Water SA 51(1) 1–10 / Jan 2025
https://doi.org/10.17159/wsa/2025.v51.i1.4102

Research paper

Dependence of long-term annual rainfall trends in South Africa on analysis period: 1921–2022

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The focus of the paper is to address the temporal discrepancies in long-term rainfall trend results in South Africa, by evaluating a systematic range of observation periods over the century-long analysis period of 1921–2022. Available long-term climate projections show that significant parts of South Africa are expected to experience progressively drier conditions, mainly in the west. To assess long-term rainfall trends over the country, historical trends should be determined – the results of published studies for which are not consistent. Arguably the most significant reason for these inconsistencies is the length of analysis period. This study investigates this effect on the magnitude and statistical significance of historical annual rainfall trends over hydrological years, with the data of 94 homogeneous rainfall districts. Trends of annual rainfall were determined for all periods up to 2022, from the 1921–2022 period up to the last 30 years, i.e. 1993–2022. The annual rainfall trends over the longest analysis period show significantly positive trends over most of the central and western parts and significant drying over extensive parts of mainly the far north-east. However, the most recent period (1993–2022) shows significantly drying trends over extensive parts of the west, south and east. Among the main findings is that the change in trends shows a consistent spatial pattern of significant negative change over most of the south-western half, and mostly significantly positive trends over the north-eastern sector. These results are in large agreement with future rainfall projections, particularly for the western half. Ultimately, the study emphasizes the wide range of long-term trends in South Africa, both spatially and temporally, and the importance of considering a range of historical analysis periods in the detection of long-term rainfall changes. In effect, the eventual results provide increased confidence to predicted future rainfall scenarios.

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DATES
Received: 18 October 2023
Accepted: 11 December 2024

KEYWORDS
South Africa
climate change
rainfall
hydrological year
rainfall trends
trend analysis

INTRODUCTION

Climate change does not only have an effect on surface temperatures through a general long-term increase, but on other weather parameters as well. Of the most immediate concern are changes in rainfall, for which changes in the features thereof (in broad terms, the hydrological cycle) have been observed by a large number of studies, global as well as regional (Caretta et al., 2022). In terms of rainfall amounts, these changes have been largely positive (i.e. more rainfall) (Seneviratne et al., 2021). The most widely accepted explanation for this observation is that, due to the warming of the atmosphere, the water-holding capacity of the air increases according to the Clausius–Clapeyron relationship, with subsequent increases in precipitation in most regions (Allan et al., 2014).

However, climate projections show that while most of the world is expected to experience increases in rainfall there are also regions that will undergo drying over the long term (Seneviratne et al., 2021). Long-term projections for South Africa indicate just that; where mainly the western, south-western and to a lesser extent the extreme northern parts of the country are expected to become progressively drier (Seneviratne et al., 2021). These changes are also confirmed in projections published in the SAWS Climate Change Reference Atlas (SAWS, 2017), particularly the annual total rainfall (mm/year) change projected for 2036–2065 and 2066–2095, relative to the present (1976–2005), under conditions of the RCP 8.5 pathway (a business-as-usual greenhouse gas emission scenario (Undén et al., 2002). This information is based on the outputs of the last Coordinated Regional Climate Downscaling Experiment (CORDEX) data (Jones et al., 2011). In addition, the latest IPCC Working Group I Report and Interactive Atlas, based on the most recent CMIP6 model projections, mostly confirms the CORDEX projections, indicating significant drying over the extreme western and south-western parts of the country over the medium- to long-term (Gutiérrez et al., 2021).

Evidence of changes in rainfall over the recent past can be understood from the analysis of the historical rainfall record, and a large number of these studies have already been published: Examples of these are Jury (2013), who obtained mixed rainfall trends in southern Africa with declining trends in eastern South Africa and Madagascar. This analysis was done with various climate datasets, from observed to model-simulated, but using mainly observed data covering various recording periods to determine the historical rainfall trends. Kruger and Nxumalo (2015) found, for the period 1921–2014, increases in rainfall over the southern interior and indications of decreases in the far northern and north-eastern parts. Makungo and Mashinye (2022) found increasing and decreasing trends in the far north of South Africa, of which the trend results mostly depended on the recording periods of the rainfall stations analysed. In contrast, Mosase and Ahiablame (2018) established upward trends for both annual and seasonal rainfall in most parts of the Limpopo River Basin. MacKeller et al. (2014) found, for the period 1960–2010, no significant trends in regionally aggregated rainfall for 6 water management sectors dividing South Africa, but with discrepancies found in rainfall trends from observed stations and model simulations in the central interior. Lakhraj-Govender and Grab (2019) established negative trends, but with large variation between observation stations, over the Western Cape Province in the south-west of South Africa over the period 1987–2017. This finding was reiterated by Jury (2020). In addition to published research, the South African Weather Service (SAWS) update trends in relevant core indices developed by the World Meteorological Organisation (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI) (Donat et al., 2013). The latest precipitation trend results for the period 1921–2022 indicate significant increases in rainfall in the interior of the Southern Cape and signals of drying in the extreme north (SAWS, 2024), in large agreement to Kruger and Nxumalo (2015).

From the above it follows that long-term rainfall trends are largely dependent on the period of analysis, but also to some degree the data sources. Long rainfall time series, with recording lengths longer than a few decades, are often characterised by wetter and drier periods presented as quasi-cyclical behaviour (Vines, 1980; Kruger, 1999; Kane, 2009; Ndebele et al., 2019; Tyson, 1986). These features in the time series have the effect that, depending on the period analysed, different trend results can be obtained, which can range from strong negative to positive trends over the same area or region. It follows then that the statistical significance of the trends will also be influenced by the selected analysis period. As presented above, rainfall trends over South Africa illustrate this, in that there are inconsistencies in the trends observed in specific regions of the country. While the different statistical methodologies applied can have an effect on the analysis results (e.g. the choice of significance test, such as parametric vs. non-parametric, and slope estimator, such as linear vs. other assessment methods), it is most often the analysis period that is the determining factor in the variation of results. While it can be assumed that the historical rainfall trends mentioned in the literature are correct, often the results are mistakenly generalised in assumptions that long-term historical rainfall trends can be considered as near-consistent.

