Trends in Probabilities of Temperature Records in the Non-Stationary Climate of South Africa

(short title: Temperature Records in the Non-Stationary Climate of South Africa)

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ABSTRACT

The temporal and spatial distribution of the frequency of breaking highest and lowest daily maximum and minimum temperature records over the period of 1951 to 2019 has been investigated for South Africa. Temperature records are station specific and defined as either larger or smaller than any previous values in a time series of specific year-days. Daily maximum and minimum temperatures from homogenised time series of 25 weather stations in South Africa were analysed. Aspects considered to influence the frequency of record-breaking events were the warming trend and variance. The study found that the record-breaking frequencies of the highest daily maximum (high Tmax) and some high daily minimum temperature (high Tmin) records were higher than the theoretically expected number in a stationary climate. This was particularly apparent near the end of the analysis period. The ratio of highest maximum to lowest minimum temperature records was almost an equal 1:1 ratio near the start of the analysis period and increased to a about 4:1 in the last decade of the period. Focusing on the last decade, i.e. 2010 – 2019 the study found that there is a different spatial pattern between the occurrence of high Tmax and high Tmin records. For high Tmax records the highest number were mostly recorded by stations over the central parts of the country (e.g. Kimberley, Glen College and Bloemfontein). In contrast, the highest number of high Tmin records were less confined spatially. Even when considering the general warming due to climate change, many more high temperature records are broken than expected in certain regions and on average. We deduce that the higher than expected numbers of high Tmax and high Tmin records in the latter part of the analysis period were mainly due to the variability in the warming trend with acceleration in the last decade.

Key words: South Africa, record-breaking temperature records, temperature extremes, warming, climate change

1 INTRODUCTION

There is general consensus among climatologists that there is sufficient evidence of climate change, especially increases in surface temperature (Donat *et al.*, 2013), confirmed in the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) (Stocker *et al.*, 2014). This change, which shows a positive warming trend over most regions of the world since at least the 1950s, cannot be explained by natural variability alone (Brown *et al.*, 2008; Collins, 2011) and the altering of the atmospheric composition by humans is changing this variability (Karl, 2003).

One of the consequences of the human-induced changes in the general climate is that specific extreme weather and climate events are likely to increase (Stott, 2016). These extreme values would fall into the tails of the variable's distribution (Zwiers *et al.*, 2013). Any change in the distribution's mean or variance or both will affect the occurrence of extreme events (Meehl *et al.*, 2000). Thus in a warming climate the mean temperature and variability are likely to change and thus so the occurrence of hot extreme events (Tamarin-Brodsky *et al.*, 2020). These changes in mean temperature and in extreme events are however not linear and small changes in the mean state can result in large changes in the occurrence of extreme events (Mearns *et al.*, 1984; Meehl *et al.*, 2000). Record breaking temperatures fall into the realm of these types of events (Rowe and Derry, 2012) and by their very nature are rare events (Stephenson et al., 2008; Field et al., 2012; Otto, 2019). This makes their analysis difficult as one considers changes in trend of a diminishing number of events (Rowe and Derry, 2012).

According to the IPPC (2019), global surface temperatures are currently increasing at around 0.2°C per decade. This increase in warming trend has also been documented in a number of studies for South Africa (Kruger and Shongwe, 2004; Kruger and Nxumalo, 2017; Van Der Walt and Fitchett, 2021). This warming trend show variability across the country with stations located in the central parts showing less of a positive trend than those located in the western and eastern parts of the country (Kruger and Nxumalo, 2017). With this warming comes the concern that in the future highest daily maximum temperature records will be broken more often than lowest daily minimum temperature records (Benestad, 2004; Finkel and Katz, 2018). This increase in temperature trend along with other climate change related threats pose challenges for how South Africa is able to respond in terms of water, food security, human and ecosystem health and development (Ziervogel *et al.*, 2014).

Policymakers are showing an interest in the risks associated with extreme weather and climate events, especially if these are likely to increase (Brulle et al., 2012; Omondi et al., 2014). In addition to policymakers, the general public who, experience climate change mostly through the occurrence of extreme events, want information on these events and how their frequencies are expected to change (Parey et al., 2007; Easterling et al., 2016). Thus the occurrence of climate change related extreme weather events has become an increasingly important climate research topic (Poudel et al., 2020), with researchers beginning to pay more attention to climate record-breaking statistics to shed light on whether and how the occurrence of daily temperature records is affected by a changing climate (Wergen et al., 2014). Understanding record-breaking events will prove to be important as any change in the frequency of extreme weather events may influence how especially developing countries are able to adapt (Mirza, 2003). With Africa being especially vulnerable to climate change (Lennard *et al.*, 2018) there is a need for more research into such events (Stephenson *et al.*, 2008) particularly in light of vulnerable communities having to respond to these events (Van Wesenbeeck *et al.*, 2016).

There is a general lack of research focused on the breaking of specific station's individual highest or lowest observed daily or monthly temperature records. Zwiers *et al.* (2013) point out that the use of in-situ data is extremely important in our understanding of changes in extremes. Studies around short-lived high-temperature extremes also provides a different look at how changes are occurring compared to studies that focus on annual or seasonal time frames (Papalexiou *et al.*, 2018). Research on breaking temperature records have largely been concentrated in the Northern Hemisphere: USA (Rowe and Derry, 2012; Meehl *et al.*, 2016); Europe (Elguindi *et al.*, 2013; Abatzoglou and Barbero, 2014; Beniston, 2015); China (Deng, 2018; Zhong-Hua *et al*., 2012); Korea (Cho *et.al*., 2011); Lebanon (Hayek, *et. al*., 2020) with Australia (Trewin and Vermont, 2010) the exception. Only one global study could be found (Anderson and Kostinski, 2010) and this contained very few stations in the Southern Hemisphere. The presented research endeavours to contributes by investigating breaking temperature records at several continental and maritime locations in South Africa. We investigate whether the changing climate, i.e. general warming, can be linked to the occurrences of extreme record surface temperatures in in-situ measurements over South Africa. Several authors (Seneviratne *et al.*, 2014; Fischer and Knutti, 2015; Li *et al.*, 2021) indicate that there has been an increase in temperature extremes in recent decades. The warmest years in South Africa's temperature record have occurred in the last decade (Blunden *et al.*, 2020) and this period will therefore be a particular focus of the analysis and discussion.

