change and South African agriculture	Dec/Jan/Feb/Mar/Apr/May (summer) Jun/Jul/Aug/Sep/Oct/Nov (winter)	Mean monthly temperatures; farming seasons
Tshiala et al., 2011[2]	Analysis of temperature trends in Limpopo	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Defined following the usual conventions
Lazenby et al., 2014[7]	Seasonal temperature prediction over southern Africa and human health	Sep/Oct/Nov; Oct/Nov/Dec; Nov/Dec/Jan Dec/Jan/Feb; Feb/Mar/Apr (summer to late summer)	Southern Africa is mainly controlled by influences from the tropics
Kruger and Nxumalo, 2017[29]	Temperature trends in South Africa	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Mean monthly temperatures
Tshiala and Olwoch, 2010[56]	Tomato production in Limpopo	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Mean monthly temperatures

Data and methodology

For this study, daily maximum and minimum temperature data were obtained from 35 selected SAWS meteorological stations (Figure 1; Table 2) that had a minimum of 30 years of data, sufficiently complete data sets and homogeneous time series, spanning the period 1980–2015. These stations were selected as they span the country, ranging from 22°S to 35°S and 15°E to 33°E with an intended 1° interval (Figure 1). Before performing any statistical techniques, exploratory data analysis was applied to investigate the data homogeneity due to inevitable changes in aspects including observation sites, station relocation, observation practices/procedures and time.[29] However, in the context of the study, sudden increases or decreases in values over a prolonged period would not have significantly influenced the results. Visible outliers in the data series were checked by comparison with data from surrounding stations spanning the period of interest as well as reports of anomalous weather in the media.

Table 2: Information on selected meteorological stations

Province	Station name	Climate number	Latitude	Longitude	Altitude (m.asl)
Eastern Cape	East London	00595729	-33.03	27.83	124
	Dohne	00798116	-32.52	27.47	899
	Mthatha	0127272A4	-31.55	28.67	745
	Port Elizabeth	00351795	-33.98	25.60	60
Free State	Bloemfontein	02615161	-29.10	26.30	1354
	Bethlehem	03315859	-28.24	28.33	1689
	Welkom	03643001	-27.99	26.66	1344
Gauteng	Johannesburg Int	*04763990*	-26.14	28.23	1706
	Zuurbekom	04755288	-26.30	27.81	1580
KwaZulu-Natal	Cedara	02394820	-29.54	30.27	1071
	Durban	0240808A2	-29.97	30.95	96
	Escourt	03006901	-29.01	29.86	1144
	Shaleburn	02376184	-29.80	29.35	1614
Limpopo	Mara	072200991	-23.14	29.56	894
	Warmbad Towoomba	05895941	-24.90	28.32	1143
	Polokwane	0677802BX	-23.84	29.45	1226
Mpumalanga	Skukuza	05961793	-24.99	31.59	276
	Carolina	04801547	-26.07	30.11	1667
Northern Cape	Calvinia	0134479A3	-31.48	19.76	975
	De Aar	01698801	-30.66	23.99	1286
	Fraserburg	01130258	-31.91	21.51	1264
	Kimberley	02904684	-28.80	24.77	1198
	Pofadder	0247668A4	-29.12	19.38	984
	Springbok	0214700B2	-29.66	17.87	1006
	Sutherland	00882931	-32.38	20.67	1459
	Upington	03174765	-28.43	21.27	836
	Vanwyksvlei	01935613	-30.35	21.82	965
North-West	Vryburg	04322383	-26.95	24.65	1245
	Mahikeng	05080470	-25.80	25.54	1280
Western Cape	Cape Agulhas	00030204	-34.83	20.01	11
	Cape Columbine	00606209	-32.83	17.86	62
	Cape St Blaze/Mossel bay	00122517/0012215	-34.18/-34.19	22.15/22.13	135
	Cape Town	0021178A3	-33.96	18.60	42
	Vredendal	0106880A2	-31.67	18.50	42
	George	00126617	-34.00	22.38	197