The basis of the paper is to present an approach to address the temporal variation in long-term rainfall trend results in South Africa, by evaluating a systematic range of observation periods over the century-long analysis period of 1921–2022. These periods are analysed up to the present, to determine whether there are recent trends in annual rainfall totals (based on the hydrological year) and since which years the trends were sufficiently robust, i.e. statistically significant. Ultimately these more robust trend results can then be compared against the projected long-term trends for rainfall in South Africa, to ascertain whether future rainfall scenarios are already manifest in trends in the historical record.

DATA AND METHODOLOGY

Data

There are a wide selection of datasets which can be utilised for historical long-term rainfall studies. These include global gridded datasets, e.g., GPCC (Schneider et al., 2014), ERA5 (Lavers et al., 2022), and others derived from in-situ and remote observations, as well as direct analysis of the actual data from weather stations. A drawback of most of the former datasets is the fact that not all observed data are included in the assimilation of the gridded values, causing biases and significant uncertainties in the datasets and analyses thereof (Lavers et al., 2022). On the other hand, the utilisation of actual observed data over a large region, e.g., South Africa, can be complicated by the various lengths of observation periods, produced by the temporal and spatial variation in operational rainfall observation stations. To overcome these various trend-influencing factors, monthly homogeneous rainfall district data, developed by the South African Weather Service (Van Rooy, 1972; Terblanche et al., 2022), are analysed. The data consist of the monthly rainfall totals of the daily averages from all available rainfall stations reporting in a district in a particular month, for all months from 1921 up to the present. Figure 1 presents the delineation of the rainfall districts, which at the time of development were deemed to be mostly homogeneous. The homogeneity of some rainfall districts can be debated, considering the complex topography of South Africa, and possible long-term seasonal changes in rainfall. Regarding the latter, Roffe et al. (2021) found that for the period 1987–2016 some changes were evident, including the lengthening of the wet season in the extreme Western Cape and Northern Cape Provinces, as well as a westward concentration around the winter rainfall months along the Southern Cape coast. These findings do not significantly impact on the delineation of the districts, as it is

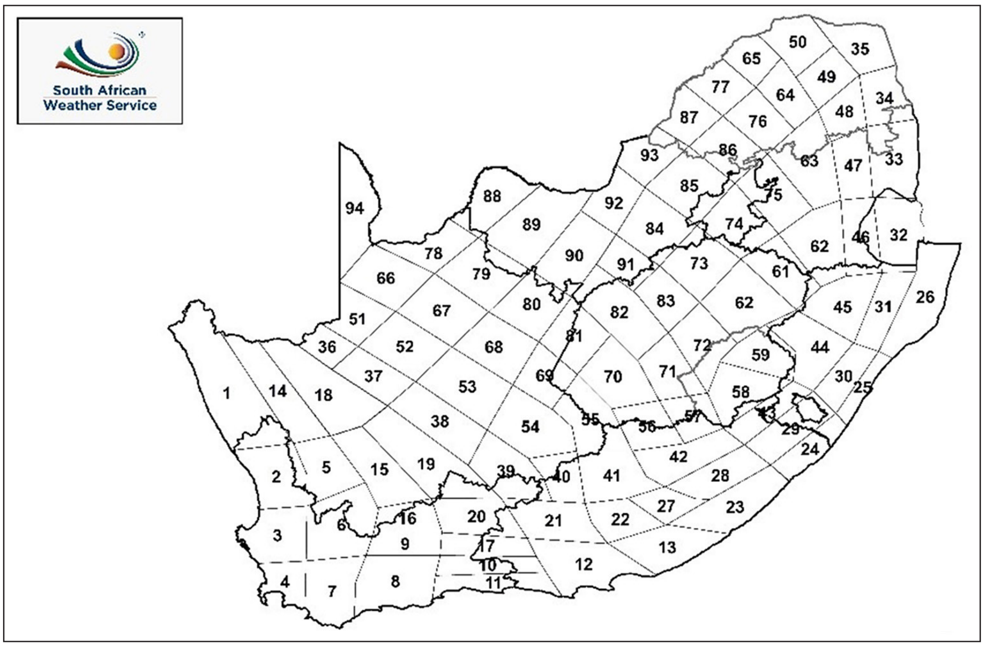

Figure 1. South African Weather Service homogeneous rainfall districts (after Van Rooy, 1972)

evident from Roffe et al. (2021) that the topographical influences on the seasonal rainfall in South Africa are still generally integral to the rainfall distribution in South Africa, allowing the continued application of the rainfall districts. In addition, it is believed that the number of stations operational at any time, on average more than 10 per district, counteracts to an extent the possibility of large inhomogeneities. Another factor is that the demarcation of the districts largely reflects the seasonal march of maximum rainfall, main topographical influences, e.g., the escarpment, as well as the general decrease in rainfall from east to west. Therefore, for most of the districts the rainfall stations within them can be deemed to be fairly similar with regards to seasonality and amount of rainfall. These factors make the district rainfall dataset arguably more homogeneous than gridded datasets, e.g., the GPCC.

The monthly district rainfall totals were totalled according to the hydrological year, depending on the season of maximum rainfall, i.e., January to December for Rainfall Districts 1 to 11 and July to June for the remainder of the districts.

METHODS

The analysis of rainfall trends was based on the Man-Kendall rank statistic (M-K test). It is well-advised to use tests of randomness that are of nearly uniform power for alternatives with non-linear trends. Rank correlation methods have this property, and are robust as well. The test is based on the ranks of the values in a time series instead of the actual values. The first step is to compute the statistic P for the series, which is accomplished as follows: Compare the rank of the first term to those of all the later terms in the series. Count up the later terms whose value exceeds the present term and denote this number by n_i and so on. P is then given by the sum:

$$P = \sum_{i=1}^{N-1} n_i \tag{1}$$

where: n_i is the count of the later terms whose value exceeds the present term for all terms in the series of length N. Thereafter the statistic τ is derived from N and P by the relation:

$$\tau = \frac{4P}{N(N-1)} \tag{2}$$

with τ distributed as a Gaussian normal distribution for all N, and can be used as the basis of a significance test by comparison with the values:

$$(\tau)_t = \pm t_g \sqrt{\frac{4N+10}{9N(N-1)}} \tag{3}$$

where t_g is the desired probability point of the Gaussian normal distribution appropriate to a 2-tailed test.

Estimations of slope or trend in the time series were conducted by application of Sen's slope estimator, which is resistant to large outliers often occurring in rainfall time series (Wilcox, 2001).