The analysis of the temperature data in this paper attempts to determine whether the breaking of temperature records in South Africa conforms to the probabilities of records in a stationary climate and if not, whether the general warming trend sufficiently explains the observed temperature records in South Africa, especially over the last decade.

2 Data

Near-surface daily observational temperature data for the period 1951 to 2019 from 25 stations across South Africa were selected for analysis. The start year of 1951 was chosen as this was the earliest year for which all of the stations in the study had sufficient data, i.e. more than 90% of data for every year in the time series. Missing data was not replaced as any attempt to do this would be unlikely to result in a record value (Rowe and Derry, 2012). Data sets did not include data for the 29th of February as these temperatures would need to be compared every 4 years making any identified records difficult to add to a yearly time series. Consolidating the start of the period between all stations ensures that the number of records broken in a set year is not affected by different number of previous years in the time series (Meehl *et al.*, 2009). The 25 stations included 16 interior and 9 coastal stations. The locations of the stations are presented in Figure 1.

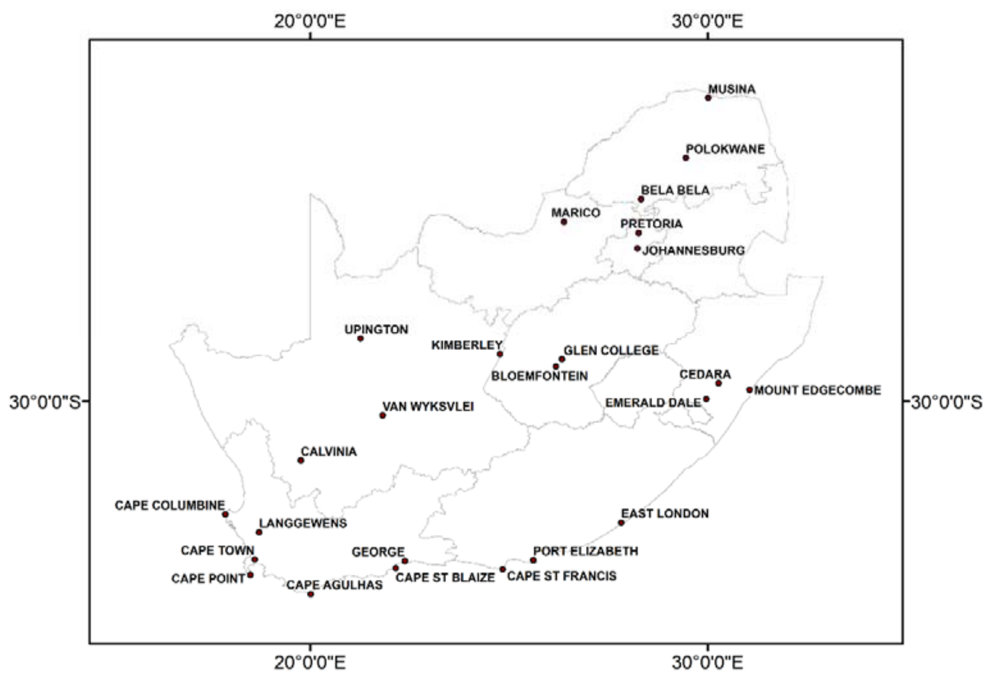

Figure 1. Locations of the 25 stations used to study the occurrences of temperature records over the period 1951 – 2019.

The station data was quality controlled and any suspicious records were checked either with the original climate hard copy return or using a graphical interface to check for non-meteorological spikes or sensor problems. The data was homogenised using the RHtestsV4 software package (http://etccdi.pacificclimate.org/software.shtml). Details of the homogenisation methods and procedures are found in the RHtestsV4 user manual (Zhang and Yang, 2004).

2.1 Methodologies

The range of analyses attempt to provide insight as to whether and how the warming in South Africa had an effect on the observed frequency of temperature records. This includes comparisons of the observed number of records against the expected in a stationary climate, and whether the observed warming can sufficiently explain the deviation from the frequencies of the expected in a stationary climate. In addition possible regional difference in the frequencies in the record-breaking occurrences were investigated. Established approaches (Franke *et al.*, 2010; Wergen and Krug, 2010; Pan *et al.*, 2013) to accommodate a warming trend in the estimation of the expected number of records were considered. Because it has been established that global warming is accelerating (Li *et al.*, 2021) deviation from expected frequencies of records during the last decade will be of particular focus. The Mann-Kendall test was used to test for trend significance at the 5% level. Possible temporal changes in long term warming trends were established with the *t*-test, and the results applied to explain the increased frequencies of daily highest Tmax and Tmin records. Following are the methodologies discussed in detail:

2.2 Expected frequencies of records in a stationary climate

To determine whether a temperature record was broken, a specific year-day was compared to all previous days in the same position within the year sequence (e.g. 9 July with all previous 9 Julys) (Pan *et al.*, 2013). The compared values can be considered to be independently and identically distributed (i.i.d) (Krug, 2007). This means that days around a record does not influences the next value in the series as each value is separated by 365 days (Wergen and Krug, 2010).

Following the above methodology and comparison of values, the first year all stations broke the particular record being checked every day (365 records per station), the following year fewer record-breaking events are probable and so on for each subsequent year. The expected frequency of breaking records should occur at a predictable probability of

$$P_n = \frac{1}{n} \quad (1)$$

where *n* is the length of the time series in years (Wergen and Krug, 2010). Therefore, in a stationary climate the annual ratio of Tmax and Tmin records would remain near-constant (Meehl *et al.*, 2009). With every year added to the data series the more unlikely it becomes to break a record if the climate is stationary, following the probability of 1/*n* (Meehl *et al.*, 2016; Arnold *et al.*, 1998). The observed deviations from the expected rate of new records and the changes in the ratios were therefore examined, to determine whether the climate records followed a non-stationary rate of probability.

