Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010

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Observed trends in seasonal and annual total rainfall, number of rain days and daily maximum and minimum temperature were calculated for a number of stations in South Africa for the period 1960–2010. Statistically significant decreases in rainfall and the number of rain days are shown over the central and northeastern parts of the country in the autumn months and significant increases in the number of rain days around the southern Drakensberg are evident in spring and summer. Maximum temperatures have increased significantly throughout the country for all seasons and increases in minimum temperatures are shown for most of the country. A notable exception is the central interior, where minimum temperatures have decreased significantly. Regionally aggregated trends for six water management zones covering the entire country are not evident for total rainfall, but there are some significant trends for the number of rain days. Temperature in these zones has increased significantly for most seasons, with the exception of the central interior. Comparison of the observed trends with statistically downscaled global climate model simulations reveals that the models do not represent the observed rainfall changes nor the cooling trend of minimum temperature in the central interior. Although this result does not rule out the possibility of attributing observed local changes in rainfall to anthropogenically forced global change, it does have major implications for attribution studies. It also raises the question of whether an alternative statistical downscaling method or dynamical downscaling through the use of a regional climate model might better represent regional and local climatic processes and their links to global change.

Introduction

Historical trends in climatic variables are of interest in a variety of academic disciplines and economic sectors, such as ecology, agriculture and water resource management. As a consequence, numerous studies[1-16] have investigated climatic trends in South Africa, mostly focusing on station records of temperature and rainfall as well as various indices derived from these quantities. The greatest restriction to such studies of historical climate is the availability of long-term meteorological station observations that have sufficient coverage to give an adequate representation of a region's climate. South Africa has a relatively good network of rainfall and temperature recording stations compared to the rest of Africa and much of the southern hemisphere,[1-3] which makes it possible to investigate trends and variability over multiple decades. However, it is often difficult to detect clear signals of long-term change given large variability across a range of spatial and temporal scales. This difficulty is particularly relevant for rainfall, which is highly variable in both space and time, thus making any trend calculation sensitive to the specific location and period of the observations. Re-evaluation of trends as new and updated observational data sets become available is therefore necessary and allows for an assessment of how representative a trend over a given record is of underlying long-term climatic changes.

Process-based global climate models (GCMs) are the primary tools used to make projections of future climate under scenarios of anthropogenic greenhouse gas forcing. Although these models generally have skill in replicating large-scale climate features, their coarse spatial resolution does not provide adequate information at local scales. Hence a variety of downscaling procedures, both empirical and dynamical, have been developed in order to represent finer spatial details.[17-19] A question that is relevant in the context of historical trend analysis is whether or not the climate models (or downscaled products derived from these models) are able to replicate local trends in rainfall and temperature. When simulating the climatic effects of anthropogenic emissions, the only persistent temporal forcing applied to a GCM is an increasing concentration of greenhouse gases. If an observed historical trend in a climate variable, for example rainfall, is not replicated by such a GCM simulation, it could imply that the change is not a result of an enhanced greenhouse effect. This subject of detection and attribution of anthropogenic climate change has received considerable attention of late.[20-22] Alternatively, disagreement between observed and modelled trends could be the result of either (1) weaknesses in the models' representation of key processes at the regional or local scale or (2) uncertainties in the observational record. Both possibilities have implications for the interpretation of both past and future climate projections.

In this paper, we present an analysis of climatic trends in rainfall and temperature indices for South Africa for the period 1960–2010 and thus provide an update that will complement previous trend analyses. We first present a review of previous climate trend studies in South Africa to provide a context for our analysis. We then summarise the important modes of variability that are associated with intraseasonal and interannual variations in South Africa's climate and which can have a marked influence on trends calculated over a 50-year period. Finally, we describe the methodology for our trend analysis and present the results. Included in the analysis is a comparison of the observed trends with statistically downscaled climate model simulations.

Review of climate trend studies in South Africa

Because South Africa's mean annual precipitation (MAP) is highly variable from year to year[4,5], few spatially coherent or statistically significant trends in this quantity have been observed[6-8]. However, of more relevance than MAP are the characteristics of how rainfall is distributed throughout the year. These characteristics include the timing of the onset and end of the rainy season, the typical durations of wet and dry periods and the occurrence of extreme heavy rainfall events. A review by Easterling et al.[2] indicates a tendency for increased extreme precipitation in the southwestern and eastern parts of South Africa during most of the 20th century. In agreement with these observations are results from Groisman et al.[9] who show a significant increase in the annual frequency of very heavy rainfall events over eastern South Africa from 1906 to 1997. Furthermore, Mason et al.[10] demonstrate increases in the intensity of high rainfall events in the 1961–1990 period relative to 1931–1960 over much of South Africa. Kruger[8] shows increases in extreme rainfall indices over the southern Free State and parts of the Eastern Cape from 1910 to 2004. New et al.[6] also show some evidence for increased rainfall extremes over parts of South Africa for the 1961–2000 period. Nel[7] demonstrated a shift in seasonality for stations in the KwaZulu-Natal (KZN) Drakensberg for 1955–2000. Here MAP showed no significant trend, but an increase in summer rainfall, accompanied by decreased autumn and winter rainfall, resulted in a shorter wet season and a more pronounced seasonal cycle. These findings are consistent with results from Thomas et al.[11] for northwest KZN, which show an increase in early-season rainfall along with a decrease in late-season rainfall between 1950 and 2000. Seasonal shifts were also observed in Limpopo for the same period, where there has been a tendency for a later seasonal rainfall onset accompanied by increased dry spells and fewer rain days.[11] A trend toward later onset of rainfall in Limpopo between 1979 and 1997 was also identified by Tadross et al.[12], but they note that this trend is likely part of low-frequency variability rather than long-term change. Increased dry spell duration is also evident for much of the Free State and Eastern Cape, and decreases in wet spell duration have been observed for parts of the Eastern Cape and the northeastern parts of South Africa during 1910–2004.[8]

Long-term trends in temperature-related indices tend to manifest themselves more strongly than changes in rainfall indices. As global mean temperature has been observed to increase over the last century, which is largely attributed to the warming effects of anthropogenic greenhouse gas emissions,[23] so different regions have experienced changes of varying magnitude. In South Africa between 1950 and 1993, Easterling[13] found an increase in annual mean daily maximum temperature (tmax) and widespread increases – although also some decreases – in annual mean daily minimum temperature (tmin). Despite a global tendency for a reduction in the diurnal temperature range (dtr), which is the difference between tmax and tmin, the results of Easterling[13] show much of South Africa experienced an increase in dtr. In contrast, however, Hulme et al.[14] show decreased dtr over South Africa during the 1950s and 1960s. They also show very strong warming in the central interior of southern Africa and in fact a cooling over the coastal regions of South Africa for the 1901–1995 period. It is not clear what the cause of this cooling may be. Kruger and Shongwe[15] examined the period 1960–2003 and found that, with a few exceptions, stations in South Africa have reported increases in annual mean temperatures, with strongest warming having occurred in the interior of the country and during autumn months. The stations showed mixed results with respect to dtr, with no clear regional pattern of change. New et al.[6] also indicate varied results for changes in dtr over a similar period, but they do show a tendency for the cold extremes of tmin to change more strongly than the cold extremes of tmax. They also reveal a general increase in hot extremes over South Africa. The most recent published work on South African temperature trends was done by Kruger and Sekele[16] for the period 1962–2009. They focused on extreme temperature indices for 28 stations and found significant changes in the exceedances of the extreme percentile values for tmin and tmax at many of the stations. More specifically, increases in daily measurements in excess of the 90th percentile of tmax and tmin have occurred along with decreases in exceedances of the 10th percentile of tmin and tmax. These occurrences are indicative of an overall increase in hot extremes and decrease in cold extremes, with the strongest changes tending to occur in the western and northern interior of the country. There is also a general tendency for stronger increases in the tmax indices than for those related to tmin.[16]

Although some general tendencies are apparent for trends in both rainfall and temperature indices, there is some disagreement between studies. This discord can to a large extent be attributed to two factors: the period over which the data were analysed and the locations of the stations from which data were obtained. Large, naturally occurring variations in climate at yearly and decadal timescales can greatly affect the calculation of trends, so it is important to consider the length of record when evaluating any trend analysis. Regional inferences based on individual stations are reliant on how representative a station or group of stations is of that area and should also be treated with caution. Some studies also rely on gridded products where station records have been interpolated in space onto a continuous surface. Such products should closely match the raw station data in places where the observational record is good, but in data-sparse regions this information is less reliable, especially where strong environmental gradients exist. Details of the methods used to calculate trends also differ between studies, but these should rarely result in substantially different results. Further factors that can influence results are data quality and quality-control measures.

