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Rising temperatures and changing rainfall patterns in South Africa's national parks

Nicola J. van Wilgen,[a]* Victoria Goodall,[b,c] Stephen Holness,[d,e] Steven L. Chown[f]
and Melodie A. McGeoch[a,f]

[a] *Centre for Invasion Biology, Cape Research Centre, South African National Parks, Steenberg, South Africa*
[b] *South African Environmental Observation Network (SAEON), Fynbos Node, Claremont, South Africa*
[c] *Department of Statistics, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa*
[d] *South African National Parks Park Planning & Development, Conservation Services, Port Elizabeth, South Africa*
[e] *Centre for African Conservation Ecology, Zoology Department, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa*
[f] *School of Biological Sciences, Monash University, Victoria, Australia*

ABSTRACT: Air temperatures have increased globally over the past decades, while rainfall changes have been more variable, but are taking place. In South Africa, substantial climate-related impacts are predicted, and protected area management agencies will need to respond actively to impacts. It is critical for management agencies to understand the way in which climate is changing locally to predict impacts and respond appropriately. Here, for the first time, we quantify observable changes in temperature and rainfall in South African national parks over the past five to ten decades. Our results show significant increases in temperatures in most parks, with increases being most rapid in the arid regions of the country. Increases in the frequency of extreme high temperature events were also most pronounced in these regions. These results are consistent with other climate studies conducted in these areas. Similar increases were identified for both minimum and maximum temperatures, though absolute minimum temperatures increased at greater rates than absolute maxima. Overall, rainfall trends were less obvious, but a decrease in rainfall was observed for the southern Cape (in three parks), and an increase was detected in one park. The observed temperature changes over the last 20–50 years have in several instances already reached those predicted for near future scenarios (2035), indicating that change scenarios are conservative. These results provide individual parks with evidence-based direction for managing impacts under current and projected changes in local climate. They also provide the management agency with sub-regional information to tailor policy and impact monitoring. Importantly, our results highlight the critical role that individual weather stations play in informing local land management and the concerns for parks that have no local information on changes in climate.

KEY WORDS climate change; protected area management; rainfall variation; South Africa; temperature increase; weather station data

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1. Introduction

A significant body of work has demonstrated increases globally in air and water temperatures over the past decades (Kaushal *et al.*, 2010; Hartmann *et al.,* 2013). Numerous studies have demonstrated similar trends in South Africa (Hughes and Balling, 1996; Hulme *et al.*, 2001; Kruger and Shongwe, 2004; New *et al.*, 2006; Hoffman *et al.*, 2011; Kruger and Sekele, 2013; MacKellar *et al.*, 2014). Much evidence also exists for an increase in the variability of rainfall, as well as the number and size of extreme wet and dry spells in several parts of the southern African region (Mason *et al.*, 1999; Richard *et al.*, 2001; Fauchereau *et al.*, 2003; Rouault and Richard, 2003; Groisman *et al.*, 2005; New *et al.*, 2006). Observed patterns of change in total annual precipitation are however more variable across the region, with few significant trends (Mason *et al.*, 1999; Kruger, 2006; MacKellar *et al.*, 2014). Although downscaled models are becoming increasingly sophisticated, the uncertainty in rainfall predictions at local scales remains high (Ratnam *et al.*, 2013; Sylla *et al.*, 2013; Zhang *et al.*, 2013), and mismatches between observed and predicted changes occur (MacKellar *et al.*, 2014).

Despite future uncertainties about the size of and spatial variation in change, it is clear that the recorded and predicted changes in temperature and rainfall will impact species performance and survival (Parmesan, 2006; Heard *et al.*, 2012). Climate change impacts will not be limited to the species level, with impacts on interactions between species, and on ecosystem functioning also expected, especially where phenological mismatches between organisms result (Parmesan, 2007; Donnelly *et al.*, 2011). The effects

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*Correspondence to: N. J. van Wilgen, Centre for Invasion Biology, Cape Research Centre, South African National Parks, PO Box 216, Steenberg 7947, South Africa. E-mail: nicola.vanwilgen@sanparks.org; nvanwilgen@gmail.com of changing climates will be realized in concert with multiple other drivers of global environmental change, such as invasive alien species, resource exploitation and habitat change (Chown, 2010; Diez *et al.*, 2012; Spear *et al.*, 2013).