Considering that the results will probably show a dependence of trend magnitude on the analysis period, it is valuable to know when the largest change in trends occurred, to later investigate the possible reasons for trend change. Therefore, the scope of the annual rainfall analysis also included the establishment of the times over which the largest change in long-term trend occurred. For this change-point analysis the standard normal homogeneity (SNH) test developed by Alexandersson (1986) was applied. The test statistic T_k is used to compare the mean of the first n observations with the mean of the remaining $(n–k)$ observations with n data points (Stepanek et al., 2009; Vezzoli et al., 2012).

$$T_k = kZ_1^2 + (n-k)Z_2^2 \tag{4}$$

where:

$$Z_1 = \frac{1}{k}\sum_{i=1}^{k} \frac{(x_i-\bar{x})}{\sigma x} \tag{5}$$

$$Z_2 = \frac{1}{n-k}\sum_{i=k+1}^{kn} \frac{(x_i-\bar{x})}{\sigma x} \tag{6}$$

and $\bar{x}$ and σx are the mean and standard deviation of the time series. The year k is considered a change point and represents a break where T_k attains its maximum value. To reject the null hypothesis, the test statistic should be greater than the critical value, which depends on the sample size n. For example, in the case for $n = 75$ the critical value is 9.1, from the available table of critical values. It follows that T_k not only attains a value above the critical value at the identified change point, where it reaches its maximum value, but often well before and after the year of maximum T_k. Thus, a period above the critical value of T_k, can be considered to be a period of significant change in values of the time series.

All trend and change-value statistics were tested for statistical significance at the 95% level of confidence.

The present climate is defined as the last 30-year period, 1993–2022, the shortest period over which specific climate parameters can be determined (e.g. average rainfall or trend thereof) (WMO, 2017). While the official WMO climate standard normal period is defined as 1991–2020 (WMO, 2017), the most recent 30-year period was used here to extract the most information from available data.

The analysis of historical rainfall trends was approached systematically, based on annual rainfall calculated according to the season of maximum rainfall, i.e., a hydrological year. For the South-Western and Southern Cape, the rainfall is a maximum in austral autumn, winter or spring. In these regions the annual rainfall is calculated over a calendar year. Over the remainder of the country, which receives its maximum rainfall in austral summer, the annual rainfall is calculated from July to June the next year: First establish the trends in the annual rainfall over the maximum analysis period, i.e., 1921–2022. Then establish whether there are significant trends in the annual rainfall in the present climate, i.e. over the last 30-year period, i.e. 1993–2022, and compare the trends manifest in the present climate to that over the longest analysis period. Differences in direction and significance of trends estimated over different time periods imply probable significant long-term changes in the trends.

Following the above the long-term trends in annual rainfall were estimated stepwise for all periods up to the present, i.e. 1921–2022, 1922–2022,…, 1993–2022, to determine progressive changes in long-term trends. Subsequently, the periods and dates with largest changes in annual trends were established.

Eventually spatial coherencies in the trend results were assessed, i.e., the identification of adjacent rainfall districts with spatially significant trends in the same direction, and compare with rainfall projections, particularly from CMIP6, as presented in the latest IPCC assessment reports (Seneviratne et al., 2021).

RESULTS

Annual rainfall trends over the longest analysis period (1921–2022) vs. last 30 years (1993–2022)

Annual rainfall trends over the full analysis period of 1921–2022, presented in Fig. 2a, show that 33, about a third of all rainfall districts, exhibit significantly positive trends. A total of 19 rainfall districts showed negative trends, situated mostly in the extreme west and north-east of South Africa. In contrast, most of the rainfall districts do not show any significant trends in annual rainfall over the last 30 years (1993–2022), presented in Fig. 2b. However, rainfall districts with significant trends were all negative, except one in the Northern Cape Province. These 28 rainfall districts are mostly situated in the western, southern and