Timescales of climate variability and teleconnections

Climate exhibits numerous modes of variability in global and hemispheric circulation patterns at intraseasonal (of the order of 1 or 2 months) and interannual (year-to-year) timescales. The El Niño-Southern Oscillation (ENSO) is recognised as the leading mode of interannual variability in the tropics and is driven by variations in sea-surface temperatures (SSTs) in the equatorial Pacific Ocean. Links between ENSO and southern Africa's rainfall have been established, such that warm ENSO events (El Niño) are commonly associated with below-average summer rainfall over much of South Africa and cold events (La Niña) are typified by above-average rainfall in this region. It has indeed been shown that severe summer drought in South Africa tends to occur under El Niño conditions[24,25] – a relationship which seems to have strengthened since the 1970s[26]. Furthermore, seasonal prediction of summer rainfall in South Africa shows more skill during strong ENSO phases.[27] However, the relationship between ENSO and South Africa's rainfall is far more complex than a simple linear association and there are many more factors that influence the region's climate. For example, the frequency of synoptic-scale patterns of convection over South Africa are modulated by ENSO events, but different synoptic regimes under the same ENSO phase can result in substantially different rainfall responses.[28]

Complexities are also introduced through the influence of other climatic modes, and interactions between these modes. The second prominent interannual mode relevant for southern Africa is a dipole pattern in SST anomalies between the southwestern and southeastern Indian Ocean. A positive phase of this subtropical Indian Ocean dipole, characterised by anomalously warm SSTs in the western part of the basin, has been linked to increased summer rainfall over parts of southern Africa[29-31] as well as extreme rainfall events in the region[32]. Increased SSTs in the southwest Indian Ocean have also been associated with an enhancement of the El Niño effect over South Africa.[26] At an intraseasonal timescale, the Madden–Julian Oscillation (MJO) has a noticeable impact on South African convection and rainfall.[33] The MJO is an eastward propagation of large-scale convective clusters in the tropics with a period of 30–60 days. It has been shown that convection over South Africa tends to be more strongly affected by the MJO during warm phases of ENSO and warm tropical Indian Ocean temperatures, such that intraseasonal variability is higher and convection is less active during El Niño events.[33] A further low-frequency mode that is present in the mid-latitudes is the Antarctic Oscillation (AAO), which is defined by pressure anomalies between Antarctica and the southern hemisphere mid-latitudes. There is some indication of a link between a positive phase of the AAO and enhanced rainfall over central South Africa, which tends to be stronger during La Niña years.[34] It has also been shown for the winter rainfall region of the southwestern Cape that particularly wet winters are associated with a negative phase of the AAO and vice versa.[35]

Beyond the interannual timescale are decadal-scale variations in climate which provide a slowly evolving background around which higher-frequency modes oscillate. For example, an approximately 18-year cycle in southern African rainfall has been identified in instrumental and proxy records extending back as far as 600 years.[36] The cause of this oscillation is not clear, but an 'ENSO-like' multidecadal pattern of variation has been identified at multiple periodicities.[37] Interaction between phases of the multidecadal and interannual variations act to enhance or mitigate regional responses.[37,38] In the context of the trend analysis presented in this study, it is very important to consider the possible influences of low-frequency variations on the calculation of long-term trends.

Data and methods

Station observations were obtained though the Climate Information Portal (CIP) hosted by the University of Cape Town's Climate System Analysis Group (http://cip.csag.uct.ac.za). The data originate from two main sources – the Computing Centre for Water Resources and the South African Weather Service – and were collated and quality controlled prior to being uploaded to CIP. Stations were selected based on their coverage of monthly data for the period 1960–2010 such that any station with 20% or more missing values was excluded from the analysis. Based on this condition, data from 73, 30 and 27 stations were available for rainfall (ppt), tmax and tmin, respectively. The indices presented in this paper are limited to ppt, number of rain days, tmax and tmin, but analysis was also performed for extreme values of rainfall and temperature. Results for the full set of indices are presented in the Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) technical report on climate trends and scenarios for South Africa.[39]

Trends in the indices for the 1960–2010 period were evaluated using a number of approaches. Firstly, the non-parametric Mann–Kendall trend test was applied. This method has the advantages of making no assumptions about the distribution of the underlying data and being relatively insensitive to outliers. In this method, a correlation coefficient, tau, is computed, which has a value between -1 and 1 and denotes the relative strength of the trend in a time series. The probability of this trend occurring by chance is also estimated, from which a measure of statistical significance can be assigned. We used a 5% level of significance, such that if the probability estimate was less than 0.05, the trend was deemed to be significant. Because tau does not provide an estimate of the absolute magnitude of the trend, we also calculated the slope of the trend using Sen's slope estimator, which is the median of the slopes calculated between all pairs of data points in the series. Like the Mann–Kendall test, this method is also statistically robust and insensitive to outliers in the data.

The above trend estimates were calculated for seasonal and annual means for all indices. The results are presented as follows. Firstly, annual and seasonal maps of the Mann–Kendall tau for each station and each variable are shown. These maps depict the relative strength of trends over the historical period at each station and give an indication of any coherent spatial patterns of change. Secondly, annual and seasonal time series plots were generated for six water management zones covering all of South Africa. The zones are those used in the LTAS programme for the assessment of climate change on water resources.[40] To calculate these regional time series, an anomaly time series was computed for each station falling within the region by subtracting the 1960–2010 station mean from each value in the series. The resulting series was then summed and divided by the number of stations in that region, after which trend statistics were calculated for the regional mean series. A smoothed curve was added to the figures using a Loess filter with a bandwidth of 0.25. The resulting figures give an indication of the direction and magnitude of long-term trends as well as illustrate interannual and interdecadal variability in the time series. Two important points should be noted here. Firstly, although the definition of the zones has value in a hydro-climatic context, the zones do not necessarily coincide with homogeneous climates and climatic trends. Opposing trends at stations within the same zone will hence weaken any regional signal. Secondly, the stations falling within a particular zone may not necessarily be a good representation of spatial heterogeneity within that zone. This point is particularly true for indices related to rainfall and for zones in which station coverage is sparse. Nevertheless, some useful information can be extracted from these spatially averaged indices.

To compare the observed trends for the six water management zones to climate model simulations for the same period, results from 11 different GCM simulations were used. The GCM simulations were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and have been statistically downscaled to the same stations used in the trend analysis. Although more model simulations exist in the CMIP5 archive, we have limited our analysis to those models that are currently available on CIP and have been downscaled to the relevant stations. The GCMs used are listed in Table 1. The method of downscaling is described in Hewitson and Crane[17] and the data are publicly available on CIP. Trends for 1960–2010 were computed using Sen's slope estimator for each downscaled GCM, aggregated over the six zones.

Table 1: Global climate models used in the study

Model name	Institute
BCC-CSM1	Beijing Climate Center, China Meteorological Administration
BNU-ESM	Beijing Normal University
CanESM2	Canadian Centre for Climate Modelling and Analysis
CNRM-CM5	Centre National de Recherches Météorologiques / Centre Européen de Recherches et Formation Avancées en Calcul Scientifique
FGOALS-s1	Institute of Atmospheric Physics, Chinese Academy of Sciences
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology
MRI-CGCM3	Meteorological Research Institute, Japan

Results

Observed trends for 1960–2010

The results for ppt, rain days, tmax and tmin are presented in Figures 1 to 8. The main findings that emerged from the analysis are summarised below for each of the six water management zones.