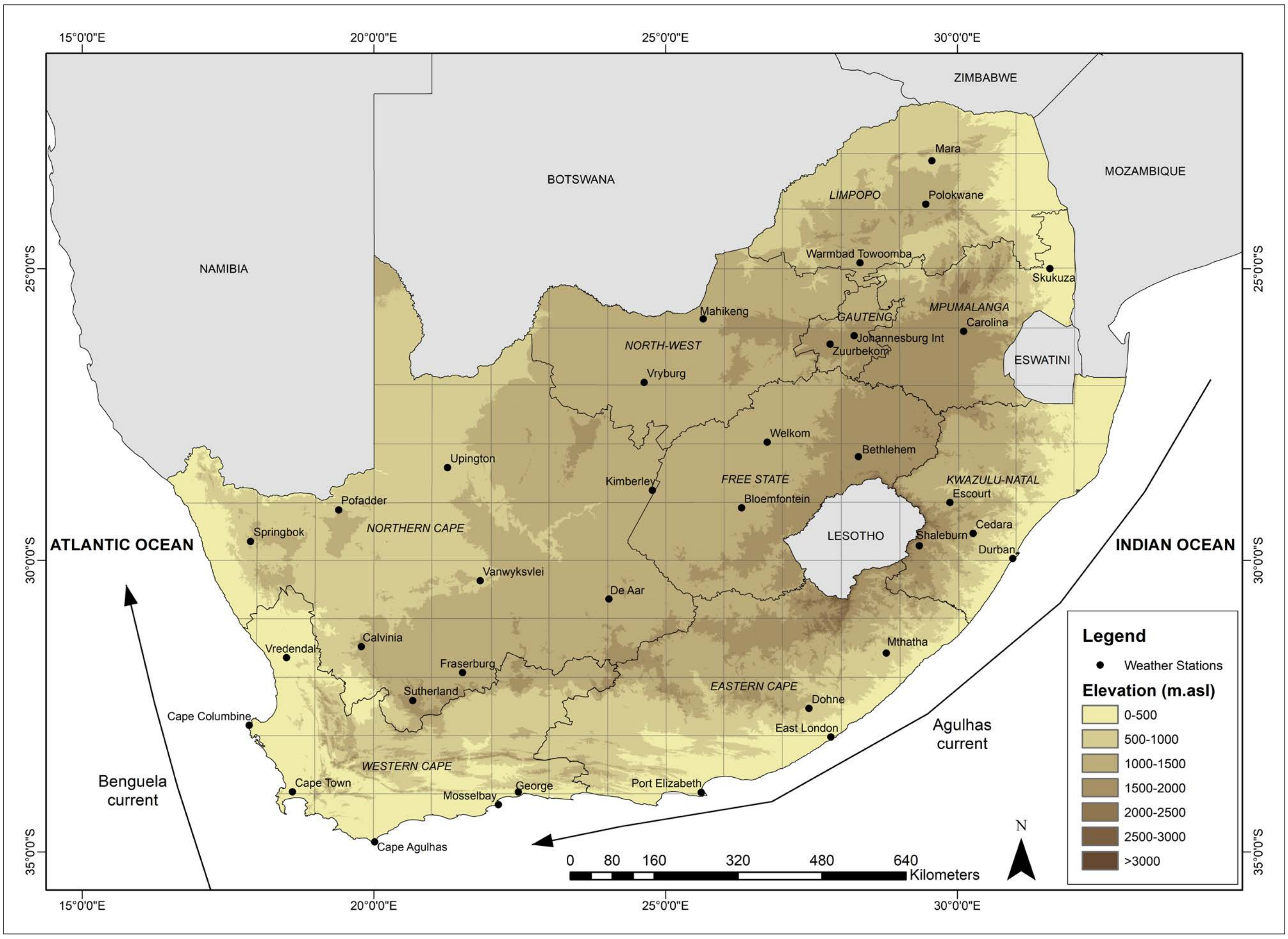

Figure 1: Map of the study region of South Africa, indicating 1° intervals used to select the meteorological stations across South Africa, the topography, the surrounding oceans and their respective ocean currents.

The data sets of the selected stations were subjected to quality control. As a first step, all dates and times were checked, and two decimal point rounding was used to maintain consistency throughout. Missing weather station data were replaced with data from a station adjacent to the site within a 10-km radius, or, if not possible, replaced with the 5-day running average. If data were not available for more than five consecutive days, that period was excluded from the analysis.

Cluster analysis

Cluster analysis was performed using Ward's D method, defined by the Euclidean distance between variables, utilising the cluster, vegan and rioja packages in R.[41-43] Euclidean cluster analysis was initially supervised at four seasonal divides and validated by using the dendogram package average silhouette width (ASW) calculation.[44] The ASW value measures the degree of confidence in between-group distances and strength of within-group homogeneity.[45] If not significant, two, three, five and six seasonal divides were used serially until the cluster was significant, using orders of magnitude put forward by Kaufman and Rousseeuw[46] as reference for measures. The ASW was calculated, together with the cophenetic correlation coefficient (CPCC) for interpretation, evaluation and validation of consistencies within the cluster and groupings.[42,47] The CPCC measures the correlation between the original pairwise distance matrix and the cophenetic distance matric of the dendrogram. This allows for the verification of the quality of the grouping.[47-49] The closer the cophenetic correlation coefficient is to a value of one, the better the grouping quality.[49] The cluster analysis results for maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperatures are given in Table 3. To investigate the spatial patterns, the cluster analysis outputs, and start and end dates of summer and winter, were spatially interpolated using the Inverse Distance Weighted (IDW) method using ArcGIS software.[50] It has been found that IDW interpolates station data accurately.[51] Additionally, annual mean graphs were produced for each of the temperature metrics.

Results

Cluster analysis

Results will mainly focus on T_{avg}, with reference to T_{max} and T_{min} only where statistically relevant. The cluster analysis reveals that the majority of the stations, 23 out of the 35, are most appropriately classified into four seasons (Table 3). The remaining 12 stations are best classified into three seasons. All the stations in the Limpopo, KwaZulu-Natal and North-West Provinces are clustered into four seasons, and those in the Eastern Cape are clustered into three seasons. All these stations have a statistically strong grouping (CPCC>0.7) and distinct cluster structures (ASW>0.5), except for Cedara (ASW=0.47) in KwaZulu-Natal, with a weaker cluster structure. The weaker cluster structures are also prominent in the Eastern Cape stations (ASW<0.5). The cluster analysis results revealed that Dohne (CPCC=0.7009) in the Eastern Cape has the lowest quality of grouping among the 35 stations analysed.

The three stations in the Free State, two of which (Bethlehem and Welkom) are classified into four seasons and one (Bloemfontein) into three seasons, have a good quality grouping (CPCC>0.7) and distinct cluster structure (ASW>0.5). A similar degree of confidence in cluster structures is found in both the Mpumalanga stations, Skukuza and Carolina, which are divided into three and four seasons, respectively. These two stations have a higher quality grouping (CPCC>0.8) than those in the Free State. A higher quality grouping is also prevalent in both the Gauteng stations, with Johannesburg Int (International) classified into four seasons, and Zuurbekom into three. However, a weaker cluster structure is calculated for Zuurbekom (ASW=0.45).

The Northern Cape and Western Cape are noticeably different from the rest of the provinces, with a more significant variation in the degree of confidence for the cluster structures. Six of the nine stations in the Northern Cape are clustered into four seasons with good cluster groupings (CPCC>0.7). However, most of these stations have a weak cluster structure (ASW<0.5), except for Fraserburg (ASW=0.5). The remaining three stations – De Aar, Kimberley and Springbok – are divided into three seasons with a good quality grouping; however, weaker structures are visible in Kimberley (ASW=0.46) and Springbok (ASW=0.42). In the Western Cape, four out of the six stations are classified in four seasons and the other two (Mosselbay and Cape Columbine) into three seasons. Similar to the Northern Cape, all stations clustered into four seasons display a good quality of grouping, but a weak cluster structure (ASW<0.5), with the weakest cluster structure calculated for Cape Agulhas (ASW=0.46). Mosselbay (ASW=0.51; CPCC=0.8011) is the only station in the WC with a distinct cluster structure and a good quality grouping. By contrast, the cluster analysis identified Cape Columbine (ASW=0.4) with the weakest cluster structure among all the stations that were analysed.

While similarities are found in the number of seasonal groupings returned for the different temperature metrics, the highest number (15 stations) have consistent classifications for T_{min} and T_{avg}. Only six stations have consistent seasonal classifications when considering T_{max} and $T_{min,}$ and three stations when considering T_{max} and T_{avg}. Only seven stations – Dohne, Port Elizabeth, De Aar, Bloemfontein, Cape Columbine, Welkom and Escourt – have the same number of seasonal groupings for all three temperature metrics.