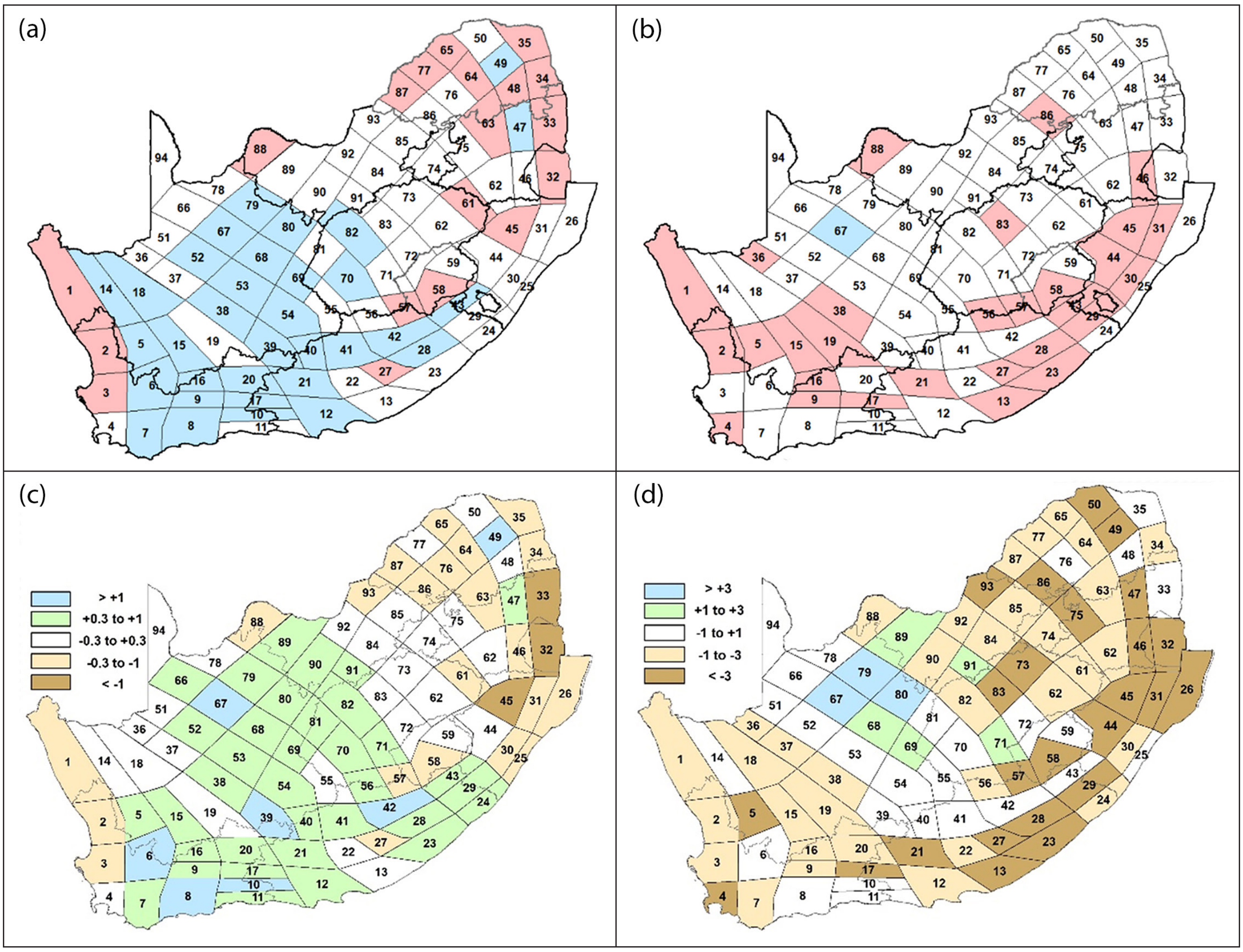

Figure 2. Rainfall districts with significant annual rainfall trends (based on the hydrological year) over the period 1921–2022 (a) and 1993–2022 (b), respectively, according to the M-K test at the 95% level of confidence. Red indicates significantly negative trends and blue significantly positive trends. Rainfall trends per year are indicated for the periods 1921–2022 (c) and 1993–2022 (d).

eastern parts of the country. The differences in the trend results between the shorter and longer analysis periods reconfirms the broad assessment from the literature, given in the introduction to this paper, that rainfall trend magnitudes are highly dependent on the periods over which the analyses are done.

A comparison between Figs 2a and b shows that for most rainfall districts in these parts annual rainfall trends have moderated over the recent period of 1993–2022. Where the annual rainfall trend over the extreme eastern parts were mostly significantly negative over the long term, trends over the more recent period of 1993–2022 show no significant trend for most districts. The KwaZulu-Natal interior experienced no significant trend for most parts over the 1921–2022 period (except Rainfall District 45) but this drying trend has over the recent period expanded and strengthened to cover the whole interior in the province (Fig. 2b).

Trends of annual rainfall trends from the longest analysis period (1921–2022) to last 30 years (1993 – 2022)

Following on the above, the M-K test was conducted on a sequential basis for the period 1921–2022 to 1993–2022, for each year from 1921 to 1993; i.e., the M-K test was calculated for the periods 1921–2022, 1922–2022, 1923–2022,…, 1993–2022; as historical rainfall trends are most relevant if the recent past is included. As an example, Fig. 3a presents the result for Rainfall District 4, which indicates that since 1933 all the time series up to 2022 show significantly negative annual rainfall trends (where $\tau < (\tau)_t$).

The statistics τ and $(\tau)_t$ are dependent on the period of analysis. To test whether the trend changed significantly, the values of $\tau/(\tau)_t$ were calculated for each of the time series defined above and tested for statistical significance with the M-K test. Figure 3(b) presents an example of the resultant time series for Rainfall District 4, in which a value of $\tau/(\tau)_t > 1$ implies a statistically positive trend, while $\tau/(\tau)_t < 1$ implies a statistically negative trend, for the indicated year in the x-axis up to 2022. One can observe that from 1933, $\tau/(\tau)_t$ is lower than −1, i.e. significantly negative. The M-K test indicating a strengthening of the negative trend as the analysis period becomes shorter: Sen's slope indicates trends of +0.58 mm/a over the period 1921–2022, −0.45 mm/a. (1933–2022) and −8.17 mm/a (1983–2022), where 1983 is the year when $\tau/(\tau)_t$ was at its lowest value. Following 1983 there is an upward trend in $\tau/(\tau)_t$ indicating that the strength of the negative trend is becoming weaker, as one approaches the 30-year threshold of 1993–2022. However, while the negative trend is weaker, it is still statistically significant.

Figure 4 presents the significance of trend in the values of $\tau/(\tau)_t$, for the time series of trends calculated over the periods 1921–2022, 1922–2022…1993–2022 for all rainfall districts in South Africa. Most parts in the western half and south-east of South Africa shows significantly decreasing trends in $\tau/(\tau)_t$, indicating that trends have changed in a negative direction. In these parts only Rainfall Districts 2 and 3 in the south-west and Districts 51 and 94 in the Northern Cape show significantly positive changes in trends. Over the central and eastern parts of South Africa trends in $\tau/(\tau)_t$, are more varied, but mostly positive.

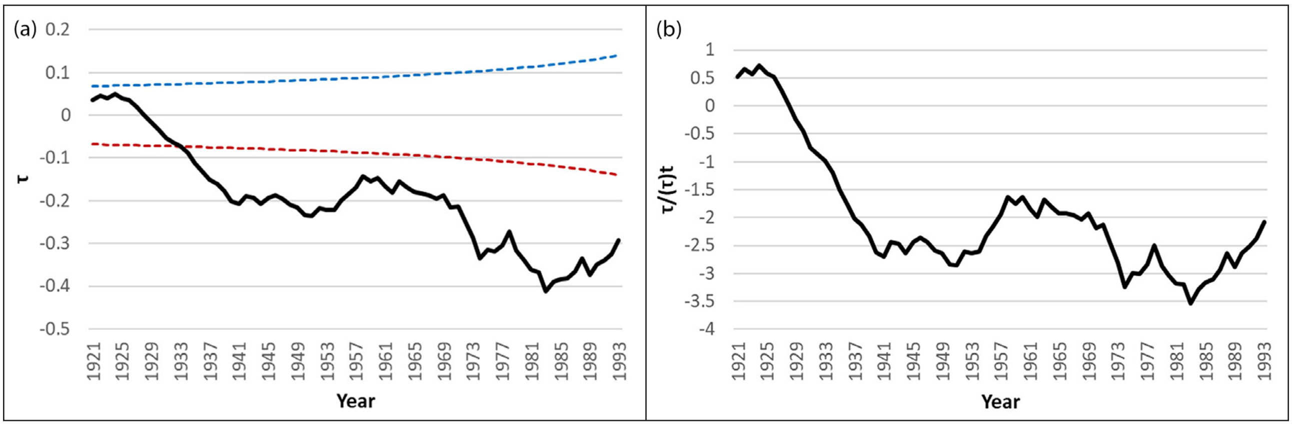

Figure 3. M-K test values for trend for the period 1921–2022 to 1993–2022, for each year from 1921 to 1993, for Rainfall District 4. (a) Values of τ and ±$(\tau)_t$ for rainfall trend up to 2022. The black line indicates τ and blue and red dotted lines $+(\tau)_t$ and $-(\tau)_t$ at the 95% level of confidence, respectively. (b) $\tau/(\tau)_t$ for rainfall trend up to 2022.

