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Dynamics of an extreme low temperature event over South Africa amid a warming climate

Hector Chikoore[a,*], Innocent L. Mbokodo[b], Mukovhe V. Singo[c], Tumelo Mohomi[a], Rendani B. Munyai[d], Henno Havenga[e], Dawn D. Mahlobo[b], Francois A. Engelbrecht[f], Mary-Jane M. Bopape[g], Thando Ndarana[h]

[a] Department of Geography and Environmental Studies, University of Limpopo, Sovenga, South Africa
[b] Climate Services, South African Weather Service, Centurion, South Africa
[c] Institute for Soil Climate and Water, Agricultural Research Council, Arcadia, South Africa
[d] Department of Economic Management Education and Social Sciences Education, University of Limpopo, Sovenga, South Africa
[e] Unit for Environmental Sciences and Management, North-West University, Potchefstroom, South Africa
[f] Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa
[g] South African Environmental Observation Network, National Research Foundation, Colbyn, South Africa
[h] Department of Geography, Geo-Informatics and Meteorology, University of Pretoria, Hatfield, South Africa

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ABSTRACT

Despite robust warming trends in surface air temperatures over southern Africa, extreme low temperature (ELT) events still occur from time to time. A recent ELT event affected South Africa resulting in disruptions in socio-economic activities amid a coronavirus pandemic. At least 27 long-term low temperature records were broken during 22–24 July 2021, with snow falls observed mostly over high ground in subtropical districts. This study employs weather station data and European Centre for Medium-Range Weather Forecasts (ECMWF)'s ERA5 and ERA5-Land reanalyses to investigate dynamics of the ELT event focusing on the South African Highveld. Our approach employs multiscale analysis, with long term trends and climatologies of surface air temperatures, snow events and ground frost days presented as background to understanding the observed extreme weather anomalies. We found consistent and statistically significant warming trends in daytime and overnight temperatures, with corresponding decreases in ground frosts. The July 2021 ELT event resulted from a combination of complex circulation anomalies which included an intense offshore cut-off low (COL) that extended to the surface (and associated wave breaking), a cold front and a Type-S ridging anticyclone, all intensifying surface cold air advection from the Southern Ocean. A most significant finding is that COLs do not need to enter South Africa to cause severe weather over the country. Our study contributes to understanding the occurrence and dynamics of cold extremes in subtropical regions, against a robust warming trend.

1. Introduction

In Africa, a dry-wet seasonality is more pronounced over large areas of the continent compared to a cold-hot seasonality as rainfall is the most important meteorological parameter (Tyson 1986; Nicholson 2000). Winter seasons in Africa's tropical region are considered mild, rarely falling below 15 °C (Leroux 2001; Ongoma and Chen 2017) compared to boreal winters. Farther south - South Africa lies predominantly in the subtropics, extending from about 22°S to 34°S, and the traditional summer, autumn, winter and spring seasons are more applicable (van der Walt and Fitchett 2020a; Mbokodo et al., 2020; Kruger and Nxumalo 2017a). The winter spans the period from mid-May to mid-August, sometimes extending into early September in the south (van der Walt and Fitchett 2020a).

Dominant weather systems affecting southern Africa during the austral winter months are the subtropical anticyclones (highs) which migrate equatorward coupled with semi-permanent upper air high pressure systems (Tyson and Preston-Whyte 2000; Ndarana et al., 2021), causing dry and stable weather over much of the region from May to August. The predominantly anticyclonic circulation produces

* Corresponding author.
E-mail address: hector.chikoore@gmail.com (H. Chikoore).

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subsidence inversions which trap pollutants causing haze over industrial regions during this time (Jury and Freiman, 2002; Wallace and Hobbs, 2006; Abiodun et al., 2014; Jury 2017). Early morning fogs (van Schalkwyk 2011; van Schalkwyk and Dyson 2013) due to radiation losses, advection or mountain-valley circulations are common during winter whilst ground frosts (Moeletsi et al., 2016) are also observed over susceptible and exposed surfaces.

Whilst most of the interior plateau over southern Africa is experiencing the dry season in winter, cold fronts, cut-off lows (COLs) and ridging anticyclones produce thunderstorms and rainfall over the southwestern Cape and southern coastal areas of South Africa during this time (Engelbrecht et al., 2015a; Barnes et al., 2021a; Omar and Abiodun 2020). Thus, the winter months in South Africa are important to the southwestern Cape region as they coincide with the main rainy season there.

The frequency and establishment of rainfall-producing systems and thus how wet (dry) or cold (cool) the winter season may be linked to remote phenomena such as the Southern Annular Mode (SAM; Limpasuvan and Hartmann, 2000). The El Niño Southern Oscillation (ENSO) is more important for the summer rainfall regions with minimal impact on winter rainfall regions (Mahlalela et al., 2019). Whereas the SAM is a dominant mode of variability in the higher latitudes of the Southern Hemisphere (SH) and is known to influence rainfall and temperature variability in parts of the hemisphere (Gillett et al. 2006; Abram et al., 2014; Thompson et al., 2011; Fogt and Marshall 2020). The SAM, at times referred to as the Antarctic Oscillation, is defined as the zonal mean sea level pressure difference between the 40°S and 65°S (Lee et al., 2019). In South African context, the negative phase of SAM has been associated with anomalously wet conditions over the southwestern Cape (Reason and Rouault 2005; Mahlalela et al., 2019) consistent with Mediterranean-type climate regions in south Australia and southern South America due to the northward shift of storm tracks (Gillett et al. 2006). Conversely, the poleward migration of mid-latitude cyclones and associated cold fronts lead to a decline in rainfall over these regions (Sousa et al., 2018; Picas and Grab, 2020) and these systems are projected to further retreat poleward in future due to climate change (Catto et al., 2019).

The passage of a westerly wave bringing winter rainfall is usually followed by intrusion of cold air from the south advected by ridging anticyclones (Ndarana et al., 2021). Thus, extreme low temperature (ELT) events are typically associated with drizzly/rainy days and in some cases snow over high ground or mountain peaks. Due to South Africa's location, the occurrence of snow over the country is rare, except over mountain tops in the south (Stander et al., 2016). When it does occur, snow causes disruptions to economic activities, property and may lead to loss of lives of the homeless (Stander et al., 2016) and livelihoods. As the country experiences limited snowfall, snowmelt in its headwater catchments may contribute to increased soil moisture, groundwater, and river flows (Wu and Xu 2005; Stander et al., 2016). Recently, an anomalous COL centered over the far northeast of the country resulted in freezing temperatures and rare but widespread snow extending to the commercial capital of Gauteng on the Highveld in July 2023 (The New York Times, 2023).[1]

Depending on the timing of ELT, a variety of negative losses can occur for different agricultural commodities. Impacts of ELT events in South Africa include severe frosts on winter crops (e.g. wheat, barley, oats), loss of young and vulnerable livestock and economic losses (Archer et al. 2021; Farmer's Weekly, 2023). An ELT event that affected South Africa in 2010 resulted in a 20% loss in vegetable production in the northern Limpopo Province, and losses of 124 000 tons of sugarcane in KwaZulu-Natal on the east coast (Farmer's Weekly, 2010). Often, severe ELT events result in elevated energy demand for agriculture, domestic heating and industrial production with implications on interruptions of electricity supply (Mail and Guardian, 2023), as was the case during 22–24 July 2021 (Eskom, 2021). It was also reported that water reticulation pipes were frozen interrupting water supply on July 22, 2021 in the central Free State Province (Timeslive, 2021).

The main weather systems associated with ELT conditions over South Africa are ridging anticyclones from the south Atlantic Ocean (Ndarana et al., 2021) coupled with mid-tropospheric COL pressure systems aloft. Cold fronts, which usually precede ridging anticyclones are responsible for most of the cold air advection from the higher colder latitudes as the South Atlantic High ridges over the south of Africa (Ndarana et al., 2021). The orientation of ridging anticyclones determines the length of fetch of cold air. Type-N (centered north of 40°S) ridging anticyclones result in deeper intrusions of cold air onto the southern Africa subcontinent compared to their Type-S (centered south of 40°S) counterparts whose influence mostly affects South African latitudes (Ndarana et al., 2022). In addition to cold air advection, they contribute to nearly half (~46%) of rainfall over the all-year rainfall region of the Cape South Coast (Engelbrecht et al., 2015a). The interaction of cold air advection with the sharp escarpment near the coasts results in orographic lifting and rain or drizzle. The frequency and duration of ridging events was also found to be related to drought in the southwest Cape during the 2015 winter (Burls et al., 2019).

COLs are closed lows that occur in the upper air over subtropical latitudes and are associated with ELT conditions, heavy rainfall and snowfalls (Singleton and Reason 2007; Favre et al., 2013; Muofhe et al., 2020; Xulu et al., 2023). They occur when a mid-tropospheric low becomes detached from the westerlies (Palmen and Newton, 1969) and are often coupled with a ridging anticyclone at the surface (Muofhe et al., 2020, Ndarana et al., 2023) and may, on occasion, extend to the surface (Barnes et al., 2021b). Mid-tropospheric low-pressure systems imply low mean air temperature values of the layer from the surface to the upper air. The ridging anticyclone at the surface advects low level moisture and cold air from the Southern Ocean. COLs are also responsible for the most number of flood events, human fatalities and damage to infrastructure in the southern provinces of South Africa (Bopape et al., 2024). More recently, floods from COLs that affected the eastern KwaZulu-Natal region resulted in more than 440 deaths in April 2022, destruction of 4 000 homes, and displacement of 40 000 people (SAWS 2023).

Several studies have found consistent and statistically significant warming trends of surface minimum and maximum air temperatures in most areas of South Africa (Karl et al., 1993; Engelbrecht et al., 2015b; Kruger and Nxumalo 2017b; Jury 2018; van der Walt and Fitchett 2020b; Mateyisi et al., 2021; McBride et al., 2021; IPCC et al., 2021). Tshiala et al. (2011) investigated trends in surface air temperatures over Limpopo Province over a 50-year period (1950–1999) and found statistically significant positive trends (0.12 °C per decade at $\alpha = 0.01$ significance level) for most stations, with winter warming faster than the summertime. Despite the observed and robust warming trends in South Africa, extreme temperature events continue to occur. However, general trend of decreasing frequency of ELTs events, cold waves and their duration were found in most stations across South Africa including on the Highveld (van der Walt and Fitchett 2020b). Summer heat wave events are frequent and often occur as compound events with meteorological droughts (Mbokodo et al. 2020, 2023), linked to sea-surface temperature variability of the tropical Indian and Pacific oceans (Klopper et al., 1998; Mbokodo et al., 2023). Whilst several environmental systems and human communities are suited to the mean climate of an area and moderate variability (Salinger and Griffiths 2001), extreme deviations from the mean may have significant impacts.

Several episodes of anomalous cold weather affected the country during the 2021 austral winter season. An ELT weather event from 22–24 July 2021 broke 27 long-term records of lowest temperatures on the South African Weather Service (SAWS) database (SAWS 2021). The event resulted in disruptions of socio-economic activities and threatened

[1] https://www.nytimes.com/2023/07/12/world/africa/south-africa-snow-johannesburg.html Accessed on 20 July 2023.

human lives amid a raging coronavirus pandemic. Our study is motivated by these impacts and the record-breaking low temperatures against a significant warming trend. Unlike heatwave events, little work has been done focusing on ELT events in South Africa, and what causes them remains unknown.