Bootstrapping simulations (1000), which is a form of Monte-Carlo simulations with replacement, were used to estimate the 95% confidence intervals of the expected number of records per year.

2.3 Interior and coastal stations

Stations were divided into interior and coastal, to possibly reveal additional insights into the occurrence of record-breaking statistics. Previous studies on monthly maximum and minimum temperature trends in South Africa found that coastal stations mostly showed larger temperature increases when compared to interior stations (Muhlenbruch-Tegen, 1992; Kruger and Shongwe, 2004; MacKellar *et al.*, 2014,).

2.4 Records in a warming climate

To accommodate for a warming trend in the climate, Krug (2007), Wergen and Krug (2010), Pan *et al.* (2013) and Wergen *et al.* (2014) developed and applied a trend term in the probability estimation of record breaking events:

$$P_n \approx \frac{1}{n} + \frac{v}{\sigma} \frac{2\sqrt{\pi}}{e^2} \sqrt{\text{In } \left(\frac{n^2}{8\pi}\right)} \quad (2)$$

where *n* is the number of years, *v* = mean temperature trend and *σ* = standard deviation, *π* = pi and e = Euler–Mascheroni constant. The first term 1/*n* is the theoretical expected number of records in a stationary climate Equation (1) and the next expression after the addition sign is defined as the trend term (Wergen and Krug, 2010). When there is no trend (stationary climate) *v* = 0. Following the approach of Wergen and Krug (2010), the expected number of high Tmax and high Tmin records was estimated taking into account the mean warming trend at each individual station. By way of example Bloemfontein after 68 years (last year of the record) should record approximately 5 highest Tmax records in a stationary climate but when taking the warming trend of 0.29°C/decade into account the expected number of records is 9.

2.5 Temporal change in trend

The Mann-Kendall test was used to test trend significance at the 5% level. To test where the warming trend is changing over time, the Student’s t-test was used to evaluate the statistical significance of the differences, at the 5% confidence level, between the linear trend of the time series for the years prior to and the years after every year. The change in trend was then used in Equation (2) to compare the probable number of records between when the trend is considered to be constant or changing over time.

3 Results

3.1 Ratios

The breaking of Tmax and Tmin records in South Africa has not always occurred at the same frequency throughout the period under investigation. The ratios of high Tmax to low Tmin records per year (Figure 2), at the start of the study period was approximately 1:1. This ratio however steadily increased in favour of Tmax over the years and since the 1980s show a marked increase in interannual variability. Even though a general increasing trend is discernible, the ratio is anomalously high in specific years. These are 1999 (5:1), 2005 (5:1), 2016 (8:1) with a maximum of 9:1 in 2019. The trend in ratio of Tmax to Tmin is statistically significant at the 5% confidence level.

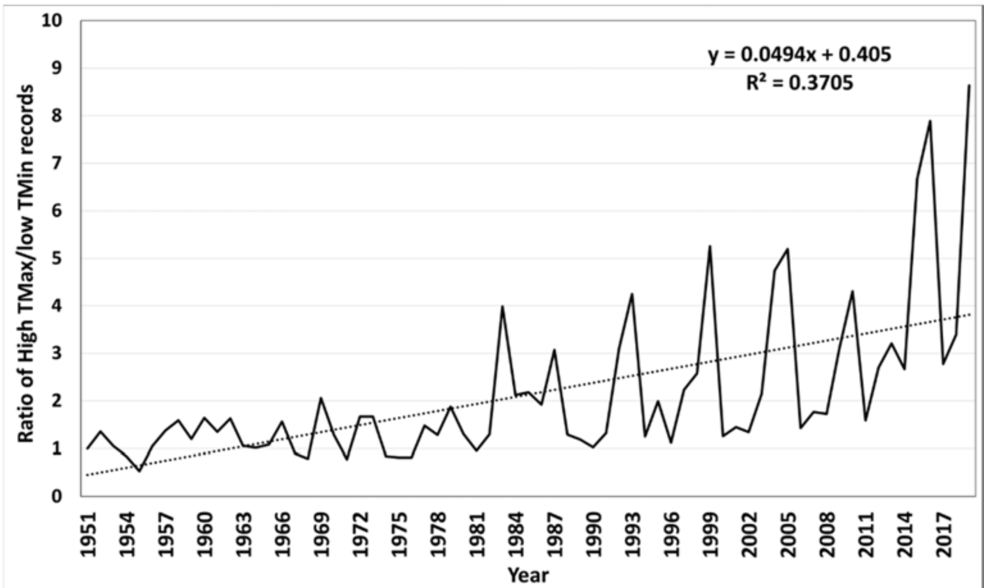

Figure 2: Annual average ratio of high Tmax to low Tmin records for all stations for the period 1951 to 2019 for the 25 stations analysed.

3.2 Frequencies of records

It is evident that there is a gradual decrease in the number of records per year (Figure 3) due to the fact that it becomes less probable to break previous records as one moves forward in the time series (following Equation 1). However, in the latter part of the analysis period, the number of high Tmax (low Tmin) records does not strictly follow the expected occurrence of records but show an increase (decrease), especially in the last decade. High Tmax records (dots) exceeded the upper 95% confidence intervals often since 1983 whereas the low Tmin records (triangles) stays within the 95% confidence interval, albeit close to the lower end. Interior stations high Tmax records showed a greater deviation from the expected number of records (Figure 3b) when compared to those of coastal stations (Figure 3c). The interior stations exceeded the upper confidence interval for the first time in 1970 but this happened much later (1998) for coastal stations. Records at interior stations also exceeded the upper 95% confidence interval 14 times while coastal stations only three times. The spread of low Tmin records shows a similar pattern for both interior and coastal stations and these rarely falls outside the confidence limits. The number of times low minimum records exceeded those of high maximum records in a given year for interior (coastal stations) was 14 (7). The last time this happened for interior (coastal) stations was 2000 (1981).