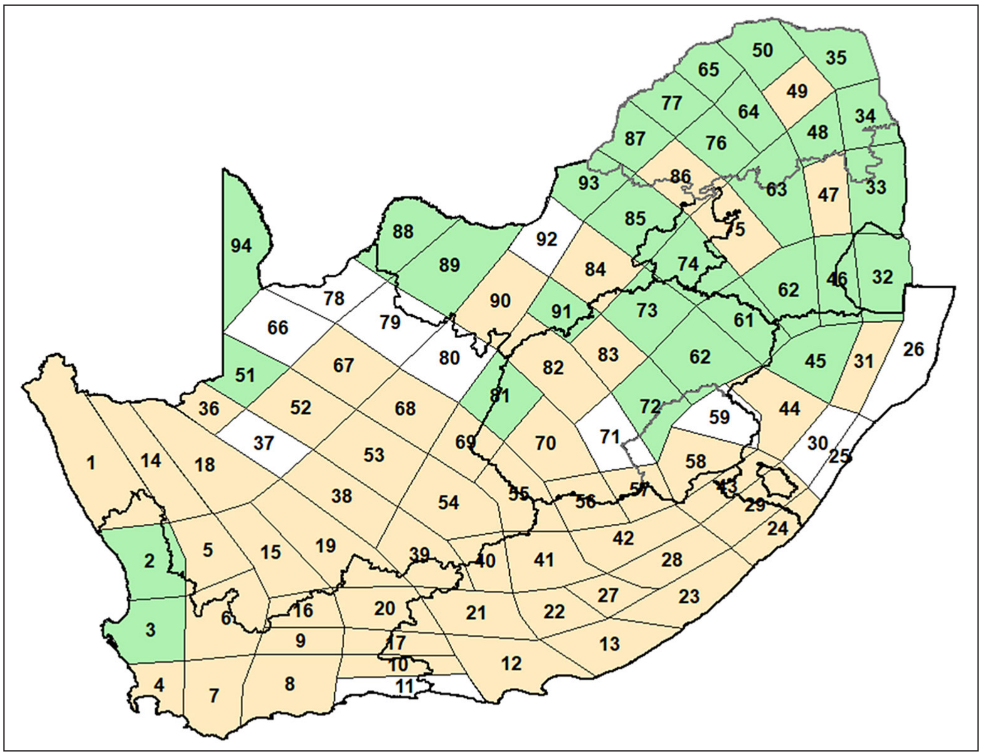

Figure 4. Significance of trends of the trend of $\tau/(\tau)_t$, calculated sequentially over the periods 1921–2022, 1922–2022 … 1993–2022. Green districts indicate significantly positive trends and yellow districts significantly negative trends at the 95% confidence level.

Periods and dates with largest changes in annual trends

From the previous section it is observed that there is spatial coherence in the temporal change in trends over the analysis period, with trends in the western and southern to south-eastern parts becoming more negative, while in the north and central to extreme north-eastern parts of the country trends are positive, for most rainfall districts.

The application of the SNH-test can provide more detailed insight into the periods or years when the trends have changed the most. This analysis is important to identify possible periods or years with anomalously high or low rainfall that could influence the trend magnitude significantly. Examples of these could be the 1982/83 and 1991/92 El Niño seasons, or the 1970s when very low (high) rainfall was experienced over the north-eastern parts of the country (Kruger, 1999). Trend analysis starting from these anomalous episodes will have a significant bearing on the result. As an example, in District 5 in the western interior, the annual rainfall trend is significantly positive over the period 1921–2022, while significantly negative over the most recent 30-year period of 1993–2022. Figure 5a presents the annual rainfall time series for Rainfall District 5 and Fig. 5b the application of the SNH test on $\tau/(\tau)_t$, the M-K statistic for the trend from the year on the x-axis up to 2022 divided by the critical value, as illustrated in Fig. 3 for Rainfall District 4. A positive value of $\tau/(\tau)_t$, above 1, indicates a significantly positive trend while a value below −1 indicates a significantly negative trend. In Fig. 5b a significantly negative trend for $\tau/(\tau)_t$, is shown. The trends for all periods with years beginning from 1921 to 1931, up to 2022, is significantly positive. The maximum positive trend is for the period 1926–2022, with a value of +0.36 mm/year. The periods beginning from 1971 to 1976, and 1983 to 1993, up to 2002, exhibit significantly negative trends. The period 1985–2022 has the strongest negative trend of −2.69 mm/year. Significant changes in the value of T_k, therefore significant changes in long-term trend, are indicated for the period 1936–1987, reaching a maximum in 1969 (which can be regarded as the year with the biggest change in trend).