Zone 1: Limpopo and parts of northern Mpumalanga

There is a mixed signal in the spatial distribution of changes in rainfall indices in most seasons, but a tendency for reductions in ppt (Figure 1) at most stations in March–May (MAM), although this reduction is significant at only two stations. A cluster of stations in the Lowveld indicate increased ppt for MAM, but although there is some spatial coherence, the trends are small and not statistically significant. More pronounced trends are seen in the number of rain days (Figure 2), for which a number of stations show significant decreases in the September–November (SON), December–February (DJF) and MAM seasons. Two pairs of nearby stations exhibit contrasting significant trends in rain days. This result could be because of localised environmental conditions interacting in different ways with larger-scale rainfall processes, but a more detailed study of these locations is required to investigate this result further.

All but one station show significant increases in tmax (Figure 3), with the strongest warming signal occurring in June–August (JJA) and the weakest in DJF. The strongest warming of tmin occurs in DJF and JJA (Figure 4). Regionally aggregated ppt time series for this zone (Figure 5, top row) show large interannual and decadal-scale variability and no significant trends, but significant reductions occur in the number of rain days in DJF and MAM and in the annual mean (Figure 6, top row). The change in annual mean rain days translates to nearly 16 days over the 50-year period. Significant increases occur in tmax in JJA (0.022 °C/year) and in the annual mean (0.018 °C/year) (Figure 7, top row), which represent approximately a 1 °C increase over the 50-year period. Changes in tmin are generally smaller, with a 0.011 °C/year increase in annual mean (Figure 8, top row).

Zone 2: Majority of KwaZulu-Natal and part of southern Mpumalanga

A consistent spatial pattern of decreased ppt is shown for MAM (Figure 1), but the trends are significant at only three stations. In the southern part of the region in SON, a cluster of stations show increased ppt, but none of these trends is significant. Many stations indicate significant changes in rain days, but spatial coherence is weak (Figure 2). There is a suggestion, however, that coastal stations have experienced decreased rain days, whereas inland locations have experienced increases. A cluster of stations in the southern Drakensberg area, which also extends into Zone 5, shows significant increases in rain days in SON and DJF.

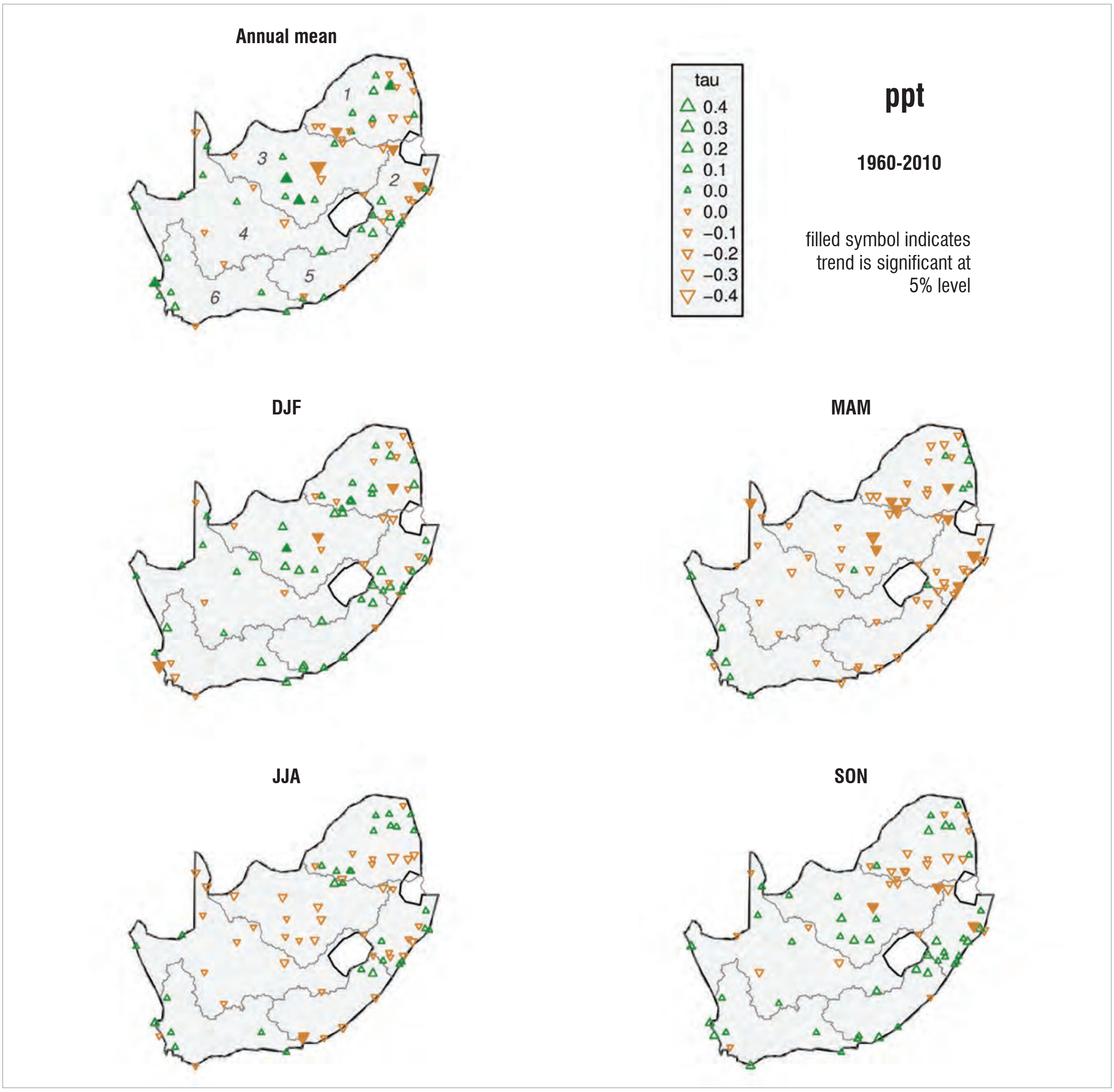

Figure 1: Trends in annual and seasonal mean rainfall (ppt) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