For the majority of stations (23), classification using T_{max} returns three seasons, with 9 stations classified into two seasons, and only 3 classified into four seasons (Table 3). The majority of these stations have a strong grouping (CPCC>0.7), except for Dohne (CPCC=0.6714), located in the Eastern Cape. However, the degree of confidence in the cluster structures is low due to the weak cluster structures (ASW<0.5) for most of the stations except for Johannesburg Int, Zuurbekom, Mara, Mahikeng, Springbok and Cape Town with an ASW>0.5. The cluster analysis for T_{min} classifies the majority of the stations (21) into four seasons, with 13 stations classified into three seasons, and only 1 station (Springbok) classified into two seasons. Similar to T_{max}, the grouping quality for the stations is good. However, the cluster structures for most of the stations are distinct with only 19 stations returning an ASW<0.5.

Spatial analysis of the cluster analysis results (Figure 2) indicates that most parts of the country experience three seasons, with the greatest spatial variability visible in T_{max}. Similarities in the classification of seasons are visible for T_{max}, T_{min} and T_{avg}, but more so for T_{min} and T_{avg}. The western and central regions of the country, and parts of the Eastern Cape, have three distinct seasons, when classified using T_{max}, T_{min} and T_{avg}. Areas surrounding Springbok are similarly classified as having only two distinct seasons.

Table 3: Output of the cluster analysis including cluster groups (CG), average silhouette widths (ASW) and cophenetic correlation coefficient (CPCC) scores

Stations		T_{max}				T_{min}				T_{avg}			
		CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups
EASTERN CAPE	East London	2	0.47	0.7293	May/Jun/Jul/Aug/Sept/Oct/Nov Dec/Jan/Feb/Mar/Apr	3	0.5	0.7487	May/Jun/Jul/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.45	0.7475	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sep/Oct/Nov
	Dohne	3	0.37	0.6714	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sep/Oct/Nov	3	0.42	0.7091	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sept/Oct/Nov	3	0.44	0.7009	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sept/Oct/Nov
	Port Elizabeth	3	0.38	0.7833	Dec/Jan/Feb/Mar/Apr Jun/Jul/Aug/Sep May/Oct/Nov	3	0.49	0.7627	May/Jun/Jul/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.47	0.7385	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sep/Oct/Nov
	Mthatha	2	0.39	0.6644	Dec/Jan/Feb/Mar/Apr/Nov May/Jun/Jul/Aug/Sep/Oct	4	0.48	0.7663	Jun/Jul May/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.42	0.7125	May/Jun/Jul/Aug Dec/Jan/Feb/Mar Apr/Sep/Oct/Nov
FREE STATE	Bethlehem	3	0.34	0.8042	May/Jun/Jul/Aug Dec/Jan/Feb Mar/Apr/Sep/Oct/Nov	4	0.48	0.8057	Jun/Jul May/ Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	4	0.53	0.8149	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Bloemfontein	3	0.34	0.7867	May/Jun/Jul/Aug Dec/Jan/Feb Mar/Apr/Sep/Oct/Nov	3	0.48	0.7565	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	3	0.5	0.7545	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug
	Welkom	4	0.44	0.7066	Dec/Jan/Feb/Mar/Oct/Nov Jun/Jul May/Aug Apr/Sep	4	0.48	0.7415	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep Jun/Jul May/Aug	4	0.54	0.8245	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov

Table 3 continues on the next page

Table 3 continued

Stations		CG	ASW	CPCC	T_{max} Seasonal Groups	CG	ASW	CPCC	T_{min} Seasonal Groups	CG	ASW	CPCC	T_{avg} Seasonal Groups
GAUTENG	Johannesburg Int	3	0.5	0.8364	Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov Jun/Jul May/Aug	3	0.45	0.8170	May/Jun/Jul/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	4	0.51	0.8458	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Zuurbekom	2	0.53	0.8299	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.47	0.8307	May/Jun/Jul/Aug Apr/Sep Dec/Jan/Feb Mar/Oct/Nov	3	0.45	0.8357	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep
KWAZULU-NATAL	Cedara	2	0.37	0.6561	Dec/Jan/Feb/Mar Apr/May/Jun/Jul/Aug/Sep/Oct/Nov	4	0.52	0.8056	Jun/Jul May/Aug Apr/Sept/Oct Dec/Jan/Feb/Mar/Nov	4	0.47	0.7686	Jun/Jul May/ Aug Dec/Jan/Feb/Mar Apr/Sep/Oct/Nov
	Durban	3	0.47	0.7316	Jun/Jul/Aug/Sep/Oct Dec/Jan/Feb/Mar Apr/May/Nov	4	0.52	0.7680	Jun/Jul May/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	4	0.52	0.7125	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/Nov May/Oct/Sep
	Escourt	4	0.37	0.8278	Jun/Jul May/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	4	0.54	0.8278	May/Jun/Jul/Aug Apr/Sep Dec/Jan/Feb Mar/Oct/Nov	4	0.54	0.8212	Jun/Jul May/Aug Apr/Sept/Oct Dec/Jan/Feb/Mar/Nov
	Shaleburn	2	0.46	0.7406	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.42	0.8214	May/Jun/Jul/Aug Apr/Sept Dec/Jan/Feb Mar/Oct/Nov	4	0.52	0.8103	Jun/Jul May/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov
LIMPOPO	Mara	2	0.52	0.8130	Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov May/Jun/Jul/Aug	4	0.50	0.8444	Jun/Jul May/ Aug Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct	4	0.5	0.8460	Jun/Jul May/ Aug Dec/Jan/Feb/Mar/Nov Apr/Oct/Sep
	Polokwane	3	0.45	0.8186	Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov Jun/Jul May/Aug	3	0.55	0.8248	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug	4	0.5	0.8332	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Warmbad Towoomba	3	0.48	0.7906	Dec/Jan/Feb/Mar/Sep/Oct/Nov Jun/Jul Apr/May/Aug	4	0.56	0.8526	May/Aug Jun/Jul Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	4	0.57	0.8729	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
MPUMALANGA	Skukuza	2	0.48	0.7837	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.51	0.8365	Jun/Jul May/Aug Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct	3	0.51	0.8307	May/Jun/Jul/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov
	Carolina	3	0.46	0.7622	Dec/Jan/Feb/Mar/Sep/Oct/Nov Jun/Jul Apr/May/Aug	4	0.52	0.8357	May/Aug Jun/Jul Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	4	0.5	0.8440	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
NORTH-WEST	Mahikeng	2	0.57	0.8271	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.56	0.8424	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	4	0.58	0.8514	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Vryburg	4	0.46	0.8226	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	3	0.5	0.7625	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	4	0.58	0.8348	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov

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Province	Stations	T_{max} CG	T_{max} ASW	T_{max} CPCC	T_{max} Seasonal Groups	T_{min} CG	T_{min} ASW	T_{min} CPCC	T_{min} Seasonal Groups	T_{avg} CG	T_{avg} ASW	T_{avg} CPCC	T_{avg} Seasonal Groups
NORTHEN CAPE	Calvinia	3	0.47	0.7246	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/May/Oct/Sep	3	0.47	0.7567	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/May/Oct/Nov	4	0.48	0.7864	Jun/Jul/Aug May/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar
	De Aar	3	0.44	0.7561	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	3	0.49	0.7198	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/May/Oct/Sep	3	0.5	0.7209	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug
	Fraserburg	3	0.48	0.7297	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug	4	0.53	0.8077	Jun/Jul/Aug May/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	4	0.5	0.7349	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/Oct May/Sept
	Kimberley	3	0.41	0.7382	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	4	0.46	0.7703	Jun/Jul May/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	3	0.46	0.7536	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug
	Pofadder	3	0.43	0.7750	Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar/Nov Apr/Oct	4	0.48	0.7947	Jun/Jul/Aug May/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	4	0.48	0.7967	May/Sep Jun/Jul/Aug Dec/Jan/Feb/Mar Apr/Oct/Nov
	Springbok	2	0.55	0.7802	May/Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar/Apr/Oct/Nov	2	0.49	0.7412	Dec/Jan/Feb/Mar/Apr May/Jun/Jul/Aug/Sep/ Oct/Nov	3	0.42	0.7426	Dec/Jan/Feb/Mar/Apr/Nov Jun/Jul/Aug May/Sep/Oct
	Sutherland	3	0.46	0.7292	Dec/Jan/Feb/Mar/Nov Apr/May/Sep/Oct Jun/Jul/Aug	3	0.51	0.7618	May/Jun/Jul/Aug/Sep Apr/Nov/Oct Dec/Jan/Feb/Mar	4	0.49	0.7774	Jun/Jul/Aug May/Sep Apr/Oct Dec/Jan/Feb/Mar/Nov
	Upington	3	0.42	0.7494	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	4	0.51	0.8192	May/Sep Jun/Jul/Aug Dec/Jan/Feb/Mar Apr/Oct/Nov	4	0.46	0.7155	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug May/Sep Apr/Oct
	Vanwyksvlei	3	0.48	0.7221	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug	4	0.51	0.7300	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/Oct May/Sep	4	0.47	0.7276	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/Oct May/Sep
WESTERN CAPE	Cape Agulhas	3	0.43	0.7670	May/Jun/Jul/Aug/Sep/Oct Dec/Jan/Feb/Mar Apr/ Nov	4	0.48	0.7685	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct	4	0.46	0.7741	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct
	Cape Columbine	3	0.41	0.7861	Dec/Jan/Feb/Mar/Apr/Nov Jun/Jul/Aug May/ Sep/Oct	3	0.37	0.7612	Dec/Jan/Feb/Mar/Apr/Nov May/Oct Jun/Jul/Aug/Sep	3	0.4	0.7666	Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar Apr/May/Oct/Nov
	Cape Town	3	0.53	0.7893	May/Jun/Jul/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.5	0.7516	May/Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar Apr/Oct/Nov	4	0.49	0.7757	Jun/Jul/Aug May/ Sep Apr/Oct/Nov Dec/Jan/Feb/Mar
	George	3	0.42	0.7453	Dec/Jan/Feb/Mar Apr/May/Nov Jun/Jul/Aug/Sep/Oct	4	0.48	0.7606	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct	4	0.49	0.7635	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct
	Mosselbay	3	0.42	0.8017	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep/Oct Apr/May/Nov	4	0.47	0.7862	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep May/Oct Apr/ Nov	3	0.51	0.8002	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/May/Oct/Nov
	Vredendal	3	0.44	0.7630	Dec/Jan/Feb/Mar/Apr/Nov Jun/Jul/Aug May/Sep/Oct	3	0.47	0.7862	Dec/Jan/Feb/Mar May/ Jun/Jul/Aug/Sep Apr/Oct/Nov	4	0.47	0.8011	Dec/Jan/Feb/Mar Jun/Jul/Aug May/Sep Apr/Oct/Nov

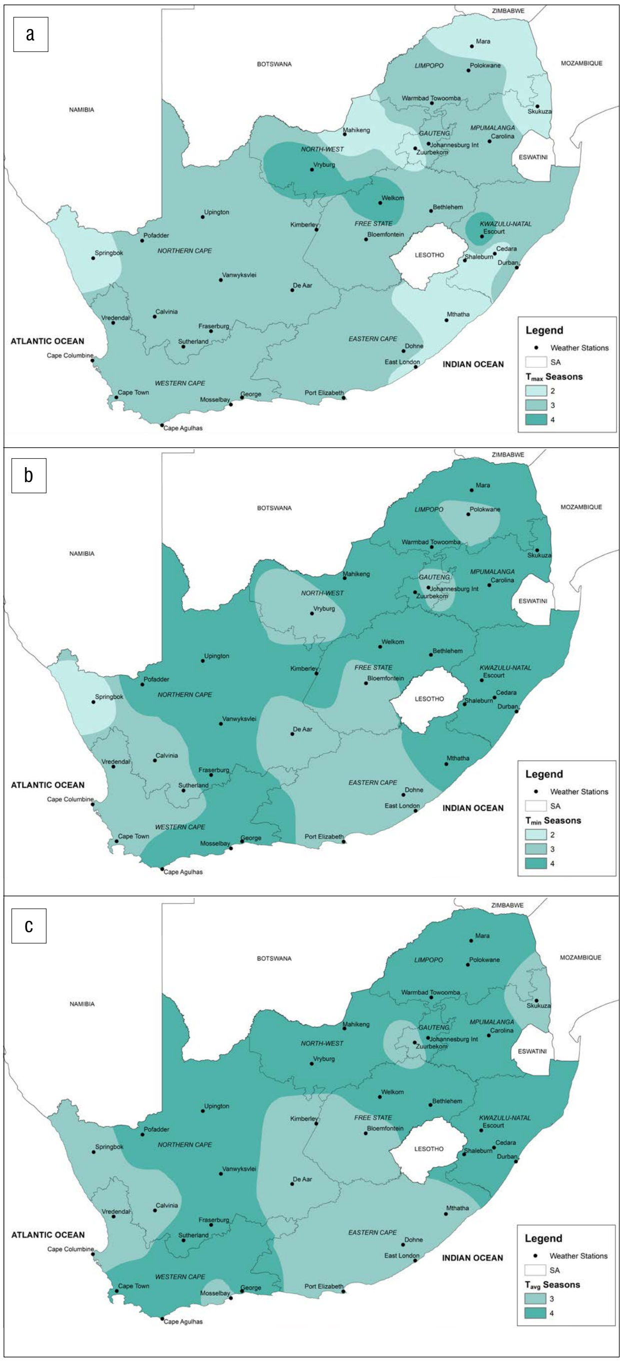


Figure 2: (a) Maximum (T_{max}), (b) minimum (T_{min}) and (c) average (T_{avg}) temperature seasonal groupings.