It is now widely appreciated that a key conservation strategy, the designation and maintenance of protected areas (Coetzee *et al.*, 2014), will not be sufficient to curb the impact of climate change on biodiversity and ecosystem function (Hannah *et al.*, 2002; Araújo et al., 2004; Willis *et al.*, 2009; Sieck *et al.*, 2011). Furthermore, traditional conservation strategies that focus on increasing connectivity between patches of protected land, although invaluable in terms of habitat protection (Kharouba and Kerr, 2010), are unlikely to be sufficient to alleviate climate change impacts. In consequence, more strategic approaches are required (Gillson *et al.*, 2013), with profound implications for the management of static protected areas (Rutherford *et al.*, 1999; Kharouba and Kerr, 2010). It is critical, therefore, that the local context of change is identified, recognised and understood within individual protected areas and across local protected area networks as early as possible (Welch, 2005) to allow for inference of impacts. Doing so can inform the management actions to be taken, and enable approaches to be adapted where necessary and possible, to deal with the local consequences of climate change (Dawson *et al.*, 2011; see also Gillson *et al.*, 2013 for several contingent management approaches which might be used depending on the local situation).

In South Africa, substantial climate-change-associated range shifts are predicted for species from multiple taxonomic groups (Erasmus *et al.*, 2002; Agenbag *et al.*, 2008; Huntley and Barnard, 2012; Kuhlmann *et al.*, 2012). This is particularly concerning given South Africa's impressive biodiversity [c.a. 23 000 plants, 3700 vertebrates, and 70 000 invertebrates; Huntley, 1989; Department of Environmental Affairs and Tourism (DEAT), 2005]. In addition, two of the world's 25 biodiversity 'hotspots' (areas of high biodiversity and endemism that are also highly threatened) are found within South Africa (Myers *et al.*, 2000) and both fall within the biomes expected to be worst affected locally by future climate change (Petersen and Holness, 2011). Appropriate land management is therefore not only a national priority, but also one of international importance.

Despite significant national progress towards ecosystem-based conservation planning (Balmford, 2003; Petersen and Holness, 2011), specific information on climate change impacts on protected areas remains limited. Where climate change will have the greatest impacts and which parks are most and least likely to be affected remains unclear. Information at a park scale is valuable because climate will not change uniformly across large areas (see Collier *et al.*, 2008; Chown, 2010). Furthermore, distinguishing local trends is especially important for national organizations to ensure that locally relevant management actions are implemented. It will also be increasingly important for protected areas to be able to assess seemingly extreme events in terms of the historical record to distinguish natural variation from novel climatic events to inform management actions (Hoffman *et al.*, 2009; Hansen *et al.*, 2012). Locally relevant case studies will also improve opportunities for garnering support for conservation from various sectors of society including national government and donor agencies (Turpie, 2003; Braschler *et al.*, 2010).

Here we quantify observable changes in climate at the scale of individual parks, and across national parks in South Africa over the past century. Although similar work has been done across South Africa as a whole (Kruger and Sekele, 2013; MacKellar *et al.*, 2014), no studies have focussed on similarities and differences in changes within and across national parks specifically with a view to informing park-level management. The work we present here will also provide a baseline for future studies of climate change impact, as well as provide evidence for policy development in national parks. To be biologically informative, it is important to consider not only mean temperature and rainfall changes, but also local changes in extremes and timing of important events (Jentsch and Beierkuhnlein, 2008; le Roux and McGeoch, 2008). We assessed (1) whether there have been significant changes in temperature or rainfall at a park scale, (2) the occurrence and temporal variation in temperature and rainfall extremes, (3) shifts in the seasonality of rainfall, and (4) the variation in these changes between parks and regions. We expected that temperature increases would be detected in most national parks, with differences in the rates of increase between minimum and maximum temperatures (Karl *et al.*, 1993; Kruger *et al.*, 2002). We also expected warm temperature extremes, as well as heavy rainfall events, to have increased (Kruger, 2006; New *et al.*, 2006; Kruger and Sekele, 2013). Climate is not expected to change uniformly across South Africa (Hewitson and Crane, 2006) and we expected that rainfall patterns and shifts in seasonality in each of the major rainfall regions of the country would differ.