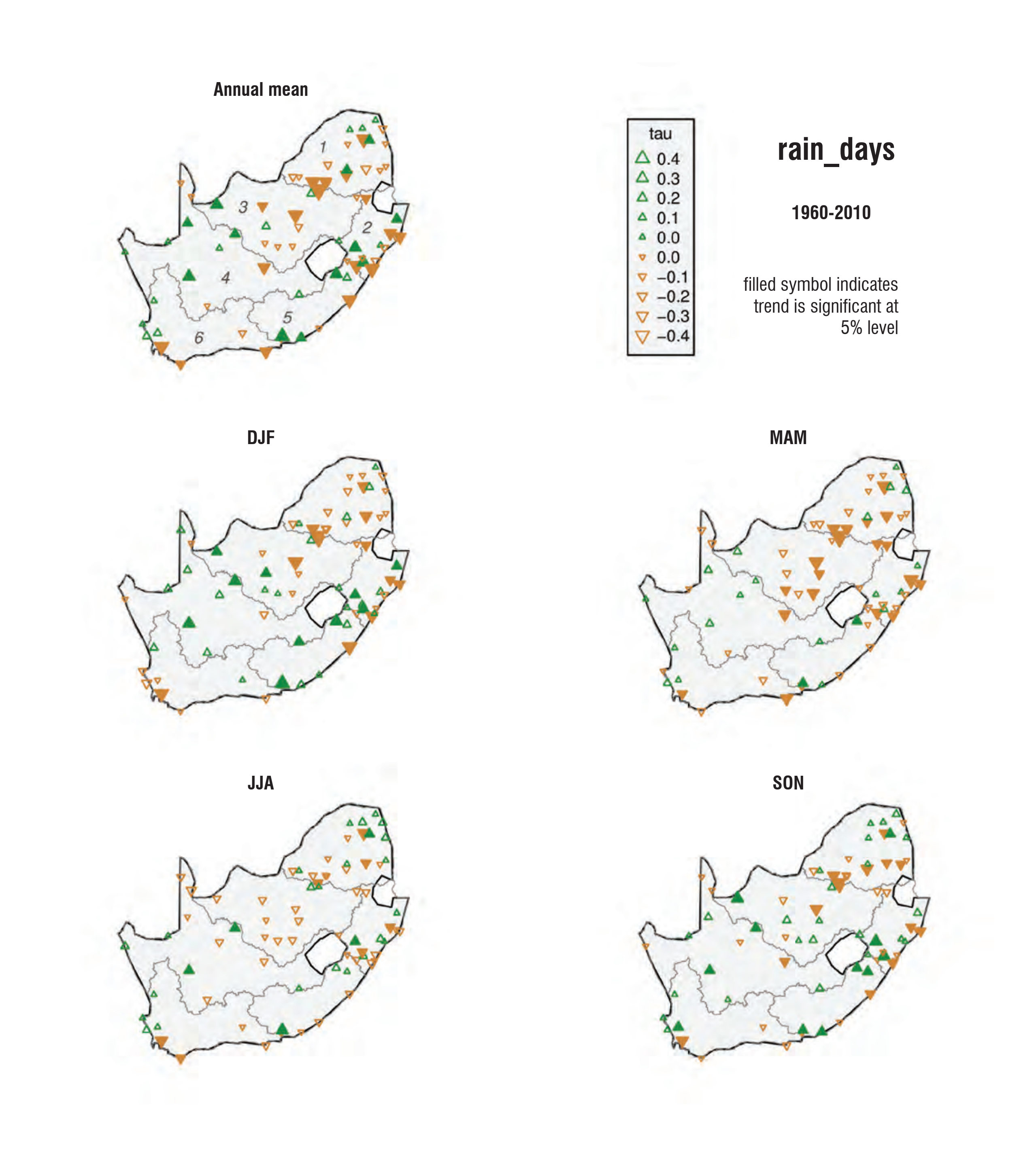

Figure 2: Trends in annual and seasonal rain days (days) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

Data from only three temperature stations were available for this zone, which all show positive trends for tmax (Figure 3) and tmin (Figure 4), but not all of these trends are significant. No regionally averaged trends are seen in ppt (Figure 5, second row), but overall decreases in rain days are shown in DJF and MAM and in the annual mean (Figure 6, second row). It must be noted, however, that spatial variability in the number of rain day trends for this zone is high, which the regional average does not take into account. The average increase in tmax for the three stations in this zone is highest for the MAM season (0.02 °C/year) and is 0.012 °C/year for the annual mean (Figure 7, second row). The increase in annual mean tmin is 0.014 °C/year (Figure 8, second row).

Zone 3: Northern and central interior

Opposing signals are shown at individual stations for ppt (Figure 1), with a rough distinction between increased rainfall in the west and decreased rainfall in the east in DJF. There is, however, a general tendency for

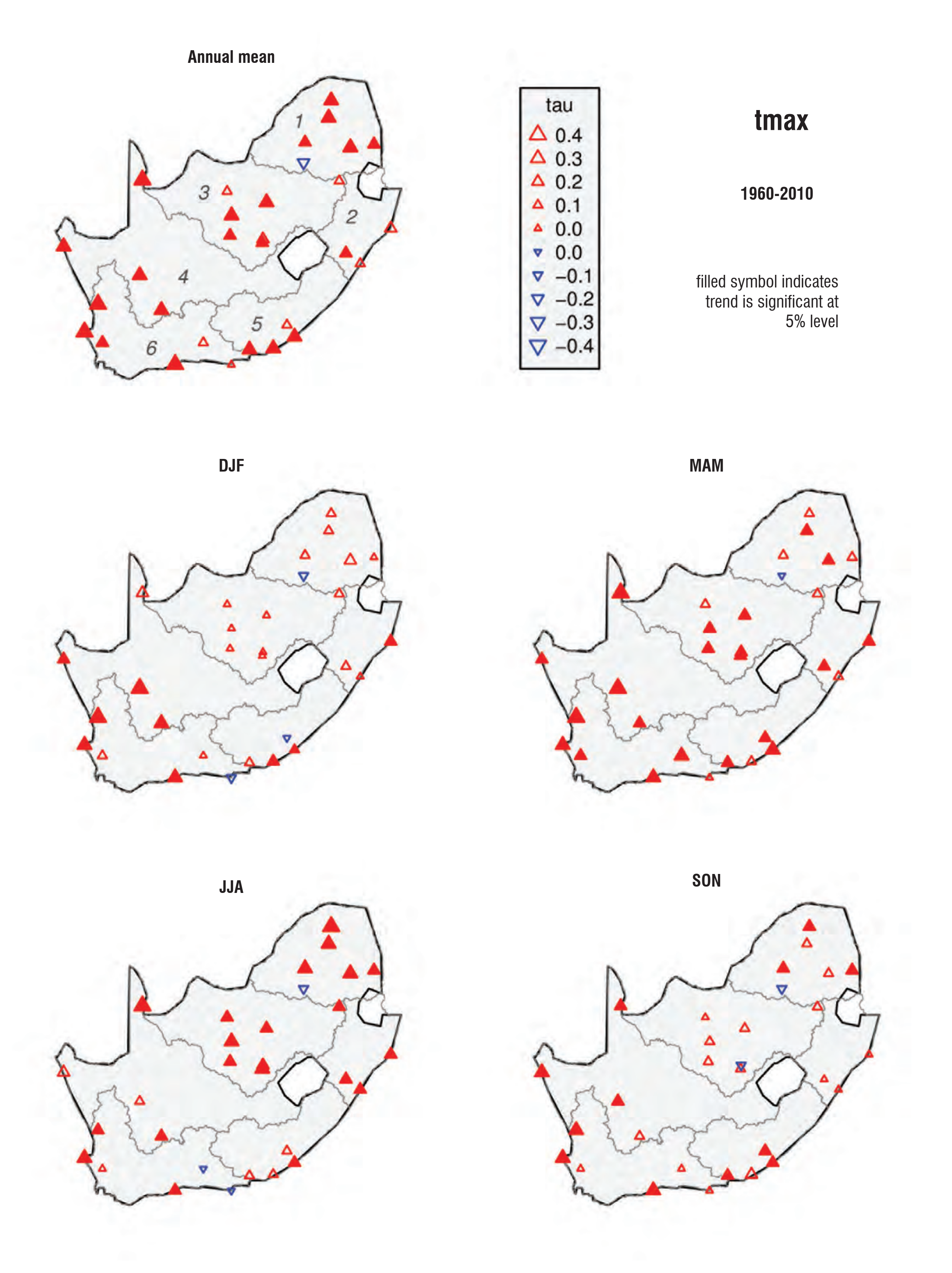

Figure 3: Trends in annual and seasonal mean daily maximum temperature (tmax, °C) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