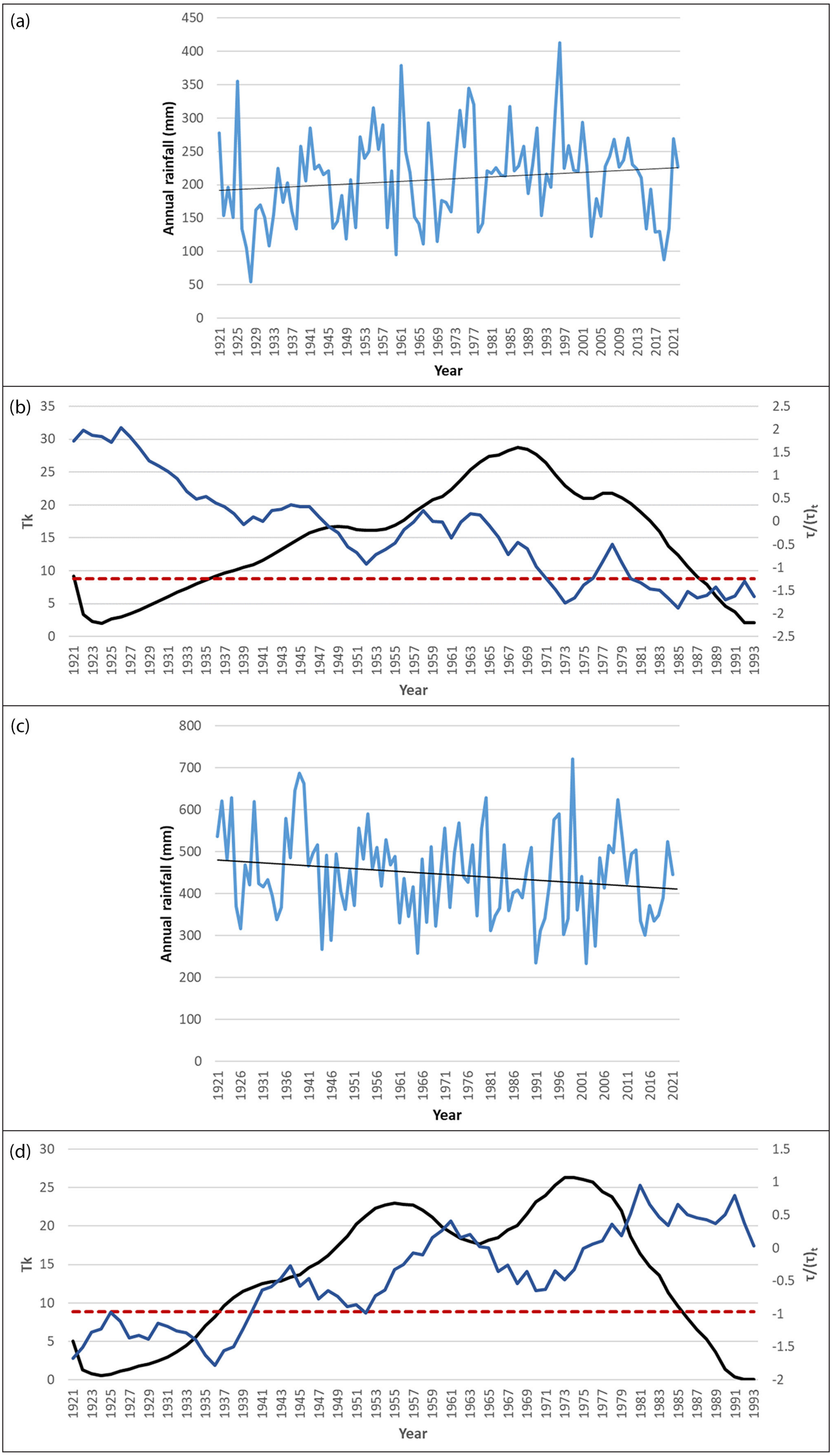

Figure 5. (a) and (c) Rainfall District 5 and 64 annual rainfall for 1921–2022, respectively. The black line represents the linear trend over the analysis period. (b) and (d) SNH test on $\tau/(\tau)_t$, where the blue line represents $\tau/(\tau)_t$, the M-K statistic for the trend from the year on the *x*-axis up to 2022 divided by the critical value. The black line represent the SNH test value T_k and the red dashed line the critical value of T_k.

An example of a rainfall district where the long-term trend changed from significantly negative over the 1921–2022 period to non-significant over the 1993–2022 period is District 64 in the central parts of the Limpopo Province, presented in Fig. 5c and 5d. The rainfall trend changed from significantly positive over the period 1921–2022 to non-significant over the most recent period of 1993–2022. As with the example for Rainfall District 5, Fig. 5c presents the annual rainfall time series for Rainfall District 64 in the north-eastern interior of South Africa and Fig 5d the application of the SNH test on $\tau/(\tau)_t$. In Fig. 5d a significantly negative trend for $\tau/(\tau)_t$ is shown. The trends for all periods with start-years from 1921 to 1939 up to end-year 2022, is significantly negative. The maximum negative trend is for the period 1936–2022, with a value of −0.97 mm/year. Over more recent periods ending in 2022, trends have moderated in a positive direction, with the 1981–2022 period significantly positive and with the strongest positive trend of +1.49 mm/year. Significant changes in the value of T_k, therefore significant changes in long-term trend, are indicated for the period 1937–1985, reaching a maximum in 1973 (regarded as the year of maximum change in trend) and also a secondary maximum in 1955.

The examples of the application of the SNH-test discussed above justified further investigation of possible spatial coherencies in the results. Table A1 (Appendix) presents a summary of this investigation, in an attempt to group similar results, taking into cognisance the change in trend where the SNH-test shows significance, as well as the spatial distribution of the rainfall districts. The SNH-tests applied to the $\tau/(\tau)_t$ revealed no results that were exactly the same in terms of period of significant T_k values (indicating periods of significant trends in $\tau/(\tau)_t$), as well as the year of maximum T_k, between rainfall districts. However, there were rainfall districts with periods of significance and maximum values that were relatively close. Although there is a measure of subjectivity in the exercise, an example is the grouping of Rainfall Districts 5 to 10, 17 and 20 in the south-west and south of the country, as presented in Table A1 (Appendix). These rainfall districts collectively have a significance range of T_k stretching from 1935 to 1941 up to 1985 to 1990. The years of maximum T_k range from 1968 to 1972 between these rainfall districts. Figure 6a presents the same statistics as Fig. 5b and 5d for the applicable districts. Figure 6b presents another example of the same statistics, with the group of rainfall districts covering a large part of the extreme north of the country, including eastern Mpumalanga and most of Limpopo, i.e. Rainfall Districts 33–35, 46, 48, 62–65, 76, 77 and 87. For the latter group, the rainfall districts collectively have a significance range of T_k stretching from 1943 to 1964 up to 1982 to 1991. The years of maximum T_k range from 1972 to 1976 between these rainfall districts.