Thus, the aim of this study is to analyse the nature and causes of anomalous ELT events during the 2021 austral winter season over South Africa, with a large part of the work focusing on the Highveld region. We use a larger domain that includes the surrounding oceans to understand the driving dynamics. The rest of the paper is organized as follows: the methodology is presented next; results are presented and discussed starting with climatologies of variables related to cold weather, then a focus on the 22–24 July 2021 extreme event. A conclusion and recommendations are offered at the end.

2. Data and methods

2.1. The South African Highveld

South Africa is characterised by complex topographic gradients with narrow coasts, sharp escarpments, and high peaks in the east, falling to the Limpopo River in the northeast (Fig. 1a). Some of the long term mean spatial patterns of minimum (Myburg, 1974) and maximum temperatures and the occurrence of snowfalls may be best explained using topographic arguments/parameters (Maisha, 2014). Local circulations due to topographic effects also affect cloudiness, fogs, and rainfall patterns (Singleton and Reason 2006; Omar and Abiodun 2021). In addition, the distance from the sea, surface ocean currents, latitude, aspect, cloudiness, and prevailing winds also contribute to observed spatial, seasonal, and diurnal variability of surface air temperatures over the country.

Much of the analyses focus on the South African Highveld which is defined as that region that lies between 1 400 and 1800 m above mean sea level and found on the eastern part of the country but north of Lesotho[2] (Fig. 1a). The Highveld covers large areas of the North West Province, Free State Province and Mpumalanga Province. Higher elevations lie southeast of the Highveld, toward the mountain kingdom of Lesotho, with elevations mostly above 2000 m (Fig. 1a). The South African Highveld includes the major population (~15 m people, STATSSA, 2023) and industrial centers of the Gauteng Province, the economic capital of South Africa. Even though the Highveld region is not a large proportion of South Africa's land area, extreme weather and climate events cause significant impacts there on transportation, economic activities, human lives, and livelihoods. This motivates our interest in this region. Besides, the winter season on the Highveld lasts longer compared to the lower altitude regions where the warmer temperatures return early (van der Walt and Fitchett 2020a). Despite the focus on the Highveld, we consider temperature patterns over the rest of the country, and circulation anomalies extending seaward to understand the extreme weather event.

2.2. Analysis of observed and reanalysis data

The spatial analysis and interpolation of surface air temperatures in this study is largely based on quality-controlled data from the extensive station network of the SAWS (Fig. 1b). The spatial distribution of stations used in this study is representative of the thermal regions (Kruger and Sekele 2013; Mbokodo et al., 2023) across the country. The temperatures were interpolated on spatial maps using the Inverse Distance Weighted (IDW) technique in an ArcGIS environment. The IDW assumes decreasing influence of a mapped variable with increasing distance from a point of sampling (Watson and Philip, 1985). The IDW method of interpolation is straightforward to understand and implement, which renders it less prone to errors in the interpretation of results. It also performs well with high spatial points density, as in this study (Harman et al., 2016, Fig. 1b). We sought to find evidence of climate change over the Highveld based on a long (1901–2020) time series of maximum temperature (Tmax), minimum temperature (Tmin), and ground frost days from the CRU TS4.04 (Harris et al., 2020). The Highveld is defined by a polygon bounded by latitudes 26° to 29°S and longitudes 26° to 30.5°E.

In winter, the coldest overnight temperatures (−2 to 13 °C) in South Africa occur typically between 03:00 UTC and 04:00 UTC whilst daytime maxima (15–27 °C) are often observed between 12:00 UTC and 13:00 UTC (Mbokodo 2017). These times would vary during cloudy and rainy days for example. Ground frost occurs when the ground/soil temperature reaches and falls below 0 °C and is often concerning to farmers whose focus is on winter crops. Frosts were traditionally measured from minimum thermometers placed on the ground and measured at 06 UTC in southern Africa. The CRU TS4.04 uses the gridded absolute Tmin variable to calculate ground frost days via an empirically determined function (Harris et al., 2020). Commercial farmers often use greenhouses and overhead sprinkler irrigation to prevent crop failure due to ground frosts. As irrigation water freezes to ice in cold weather, the latent heat of fusion released replaces the heat lost by crops to the environment (Perry 1998; Yongguang et al., 2016).

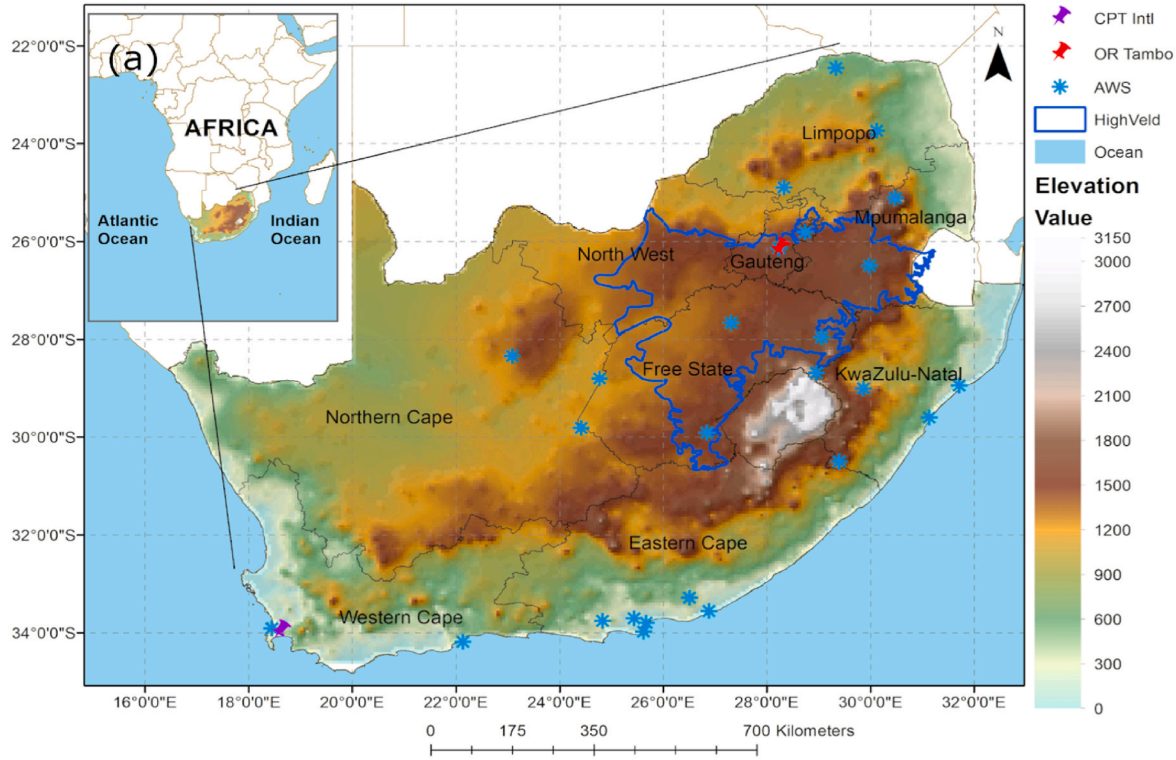
We analysed key aspects of a time series including the seasonality, and long-term trends in anomalies of Tmin and Tmax and frequency of ground frost days. Anomalies were calculated based on 1991–2020 long term climatologies whilst trends were tested for statistical significance using the Mann-Kendall test at the 95% confidence level. Long-term trends provide context of the 2021 winter event, to demonstrate that it was one of the most extreme events, hence our interest in it. The winter season is defined in this study as spanning the months June, July and August (JJA), as in van der Walt and Fitchett (2020a, b). For completeness, the long-term (1991–2020) mean spatial patterns for the austral spring (September, October and November; SON), summer (December, January and February; DJF) and autumn (March, April and May; MAM) seasons are also analysed.

Trends in cold nights (TN10P), cool days (TX10P), warm nights (TN90P), and hot days (TX90P) from 1991 to 2020 were calculated using the RClimDex version 1.0 software (Zhang and Yang, 2004). The RClimDex is an R-based library that conducts quality control for climate data and also computes indices of climate extremes as defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). This tool was developed and is maintained by the Climate Research Branch of the Meteorological Service of Canada and is freely available on the ETCCDI website.[3] We calculated the RClimDex trends for Johannesburg's Oliver Reginald Tambo International Airport station which is the only station on the Highveld whose daily records span at least 30 years (1991–2020) from the SAWS database. This RClimDex has been used in several studies (e.g., Kruger et al., 2019; Mbokodo et al., 2020; Mbokodo et al., 2023) to analyse historical trends in climate extremes over South Africa.

We analysed the occurrence (frequency and location) of snow events obtained from the SAWS Caelum publication which documents information on weather extremes and their impacts in South Africa dating back to the 1500s (SAWS 2023). The Caelum publication is maintained by the SAWS and provides a continuously updated history of notable weather-related disasters in South Africa (Viljoen, 1991; Caelum, 2022; Mashao et al., 2023). This publication provides information such as dates of extreme weather events, resulting socio-economic impacts and also the regions affected. Two snow datasets were used in this study. While the snow data from Caelum provided a 1981–2020 climatology

[2] https://www.oneearth.org/ecoregions/highveld-grasslands (Accessed on 22 June 2023).

[3] http://etccdi.pacificclimate.org/software.shtml (Accessed on 22 June 2023).



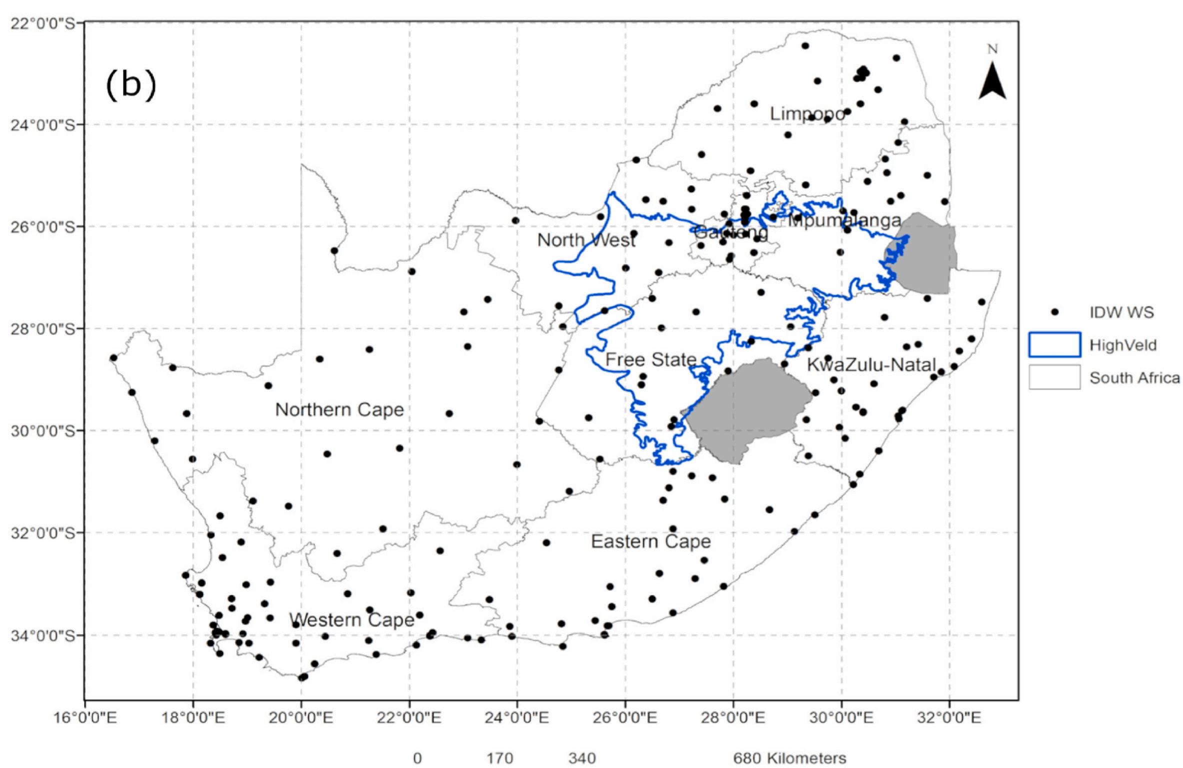


Fig. 1(a). The Highveld of South-Africa (demarcated in blue) lies at a mean altitude of 1 500 m. The area covers most of central South Africa and is also home to various industries. Johannesburg and Pretoria are two major metropolitans in the region, and the economic hub of Africa. The locations of Automatic Weather Stations (AWS) that broke temperature records are shown as asterisks. The locations of Oliver R Tambo Airport and Cape Town Airport are pinned in Gauteng. Fig. 1 (b) shows the location of weather stations (WS) (represented by black points) used for the interpolation of temperatures across South Africa by using the inverse distance weighted (IDW) method.