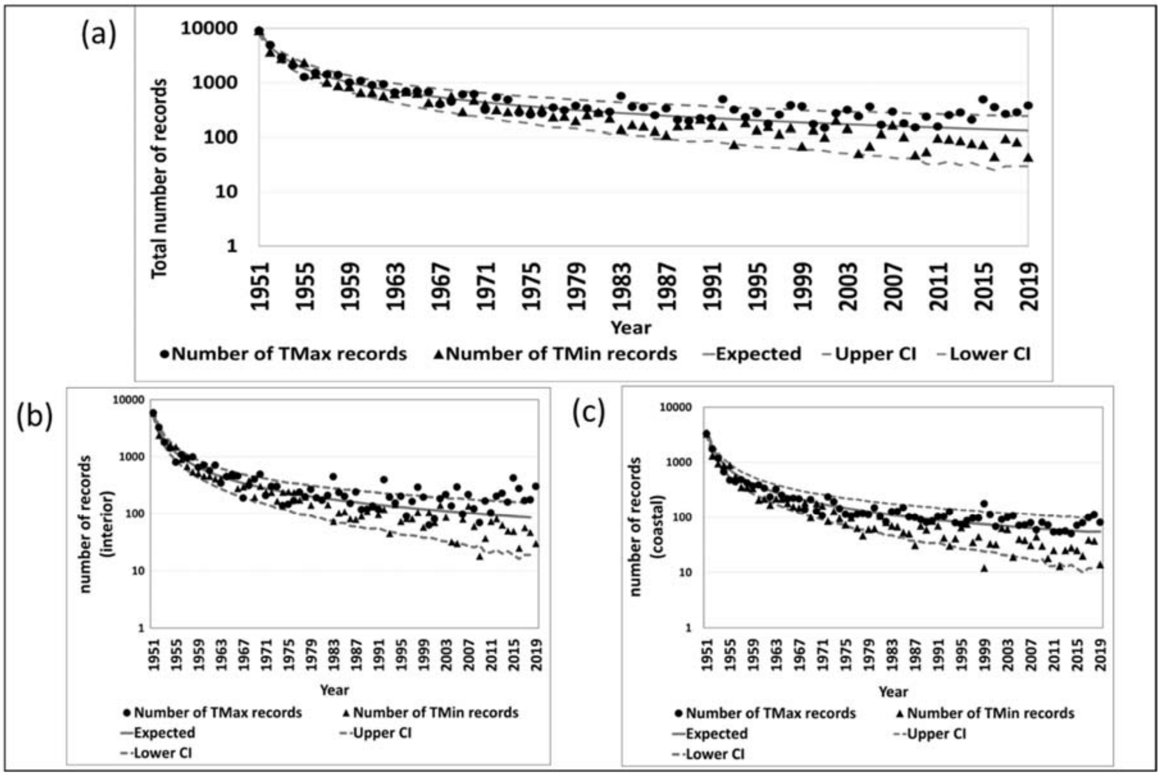

Figure 3: Yearly total number of high Tmax (dots) and record low Tmin (triangles) records for all stations (a), interior stations (b) and coastal stations (c). Grey dashed lines are upper and lower 95% confidence intervals. Solid grey line is the expected number of records in a stationary climate based on the 1/n where n is the number of years from the start of the time series.

The frequency of the occurrence of high Tmax and high Tmin and low Tmax and low Tmin records was investigated from 1951 to 2019. The annual sum of records of high Tmax and high Tmin exceeded the expected number of records from the 1980s to present for most years (Figure 4). This exceedance of the expected number of records was similar for high Tmax and high Tmin for most of the period except for the last 4 years from 2015 (Table 1). For the period 2010-2019 the year with the highest number of records for high Tmax and high Tmin was 2015, one of the hottest years on record for

South Africa (Blunden and Arndt, 2016). For the year 2015, the number of high Tmax records is more than three times what is expected in a stationary climate (Table 1). Low Tmax and low Tmin records occurred at lower frequency than the expected number of records in a stationary climate, and toward the end of the period showed a similar deviation from the expected as with the Tmax but in the opposite direction (Figure 3). In the last decade, in some years, some stations fail to break even a single low Tmax or Tmin record.

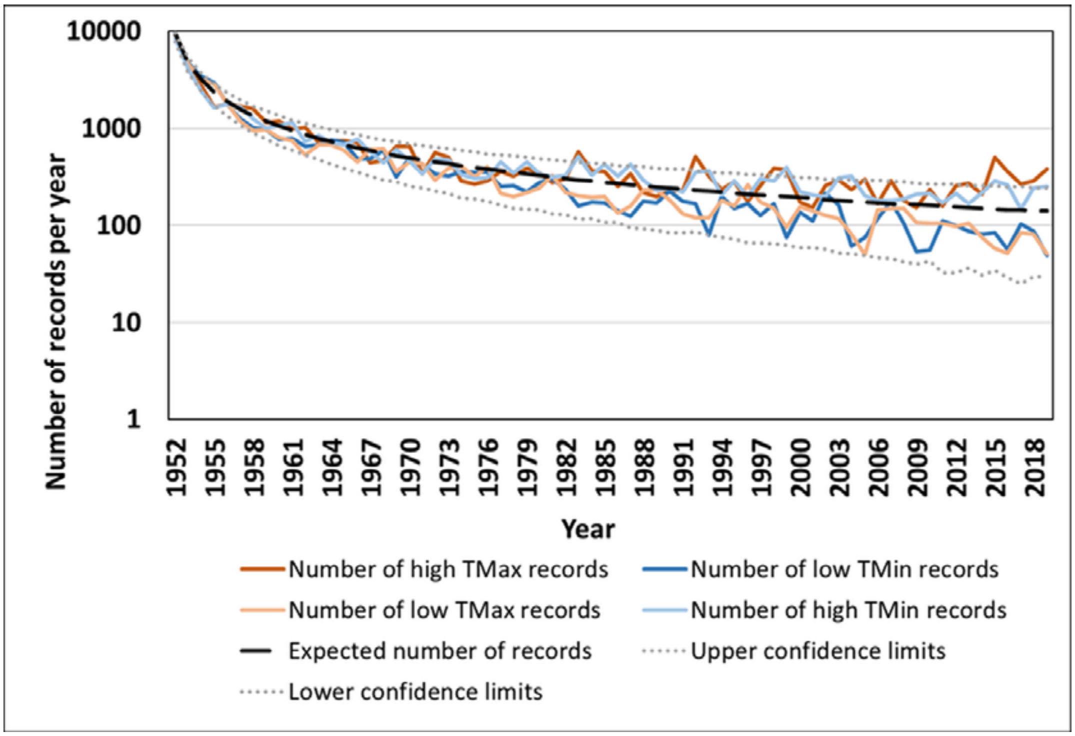

Figure 4. Annual total temperature records for 25 stations over South Africa from 1951 to 2019. Black dashed line is the expected number of records 1/n in a stationary climate, high Tmax: dark orange, low Tmax: light orange, low Tmin: dark blue and high Tmin: light blue. Grey dotted line the 95% confidence limits.