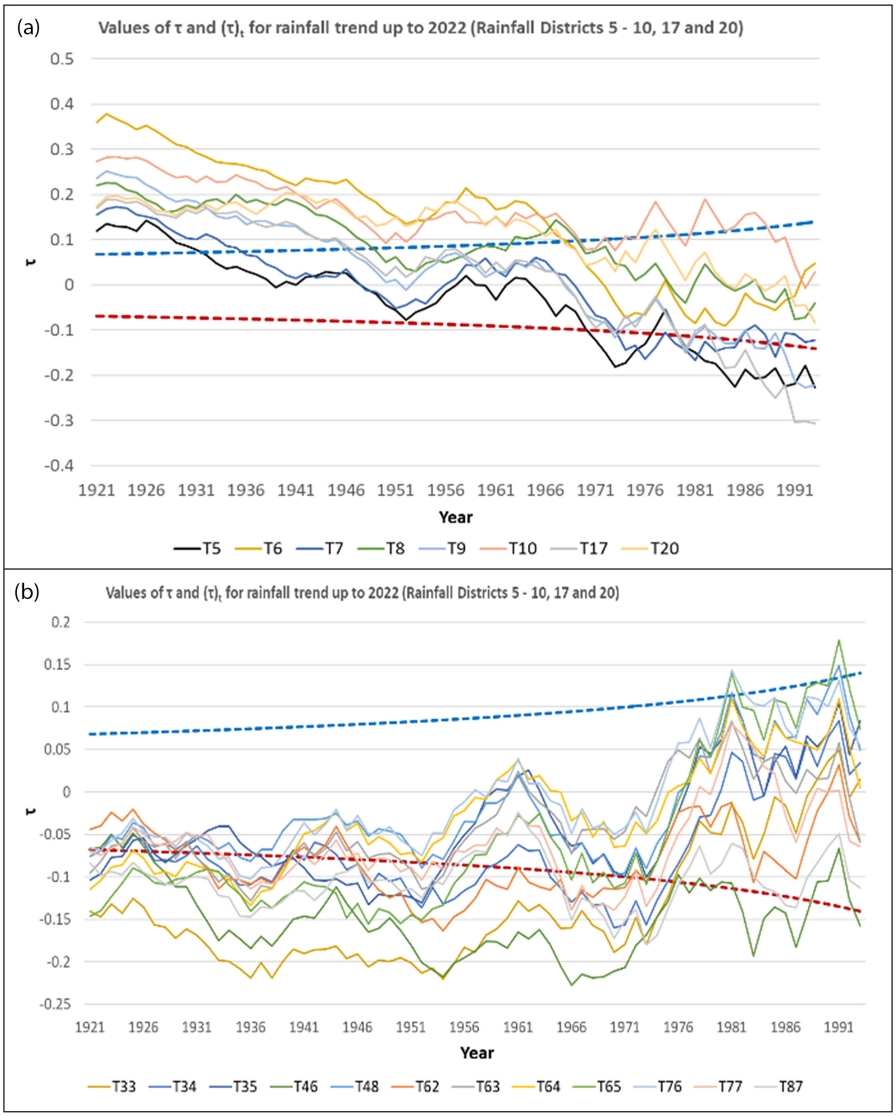

Figure 6. M-K test values for trend for the period 1921–2022 up to 1993–2022, for each year from 1921 to 1993. (a) Group of rainfall districts in the extreme west and south and (b) the far northern and north-eastern parts of South Africa. Values of τ and $\pm(\tau)_t$ applicable for the rainfall trend up to 2022. The coloured lines indicate τ for each rainfall district, and blue and red dotted lines $+(\tau)_t$ and $-(\tau)_t$ at the 95% level of confidence, respectively.

DISCUSSION

Provincial summary of trends

Following is a general overview of the analysis results for the nine provinces of South Africa, starting with the Western Cape and moving northwards to Limpopo. Apart from the recent drought in the South-Western Cape (centred in Rainfall District 4), which was caused by persistently below-normal rainfall from 2015 to 2017 (Otto et al., 2018), preliminary data indicate that 2022 was the driest on record (according to the average of the available rainfall station data for 2022 in Rainfall District 4). The temporal analysis, as described in the methodology section, indicates that the correlation factor for Rainfall District 4 is persistently negative from 1933 to the present, which indicates significantly negative trends over any time period from at least 1933, up to 2022. For the period 1933–2022 (the longest period over which the trend is significantly negative), the trend magnitude is −0.45 mm/year, and for the most recent 30-year period (1993–2022) it is −8.5 mm/year, which indicates that the drying trend has strengthened over the course of the analysis period. Further to the east in the province most rainfall districts also show a strengthening drying trend, which mostly shows significant increases in rainfall for 1921 to 2022, but non-significant trends or significantly drying over the last 30 years. As shown in Fig. 6a, the change in trend occurred gradually from the 1930s to the present. Along the West Coast the trends in Rainfall District 3 showed a moderating of the drying trend but this is more stable in Rainfall District 2. Rainfall District 1 in the Northern Cape, however, indicates a strengthening of the drying trend, consistent with most of the rainfall districts in the Western Cape.

Most of the Northern Cape Province experienced significantly positive trends in rainfall over the last 100 years. However, over most of the province the trend is the opposite over recent time periods, since the 1960s up to 2022. In the west and south the trends are significantly negative for Rainfall District 5 since 1972, Rainfall District 17 since 1991 and Rainfall District 18 since 1973.

As is the case for the largest parts of the Western and Northern Cape Provinces, the rainfall districts in most of the Eastern Cape Province show significantly positive trends over the 1921–2022 period, which changed to more negative trends, with several significantly so. The longest periods with significantly negative trends per rainfall district in the province are Rainfall District 22 (1968–2022), Rainfall District 27 (1958–2022), Rainfall District 28 (1993–2022), Rainfall District 56 (1973–2022) and Rainfall District 57 (1970–2022).

As indicated in Fig. 2b, most rainfall districts in KwaZulu-Natal show recent significantly negative trends. The longest time periods over which these trends were negative are: 1951–2022 for Rainfall District 30 and 31, 1983–2022 for Rainfall District 44 and 1921–2022 for Rainfall District 45. These districts cover most of the province, and one can conclude that, in general, the KwaZulu-Natal Province has experienced significantly negative rainfall trends over different time periods since 1921. One exception is Rainfall District 25 on the eastern South Coast, including the eThekwini metropole, because the area experienced very heavy rainfall episodes in April 2022 (Thoithi et al., 2022). Further analysis shows that Rainfall District 25 has a significant negative rainfall trend over the period 1983/84–2020/21. This example illustrates that a few exceptionally high rainfall events can have a significant effect on the long-term trend, even in regions which receive relatively high rainfall, such as the KwaZulu-Natal coast.