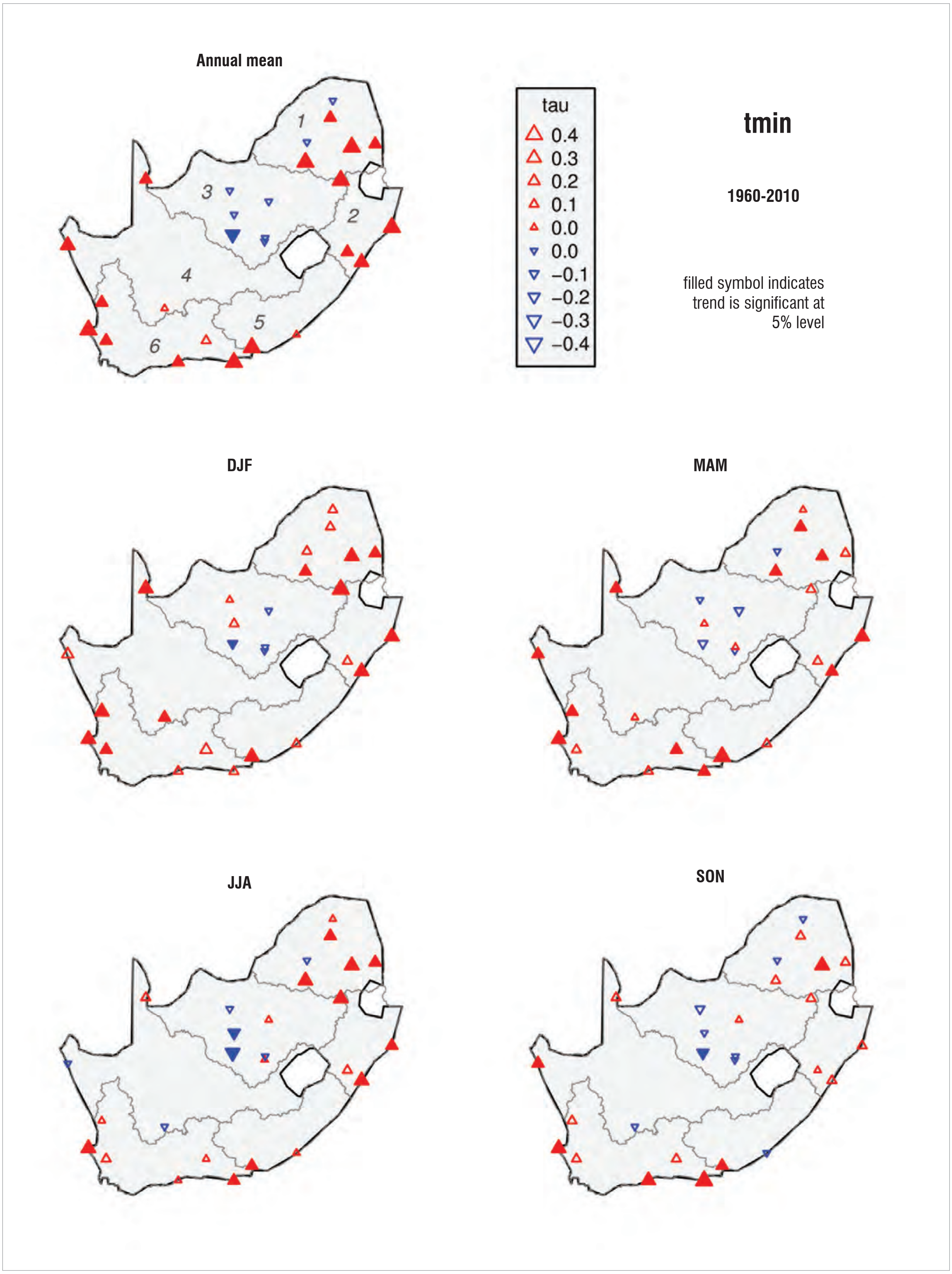

Figure 4: Trends in annual and seasonal mean daily minimum temperature (tmin, °C) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

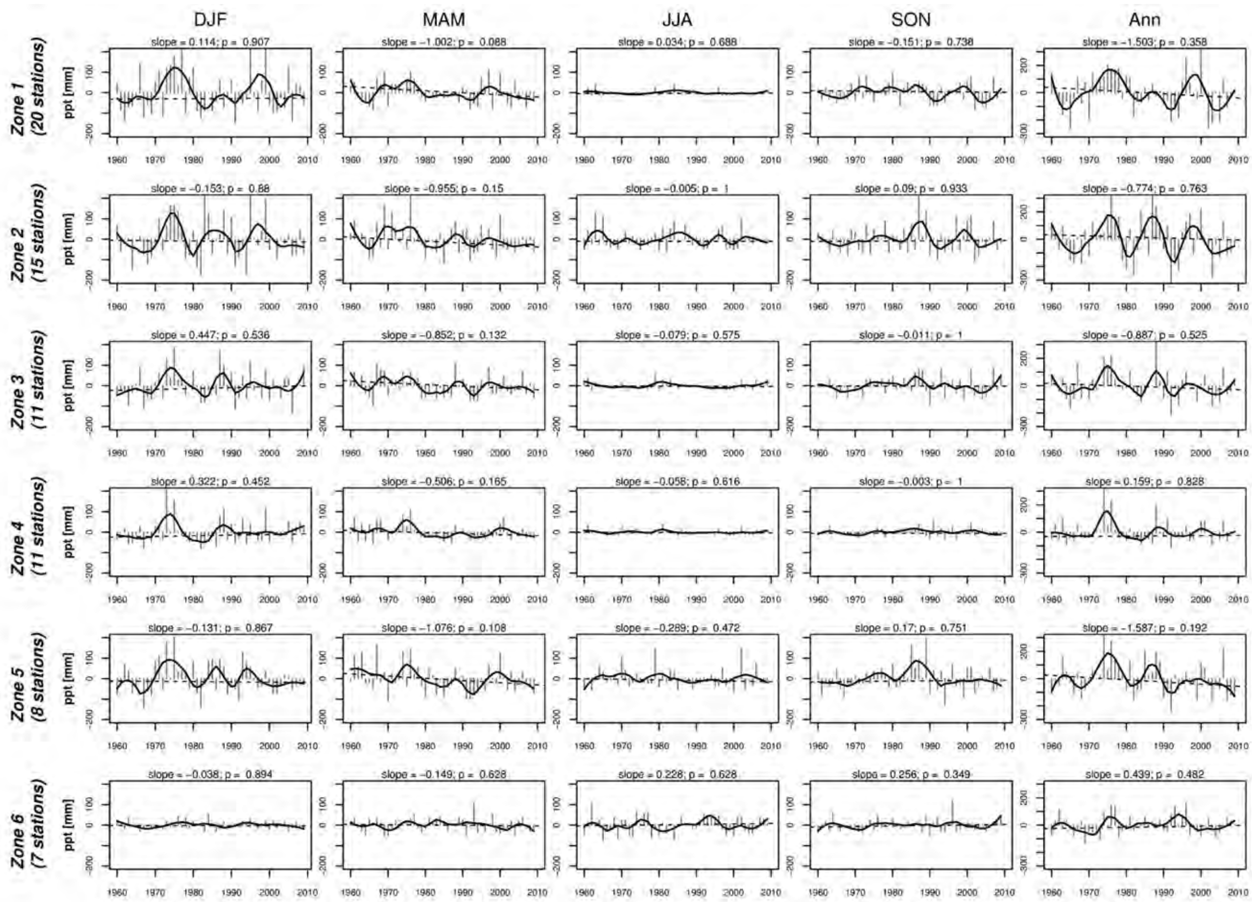

Figure 5: Regional mean time series and trends in total rainfall (ppt) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

decreased ppt in MAM. The pattern is similar for the number of rain days (Figure 2), but more stations show significant decreases for MAM.

Increases in tmax occurred for all seasons, with the strongest trends seen in JJA (Figure 3). There is, however, a general tendency for reductions in tmin in all seasons (Figure 4). Trends in regional mean ppt are not evident (Figure 5, third row), but decreases in rain days in MAM and in the annual mean of about 6 and 13 days, respectively, are seen over the 50-year period (Figure 6, third row). Strong warming trends in tmax of almost 2 °C (0.034 °C/year) in MAM and almost 1.5 °C (0.029 °C/year) in JJA are evident (Figure 7, third row). The decreases in tmin as seen at individual stations are not reflected in the aggregated results (Figure 8, third row).