Table I. The annual total number of temperature records for all stations in the study over the last decade (2010 – 2019).

Year	High Tmax	Low Tmax	Low Tmin	High Tmin	Expected
2010	237	106	55	215	152
2011	156	106	98	188	150
2012	254	98	94	248	147
2013	282	105	88	192	145
2014	208	76	78	238	143
2015	494	58	74	331	140
2016	355	52	45	302	138
2017	267	85	96	164	136
2018	285	81	84	260	134
2019	380	51	44	288	132

The last column is the expected number of records in a stationary climate 1/n.

3.3 Records in a warming climate

Focusing on the last 10 years of the study period, the annual average expected number of records in a stationary climate for a station with data from 1951 is six per year. With the addition of the warming term presented in Equation (2) the frequency in the number of expected records is expected to be higher. The normalized warming trend *v/σ* for both high Tmax and high Tmin, interpolated with the inverse distance weighting method, show where approximately the greater number of records should occur (Figure 5 a and b). Regions with relatively higher *v/σ* should correspond with those regions where relatively more record-breaking events occur (Wergen and Krug, 2010). Figure 5 (c and d) shows the expected number of high Tmax and Tmin records by application of Equation (2). Figure 5 (e and f) presents the observed frequencies of records. The observed number of high Tmax records (Figure 5e) far exceed the expected estimation (Figure 5c). Stations over the central parts of the country showed the highest number of high Tmax records (Figure 5e) with more than double of observed high Tmax records, compared to what was expected (Figure 5c). Only Musina in the north of the country, by observing an average of four high Tmax records per year for the period, had less than the expected number of records.

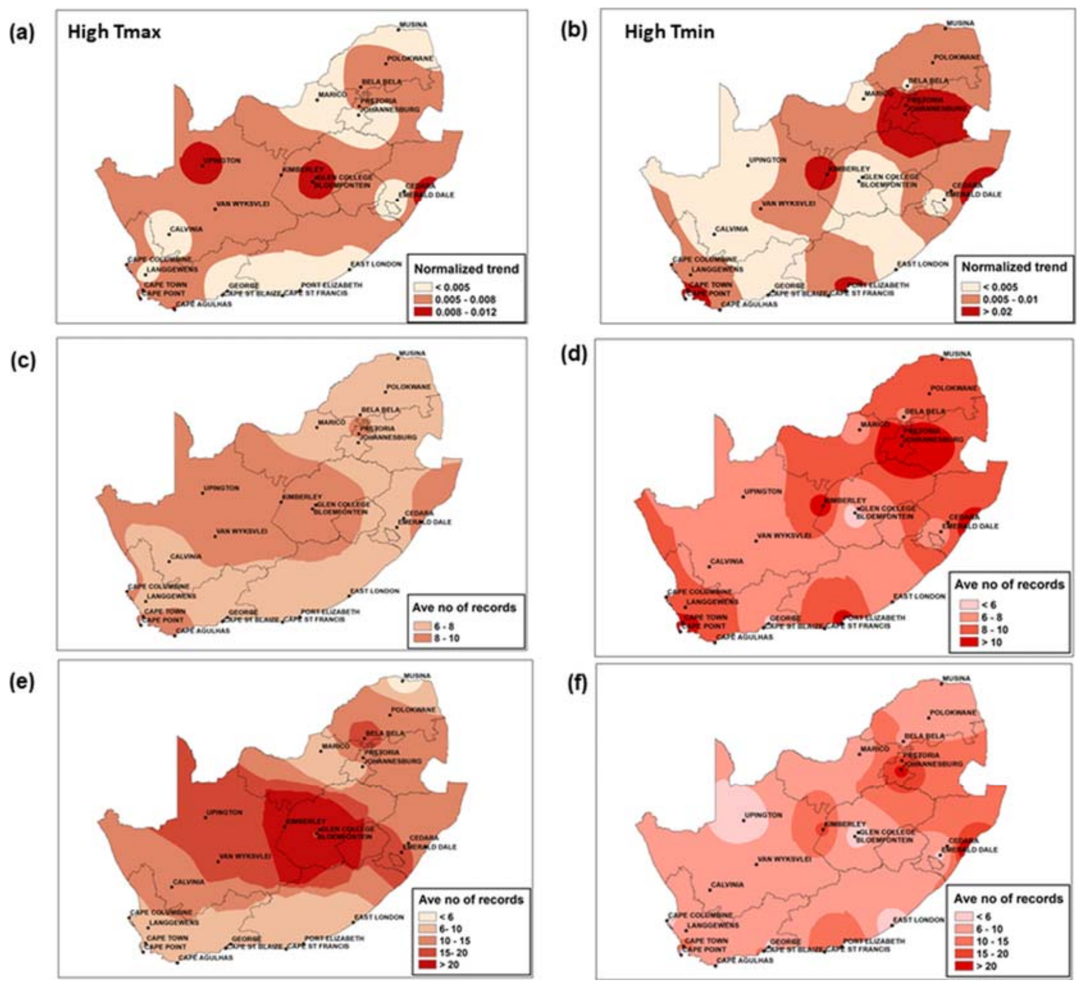

Figure 5: The normalized warming trend v/σ for high Tmax (a) and high Tmin (b). Spatial distribution of the annual average number of expected high Tmax (c) and high Tmin (d) records with warming considered for period 2010 to 2019. The annual average number of observed high Tmax (e) and high Tmin (f) records for period 2010 to 2019. Inverse distance weighting was used as the interpolation method.