Seasonal timetable

Several variations of monthly classifications have been calculated (Tables 3 and 4), which will be referred to as 'seasonal brackets'.

Summer: There is unanimous agreement across seasons and temperature metrics that December, January, February and March can be grouped into the summer seasonal bracket. October and November can tentatively be included in the summer season, with a 31% agreement among stations for October and an overall 59% agreement for November. A total of 30% of stations classify October as falling within spring, 26% in late spring, 5% in early spring, and 8% in the winter seasonal bracket. In comparison, 21% of the remaining stations classify November as falling in spring, 17% in late spring, and 3% in winter. The latest start of summer is December. The longest summer season is calculated for Mthatha (Eastern Cape) using T_{avg} as the classifier, spanning the earliest start month of September and persisting until April.

Autumn: For 43% of the stations, April falls within the early autumn bracket, whereas for 39% of stations, April is grouped in the main autumn seasonal bracket. The remainder of the stations group April into summer (15%), winter (2%) and late autumn (1%). A total of 41% of the stations classify May into the late autumn bracket, 35% into the winter bracket, and 24% into the main autumn bracket. Autumn starts as early as March for Bethlehem, Bloemfontein and Zuurbekom using T_{max} and T_{min} as the classifier. Using T_{avg} as the classifier, the majority of stations indicate the start of autumn in April. Springbok (Northern Cape) has the latest classified start of autumn, in the month May. Stations with only 1 month of autumn, using T_{avg} as classifier, include Bloemfontein, Zuurbekom, Skukuza, De Aar, Kimberley and Springbok

Winter: There is unanimous agreement across stations and temperature metrics that June and July are grouped into the winter bracket. There is 71% agreement among stations that August additionally forms part of the winter bracket with only 25% of stations classifying August in early spring and 4% in the main spring seasonal bracket. Cedara and Vanwyksvlei experience the longest winter, commencing in April and ending in November for Cedara and October for Vanwyksvlei, both using T_{max} as the classifier. Winter in East London and Springbok starts a month later in May and ends in November. Stations with the shortest winter (June to July) classified by T_{avg} include Shaleburn, Mara, Polokwane, Warmbad Towoomba, Carolina, Bethlehem, Welkom, Johannesburg Int, Cedara, Escourt, Mahikeng, Vryburg, Cape Agulhas, Cape Columbine and George.

Spring: Interestingly, the most disputed month across all stations is September. However, 29% of the stations agree that September can tentatively be included in the spring bracket. The remainder comprise a 25% agreement that September can be included in the winter, 23% in early spring, 16% in late spring and 9% in the summer bracket. Some stations are classified as experiencing early spring in August, using T_{min} as the classifier. These stations are Mthatha, Bethlehem, Welkom, Cedara, Durban, Escourt, Mara, Warmbad Towoomba, Skukuza, Carolina, Mahikeng and Kimberley. Stations with the shortest spring (only the month of August), calculated using T_{max}, are Johannesburg Int, Polokwane, Warmbad Towoomba, and Carolina. Interestingly, all these stations are situated in the northern parts of the country. Classified by T_{min}, the longest spring is observed in Mthatha (Eastern Cape) and Durban (KwaZulu-Natal), starting in August and ending in November. The latest start for spring – November – classified by T_{max}, is visible in Durban, Cape Agulhas and Mosselbay. Stations at East London, Mthatha, Zuurbekom, Cedara, Shaleburn, Mara, Skukuza, Mahikeng and Springbok each have two classified seasons, and therefore no autumn or spring.

Start and end dates of summer and winter

A distinct, southwest to northeast spatial pattern is apparent for the start and end dates of summer and winter across all the temperature metrics (Figures 3a–f and 4a–f). Summer broadly commences earlier in the northeastern and interior parts of the country and later along the southwestern parts and the south coast. The earliest start of summer is visible in T_{max} for the northern parts of the country, and in parts of KwaZulu-Natal for T_{avg}. The earliest end of summer is calculated using T_{min}, with parts in KwaZulu-Natal and Gauteng ending in February (Figure 3e). The greatest variability in the spatial patterns is recorded T_{max}, for which the northern and southern region summer ends in April, similar to T_{avg} for the southern region. However, there is a consensus amongst the temperature metrics that, for most parts of the country, summer ends in March, whereas for the western parts of the country, the season ends a month later in April.

For the majority of the country, winter starts in June, with the season starting earlier for a few interior regions. The greatest spatial variability in the timing of the start of winter is observed in T_{max} (Figure 4a). For areas in the Western Cape and Northern Cape, winter is classified as starting in May, similar to the start of winter using T_{min}. For parts of KwaZulu-Natal, winter is calculated to start as early as April. Regarding the end of winter, the greatest spatial variability is similarly observed for calculations using T_{max}, for which winter ends latest in the southwest of the country and along the east coast. For the western parts of the Northern Cape, winter ends later using T_{max} and T_{min}. Similar to the end of summer maps (Figure 4d–f), a distinct southwest to northeast spatial movement of end dates is visible for all the temperature metrics used. For the southwestern parts of the country, winter ends later, whereas moving northeastwards to the interior, the winter months end earlier, except for some parts in Gauteng, Limpopo and the North-West.