Zone 4: Northern Cape, southern Free State and parts of Eastern Cape

Trends in ppt are weak for all stations (Figure 1), but some stations show significant increases in rain days in SON, DJF and JJA and one station shows significant decreases in rain days in MAM and SON (Figure 2). Data available from four stations for tmin indicate mostly significant positive trends (Figure 3) but three of the stations show weaker trends, particularly in JJA and SON (Figure 4). This zone is somewhat problematic as it spans a large climatic range and station coverage within this range is sparse. Regional means should therefore be interpreted with caution. Nevertheless, there are no trends in the aggregated time series of rainfall indices (Figures 5 and 6, fourth row).

Tmax shows large significant increases of between 0.025 °C/year and 0.039 °C/year in all seasons, largely as a result of persistently above-average temperatures in the last 10 years of the record (Figure 7, fourth row). Increases in tmin are weaker than those for tmax, ranging from 0.007 °C/year to 0.019 °C/year (Figure 8, fourth row).

Zone 5: Majority of Eastern Cape and southern part of KwaZulu-Natal

Changes in ppt are weak (Figure 1), but there are some significant increases in rain days across the region (southern Drakensberg and southern coastal areas) in all seasons (Figure 2). A single station on the northern coast, however, shows a significant reduction in rain days.

Stations with temperature data are confined to the southern part of the region, where tmax and tmin have generally increased in all seasons (Figures 3 and 4). Regional means show no significant rainfall changes (Figures 5 and 6, fifth row). Significant increases in tmax (from 0.017 °C/year to 0.03 °C/year) have occurred in all seasons except DJF (Figure 7, fifth row). Aggregated increases in tmin are generally weaker than for tmax, ranging from 0.008 °C/year to 0.014 °C/year (Figure 8, fifth row).

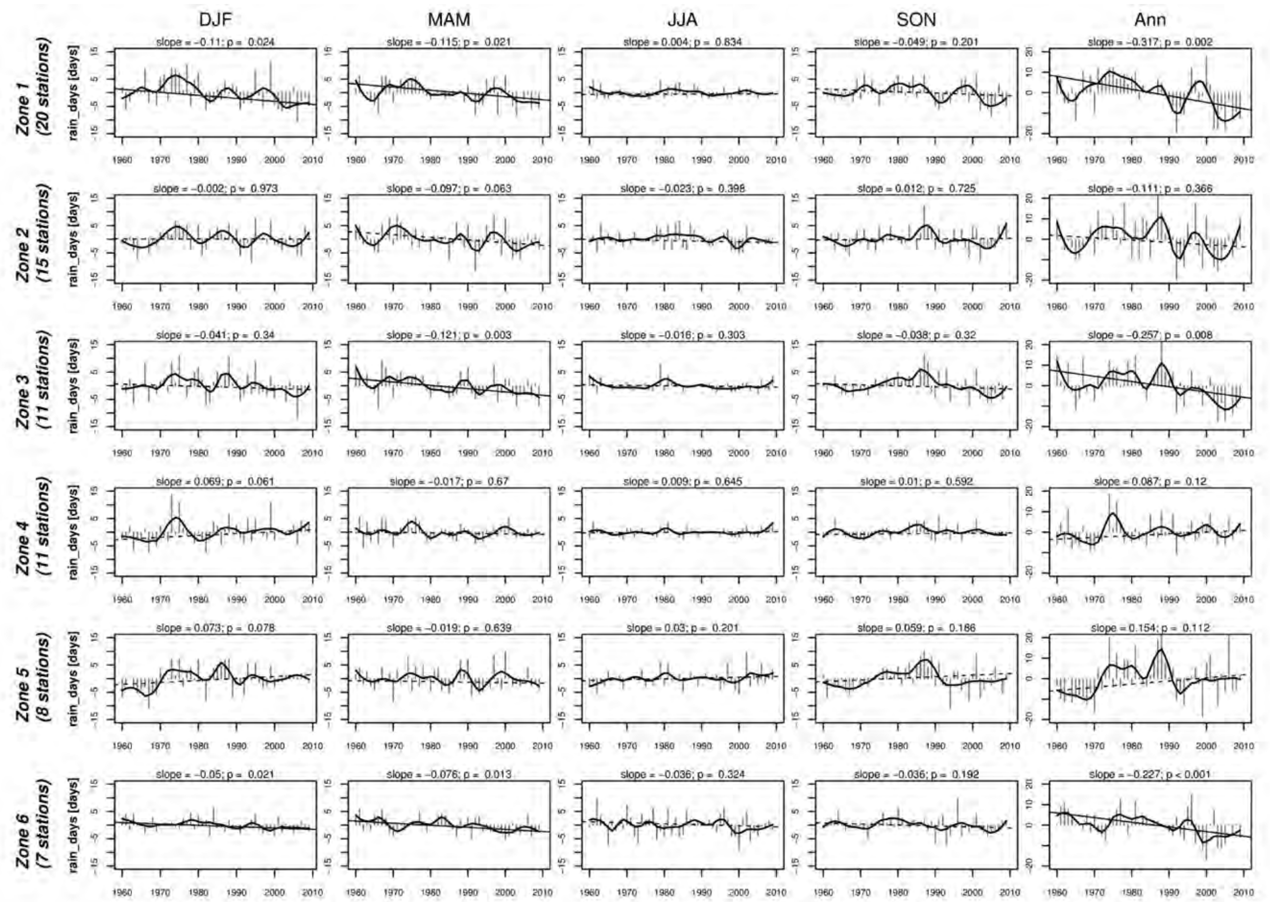

Figure 6: Regional mean time series and trends in number of rain days (days) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

Zone 6: Western Cape and parts of Northern and Eastern Cape

Trends in rainfall indices are generally not significant and show little consistency across the region (Figures 1 and 2). The number of rain days do, however, indicate drier conditions along the southern coastal regions, although the stations near the west coast show a tendency for increased rain days.

Tmax and tmin have increased significantly at almost all stations in all seasons (Figures 3 and 4). The regionally aggregated ppt time series show no significant changes (Figure 5, bottom row), but rain days have decreased significantly in DJF (2.5 days) and MAM (3.5 days) and the annual mean has decreased significantly by 11.3 days over the 50-year record (Figure 6, bottom row). Significant increases in tmax are seen for all seasons and range from 0.015 °C/year to 0.027 °C/year, with strong warming occurring in the last 10–12 years of the record (Figure 7, bottom row). Increases in tmin are mostly smaller (0.011 °C/year to 0.021 °C/year) and are not significant for JJA (Fugure 8, bottom row).

Comparison of model and observed trends for 1960–2010

Figure 9 shows a comparison of observed versus modelled trends aggregated for each of the six zones. This comparison gives an indication of whether or not the models captured the long-term trends that emerged from the analysis of observations. Both observed and modelled results represent the same stations and same period, so a direct comparison can be made between the two. Some interesting points can be made. The reductions in ppt for MAM that are evident in the observed trends for almost all regions is not captured by the models. In fact, the models tend to show an opposite trend. Similarly for rain days, the negative trends in Zones 1, 2, 3 and 6 fall outside the range of model simulations. In contrast, for SON, where observed trends are weak, the models show a tendency for reduced ppt in all regions. Strong trends in observed annual rain days lie well outside the model ranges. Overall, the observed trends in rainfall indices are poorly represented by the model simulations. Observed temperature trends generally fall within the range of model simulations, with the notable exception of tmin in Zone 3. Zone 3 is the region for which decreases in tmin were observed and it is interesting that none of the models is able to simulate this decrease. Tendencies for the models to over- or underestimate trends in tmin and tmax vary according to season, region and variable, but some consistencies are apparent – for example, a general underestimation of tmax in MAM and JJA, but an overestimation for both tmin and tmax in DJF.