2. Methods

2.1. Study area and data

The South African National Parks (SANParks) network comprises 19 terrestrial national parks situated across South Africa, that range in size from about 35 to 20 000 km^2 and total about 40 000 km^2 (Figure A1). The vegetation of the country comprises nine biomes (Mucina and Rutherford, 2006), eight of which are represented in the national park network. These biomes include Fynbos (four parks), Savanna (four parks), Succulent Karoo (three parks), Nama Karoo (three parks), Thicket (two parks), Grassland and Forest (one park each, although elements of both these biomes occur in patches in several other parks), as well as Desert which makes up part of one park (Mucina and Rutherford, 2006). Only the Indian Ocean

Coastal Belt is not represented in any parks managed by SANParks.

Rainfall and temperature data were sourced from the South African Weather Service (SAWS) for all 19 parks. In some instances data were sourced from suitable stations adjacent to parks if no suitable stations were present within the park. Data from some of these weather stations have been used in other publications investigating regional climate patterns, e.g. Cape Agulhas, Skukuza and Musina (Kruger and Sekele, 2013), Pofadder, Kimberley and Twee Rivieren (Cunningham *et al.*, 2013a; Kruger and Sekele, 2013) and Calvinia and Henkries (Cunningham *et al.*, 2013a), although none of these studies have focussed on the local changes and the implications for protected areas. Only stations with ≤1% missing data for rainfall or 10% for temperature, and spanning >30 years for rainfall or >20 years for temperature were included in the analyses (see extended methods, Appendix S1 in Supporting Information). The rainfall data from Agulhas could not be used due to irregularities and therefore data from a nearby farm (see Acknowledgements section) were used as a proxy. A list of the localities, data availability and quality (in terms of missing data) for weather stations used is provided in Table A1, and the park and station locations are shown in Figure A1. In places where a park formed part of a broader transfrontier national park (e.g. Kgalagadi Transfrontier Park or |Ai-|Ais/Richtersveld Transfrontier Park), we only obtained data from the South African component and therefore we refer throughout the manuscript only to the South African portion of these parks (e.g. Kalahari Gemsbok or Richtersveld). For brevity, we omit the ‘National Park’ suffix.

2.2. Data analysis

To quantify region-specific trends, parks were grouped into four major climate clusters (Figure 1) using correspondence analysis of the monthly rainfall time series across the parks (with >80 years of data) in the ‘ade4’ package (Dray and Dufour, 2007) in R (R Development Core Team, 2011; Appendix S1). The clusters differentiated four regions: a winter rainfall region, two summer rainfall regions – one arid, one subtropical, and an aseasonal region that receives rainfall at any time of the year (Figure S1 in Appendix S1). Annual trends were analysed using linear regression across years (le Roux and McGeoch, 2008), as well as locally weighted polynomial regression (LOWESS), which reduces the influence of extreme events on the trend and allows the gradient of the trend line to vary over time (Cleveland, 1979,1981). Trends were assessed for annual mean maximum and annual absolute maximum temperature, annual mean minimum and annual absolute minimum temperature, daily temperature range (DTR), total annual rainfall, rainfall event size, rain days, percentage of dry days, and the longest span of consecutive dry days (CDDs). CDD was calculated as the longer of (1) the longest spell without rain in the current calendar year and (2) the overlapping period from last rain in the previous year to first rain in the current year. Trends in rainfall variability were assessed using the slope of the coefficient of variation (% CV) of 20-year moving averages of annual rainfall (New *et al.*, 2000). The period of 20 years was chosen to include the full identified rainfall cycle of 18–20 years (Tyson *et al.*, 1975). Shorter cycles were tested but had little effect on the outcome of the analysis. All analyses were conducted in the R statistical freeware (R Development Core Team, 2011). Exploratory analyses were also conducted using the source code RClimDex (Zhang and Yang, 2004).