The expected number of high Tmin records (Figure 5d) showed a different spatial pattern than high Tmax. George and Bloemfontein, on the south coast and central interior respectively, were expected to record less than an average of six Tmin records per year for the period 2010 to 2019, due to their negative warming trend for Tmin of -0.06°C/decade and -0.12°C/decade respectively. All other stations had positive warming trend for their Tmin and were expected to have more than six records per year. Eight stations recorded less than six high Tmin records per year for the period (Figure 5f). The rest of the stations all reported more than the average 6 high Tmin records per year. The stations recording the highest Tmin records were not confined to one region but were reported by stations distributed across the country, e.g. Kimberley, Johannesburg, Pretoria and Mount Edgecombe (Figure 5f). These stations showed observed high Tmin records more than double the expected.

3.4 Acceleration of warming trend

The breaking of more high Tmax and high Tmin records is to be expected in a warming climate. However in this study, the frequency in occurrence of these records did not show a steady increase above the expected but rather showed periods where relatively high numbers were recorded, followed by periods with less than expected records. Towards the end of the analysis period (2012 to 2019) Tmax records showed an upward trend in the number of records being recorded, compared to the expected number of records considering the mean warming trend, as can be observed in Figure 4. The Student's *t*-test for the difference in means before and after every year in the period from 1951 to 2019 was done to investigate if there were abrupt changes in the mean. Abrupt changes from a decrease to an increase in the absolute value of the t-test indicate abrupt changes in the trend before and after the specific year. The highest absolute value of the test indicates the year at which the mean before and after a specific year is the most significant. For annual average Tmax this occurred around 1997 and for Tmin around 1982. Kruger and Shongwe (2004) also found an abrupt change in trend in the early 1980s, since when an acceleration in the mean warming trend in South Africa was observed. Other years of abrupt changes for Tmax in this study are 1981, 1991, 2001, 2012 and 2014 as shown in Figure 6 (a) (open circles), and for Tmin the years 1956, 1990, 1997, 2008 and 2013 (Figure 6b).

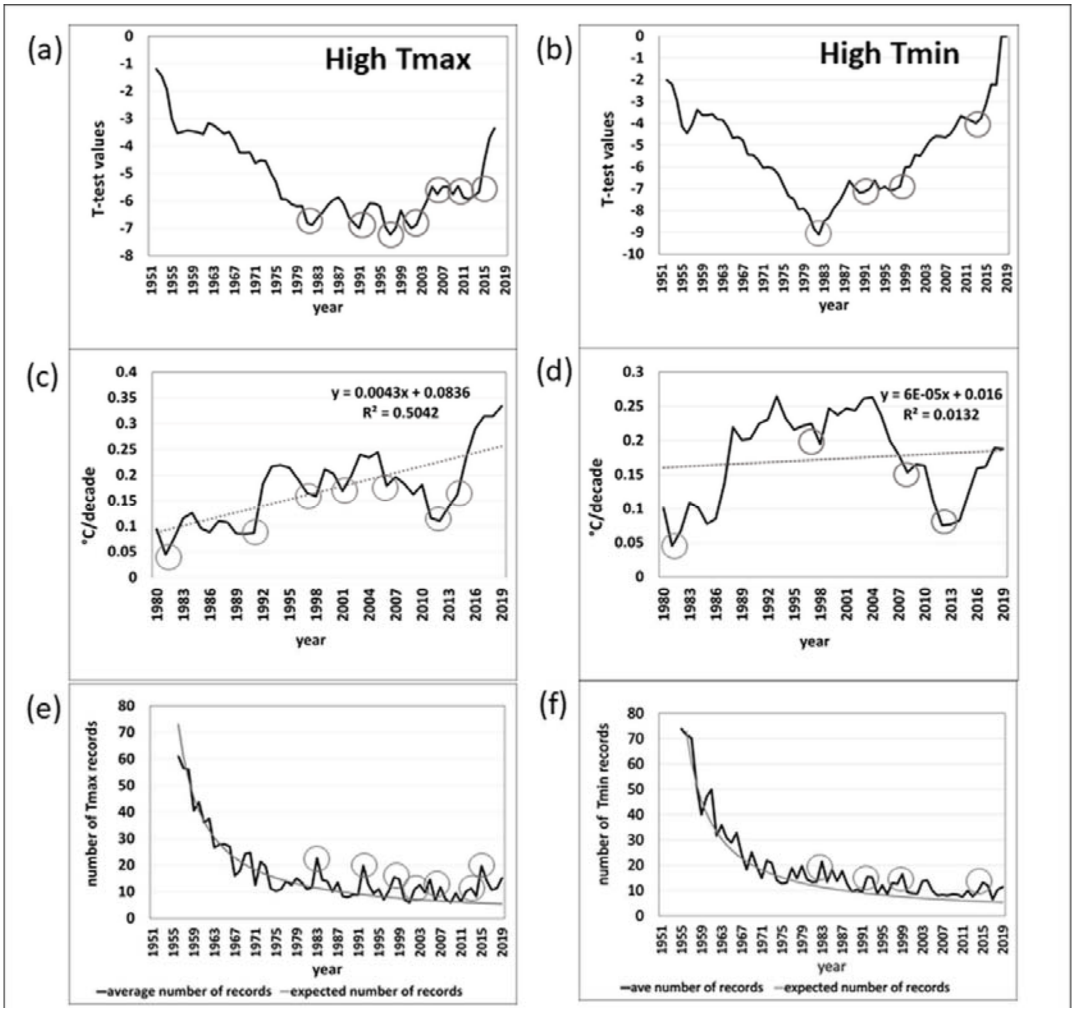

Figure 6: T-test result of the difference in average mean temperature before and after the specific year in the time series for Tmax (a) and Tmin (b). Tmax (c) and Tmin (d) show the linear trend over a 30-year window centred on the specific year. Average number of high Tmax (e) and high Tmin (f) records for all stations per year for analysis period – black line, the grey dotted line is the expected number of records in a non-stationary climate (warming considered). The open circles show abrupt changes in the mean temperature (a and b), changes in mean trend (c and d) and these changes occur a year before peaks in records (e and f).