A number of studies have shown that the far northern part of South Africa, which includes amongst others the Limpopo Province, experienced drying, and is also expected to become drier in future (Shikwambana et al., 2021). However, in the trends in rainfall is analysed over the last 30 years, only two rainfall districts show significant drying, i.e. Rainfall District 32 in North West, Rainfall District 86 in Limpopo and Rainfall District 46 in Mpumalanga Province. Nevertheless, Rainfall District time series show significantly negative trends if analysed from further back in the past up to the present, for Limpopo this is specifically mostly since 1921.

Comparison of results with projected trends

The latest climate projections are available from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (Phase 6) (CMIP6), of which assessments of the future climate are presented in the latest IPCC reports (Seneviratne et al., 2021). Application of the IPCC Working Group I Interactive Atlas (Gutiérrez et al., 2021) provides access to rainfall projections, amongst others. Considering the change in annual precipitation at 4°C warming of the global climate, compared to the 1850–1900 period, based on 19 climate projection models, there is large agreement between models of a decrease in the western half and extreme eastern section of South Africa. (A 4°C warming is plausible since the global near-surface temperatures have already warmed by about 1°C (IPCC, 2021) in 2011–2020, compared to pre-industrial levels, and since then the warming continues unabated (NOAA, 2023).) While the remainder of the country also shows a decrease in annual rainfall on average between the models, there is not sufficient agreement to make firm conclusions. A comparison between the projections and the analysis in Fig. 4 shows general agreement between projections and recent trends, with the trend in annual rainfall becoming more negative in recent times, primarily over the western half of South Africa and isolated areas in the east.

General remarks

A systematic analysis of annual rainfall trends from 94 homogeneous rainfall districts over the period 1921–2022 has been conducted. The results, considering all possible analysis periods, and including the most recent climatological period, emphasise the necessity of considering a range of analysis periods instead of only the maximum period that available data provide for. It is demonstrated that the latter approach has led to inconsistencies between studies, depending on the analysis period, and projections. These different results can confuse the potential end-users thereof, including long-term developers and policy makers.

The summary of the results lends confidence in, and largely corresponds, with the long-term rainfall projections, which points to a generally drier climate in the west. Relatively large metropolitan areas and/their main water sources, such as Cape Town, are situated in the drying regions. Confidence in the future rainfall scenarios, indicating the projected trends already occurring, calls for urgent adaptation measures, since the affected regions are projected to undergo substantial increases in population as well as urbanisation (Le Roux et al., 2019).

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APPENDIX

Table A1. Results of the standard normal homogeneity (SNH) test, grouped in a spatially coherent manner, considering periods and maximum values of significant T_k, for $\tau/(\tau)_t$, the M-K statistic for the trend for all periods from 1921 up to 2022. N/A indicates no significant T_k values in the time series.

Region	Rainfall District	Period of significant T_k	Years of maximum value of T_k	Trend in $\tau/(\tau)_t$ when T_k significant
Extreme north-west	1	1969–1990	1979	Decrease
West Coast	2	N/A	N/A	No significant T_k values
West Coast	3	1947–1989	1957	Increase
South-Western Cape	4	1932–1950, 1960–1980	1939, 1980	Increase
Western and southern interior	5 – 10, 17, 20	(1935–41) – (1985–90)	1968–72	Decrease
Western interior	14	1952–1988	1969	Decrease
Western interior	15, 16	1939–1989	1965	Decrease
Western interior	18, 38, 53 – 54, 66	(1937–48) – (1971–88)	1960,61, 63, 66	Decrease
Western interior	19	1940–1970	1948	Decrease
Western interior & W Free State	36, 52 , 82, 89	(1976–82) – (1985–91)	1982, 1983, 1984	Decrease
W North West	90	1990–1991	1990	Decrease
Central interior	37, 51, 81, 88, 94	(1954–66) – (1973–81)	1967, 1972–74	Increase
Western and Central interior	67 - 69	(1943–1955) – (1988–1991)	1982–83	Decrease
NW interior	78, 84	N/A	N/A	No significant T_k values
South Coast	11	N/A	N/A	No significant T_k values
South Coast	12	1938–1950	1946	Decrease
South-east coast	13	1940–1973	1959	Decrease
South-east coast and interior	23, 42	1940– (1984–88)	1967	Decrease
South-east coast	24	1977–1982	1980	Decrease
South-eastern interior	21, 28 - 29	(1942–44)–1991	1965, 1978, 1980	Decrease
South-eastern interior	22, 27, 41	(1941–47)– (1967–68)	1945, 1954, 1963	Decrease
South-eastern interior	39, 57–58	1940–1950	1945	Decrease
South-eastern interior	40	1955–1984	1966	Decrease
South-eastern interior	43	1937–1981	1951	Decrease
East coast and KZN interior	25, 26, 30	(1972–84)– (1988–89)	1986	Increase
KZN interior	31	1944–1950	1949	Decrease
KZN interior	44	1937–1981	1951	Decrease
KZN interior	45	1940–1991	1986	Increase
E Mpumalanga and Limpopo	33–35, 46, 48, 62–65, 76–77, 87	(1943–64) – (1982–91)	1972–76	Increase
SW Limpopo	86	1943–1965	1962	Decrease
Eastern Mpumalanga	47	1934–1949	1943	Decrease
Eastern Limpopo	49	1939–1970	1963	Decrease
Northern Limpopo	50	N/A	N/A	No significant T_k values
Central interior	55	N/A	N/A	No significant T_k values
Central interior	70	1936–1950	1944	Decrease
Central interior and North West	71, 79, 80, 91–92	(1968–81))– (1979–81)	1974, 75	Increase
SE interior	56	1935–1981	1964	Decrease
E Free State	60, 72	(1948–53)– (1971–80)	1958, 1959	Increase
E Free State	61	1939–1987	1973	Increase
NW Free State	83	1961–1971	1965	Decrease
NE Free State	73	1949–1971	1967	Decrease
Gauteng and W North West	74, 85, 93	(1947–51)– (1978–87)	1973-74	Increase
Gauteng and W Mpumalanga	75	N/A	N/A	No significant T_k values