We used two methods to assess changes in temperature extremes. First, we identified months considered to be exceptionally warm or cool compared to the climate norms for a particular park, i.e. those months in the top and bottom 2.5% of normalized (relative to the same month in other years) average monthly minimum and maximum temperatures. We also assessed the occurrence of temperatures above 35 °C and below 0 °C in parks where these thresholds were relevant ($n = 10$ for parks with 20 years or more of data and daily temperatures above 35 °C, and $n = 12$ parks where temperatures are known to drop below zero each year. However, for seven of these parks, the average number of below-zero days was less than three, and changes in below zero days were therefore only evaluated for the five parks where temperatures regularly dropped below 0 °C in winter). In addition, we looked for changes in rainfall seasonality, extreme wet and dry months, and uncharacteristic rainfall events per month, but no significant trends were apparent (see Appendix S1). Analysis of monthly data is presented in Appendix S1.

3. Results

3.1. Trends in temperature

There were significant annual increases in at least one of four temperature variables (mean maximum, mean minimum, absolute maximum or absolute minimum temperatures) in nine of the 13 parks with sufficient data. Associated positive trends in DTR were recorded in two of these parks, as well as in two additional parks where no absolute temperature changes took place (Figure 1; Figure S2 in Appendix S1). There were no strong regional patterns in temperature increases, but rates of increase were highest in the arid north-western parks (Kalahari Gemsbok, Augrabies Falls and Richtersveld, Table 1). Six of the nineteen national parks had insufficient data to analyse annual trends in temperature (Figure 1 and Table 1; Figure S2 in Appendix S1).

The average rate of change in mean maximum temperature was 0.024 °C year^{-1} ± 0.003SE in parks with 50 years of data ($n = 6$, Table 1), the highest rate over 50 years being recorded in Kalahari Gemsbok (0.039 °C ± 0.007SE). This equates to a change in average annual maximum temperature of 1.95 °C since 1960. Mean maximum temperature appeared to have increased even faster for Richtersveld (0.06 °C year^{-1} ± 0.02SE, over 20 years, Table 1). However, when comparing rates over the same period of time (1990–2009), temperature increases were still faster in