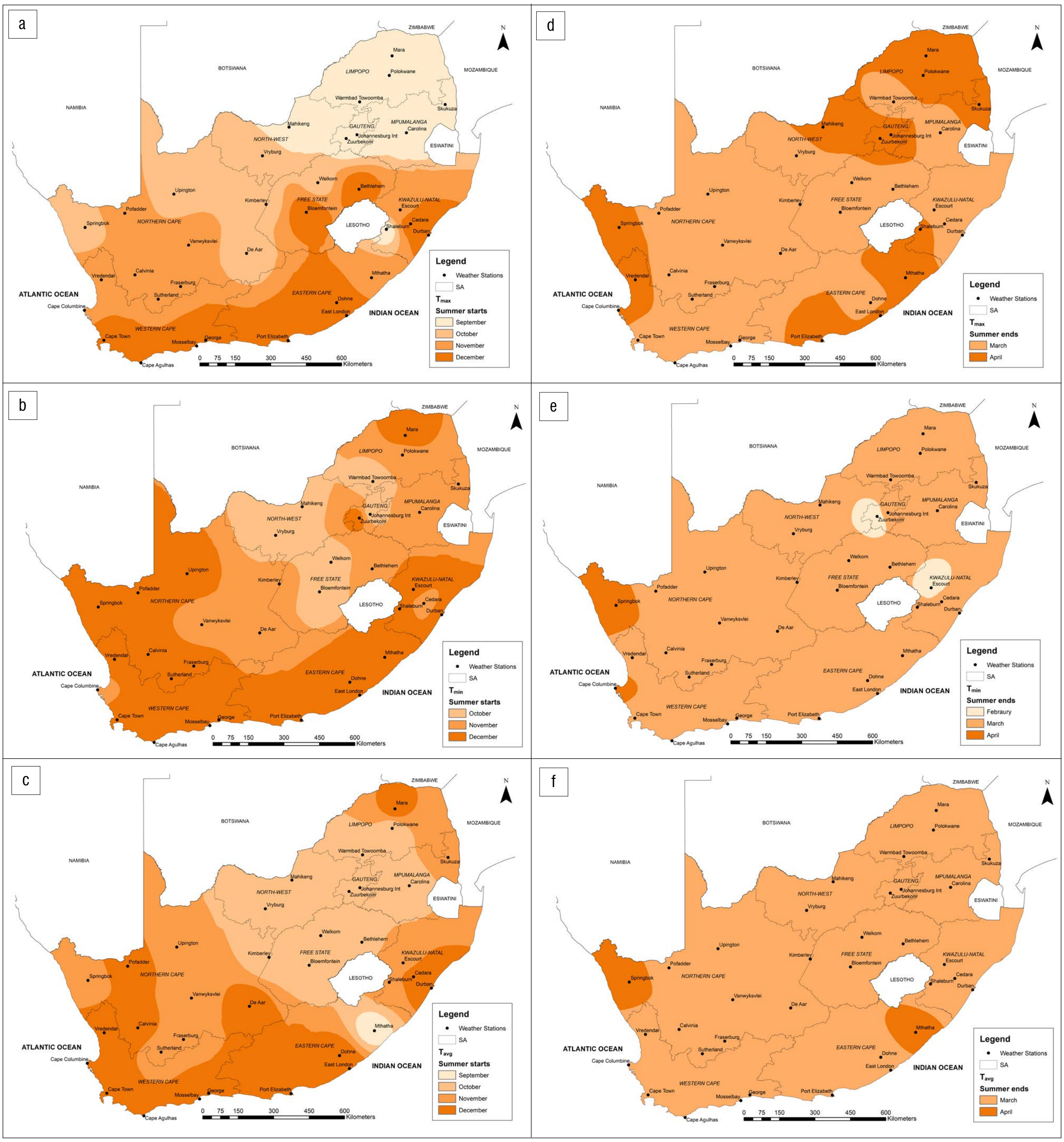
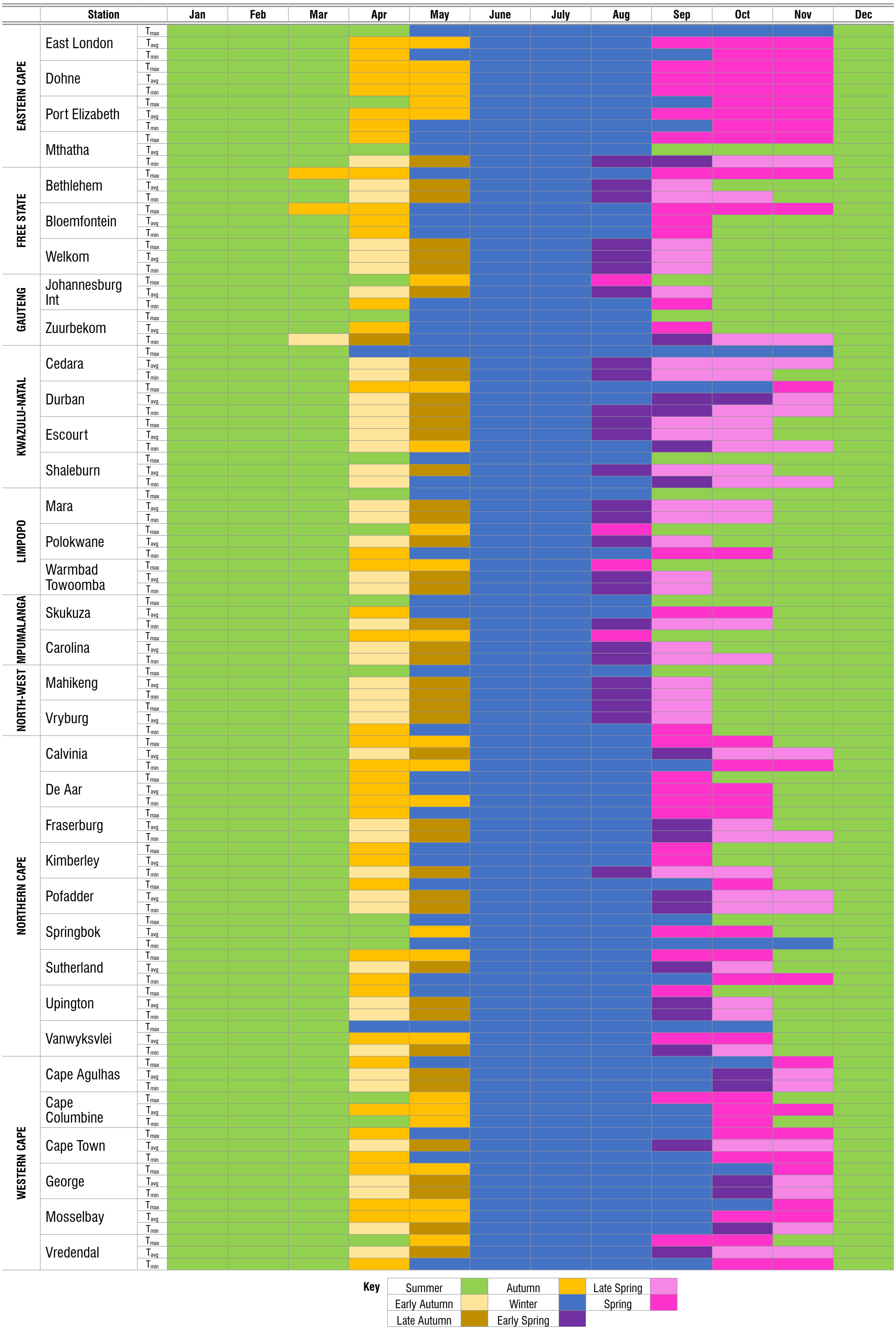


Figure 3: (a–c) Start of summer and (d–f) end of summer.