The 30-year annual mean Tmax and Tmin temperature trends for all stations was calculated (Figure 6 (c and d)). The Mann-Kendall test found the trend for mean temperatures to be significance at the 5% level. The trends are not constant for the whole period. For Tmax (Tmin) the average trend for the period 1951 – 1980 is 0.09°C/decade (0.10°C/decade) while for the period 1990 – present is 0.33°C/decade (0.19°C/decade). Abrupt changes in the mean (Fig. 6a and b) corresponds to years where abrupt changes in the temperature trend occurred. In the following year, after the abrupt change, the number of records are higher than the general trend in the frequency of the occurrence of these records, as presented in Figure 6 (e and f) for Tmax and Tmin respectively. These abrupt changes, i.e. increases, in the mean and temperature trend is the cause for the number of records of both high Tmax and high Tmin to occur beyond the expected frequency taking into account the average warming trend.

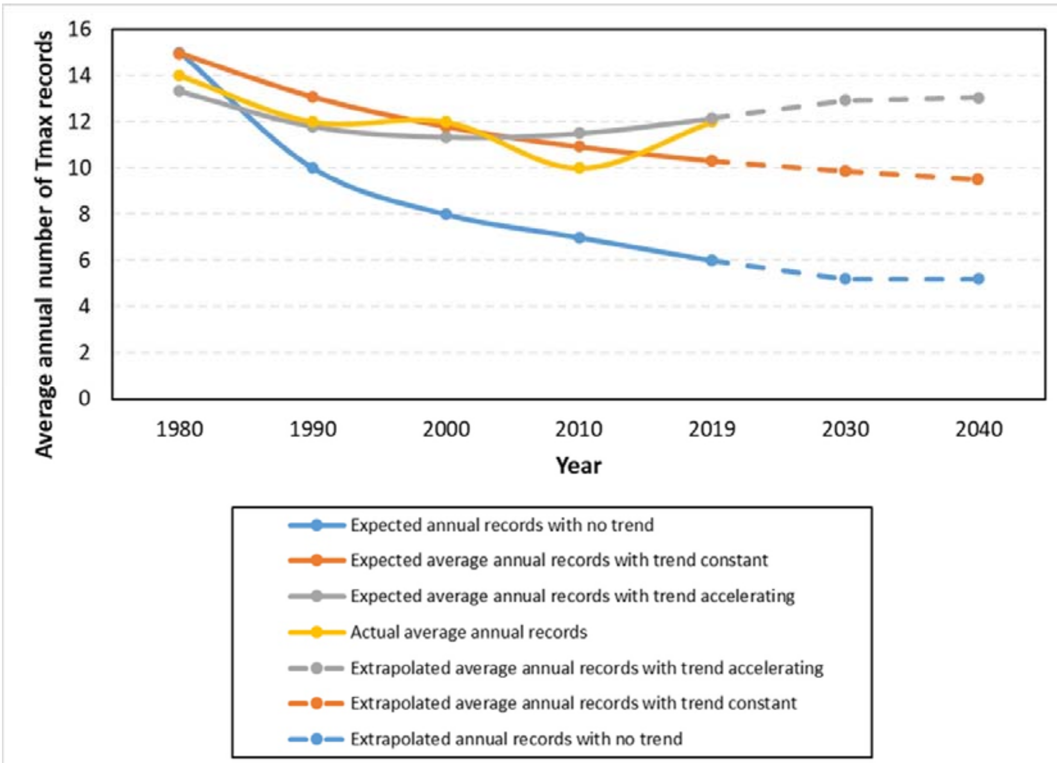

Figure 7: The expected annual average number of records over the previous decade in the case of no trend (blue line), constant warming trend of 0.20°C/decade (orange line) and the variable warming trend with the trend over the latest decade 0.34°C/decade (grey line). The dotted lines show the extrapolated values for each line up to the year 2040.

To investigate whether the acceleration in trend can explain the anomalously large numbers of Tmax records over the last decade, the trend *v* in Equation 2 was adjusted for each decade according to the average trend over the previous 30 years. Figure 7 presents the expected annual average number of records over the previous decade in the case of no trend, constant warming trend of 0.20°C/decade and the variable warming trend with the trend over the latest decade 0.34°C/decade. The observed annual average number of records over the previous is also shown. It can be seen that the observed records over the last decade (2010 – 2019) coincide most closely with the variable warming trend line. Therefore the increased warming rate explains the recent relatively high number of high Tmax records better than if constant warming is assumed.

4 Summary and discussion of results

The occurance of high Tmax, low Tmin, high Tmin and low Tmax records for a selected number of stations for the period of 1951–2019 across South Africa were analysed. This study is the first in South Africa that focus on record-breaking events, rather than trends in the mean temperature or extreme temperature indices. This analysis was based on in situ climatic data rather than model data as model data are not always able to simulate extreme events effectively (Choi *et al.*, 2009).

4.1 Ratios

The ratio of high Tmax versus low Tmin records was the expected 1:1 in 1951 but increased to a record 9:1 in 2019, the last year of the analysis period. This shows that recently record high temperatures occurred much more frequently than record lows. Researchers such as Meehl *et al.* (2009) and Trewin and Vermont (2010) found in their studies of record-breaking events in USA and Australia that record highs were declining less slowly then record lows. The ratios in the USA and Australia were below 1:1 around the 1960 with this ratio increased to around 2:1 in late 1990 to early 2000. Similar findings were found in this study as during the first decade (1951-1960) South Africa's ratio was 1.2:1 and during the period 1997 to 2009 averaged 2.4:1. The ratio values found in this study show that high Tmax records were increasing at a higher rate towards the end of the study period than what USA and Australia studies found, which only considered the years up to 2006 and 2009 respectively. Studies in Europe for the period 1951 to 2013 showed similar high ratios in favour of high Tmax from the 1990s (Beniston, 2015), comparable to the South African results. In a study over a period of 1880-2010 (Coumou *et al.*, 2013) found a fivefold increase in the number of high records globally while studying monthly mean values. This seem to suggest that high ratios in favour of maximum temperatures are rapidly increasing due to the increase in number of high Tmax records, rather than just a reduction in low Tmin records.