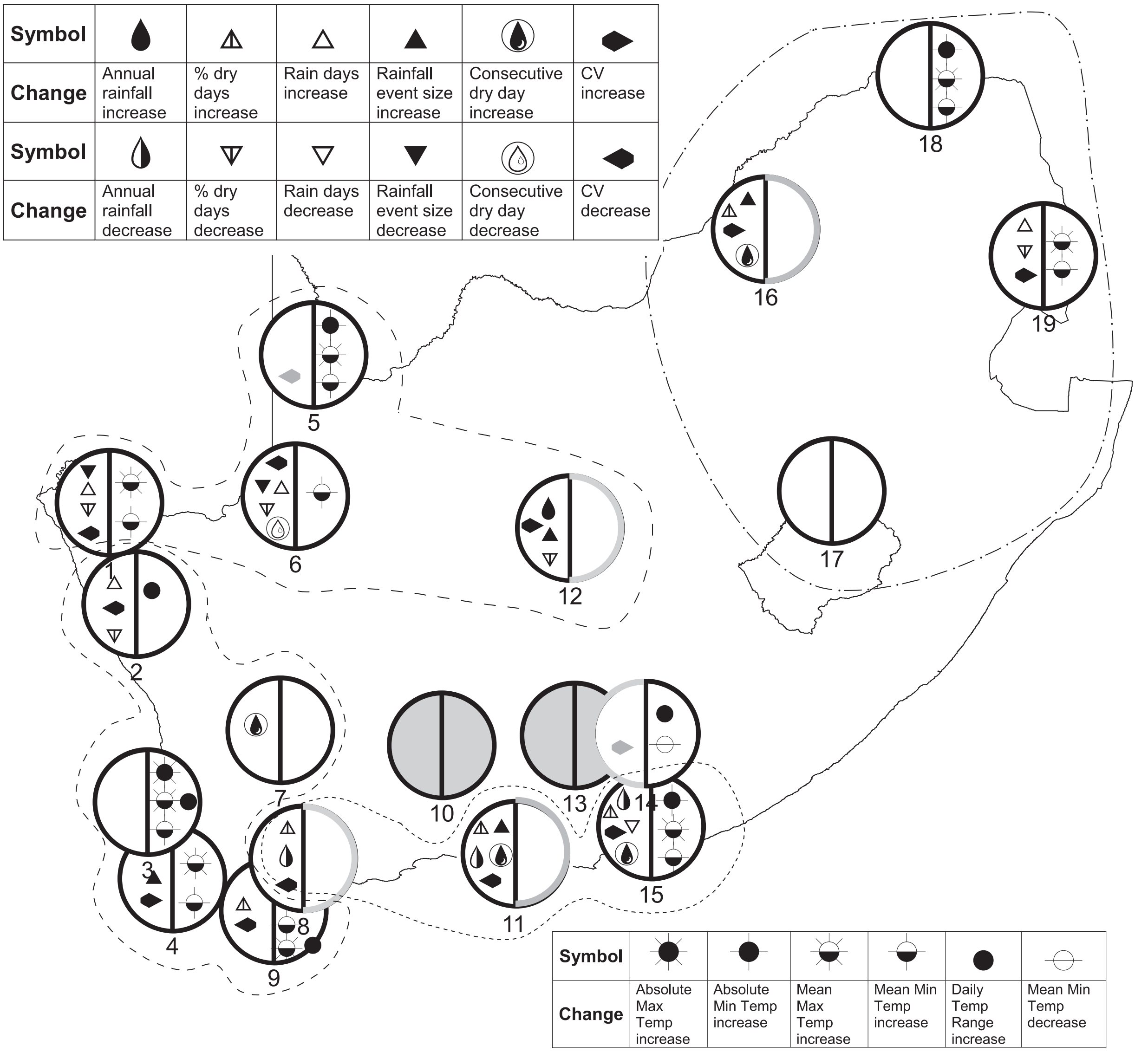

Figure 1. Spatial distribution of significant annual trends in rainfall- (left of circles) and temperature- (right of circles) related variables for available data up until 2009. Park names are as follows: 1, Richtersveld; 2, Namaqua; 3, West Coast; 4, Table Mountain; 5, Kalahari Gemsbok; 6, Augrabies Falls; 7, Tankwa Karoo; 8, Bontebok; 9, Agulhas; 10, Karoo; 11, Garden Route; 12, Mokala; 13, Camdeboo; 14, Mountain Zebra; 15, Addo Elephant; 16, Marakele; 17, Golden Gate Highlands; 18, Mapungubwe; 19, Kruger. Grey-shaded parks had less than 30 years of rainfall or 20 years of temperature data available. Parks with no associated symbols demonstrated no significant annual trends over the available time period. The four major rainfall regions identified using correspondence analysis (see Appendix S1) are depicted by dotted lines. *Note:* this plot for temperature only is shown in Figure S2 of Appendix S1, and for rainfall only in Figure S3 of Appendix S1.

Kalahari Gemsbok and Mapungubwe. Mountain Zebra was the only park that experienced a significant annual decrease in any temperature variable (mean minimum temperature declined by 0.046 °C $\text{year}^{-1} \pm 0.016$SE, over 25 years). Although missing data could have contributed to the trend because mean minima were missing for 8 of the 25 years, including 4 years towards the end of the series, this finding for the region is supported by MacKellar *et al.* (2014).

There was no difference in the rate of mean maximum temperature increase (mean = 0.024 °C $\text{year}^{-1} \pm 0.003$SE) and mean minimum temperature increase (mean = 0.021 °C/year ± 0.002SE) in parks with 50 years of data ($n = 6$, $t = 0.99$, $p = 0.36$). Annual absolute minima however increased (became warmer) at a faster rate (mean = 0.032 °C $\text{year}^{-1} \pm 0.007$SE) than annual absolute maxima (0.015 °C $\text{year}^{-1} \pm 0.003$SE) across the six parks with 50 years of data ($n = 6$, $t = -2.3$, $p = 0.05$; Table 1). Only three parks had significant changes in annual absolute minima (Addo Elephant, Kalahari Gemsbok and Mapungubwe) and only West Coast had a significant change in annual maximum temperature. The rate of change in absolute minimum temperature in Mapungubwe was particularly high (0.061 °C $\text{year}^{-1} \pm 0.016$SE over 50 years, Table 1).