Discussion

Rainfall indices are particularly influenced by multi-year variations and therefore are highly sensitive to the temporal coverage of observations used. As expected, we demonstrated weak or non-

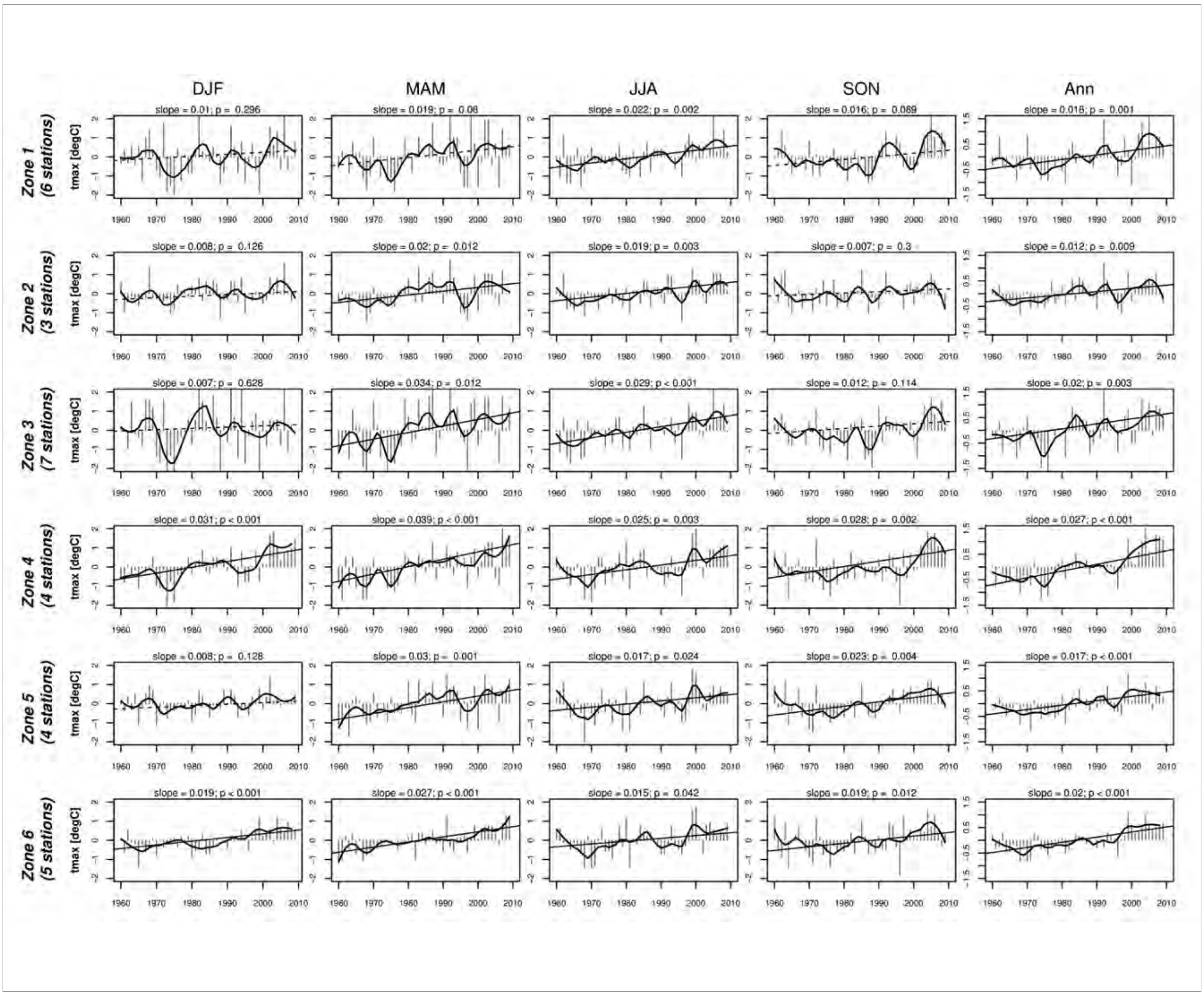

Figure 7: Regional mean time series and trends in mean daily maximum temperature (tmax, °C) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

existent trends in regionally aggregated ppt, which is consistent with previous analyses.[6-8] More pronounced trends are seen at individual stations, with the most spatially coherent result being an overall tendency for decreased ppt in MAM and a reduction in rain days over the central and northeastern parts of the country. Our results also show a strong and cohesive tendency toward increased rain days, and to a lesser degree ppt, around the southern Drakensberg in DJF and SON. This summer increase is consistent with results previously shown for this location,[7] and the springtime increase is suggestive of an earlier seasonal onset. Although other authors[9,10,13] have reported increases in rainfall extremes during the 20th century for eastern South Africa, our analysis of the 90th percentile rainfall events (not shown in this paper) do not show much spatial coherence in trends, except for MAM, for which widespread decreases have occurred in line with the decreases shown for ppt and rain days.

For the temperature indices, a significant warming trend in tmax is shown for almost all stations, which is in line with recent global and regional warming trends.[23] The strongest regionally averaged increase in tmax over the 50-year analysis period reached close to 2 °C in the central interior in autumn, whereas the weakest increase (0.35 °C) occurred in the same region in summer. An interesting result for the central interior is that it experienced a cooling trend in tmin, thus resulting in an increased diurnal temperature range (dtr). The reasons for this finding have not been rigorously explored in this study, but it is possibly related to a reduction in nocturnal cloud cover, more stable ambient atmospheric conditions, or both. Decreases in the number of rain days for much of this region suggest that cloud cover may indeed have been reduced, which would allow for greater radiative cooling of the surface at night. The cause of a reduction in cloud cover could in turn be an enhancement of the mid-tropospheric high pressure system as demonstrated by Engelbrecht et al.[41] for a warming climate. Even in the absence of a change in cloud cover, an increase in atmospheric subsidence can promote stable conditions and the formation of nocturnal temperature inversions[42] which trap cold air near the surface.

We extended our analysis by comparing the observed trends to simulated trends for the same stations and same period from 11 downscaled GCMs. This analysis revealed stark differences in the modelled and observed trends in rainfall indices, but closer agreement for temperature indices. One possible reason for the disagreement in rainfall trends is that the observed trends are not attributable to the effects of increased radiative forcing from greenhouse gases. Although we did not set out to make any robust statements regarding attribution, our findings are consistent