over the country, the ERA5-Land (Munoz-Sebater et al., 2021) snow dataset was used for event scale analyses during 22–25 July 2021. The ERA5-Land snow data was detailed in Munoz-Sebater et al., 2021 and evaluated against two sets of observations including station data and from the Global Historical Climatology Network-Daily (GHCN-daily; Menne et al., 2012). Radiosonde soundings made at Cape Town International Airport and Bloemfontein were obtained from the University of Wyoming are used to investigate the vertical profiles of environmental air during 22 July at 00Z and 12Z respectively. The vertical profiles provide information on freezing levels, upper winds and vertical wind shear.

We employed ECMWF ERA5 reanalyses at 0.25° resolution (Hersbach et al., 2020) to analyse anomalies in the atmospheric circulation focusing on geopotential heights (m), wind vectors and isotachs (m/s) in the lower (850 hPa) and middle (500 hPa) troposphere at the event timescale to understand dynamical processes. We isolated and shaded streamlines greater than 30 m/s and identified the jet streak (region of very strong winds above 30 m/s in the upper air) on the plots. The location and interaction of jet streaks with surface weather systems may result in low-level advection of colder/warmer air into a region (Chang and Lau 1980; Singleton and Reason 2006). In addition, the 1 000-500 hPa thickness (m) is analysed as an important indicator for the likelihood of frozen precipitation and hence snowfalls. Thickness is a measure of the distance between two pressure levels and depends on the mean temperature and moisture. The 540 dam (decameters) contour is a critical isopleth of constant thickness below which snow falls are most likely (Grumm, 1998).

3. Results and discussion

3.1. Climatologies

3.1.1. Seasonal mean temperatures

We present spatial climatologies (Figs. 2 and 3) of seasonal mean surface air temperatures (Tmin and Tmax) for all seasons from DJF, MAM, JJA, to SON from the SAWS station data. The winter season over South Africa is, as expected, the coldest season across the country (Fig. 2c), but low temperatures are also experienced on occasion during autumn and spring especially over high ground (Fig. 2b–d). Tmin averaged below 6 °C during JJA over the interior plateau, with slightly warmer temperatures near the east coast and the northeast Lowveld. The coldest overnight temperatures occur over the region south of the Highveld, extending into the mountains of the Eastern Cape Province (Fig. 2c) and Lesotho (inferred, not shown). During JJA, minimum temperatures drop below freezing/0 °C, particularly in the south of the Highveld, which includes parts of the Free State, the Eastern Cape, and Lesotho's Maluti Mountains. Tmin is generally mild during DJF with mean values between 12 and 15 °C over the eastern Highveld and higher in the west (Fig. 2a). The rest of the country is much warmer overnight during the summertime, with mean temperatures above 18 °C over the far northeast Lowveld and the arid Kalahari in the Northern Cape Province. During the transition seasons (MAM and SON), Tmin are generally cool, although the spring appears about 3 °C warmer particularly in the south of the Highveld (Fig. 2b–d). The SON spring season (Fig. 2d) also coincides with the peak of the fire season (Singo et al.,

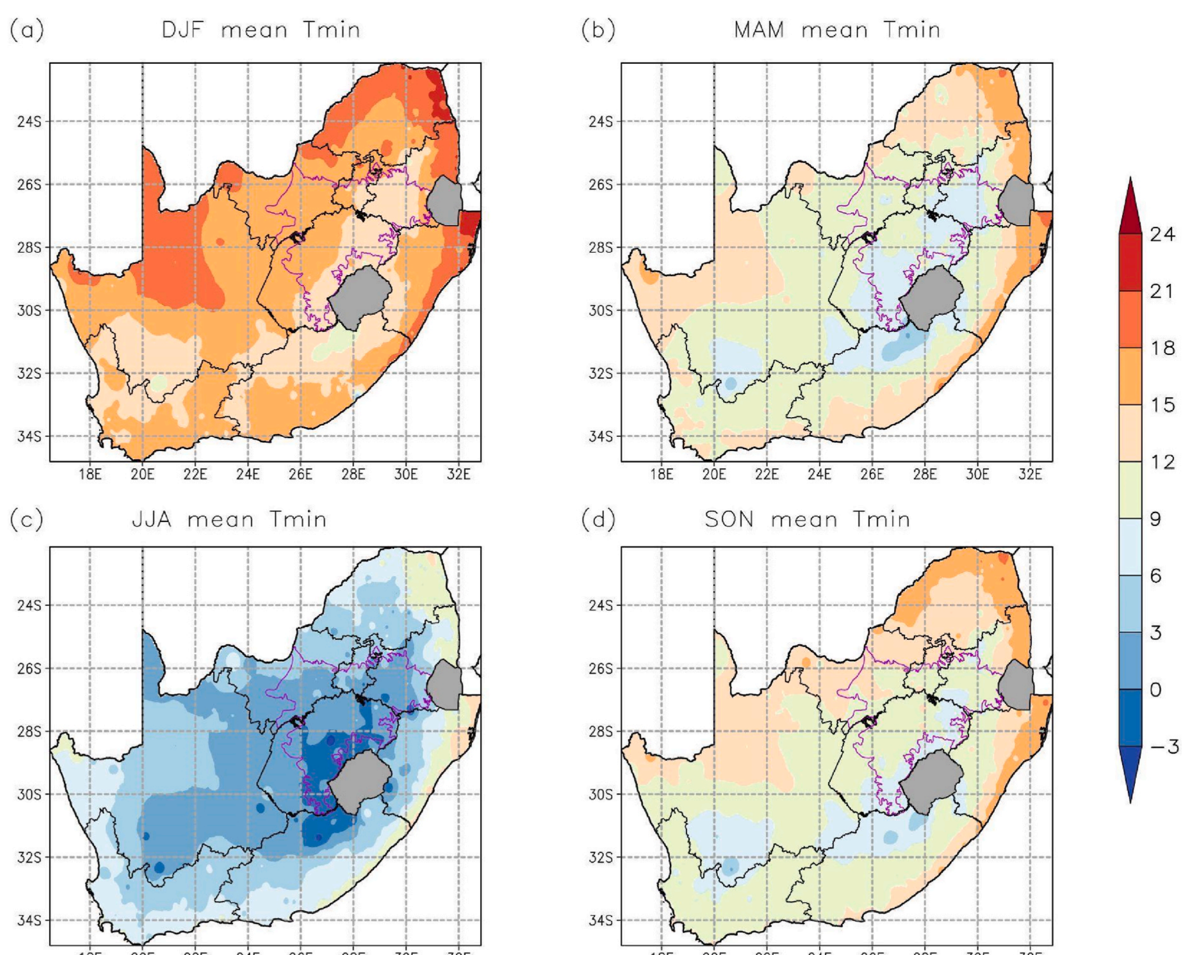


Fig. 2. Seasonal mean spatial patterns of minimum temperatures during (a) DJF, (b) MAM, (c) JJA, and (d) SON over South Africa based on a 1981–2020 climatology from the SAWS station observations The purple polygon indicates the Highveld, while Lesotho and Eswatini have been masked out.

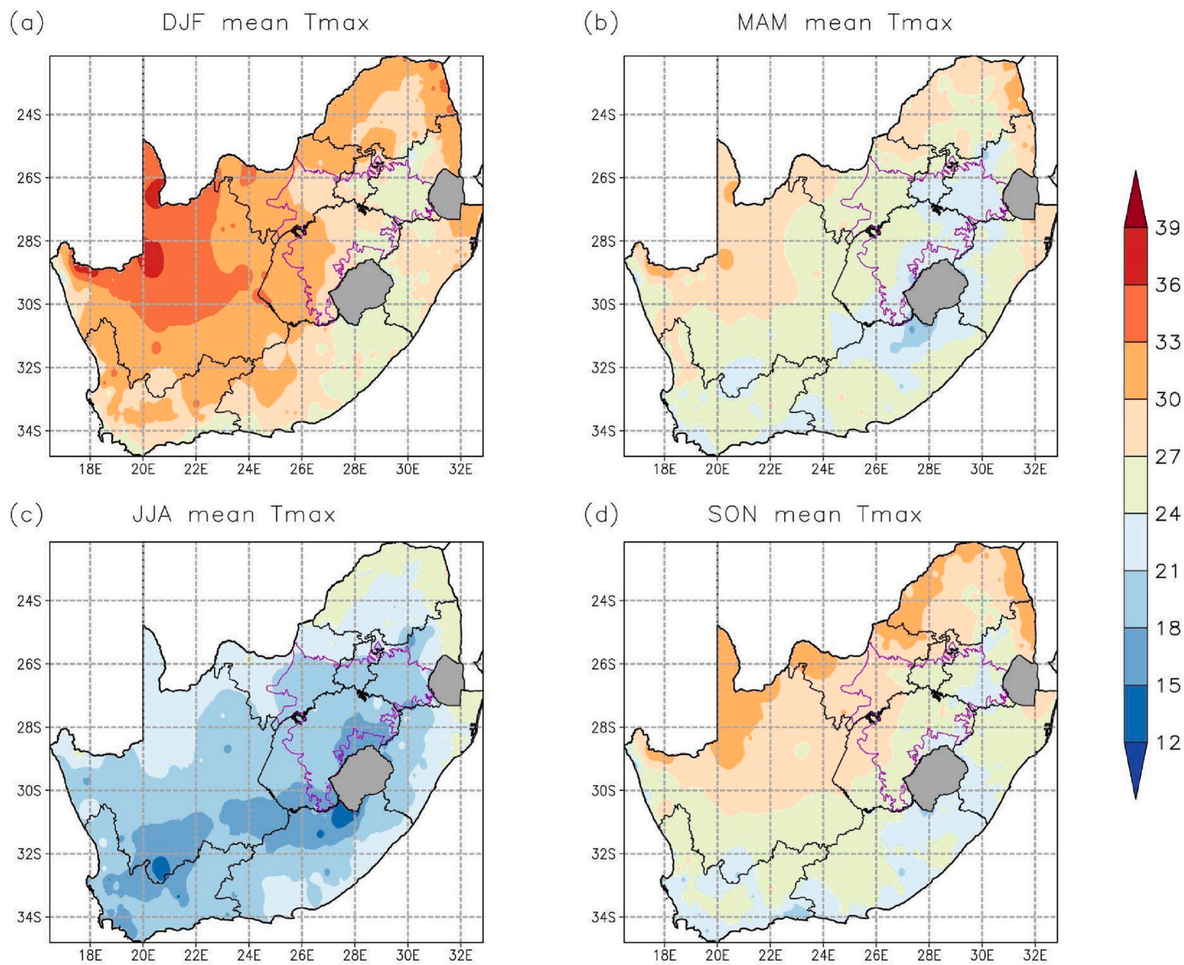


Fig. 3. Seasonal mean spatial patterns of maximum temperatures (°C) during (a) DJF, (b) MAM, (c) JJA, and (d) SON over South Africa based on a 1981–2020 climatology from the SAWS station observations The purple polygon indicates the Highveld, while Lesotho and Eswatini have been masked out.