Table 4: Seasonal timetable of maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperatures



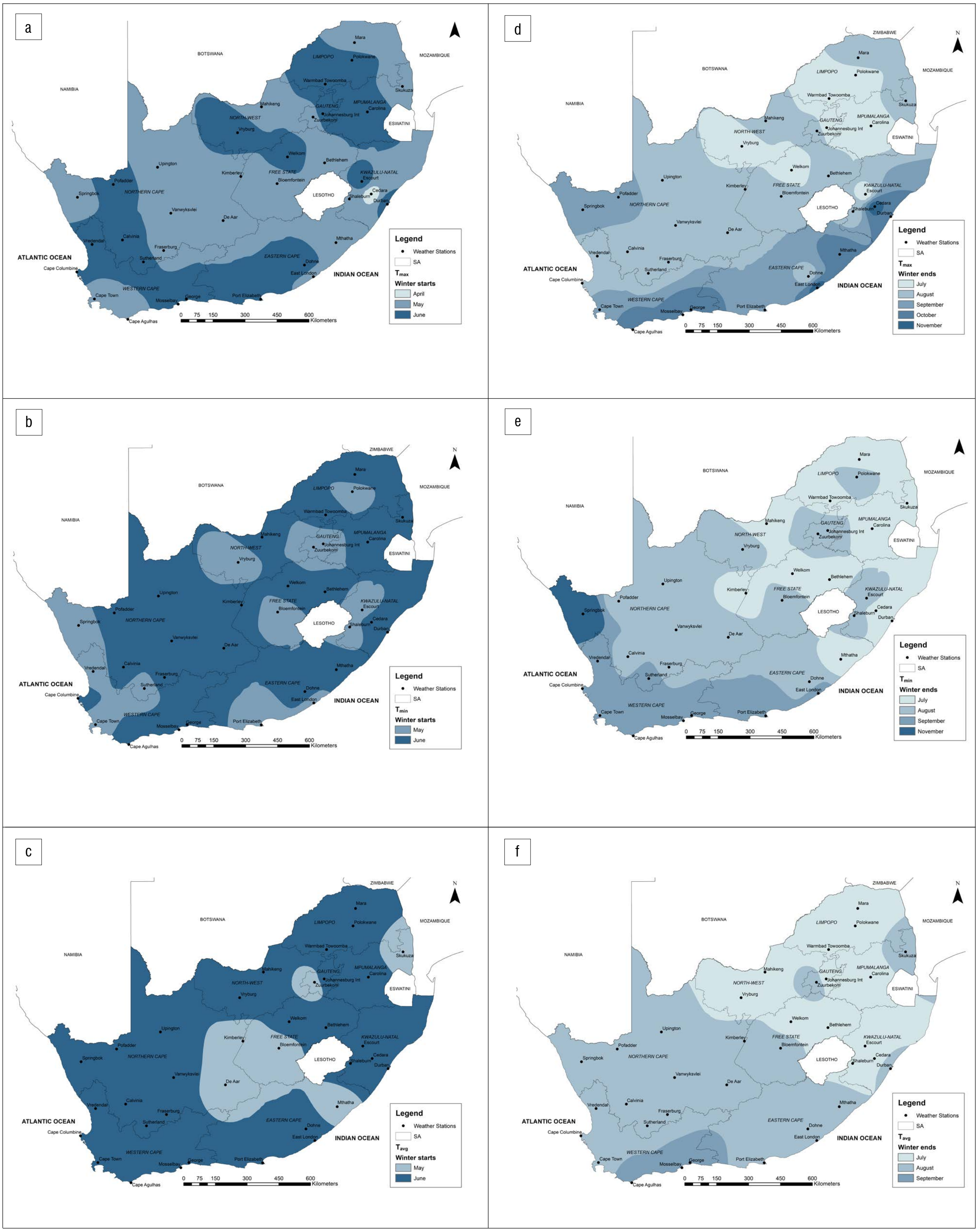


Figure 4: (a–c) Start of winter and (d–f) end of winter.