For the six parks with 50 years of temperature data, LOWESS trends (especially in mean annual maximum temperatures) showed clear inflection points where temperatures began to increase or began to increase

Table 1. Annual rates of change of measured variables in parks. Parks have been grouped in four major regions determined by correspondence analyses (see Appendix S1). Statistics are provided for the station with the longest data series in each park (column 2 provides the starting year for rainfall and temperature data) and bold values are statistically significant ($p < 0.05$).

Park	Data series start year (rainfall, temperature)[a]	Max temp Δ°C^{-y}	Min temp Δ°C^{-y}	Daily temp range Δ°C^{-y}	Mean max temp Δ°C^{-y}	Mean min temp Δ°C^{-y}	Days in year >35 °C	Days in year <0 °C	Annual rainfall Δmm^{-y}	Rainfall event size	Coeff of var of rain %Δ	Rain days Δdays^{-y}	Max rain event Δmm^{-y}	% dry days Δdays^{-y}	Consecutive dry days Δdays^{-y}
Aseaonal															
Addo Elephant	1919, 1960	0.004	**0.027**	−0.006	**0.016**	**0.023**	**0.142**	–	**−2.997**	0.015	**0.08**	**−0.373**	−0.062	**0.102**	**0.155**
Bontebok	1900, no data	–	–	–	–	–	–	–	**−1.943**	−0.015	**−0.14**	−0.092	−0.309	**0.053**	0.028
Garden Route	1900, no data	–	–	–	–	–	–	–	**−1.438**	**0.021**	**−0.05**	**−0.238**	−0.205	**0.078**	**0.057**
Winter rainfall															
Agulhas	1909, 1960	0.014	0.030	**0.009**	**0.024**	**0.015**	–	–	0.239	0.007	**−0.02**	−0.040	−0.007	**0.018**	0.032
Namaqua	1953, 1990	0.065	0.032	**0.094**	0.061	−0.034	0.509	–	1.154	−0.004	**−0.39**	**0.161**	0.072	**−0.055**	−0.537
Table Mountain	1900, 1960	0.028	0.018	0.005	**0.025**	**0.021**	–	–	0.520	**0.006**	**0.07**	0.013	0.060	0.002	−0.032
Tankwa Karoo	1933, 1986	−0.022	0.037	0.026	0.031	0.005	0.267	−0.091	−0.105	0.015	0.10[b]	−0.015	0.011	0.005	**0.567**
West Coast	1973, 1973	**0.082**	0.020	**0.015**	**0.028**	**0.013**	**0.172**	–	0.325	0.009	0.11[b]	0.059	−0.042	0.091	0.637
Summer rainfall															
Camdeboo	1993, no data	–	–	–	–	–	–	–	−2.220	−0.165	–	0.095	0.855	−0.151	0.618
Golden Gate Highlands	1977, 1980	0.017	−0.007	0.018	0.016	−0.002	–	0.217	3.505	0.015	−0.03[b]	0.264	0.071	−0.136	−0.108
Karoo[c]	1993, 1993	−0.045	0.131	0.032	0.056	0.023	–	–	−2.117	−0.003	–	−0.245	0.184	0.013	−0.396
Kruger	1920, 1960	0.009	0.019	0.001	**0.017**	**0.017**	0.218	–	0.696	−0.046	**0.31**	**0.166**	**−0.266**	**−0.030**	−0.053
Mapungubwe	1927, 1960	0.020	**0.061**	0.002	**0.025**	**0.024**	**0.439**	–	−0.034	−0.004	0.06	−0.169	−0.010	−0.010	−0.024
Marakele	1937, no data	–	–	–	–	–	–	–	−1.358	**0.074**	**0.18**	−1.074	0.156	**0.045**	**0.851**
Mountain Zebra	1985, 1985	0.013	−0.055	**0.068**	0.024	**−0.046**	0.452	0.164	2.420	0.007	**0.39**[b]	0.280	0.218	−0.077	0.755
Arid summer rainfall															
Augrabies Falls	1945, 1978	0.004	−0.022	−0.020	0.019	**0.036**	0.128	–	0.323	**−0.118**	**−0.30**	**0.223**	0.010	**−0.052**	**−1.545**
Kalahari Gemsbok	1960, 1960	0.015	**0.039**	0.015	**0.039**	**0.024**	**0.727**	**−0.263**	−0.511	−0.011	**−0.70**[b]	−0.033	0.010	0.002	−0.174
Mokala[c]	1914, 1991	0.005	0.126	−0.015	0.038	0.053	–	**−1.233**	**1.402**	**0.027**	**0.23**	0.044	0.159	**−0.021**	−0.035
Richtersveld	1952, 1990	−0.004	−0.010	0.004	**0.060**	**0.055**	**1.293**	–	0.109	**−0.061**	**−0.007**	**0.084**	−0.006	**−0.023**	−1.056