2023).

Mean daytime temperatures (Tmax) over the Highveld are considered cool during JJA, mostly ranging between 18 and 21 °C (Fig. 3c). The lowest Tmax temperatures during winter occur in a region extending from southeast of the Highveld, south through Lesotho and zonally along about 32°S (Mountain range). Across the country, most temperatures during this time are generally below 21 °C, with the Lowveld of Limpopo and narrow coastal areas of KwaZulu-Natal being slightly warmer. The spring season (SON) is characterized by rising temperatures particularly over the northern districts, whilst the south remains relatively cool (Fig. 3d). This is a significant finding, supporting the argument that the winter season lasts longer in the south, including eastern parts of the Highveld. The highest seasonal mean Tmax are observed during DJF with maxima (exceeding 33 °C) in the Northern Cape bordering Botswana and Namibia (Kalahari) and (Fig. 3a). The very high temperatures observed over the Northern Cape coincide with a surface heat low that becomes semi-permanent during this time (Howard and Washington 2018). Following the summer, the transition MAM season is often considered the most pleasant time of the year (Torrance 1981), when the rainy season has ended and as temperatures are mild (Fig. 3b).

Overall, the mean Tmin and Tmax across all seasons are warmer in the west of the South African Highveld (Figs. 2 and 3). As shown in Fig. 1, the Highveld has a stepper topography in the east, hence the cooler temperatures. Both altitude and latitude play a role as we move farther south. As expected, the narrow coasts around the country are generally warmer compared to the interior plateau.

3.1.2. Seasonal cycles and interannual variability of Tmin, Tmax and ground frosts

The annual cycle of Tmin over the Highveld shows the coldest conditions occurring during June and July (Fig. 4a). July is slightly colder with a mean Tmin of 2.42 °C while June has a mean of 2.76 °C. This coldest period also corresponds with the highest frequency (13–14 days) of ground frost days (Fig. 4b). Tmin peaks during DJF at mean values of 15–16 °C. Whilst intrusions of cold air onto the interior plateau may result in cold days even during summertime, ground frost occurs only during April to September (Fig. 4b). Frost free days (maize growing season) occur from September/October to April/May/June southwest of the Highveld (Free State Province, Moeletsi et al., 2016). The annual cycle of Tmax closely resembles that of Tmin, though with June recording the lowest temperatures (18.4 °C). The highest average Tmax (28.48 °C) occurs during January over the Highveld, consistent with large areas of the country (Mbokodo et al., 2023).

Anomalies or Tmin over the period 1901 to 2021 show random fluctuations but with a general upward trend suggesting warming overnight temperatures over the Highveld (Fig. 4c). The Mann-Kendall trend and Sen's slope test shows a statistically significant (cf. appendix a) and increasing trend in Tmin (Fig. 4c) and Tmax (Fig. 4d) over the 121-year period. Anomalies in the frequency of ground frost days show gradual and statistically significant declines over the area (Fig. 4e), consistent with a warming trend in mean surface air temperatures. Similarly, Moeletsi et al. (2016) found increasing trends of frost-free periods over South Africa's Free State Province focusing on the period 1960–2015.

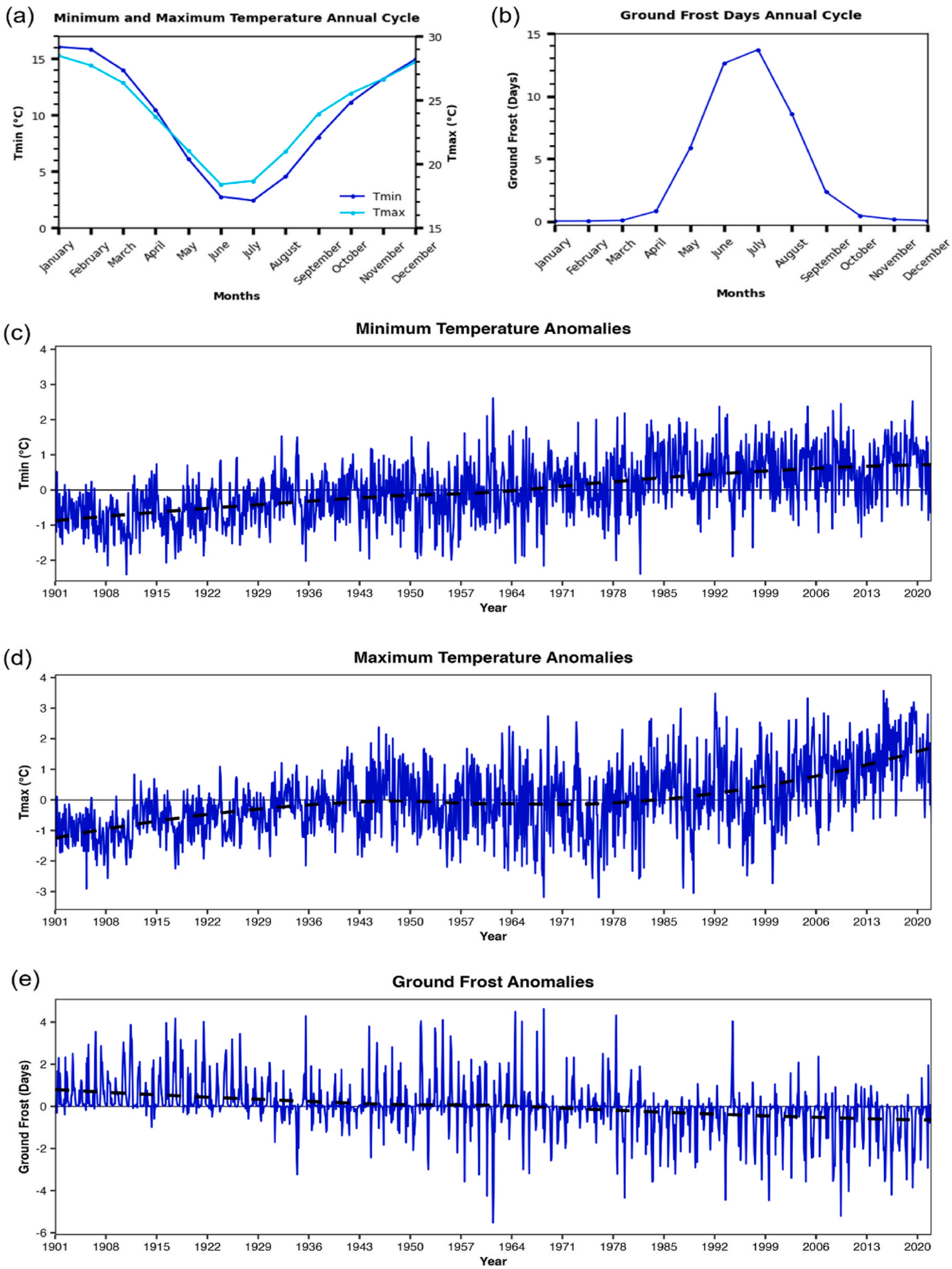


Fig. 4. Mean annual cycles of CRU TS4 (a) minimum and maximum temperature (Tmin) (b) ground frost days, and (c) long-term (1901–2021) interannual anomalies of Tmin, and (d) ground frost days. The anomalies are calculated based on a 1991–2020 climatology.

3.1.3. Trends in temperature extremes over Johannesburg airport

Johannesburg's OR Tambo International Airport is located on the Highveld at about 1700 m above mean sea level (Fig. 1a). We ran RClimDex for Tmin and Tmax to calculate trends at the airport and found declining trends in cold nights and cool days over the period 1991–2020 (Fig. 5a–c). Warm nights and hot days exhibit increasing trends in Johannesburg (Fig. 5b–d), consistent with country (McBride et al., 2021) and regional trends (Engelbrecht et al., 2015b; Singo et al. 2023). All trends are statistically significant at the 95% confidence level (cf. appendix b). While the trend for cold nights and cool days is clearly declining, very cold days still occur regularly, occasionally breaking long-term records (SAWS 2021; McBride et al., 2021).

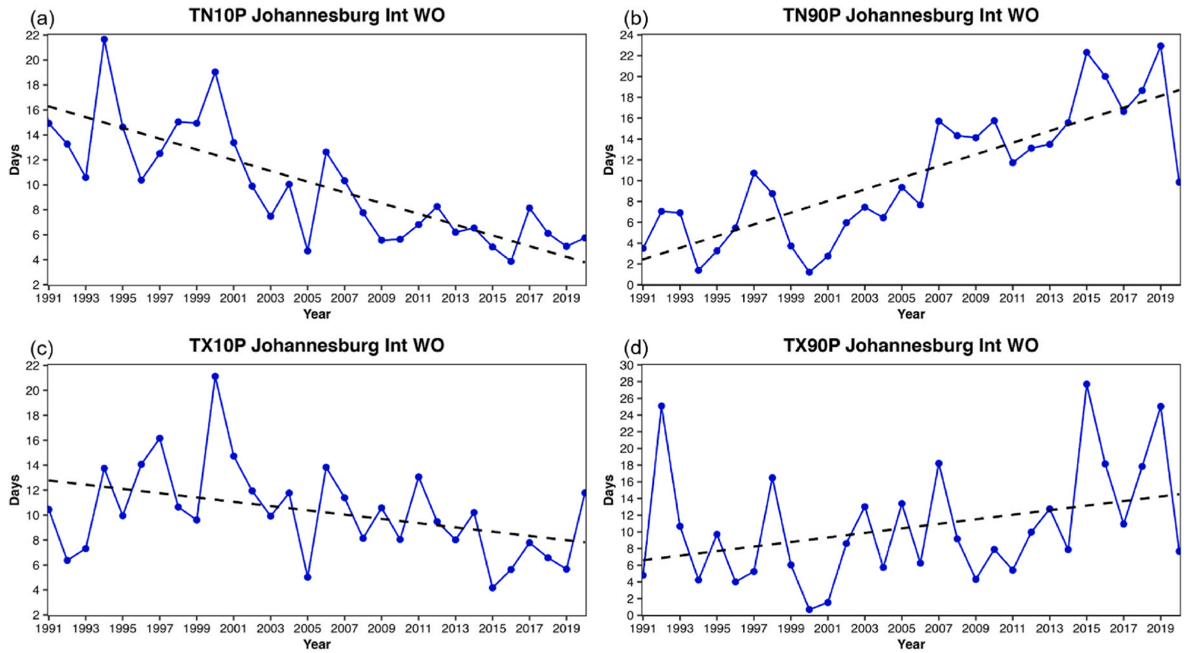


Fig. 5. RClimDex trends from 1991 to 2020 (dotted lines) in (a) COLD NIGHTS and (c) COOL DAYS and (b) WARM NIGHTS and (d) HOT DAYS over the Johannesburg Intl Airport station on the South African Highveld, one of the stations that broke records during July 2021.