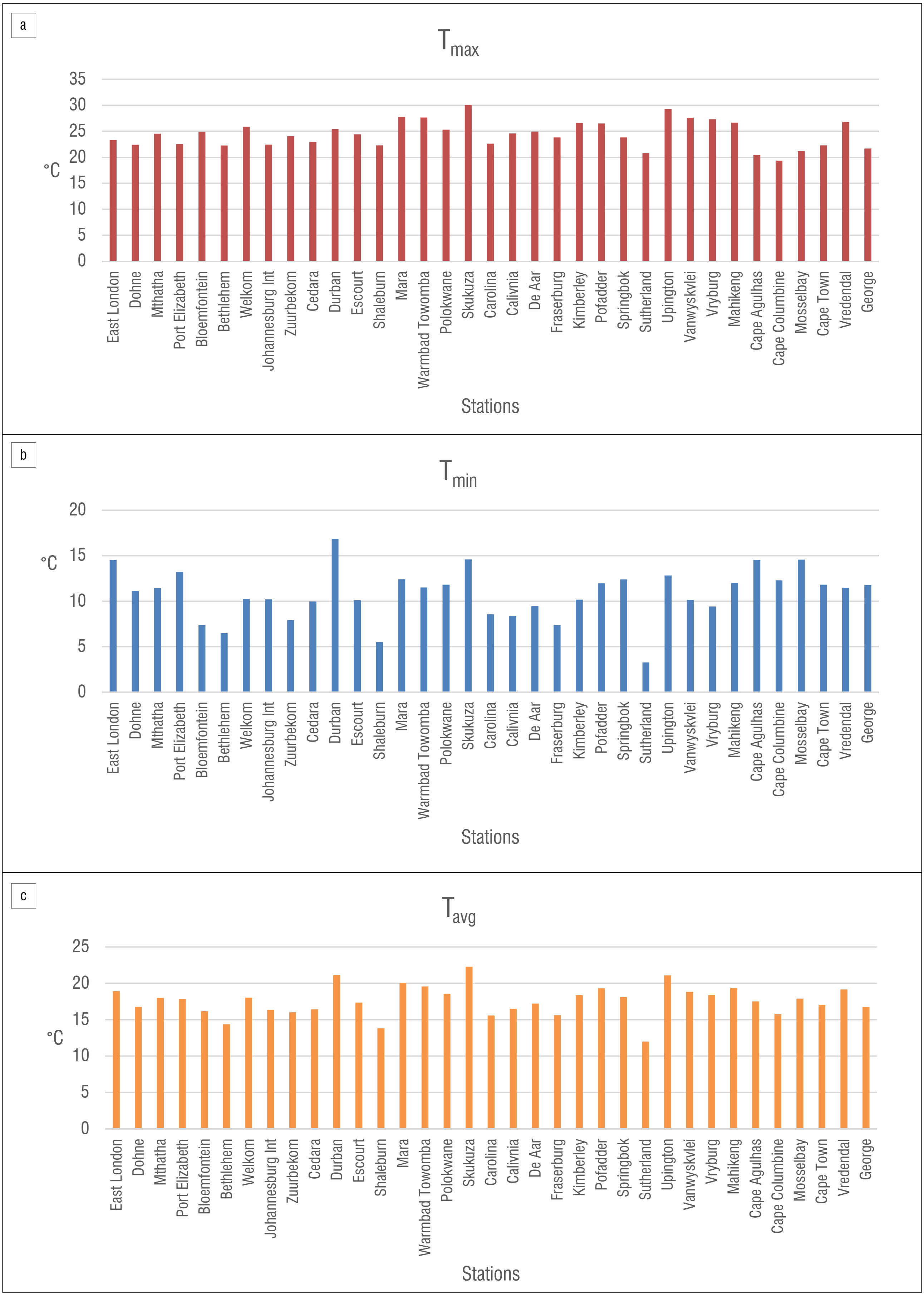


Figure 5: Annual mean of (a) maximum (T_{max}), (b) minimum (T_{min}) and (c) average (T_{avg}) temperatures for the selected stations, 1980–2015.

Discussion and conclusion

We present one of the first statistical classifications of seasons across South Africa using daily temperatures. Daily temperature data across the country were used as a distinctive marker to classify the seasons due to the detectability of temperature changes compared to rainfall across South Africa. Through statistical analysis and results captured in the seasonal timetable (Table 4), new seasonal brackets are put forward in accordance with the agreement of seasons and temperatures among stations used in this research.

Aggregated for the whole country, based on T_{max}, T_{min} and T_{avg}, our results show that the weather stations agree that the following seasonal brackets can be used:

- Summer (October/November/December/January/February/March)
- Early autumn (April)
- Late autumn (May)
- Winter (June/July/August)
- Spring (September)

These proposed seasonal brackets challenge our 'common knowledge' of four equal length seasons of 3 months each[2,26-29], and the ad-hoc approaches some researchers use in South Africa[25-27]. Noticeable similarities occur between the two seasonal divisions of months used to define farming seasons[30] as well as monthly summer divisions related to the positions of South Africa related to disease-risk seasons.[7] However, the proposed longer duration of summer and shorter spring seasons may conflict with the agricultural practices used currently, in particular, the current observed length and timing of the growing season across the country.[1-3] Additionally, these proposed seasonal brackets may assist in the explanation of current delays and advances in seasonal phenological events[33], and challenges in the tourism sector where most outdoor attractions are dependent on the seasonal climate[5].

However, the high spatio-temporal variability in temperatures (e.g. annual mean temperatures Figure 5) presents a complex picture of seasonality. This presents challenges in defining seasonal brackets for a given location or region, particularly where regional climate regimes change within a small geographic area[24], and due to the complexity of South Africa's climate[29]. Discrepancies have been found among the different temperature metrics. However, the majority of the stations (23 out of the 35), are divided into four seasons, using T_{avg} as the classifier, with the remaining 12 stations clustered into three seasons. Interestingly, some stations within the same province (e.g. Johannesburg Int and Zuurbekom in Gauteng) have different seasonal groupings. With closer inspection, these differences may occur due to the location and elevation of the stations (Table 2). For example, it has been found that built-up areas such as Johannesburg may be warmer in late winter than rural areas due to the urban heat island[52] and higher elevations tend to be cooler than lower elevations[53]. Taking the above-mentioned into consideration, the importance of selecting the relevant temperature metric, e.g. T_{max}, T_{min} and T_{avg}, is highlighted for analysis purposes, as this selection can return different results as portrayed in the results.

In general, the findings of the start and end dates of summer and winter (Figures 3 and 4) coincide with the pressure regimes, as well as the interannual migration of the ITCZ.[19,37] The results indicate that summer starts later (ending earlier) and winter starts earlier (ending later) in the southwestern and southern regions of the country. These results coincide with the movement of the cold front of the mid-latitude cyclones during the winter months.[38] While, during summer, the southward movement of the ITCZ and the position of the subtropical high-pressure system are associated with warmer conditions, which may result in the patterns found. Summers start earlier, and winters start and end later in the northeastern parts of the county. These patterns are found independently from the notable link between temperatures and weather systems. The patterns also show the annual progression of temperatures which follow a southwest to a northeastwards spatial pattern across the country.

The key limitations of this study are the nature of the temperature data sets. The data sets are not perfect and inherent errors may be present for a number of reasons.[29] Furthermore, inhomogeneity is not likely to play a significant role in this study as the consistency was ensured by using only SAWS data sets.[54] Mean daily temperature data were quantified using T_{max} and T_{min}; this is a limitation as hourly temperature readings may provide accurate values of mean daily temperatures.[54] Furthermore, we acknowledge that station measurements are unable to display complete areal coverage as these are location-specific[54,55], which is particularly an issue for the interpolated maps presented throughout. A limited number of stations that have long-term temperature records was selected using a broad grid approach, as discussed, to get a relatively good spatial representation of the country. To overcome this limitation, future research may benefit from the inclusion of temperature data from additional weather stations from other organisations, such as the South African Agricultural Research Council. Such addition would, however, require greater efforts at data homogenisation and quality checking, which introduce a further set of limitations.

Finally, this research provides an insight into the complexity of seasonality across South Africa, as well as direction for climate-relevant research with temperature data as the primary input. Possibly the most significant contribution of this research is the newly proposed seasonal brackets using temperature metrics. The knowledge presented here is crucial for agriculture practices, resource management, tourism and other temperature-dependent activities, especially to develop adaptive strategies in monitoring seasonal changes in temperatures under climate change.

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Competing interests

We declare that there are no competing interests.

Authors' contributions

A.v.d.W.: Data collection, data analysis, data curation, validation, writing – the initial draft, writing – revisions. J.M.F.: Conceptualisation, methodology, validation, writing – revisions, student supervision, project leadership.

Data availability

Data are owned by the South African Weather Service and can be obtained from them on request.

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