4.2 Occurrence of records

This study found that there was a different spatial pattern in the occurrence of the number Tmax and Tmin records. Stations that records the highest occurrence of Tmax records don't necessarily record the highest number of Tmin records. For high Tmax records the largest exceedances of observed vs. expected number of records were recorded by stations over the central parts of the country (Kimberley, Glen College and Bloemfontein). For high Tmin records the spatial distribution of stations where the largest exceedances of observed vs. expected records was not confined to one region but was more widely distributed (Kimberley, Johannesburg, Pretoria and Mount Edgecombe). Research by Driver and Reason (2017) show how the stronger than average Botswana High can be associated with an increased subsidence and reduced cloud cover leading to dry summers and above average day time temperature over most of southern Africa. While Mahlobo et al. (2019) has also noted a decreasing cloud cover and increasing sunshine or solar radiation due to the strengthening of the Hadley cell. These finding can be associated with the expected number of Tmax records as observed in the regions.

4.3 Interior and coastal stations

When comparing the interior and coastal stations, coastal stations are not showing as high ratios in favor of high Tmax records as interior stations and this could be due to the role the ocean plays in regulation of temperature (Newell, 1979; Lambert and Chiang, 2007). In the last ten years of this study period Cape Town and Cape Agulhas observed fewer average number of Tmax records per year than expected when considering their warming trend. For Tmin records the coastal stations recording less than expected records were East London, George and Cape Columbine. These differences in the occurrence of records between interior and coastal stations will require further investigation if South Africa wants to formulate its climate change response strategy into local planning regimes as stated in its National Climate Change Response Green Paper (DEA, 2011).

4.4 Acceleration of warming trend

This study shows that the number of high Tmax records and some high Tmin records have increased above what is expected even when the mean warming trend per station is considered. The increase in the number of records in recent years is due to the increase in the long term climatic warming trend. This increase in trend is nonlinear and concurs with studies by Trewin and Vermont (2010) in Australia and Pan *et al.* (2013) for China.

The change in the warming trend was to some extent able to predict the occurrence of temperature records. This agrees with studies by Wergen and Krug (2010) in their analysis of temperature records in central Europe. The increase in warming implies that a stabilization of the expected number of records will occur later in the future than is the case where near-constant warming (the same as over the analysis period) is assumed. Figure 7 presents an extrapolation of the increase in warming and an assumed constant warming trend. It is shown that by 2040 the difference between the expected records with accelerated warming is on average about four more per year (13 vs. 9) while currently it is about two per year (12 vs. 10). The expected increase in Tmax records into the future also agrees with studies that show that temperature trends over South Africa are likely to increase (Engelbrecht *et al.*, 2015; Kruger *et al.*, 2019). Extended period of high temperature by way of heat wave have also be projected to increase over South Africa (Russo *et al.*, 2014; Engelbrecht *et al.*, 2015; Russo *et al.*, 2016; Perkins-Kirkpatrick and Gibson, 2017; Mbokodo *et al.*, 2020), which will likely increase the occurrence of record-breaking temperatures. The mechanisms for driving the occurrence of record-breaking heat extremes and heat waves have been cited in the literature as El Niño, blocking high pressure systems and soil-moisture feedbacks (Coumou *et al.*, 2013;

Perkins, 2015). Particularly, over Southern Africa, the strengthening of the subtropical high pressure belt is likely to play a role (Engelbrecht et al., 2015), in that the subsiding branch of the circulation system is associated with clear skies and adiabatic warming.

The occurrence of record-breaking temperature extremes has different ramifications due to their spatial location. For high Tmax records the exceedances occurred over regions which are important to South Africa agriculturally (Mbiriri, 2018). This is of concern as extreme temperature events can have disastrous effects on agriculture (Mearns et al., 1984). Shew et. al. (2020) showed that wheat yield losses were linked to heat extremes in South Africa. Maize yields, a stable crop for many South Africans, were also likely to decrease in yields as a result of the number of days where temperatures are great than 30 °C (Mangani et al., 2019). There is further concern in terms of the spread of pests and pathogens in a warming climate which will add to the crop losses (Mafongoya et. al. 2019). South Africa also has a rich biodiversity and changes in temperature can change the vegetation structure of biomes where woody vegetation encroachers grasslands due to increases in temperature and CO^2 (Ziervogel *et al.*, 2014; Engelbrecht and Engelbrecht, 2016). The increased above expected number of high Tmin temperatures occurred over highly populated areas such as Johannesburg and Pretoria. These high temperatures can cause heat-related illnesses which put certain sectors of the population such as the elderly, very young and people with certain pre-existing medical conditions, especially those without access to air conditioning, at risk (Luber and McGeehin, 2008). This is further exacerbated by the fact that many in South Africa live in informally constructed homes which result in highly fluctuating temperatures with indoor temperatures being between 4 to 5 °C warmer than outdoor temperatures (Maller and Strengers, 2011). This is a concern as research in South African major cities found that a 1°C increase in daily ambient apparent temperature resulted in a 0.9% increase in the mortality rate (Wichmann, 2017). These are just some consequences of an increase in temperature for South Africa but many more related to a wide range of social, economic and developmental aspects are possible (Ziervogel et al., 2014).

With Africa projected annual-average temperature to increase by 1.5 times the global rate (Engelbrecht *et al.*, 2015) adaptation could prove to be increasingly difficult especially if the warming trend is nonlinear rather just a monotone altered mean condition (Rahmstorf and Coumou, 2011). There will be even more stress on the more vulnable sectors of society who are more susceptible to change, suffer greater costs, and have less capacity to take mitigating action compared to those with access to resources (Mirza, 2003). With this in mind policymakers, governmental departments, none profit oganizaion (NGO), disaster managers, farmers and developers of infrastructure to name a few will need to understand the consequences and risks of the increased frequency of record-breaking temperature events in order that their response strategies are more meaningful. This also means that any international investment and/or donor funding need to be more focused on creating adaptive capacity rather than just responding to certain disasters (Mirza, 2003). With the impacts of climate change with respect to increases in extremes being substantiated by observations, adaptation measures to expect climate extremes should become more focused.

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