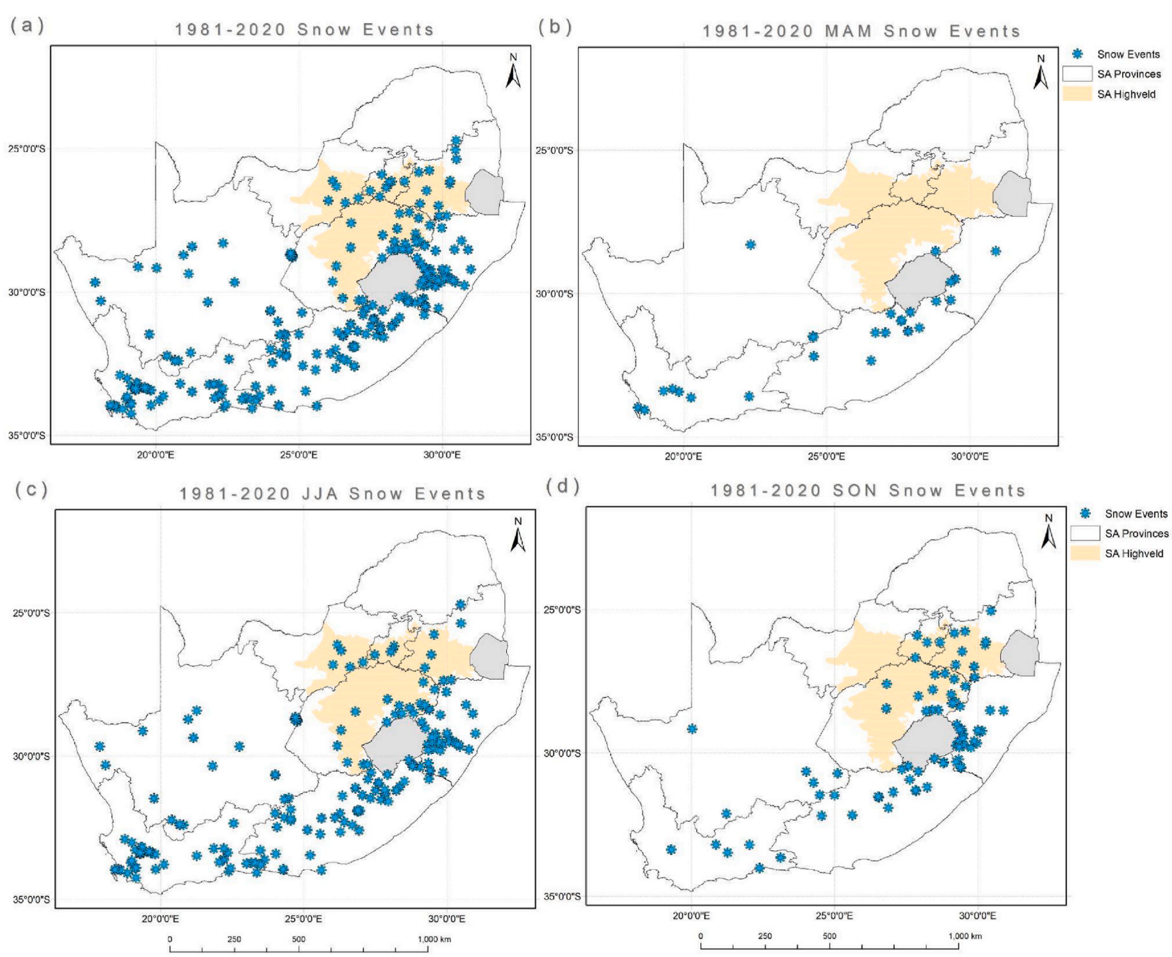


Fig. 6. (a) Total snow events and seasonal mean spatial patterns during (b) MAM, (c) JJA, and (d) SON over South Africa based on a 1981–2020 climatology from the Caelum database. The Highveld area is shown as the shaded polygon while Lesotho and Eswatini have been masked out.

3.1.4. Snow occurrence over South Africa

A total of 476 snow events were recorded in South Africa on the SAWS Caelum between 1981 and 2020 (Fig. 6a). From this total number, no event was reported during the mid-summer (DJF) season (not shown), with only 38 events (8%) during the autumn (MAM) season (Fig. 6b). As expected, most (92%) snow events occurred during the winter (JJA; Fig. 6c) and spring (SON; Fig. 6d) seasons with a winter peak of 332 events (70%). Spatially, most snow events have occurred on high-lying areas, extending from the Western Cape, Eastern Cape, through Lesotho mountains (inferred), the eastern Highveld and along the north-eastern escarpment of the country (Fig. 6a). The tropical far north of the country (<25°S), which includes the entire Limpopo Province, did not experience snow falls during the study period. The propagation of COLs from the west over the arid/semi-arid Northern Cape may account for the snow events observed over the region.

3.2. Case study: ELT weather during 22–25 July 2021

3.2.1. Temperature observations and anomalies

(a) Long-term records broken

Twenty-seven (27) extreme low temperature records were broken at 26 stations during July 2021 over South Africa, with more records during periods before 22–24 July. Most broken records had been set more than twenty (20) years prior, with 61-year records broken at Johannesburg International Airport, Kimberley, and Warmbad Towoomba (Table 1). Several other lowest Tmin or lowest Tmax were broken during 12, 14, 15, 16 and July 20, 2021. The geographical distribution of broken records was mainly over the eastern high ground (>1 000 m) over the interior plateau, and along the coast of the Eastern Cape,

Table 1
Twenty-seven (27) temperature records that were broken at weather stations in South Africa during 22–24 July 2021. The asterisk (*) indicates stations over the Highveld. (Data Source: SAWS).

Station	Co-ordinates	Elevation (M)	Nature of records	Old records	New records	Date	Length of records
Warmbad Towoomba	−24.8992, 28.3239	1 143	Lowest Tmin	−5.5 °C	−5.6 °C	2021-07-23	61 years
Johannesburg Int WO*	−26.143, 28.2346	1 695	Lowest Tmin	−6.3 °C	−7.0 °C	2021-07-23	61 years
Kimberley WO	−28.8061, 24.7698	1 196	Lowest Tmin	−8.1 °C	−9.9 °C	2021-07-23	61 years
Estcourt	−29.0091, 29.8627	1 159	Lowest Tmin	−4.6 °C	−4.8	2021-07-22	48 years
Kroonstad*	−27.6665, 27.3136	1 440	Lowest Tmin	−7.7 °C	−8.0 °C	2021-07-23	43 years
Royal National Park	−28.6858, 28.9542	1 392	Lowest Tmin	−7.6 °C	−7.9 °C	2021-07-24	42 years
Lydenburg	−25.1119, 30.4766	1 439	Lowest Tmin	−3.2 °C	−4.3 °C	2021-07-23	34 years
Cape town - Royal Yacht Club	−33.9206, 18.443	11	Lowest Tmin	4.3 °C	2.5 °C	2021-07-24	32 years
Warden – Heritage*	−27.9611, 29.0594	1765	Lowest Tmin	−6.3 °C	−6.7 °C	2021-07-23	32 years
Patensie	−33.7653, 24.8233	95	Lowest Tmax	10.2 °C	9.0 °C	2021-07-22	32 years
Grahamstown	−33.2907, 26.5026	642	Lowest Tmax	7.2 °C	6.8 °C	2021-07-22	29 years
Mtunzini	−28.9474, 31.7079	41	Lowest Tmin	1.8 °C	1 °C	2021-07-23	28 years
Ermelo WO*	−26.4977, 29.9838	1774	Lowest Tmin	−4.7 °C	−5.1 °C	2021-07-23	28 years
Uitenhage	−33.7141, 25.4352	156	Lowest Tmax	10.6 °C	10.2 °C	2021-07-22	28 years
Postmasburg	−28.3454, 23.079	1 321	Lowest Tmin	−7.2 °C	−7.5 °C	2021-07-22	28 years
Orania AWS	−29.8185, 24.4112	1 122	Lowest Tmin	−7 °C	−7.4 °C	2021-07-23	27 years
Wepener*	−29.9157, 26.847	1 414	Lowest Tmin	−9.8 °C	−10.2 °C	2021-07-24	22 years
Cape Town - Royal Yacht Club	−33.9206, 18.443	11	Lowest Tmax	12.4 °C	11.6 °C	2021-07-23	20 years
Port Alfred - Airport	−33.5595, 26.8809	84	Lowest Tmax	11.7 °C	8.1 °C	2021-07-22	20 years
Ngqura - Coega	−33.8051, 25.6695	47	Lowest Tmax	11.1 °C	10 °C	2021-07-22	18 years
Kokstad	−30.5028, 29.3942	1 451	Lowest Tmin	−6.1 °C	−8.6 °C	2021-07-24	15 years
Tzaneen-Westfalia Estate	−23.7367, 30.1127	840	Lowest Tmin	5.4 °C	4.2 °C	2021-07-24	14 years
Mossel Bay	−34.1894, 22.1318	135	Lowest Tmin	5.7 °C	5.2 °C	7/22/2021	13 years
Bronkhorstspruit AWS*	−25.8087, 28.7386	1 394	Lowest Tmin	−7.1 °C	−7.4 °C	7/23/2021	12 years
Port Elizabeth AWS	−33.9827, 25.6138	60	Lowest Tmax	12 °C	10.9 °C	7/22/2021	12 years
King Shaka AWOS	−29.6019, 31.1295	91	Lowest Tmin	2.1 °C	0.9 °C	7/23/2021	11 years
Venetia Mine	−22.4517, 29.3315	697	Lowest Tmin	0.9 °C	−0.1 °C	7/23/2021	11 years

KwaZulu-Natal and Western Cape (Fig. 1a). The majority of the stations that broke records were located east of 24°E, apart from Cape Town - Royal Yacht Club in the Western Cape (Fig. 1a). The longest records were broken on July 23 by Kimberly WO (61 years) in the North West and the two highveld stations, Johannesburg Int (61 years) and Kroonstand (43 years), and on July 24 at Royal National Park (42 years) in the interior (SAWS 2021). Most of the lowest Tmax during the period occurred along the coast of the Eastern Cape Province. The extreme temperature drops experienced by interior stations are therefore reflected in the overnight minimum temperature as a result. (Table 1). Stations on the interior plateau dominated the highest records broken on July 22nd, the coastal Eastern Cape stations dominated in extreme cold conditions (Fig. 1a; Table 1). Three of the top five stations, based on their coolest/lowest temperature record on 22–23 July, are located in the Highveld region.