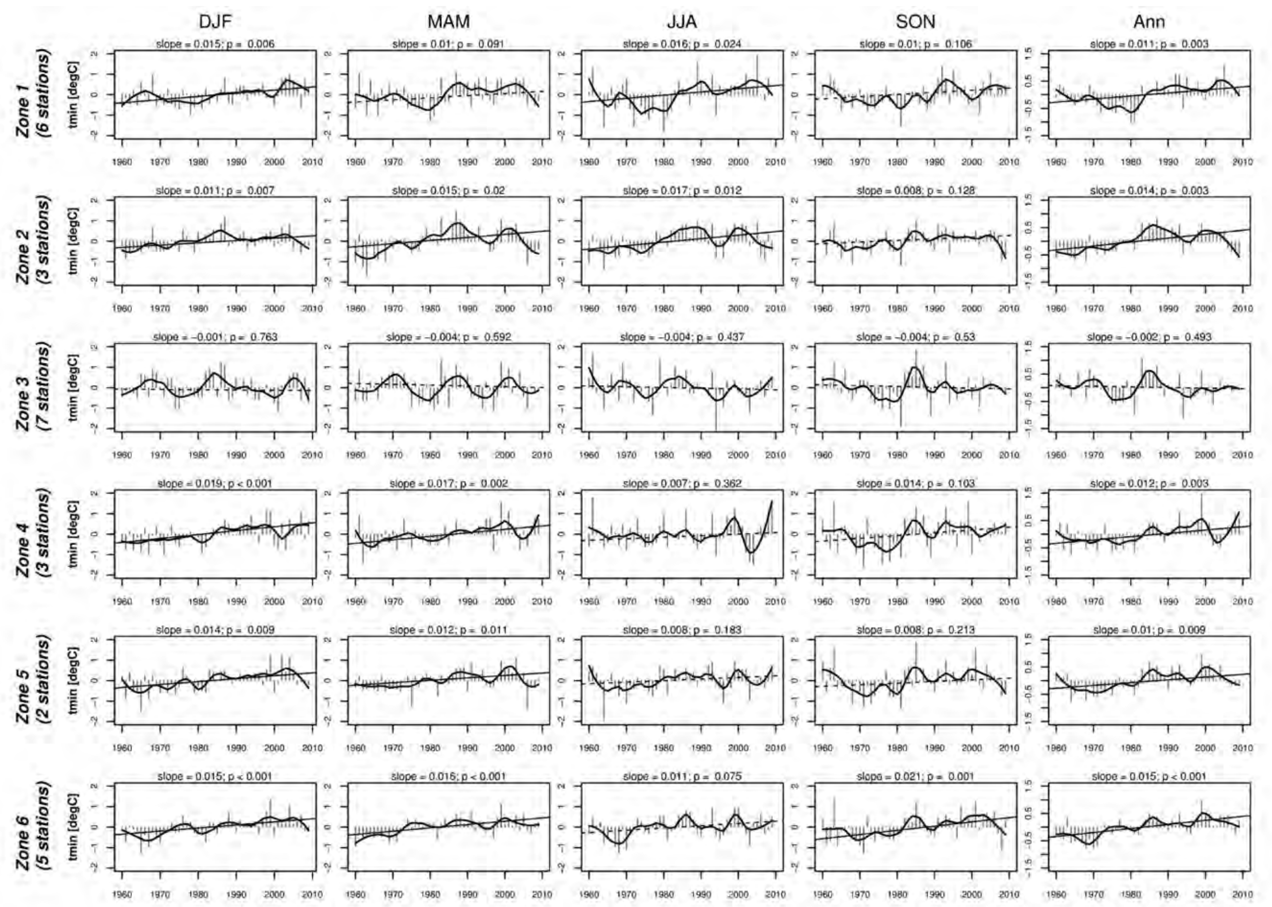

Figure 8: Regional mean time series and trends in mean daily minimum temperature (tmin, °C) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

with those of Hoerling et al.[20] who found similar inconsistencies between observed and GCM-simulated rainfall in southern Africa. Other studies, however, do find a detectable anthropogenic signal in rainfall at larger scales.[21,22] Other potential causes of the discrepancies lie in either the GCM formulations themselves, or in the method that has been used to downscale the GCM results to the individual stations. As the downscaling method does not directly use the modelled rainfall, but rather a selection of variables representing regional atmospheric circulation (eg. wind fields and temperature lapse rate),[17] these poor results cannot be blamed on the GCM formulation of cloud and rainfall processes. Likely causes are rather (1) poorly replicated atmospheric circulation patterns by the GCMs, (2) an inadequate empirical model linking the circulation fields to local-scale rainfall, or (3) differences in the interannual and decadal-scale temporal variations in climate. The latter point can be interpreted as either the models' inability to adequately represent the regional impact of global climate phenomena such as ENSO, or simply that the temporal evolution of low-frequency climate variations differs markedly from observed (in a freely evolving long-term climate simulation, such variability should not be expected to match observed). In any case, this disagreement between models and observations has implications for assessing projections of future climate over South Africa.

Despite the challenges of identifying (and modelling) long-term trends in rainfall over South Africa, there is nevertheless a clear signal of increased temperatures since 1950. This finding has important implications for the functioning of natural systems and related societal impacts and sets a precedent for likely future changes resulting from further anthropogenic global warming.

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Authors' contributions

N.M. wrote the manuscript, performed the analysis and produced the figures; M.N. provided conceptual oversight; and C.J. provided conceptual input and technical support.

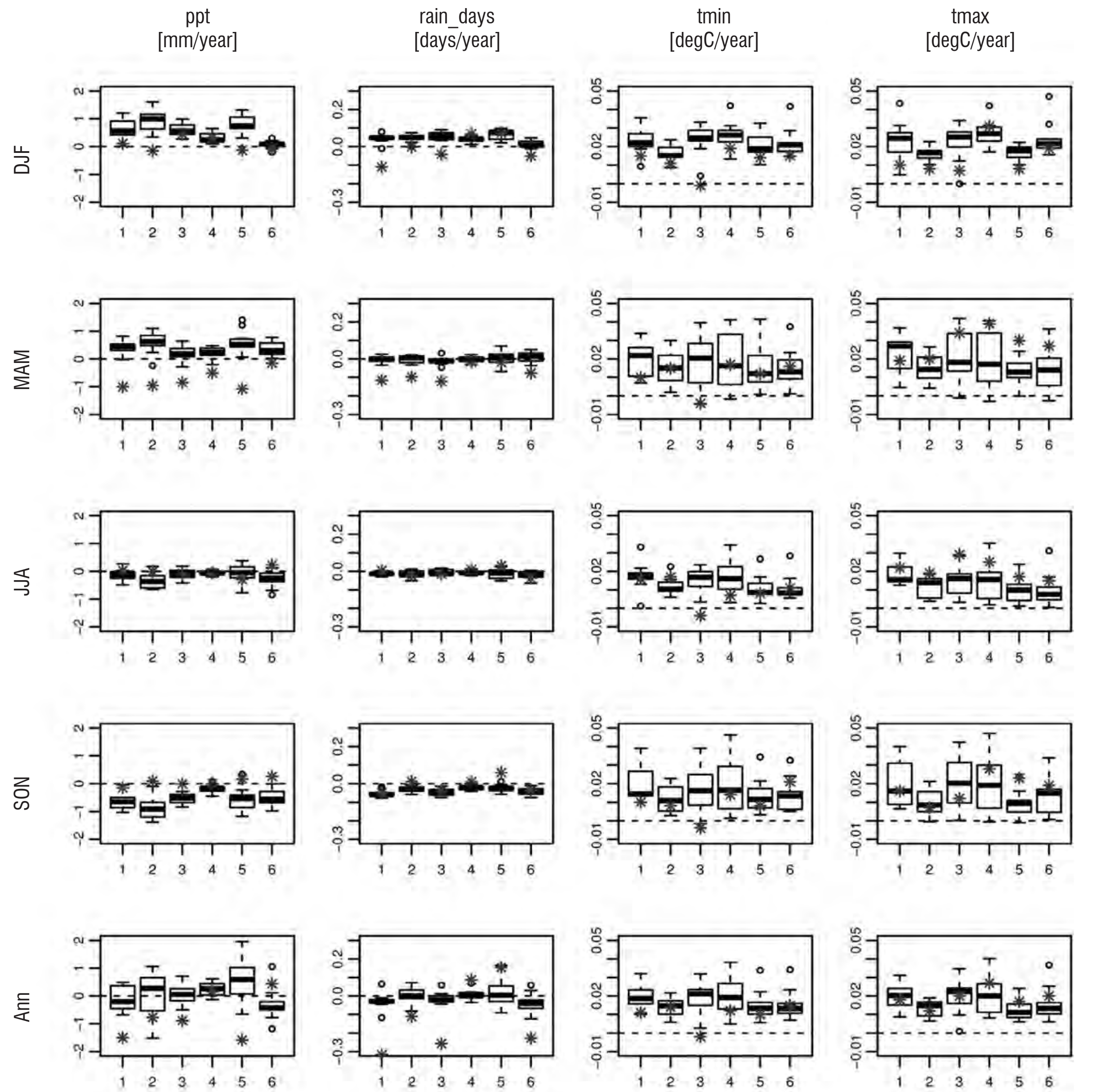

Figure 9: Correspondence between observed trends and downscaled global climate model trends for 1960–2010. Trends are averages for stations in each of the six water management regions (abscissa) for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Asterisks show observed trend and box-and-whisker plots represent the 11 downscaled model trends. Black circles indicate models lying outside 1.5 times the interquartile range.

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