(b) Diurnal Temperature Range

The mean monthly diurnal temperature range (DTR) is large (15–21 °C) during the austral winter in most interior parts of South Africa (Mbokodo 2017), as observed during July 2021. The DTR time series of record-breaking stations above high ground (>1 000 m; Fig. 7a) which are essentially stations within the Highveld and its proximity, are compared with DTR for record-breaking stations near sea level (<200 m; Fig. 7b). Overnight temperatures dipped below freezing levels over the high ground stations whilst the coastal stations remained above 0 °C, despite bitter cold conditions (Fig. 7a and b). Overall, stations over high ground exhibited a strong DTR between 18 and 20 °C (Fig. 7a) while lower elevation stations near the coast showed a very weak DTR (5–7 °C; Fig. 7b) during 22–23 July. This period corresponds with the days when most records were broken (Table 1). It seems elevation accounts for the differences in DTR between the coastal stations and the interior plateau. It must be noted that daily changes of local factors such as soil moisture, ground heat capacity and albedo also influence variations in DTR trends (Tshiala et al., 2011). This may account for the differences between the daily and monthly temperature anomalies.

(c) Anomalies

Monthly Tmin anomalies for July 2021 were below normal over much of the country including the Highveld, apart from a few stations in the far north and far west (Fig. 8a). Over the Highveld, the mean monthly Tmax was near normal (Fig. 8b). However, when considering temperature anomalies during the 22–25 July, the whole country was colder than normal with Tmin values up to −7 °C below (Fig. 8c). Regarding Tmax anomalies, colder than normal conditions were observed mainly over the east of the country (Fig. 8d). Consistent with Fig. 1a, it appears this ELT event was most intense over the east of the country.

(d) Snowfall patterns

Frozen precipitation often occurs when the freezing level is at or near ground level. We found low freezing levels for radiosonde profiles for July 22, 2021 falling to below 880 hPa (00 UTC) at Cape Town (Fig. 9a) and 820 hPa (12 UTC) at Bloemfontein (Fig. 9b). As a result, up to 2.5 cm of snow falls were observed mainly over the southern mountains of the country in the Eastern Cape extending to the Western Cape (Fig. 10). Some snowfalls were also observed atop the Tsitsikamma Mountains near the Cape South Coast. However, the entire Highveld area did not experience any snow falls during 22–25 July 2021 despite some snow deposits over the Maluti Mountains in the south of Lesotho (Fig. 10). The distribution of snow cover over the Eastern Cape prevented a more positive flux of sensible heat from the ground into the lower atmosphere compared to the interior, resulting in a greater drop in maximum temperature as the surface and surrounding air remained colder over the Eastern Cape. The 1 000-500 hPa thickness values were typically low across the country due to the extreme low mean temperatures of the lower levels of the atmosphere. Much of the country lies poleward of the critical 540 dam (5 400 m) isopleth, below which snow falls are most likely. Interestingly, some snow fell on the 25th over the Western Cape mountains at thickness values of up to 5 480 m (Fig. 10d).

3.2.2. Circulation dynamics during 22–25 July 2021

We analyse the synoptic dynamical environment during the ELT event that affected southern Africa during 21–24 July 2021. An upper

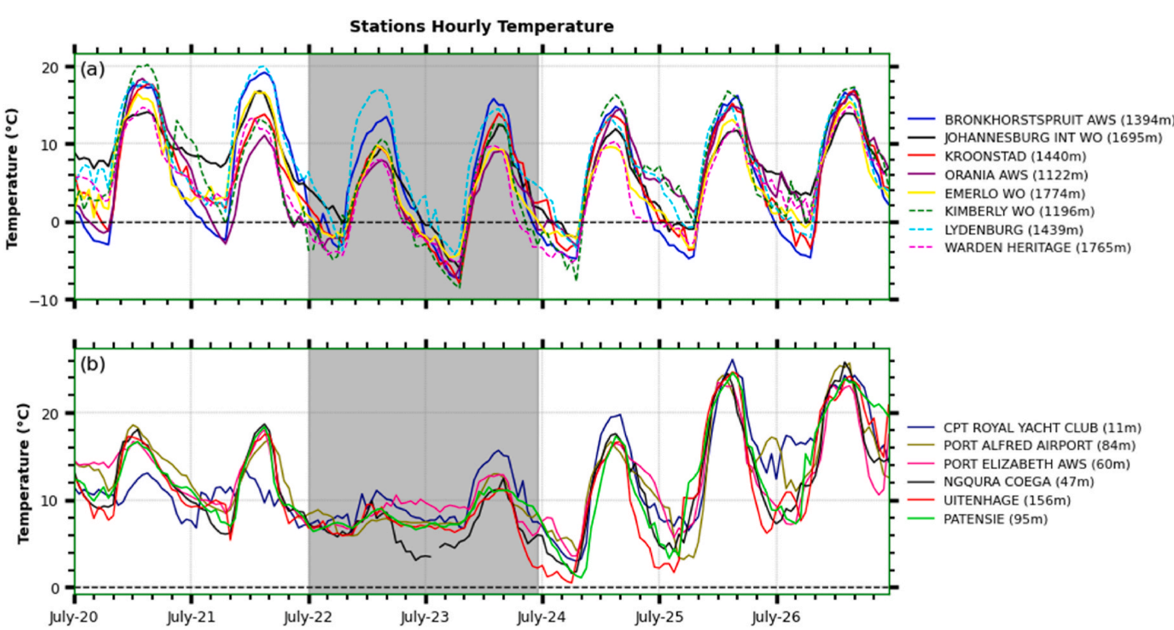


Fig. 7. Hourly dry-bulb temperature (C) data (a) for stations on high ground (above 1 000 m) with those stations outside the South African Highveld in dotted lines, and (b) stations near sea level (<200 m) during the period 20–26 July 2021. The extreme low temperature period 22–23 July is highlighted by gray shading.

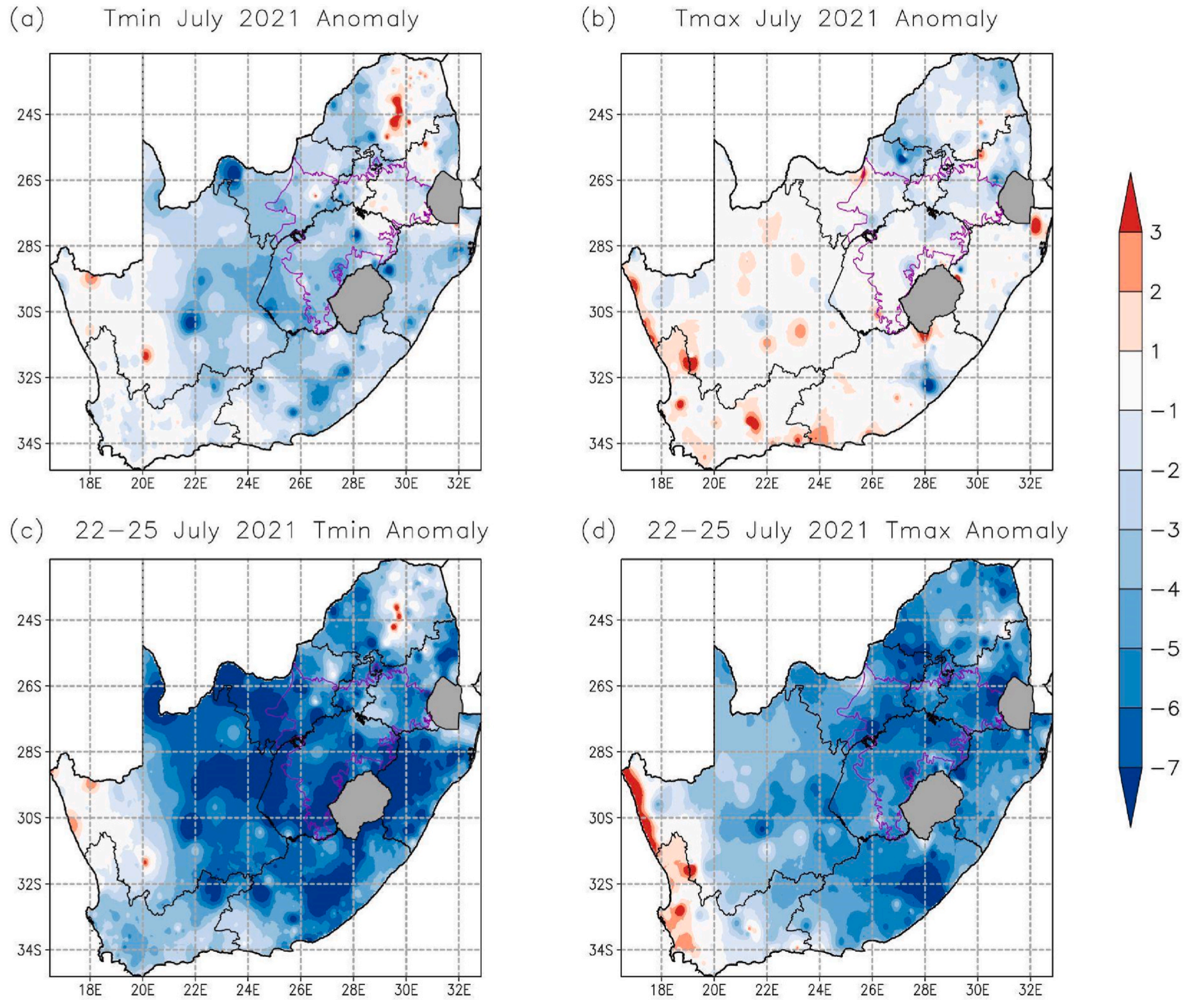


Fig. 8. Climatological (1981–2020) anomalies of (a) minimum temperature (Tmin; °C) for July 2021; (b) maximum temperature (Tmax; °C) for July 2021; (c) minimum temperature for the period 22–25 July 2021; and (d) maximum temperature for the period 22–25 July 2021 over South Africa from the SAWS station observations The purple polygon indicates the Highveld, while Lesotho and Eswatini have been masked out.

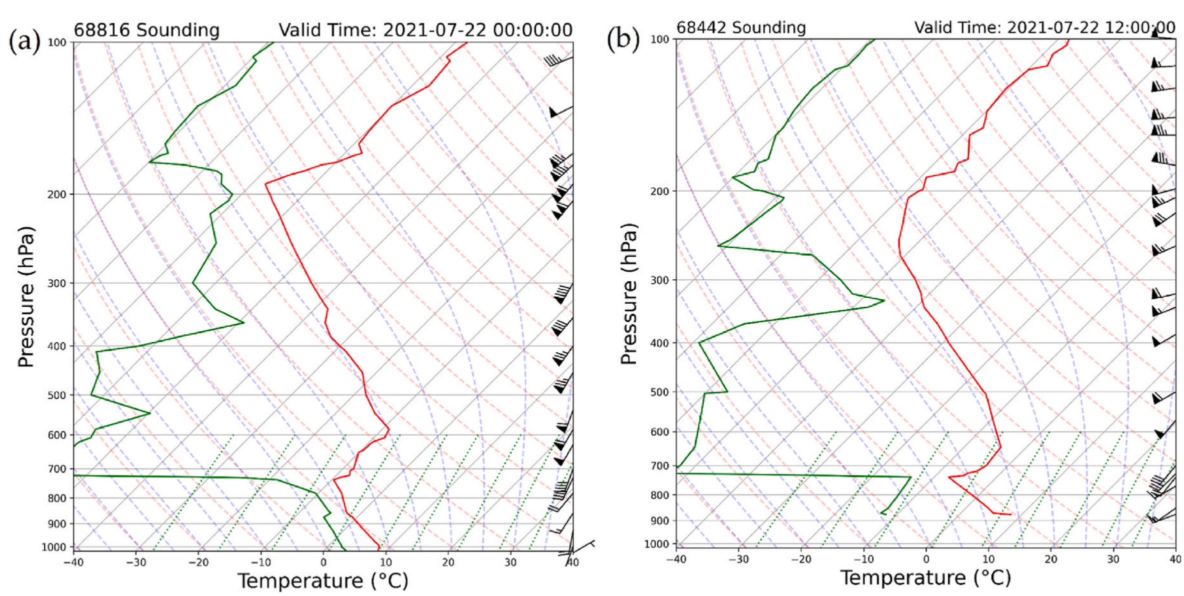


Fig. 9. Radiosonde sounding profiles for (a) Cape Town Intl Airport and (b) Bloemfontein launched at 00Z and 12Z respectively during July 22, 2021.

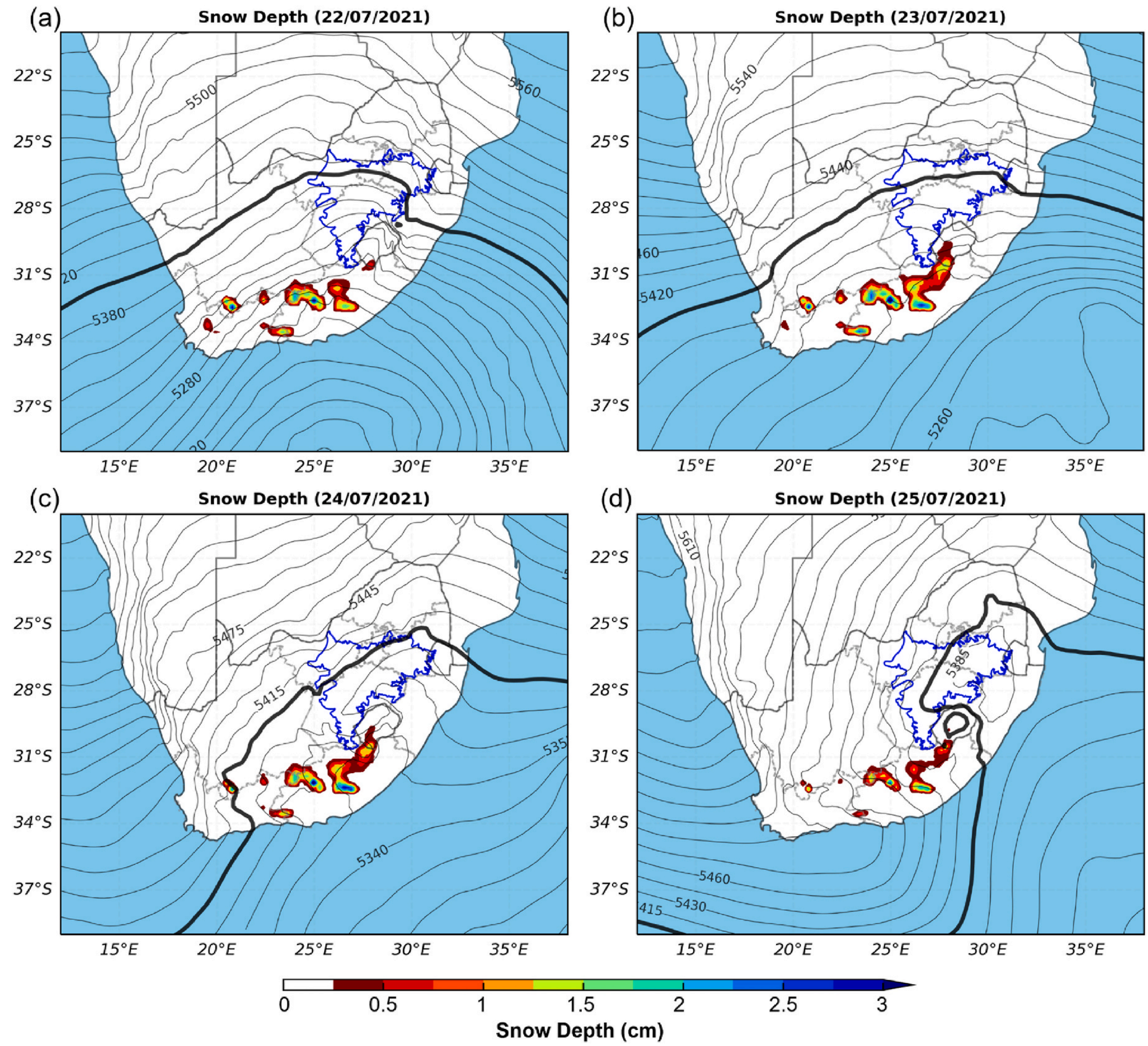


Fig. 10. Snow depth (cm, shading) and 1 000-500 hPa thickness (m; thin solid contours) from 00Z–03Z during (a) 22, (b) 23, (c) 24, and (d) July 25, 2021. The dark bold black contour represents the critical 540 dam (5 400 m) thickness isoline while the purple polygon indicates the Highveld.

trough was observed over the subcontinent propagating slowly eastwards (Fig. 11a). The trough developed into a COL over the ocean during 22–23 July and extended to the surface. Barnes et al. (2021b, see their composite Fig. 10), showed that this category of COLs is climatologically linked to negative surface temperature anomalies that are oriented such that they are located along the trough axis. In the case of the COL observed for this ELT event, the location of low temperatures is over South Africa. Because the system extends to the surface, it may then be categorised as intense (Pinheiro et al., 2021). Behind the upper trough, a high pressure system over the South Atlantic Ocean, combined with the action of the cyclonic flow associated with the surface component of the COL, was pushing and driving divergent southwesterlies into the country (Fig. 11a,b,c,d). The observed COL on 22 July (Fig. 11 b) has an Omega shape with two jet streaks on either side of the trough axis. The upstream jet streak extends to the surface, as the COL resulting in strong southerly flow west of the surface low with intense cold air advection from the south into the country (Fig. 11e and f). This then led to very cold temperatures over South Africa (Fig. 8) thus leading to persistent ELT conditions throughout the country (Fig. 8). As a result, long-term records were broken, with the coldest Tmax observed along the south coast of the Eastern Cape (Fig. 1a).

The orientation of the near surface and mid-tropospheric isopleths of constant geopotential is in the same direction on 22 July (Fig. 11a–e), suggesting weak vertical wind shear through the layer. This is supported by the upper sounding profiles which show southwesterlies from near the surface to at least about 200 hPa (Fig. 9a and b).

The ELT event followed the passage of an intense cold front which approached Cape Town on the 19th, propagating across South Africa (Fig. 12a), allowing southwesterly air flow to approach the country with a massive fetch on 21–22 July (Fig. 11e and f). The July 19, 2021 EUMETSAT satellite image shows a distinct and well-defined field of cold air cumulus behind the cold front (Fig. 12a), with a cloud pattern depicting cold environmental air. Such a pattern warns bench forecasters of imminent cold air advection and possibility of an ELT event. The cold front is seen propagating gradually eastwards to lie over the southwest Indian Ocean by the 23rd (Fig. 12b and c). Behind the cold front was an intense Type-S (Ndarana et al., 2022) ridging South Atlantic anticyclone which, in addition to introducing very cold air from the southwest as discussed above, transported moisture into the country. The influence of the ridging process extends well onto the interior plateau as far north as ~20°S in Zimbabwe (Fig. 12d). Typically, low clouds of a stratiform type (stratocumulus) seen here occur over the Lowveld of South Africa and enter southeast Zimbabwe, associated with ridging anticyclones over the KwaZulu-Natal coast.

As the ridging process progresses, the surface winds back from southwesterly to southerly becoming southeasterly over the KwaZulu-

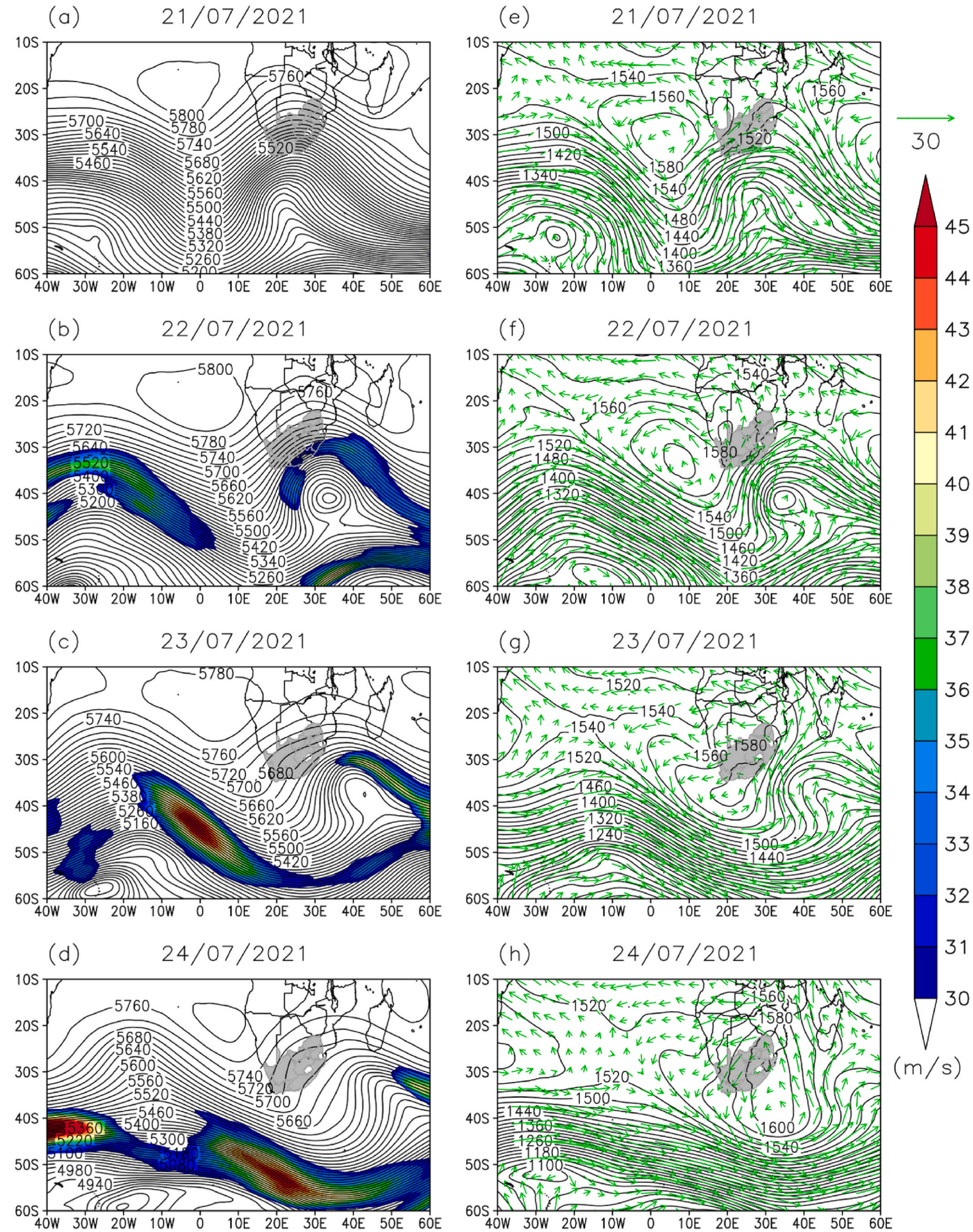


Fig. 11. Geopotential heights (m) in the mid-troposphere (500 hPa) with wind isotachs (m/s) during (a) 21, (b) 22, (c) 23, and (d) July 24, 2021. The panels (e) to (h) show geopotential heights and winds near the surface (850 hPa) for the corresponding period.

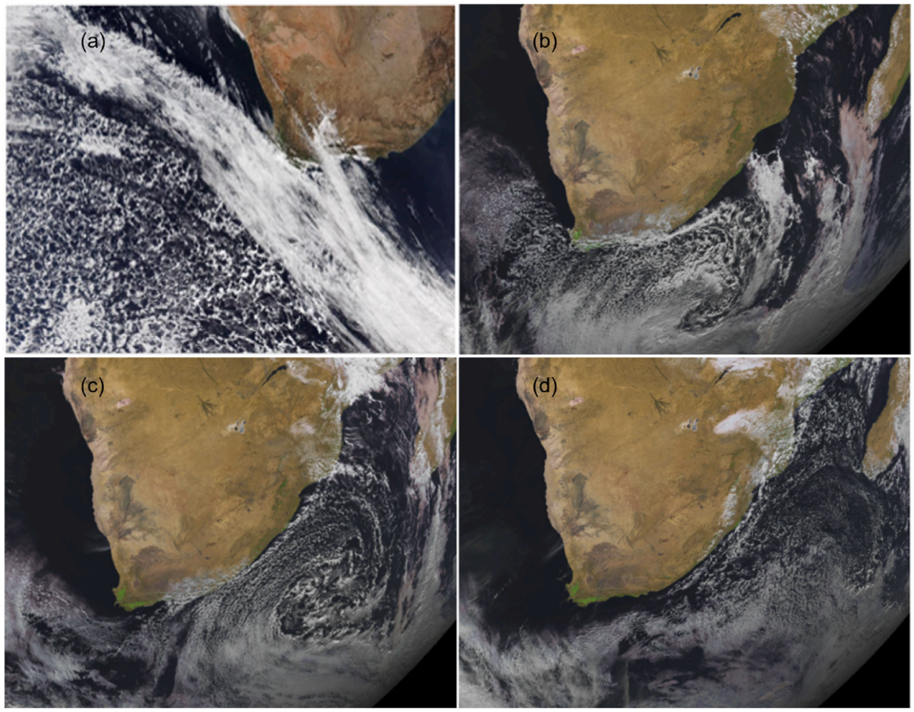


Fig. 12. EUMETSAT Infrared (IR) satellite images before and during the ELT event on (a) 19, (b) 22, (c) 23 and (d) July 24, 2021. The field of cold air cumulus is prominent behind the cold front.

Natal coast (Fig. 11e,f,g,h). The orientation of the isopleths on 23 July as the winds are backing suggest that the geostrophic component of the flow is parallel to the coast (Ndarana et al., 2021) so the component of the flow that is ageostrophic is onshore. This enhances moisture fluxes and cold air advection to penetrate the interior plateau. A strong moisture flux is consistent with the observed Type-S ridging high (Ndarana et al., 2022) and this ridging event is induced by the presence of an anticyclonic wave breaking (Ndarana and Waugh, 2011). The breaking itself is caused by intensification of the extratropical jet streak that is first located just upstream of the Greenwich Meridian on 22 July (Fig. 11b); after which it propagates east and intensifies. As it does, it increases the shearing strain rate on the anticyclonic barotropic shear side of its axis (Nakamura and Plumb, 1994; Ndarana et al., 2023). This caused the wave to break anticyclonically, changing the orientation of the COL, as indicated by the 500 hPa isopleths. The curious issue raised by this case study is that COLs (and their associated wave breaking events) do not have to propagate into South Africa to affect the country.

4. Conclusion

Whilst several studies (e.g., Karl et al., 1993; Jury 2018; Kruger and Nxumalo 2017b; van der Walt and Fitchett 2020b; Mateyisi et al., 2021; McBride et al., 2021; IPCC et al., 2021) have found significant warming trends across South Africa consistent with global patterns in the subtropics, ELT events remain a key feature of the regional climate. This is despite a reduction in frequency and duration of cold days (Mbokodo et al., 2023) and cold waves in the country (van der Walt and Fitchett 2020b). The frequency of ground frost days over the country has also declined significantly in recent years according to ERA5 data. The coldest period of the year occurs during June and July over the South African Highveld and nearly everywhere else across the country. However, South African winter temperatures are comparatively higher than typical boreal winters in the high latitudes of the Northern Hemisphere. In the Southern Hemisphere, ELTs and cold waves are more common in South America due to its high elevation which reaches 3 000 m over the Andes Mountain Range (e.g., Marengo et al., 2023).

We employed station, upper-air, satellite, and model data to analyse an ELT weather event over South Africa that broke 27 long-term records during 22–24 July 2021. We also investigated historical trends in key ETCCDI temperature indices, including the occurrence of ground frost and snow falls with a focus on the South African Highveld. We found that the 2021 austral winter season over South Africa experienced some of the coldest episodes, as long-term records were broken repeatedly throughout July 2021 (including before 22–24 July). The 20–24 July 2021 period was also colder than normal over large areas of southern Africa including neighbouring Botswana and Zimbabwe (not shown), as cold air intrusions penetrated deeper into the interior. Low level *guti* cloud was shown extending well into the southeast of Zimbabwe as positive sea level pressure anomalies developed over South Africa's east coast. Snowfalls of up to 2.5 cm were deposited over high ground, mainly over the southern districts (south of 30°S). Results reveal that both overnight minimum and daytime temperatures were colder than normal across the country, with larger anomalies over the Highveld, hence the focus of this study.

For context, the July 2021 ELT event occurred following an anomalously wet season characterized by positive rainfall and soil moisture anomalies during La Niña over the equatorial Pacific Ocean. Most La Nina conditions are associated with above average seasonal rainfall over large areas of southern Africa resulting in high soil moisture (Chikoore and Jury, 2021). Soil moisture anomalies have been found to affect and modify the atmospheric circulation over an area at seasonal and longer time scales (Shukla and Mintz 1982; Delworth and Manabe, 1988; Qi et al., 2023).

We found that circulation anomalies during 22–24 July 2021 were dominated by a combination of a cold front, a Type-S ridging anticyclone, and an intense COL aloft. The strong south westerly fetch through a deep layer of the troposphere minimized mixing and resulted in freezing mean temperatures of the 1 000-500 hPa layer. Consequently, much of the southern districts of South Africa lay poleward of the critical 540 dam thickness isopleth values, creating conditions conducive for snow falls especially over high ground. A steep 500 hPa trough developed into a COL that extended to the surface over the ocean south of Africa during 22–23 July 2021. COLs that extend to the surface are often intense (Pinheiro et al., 2021) and induce negative temperature anomalies near the surface (Barnes et al., 2021b). A key finding from this case study is that South African weather can be severely affected by COLs (and their associated wave breaking events) located at sea.

A ridging anticyclone with a strong meridional fetch from the south/polar region is often the main weather system associated with ELT events over South Africa. In this event, intensification of the extra-tropical jet streak upstream resulted in anticyclonic wave breaking which, in turn, induced a Type-S ridging event. Jet streaks have been linked to extreme temperature events which may include heatwaves in several regions as they modulate the location and orientation of surface systems (e.g., Chang and Lau 1980; Singleton and Reason 2006). Due to the complex topography characterized by a high plateau and a narrow coastal belt, our results suggest that the impact of cold advection and ELT events is greater over the interior than near coasts. This characterization of synoptic circulation anomalies that combined and produced the ELT event of 22–24 July 2021 does not present a generalization for a broader set of ELT events affecting the South African domain. Rather, this paper provides a valuable foundation for future research and more extensive analyses towards development of a typology of synoptic conditions associated with ELT events. Such a typology may be constructed via Self-Organizing Maps or similar machine learning algorithms.

Whilst van der Walt and Fitchett (2020a) proposed an aggregated winter season across South Africa spanning JJA, their study also showed that only the months of June and July are consistently classified as winter across the whole country. They found winter ends early in some districts in the far north and northwest, while persisting for longer in the south. Our study also determined that cool conditions persist into the SON season in those areas. We argue that mid-May to mid-August may be a more realistic definition of the winter season over northern South Africa whilst May to September should apply in the south.

Predictability of extreme temperature events at seasonal (e.g., Lazenby et al., 2014) and medium range weather time scales are critical for early warning systems and natural disaster risk reduction. Understanding the role of jet streak dynamics in cold advection and ELT events can lead to better medium range weather forecasts. Whilst observing systems and forecasting capabilities have improved markedly in recent decades, communicating weather alerts and warnings still requires concerted effort. The limitations of the science including implications of uncertainties also need to be communicated effectively.

In addition to warming trends, several studies have projected significant rises in mean surface air temperatures over South (ern) Africa in future (Englebrecht et al. 2015b; Garland et al., 2015; Singo et al. 2023). Future changes in intensity, frequency and return periods of both hot and cold extreme temperature events may become more significant and require further investigation. Periods of ELTs often result in profound impacts on society, winter agriculture and the environment (van der Walt and Fitchett 2020b). Assessments of present and future vulnerabilities to impacts of ELT hazards are necessary for proactive civil protection and reduction of economic losses. This paper highlights the importance of understanding ELTs, in an era of increasing weather and climate extremes. Government policies should be targeted at increasing societal resilience to a new climate through effective climate change adaptation, also recognizing other extreme events not discussed in this paper.

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CRediT authorship contribution statement

Hector Chikoore: Conceptualization, Resources, Writing – original draft, Writing – review & editing, Formal analysis. **Innocent L. Mbokodo:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Mukovhe V. Singo:** Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Tumelo Mohomi:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Rendani B. Munyai:** Investigation, Writing – original draft, Writing – review & editing. **Henno Havenga:** Visualization, Writing – original draft, Writing – review & editing. **Dawn D. Mahlobo:** Writing – original draft, Writing – review & editing. **Francois A. Engelbrecht:** Writing – original draft, Writing – review & editing. **Mary-Jane M. Bopape:** Conceptualization, Writing – original draft. **Thando Ndarana:** Conceptualization, Formal analysis, Investigation, Writing – original draft.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The authors do not have permission to share data.

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Daily and monthly temperature and rainfall data, records of extremes and synoptic maps we analysed here were obtained from the South African Weather Service (SAWS). The ERA5 and ERA5-Land reanalyses were obtained from the ECMWF. The University of East Anglia's CRU Timeseries 4 (TS 4) data were also analysed.

APPENDICES.

Appendix a. Mann-Kendall and Sen's slope trend test for Tmin, ground frost days and Tmax

Variable	p-value	Z score	Sen's slope
Tmin	2.2×10^{-16}	22.632	0.0011 °C/month
Tmax	2.2×10^{-16}	19.865	0.0014 °C/month
Ground Frost	2.2×10^{-16}	−17.993	−0.0003 days/month

Appendix b. *RClimDex slope trend test (trends computed by linear least square and locally weighted linear regression) for COLD NIGHTS, COOL DAYS, WARM NIGHTS and HOT DAYS over the Johannesburg Intl Airport station on the South African Highveld, one of the stations that broke records during July 2021. The period did not include 2021 which had extreme old temperature anomalies.*

Indices	Start year	End year	Slope	P_Value
TX10P	1991	2020	−0.319	0.021
TX90P	1991	2020	0.377	0.022
TN10P	1991	2020	−0.236	0.02
TN90P	1991	2020	0.65	0

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