[a] Year of first available analysed data for rainfall and temperature, respectively.

[b] Trend unreliable due to few data points or a high percentage of missing data.

[c] Less than 20 years of temperature data.

more rapidly (Figure 2). The timing of this change was fairly similar across parks and regions, occurring in the late 1980s to early 1990s for mean maximum temperature, while mean minimum temperatures appear to have started increasing earlier, in the late 1970s to early 1980s, especially in the southern parks (Figure 2(d) and (e)).

3.1.1. Changes in extremes

There has been a marked increase, especially since the mid-late 1990s, in the number of days above 35 °C in most parks where this threshold is relevant (Figure 3 and Table 1). Significant increases in days above 35 °C were recorded in five parks (Addo Elephant, Kalahari Gemsbok, Mapungubwe, Richtersveld and West Coast) with overall change being as extreme as an average increase of 36 additional extreme days in Kalahari Gemsbok now compared to 1960 (Figure 3). For most parks, there was also a clear trend for the most extreme minimum and maximum monthly temperatures to be recorded in the latter half of each data series (Appendix S1). Data for Table Mountain for example, (Figure S7 in Appendix S1) show that of the lower 2.5 percentiles of minimum and maximum monthly temperatures, only 17 and 10%, respectively, occurred during the second half of the time-series (i.e. since 1985). In contrast, 97% of extreme high maximum temperatures (top 2.5 percentile) and 85% of the extreme high minimum temperatures (top 2.5 percentile) occurred in this latter period.

Temperatures below zero degrees are becoming significantly less common in the Kalahari Gemsbok (-0.26 days $\text{year}^{-1} \pm 0.13\text{SE}$) and Mokala ($-1.23$ days $\text{year}^{-1} \pm 0.41\text{SE}$), while no changes were detected in the other three parks where data were available and temperatures annually drop below this threshold (Mountain Zebra, Tankwa Karoo and Golden Gate Highlands; Table 1).

3.2. Trends in rainfall

Rainfall patterns were generally less obvious than those detected for temperature and were clearly influenced by extreme events and also the length of the available time series (e.g. the LOWESS trend for Table Mountain (Figure 4(a)), reflects a decrease in rainfall over the last 50 years of data, whereas rainfall has not changed significantly over the last 110 years). Only four significant trends were detected in annual rainfall. A significant increase in rainfall was recorded only for Mokala National Park (Figures 1 and 4(d), and Table 1; Figure S3 in Appendix S1). Significant decreases in total annual rainfall were recorded in three parks (Addo Elephant, Bontebok and Garden Route), all of which occur in the aseasonal rainfall belt to the south of the country (Figures 1 and 4(b)). These decreases in total rainfall (recorded over a minimum of 90 years) were also associated with an increase in the percentage of dry days and the number of CDDs in a year, as well as a decrease in the number of rain days in Addo Elephant and an increase in rainfall event size in Garden Route (Figure 1; see also MacKellar *et al.*, 2014). The decrease in Addo Elephant was most dramatic with an approximately 29% reduction in annual rainfall at the Alexandria-bos station over a 91-year period. Only two parks (Camdeboo and Karoo) had insufficient rainfall data on which to conduct analyses (Figure 1 and Table 1; Figure S3 in Appendix S1).

There were significant changes in the number of CDDs experienced per year in several parks, as well as the number of days with rain and intensity of rainfall. However, the direction and size of these changes varied between regions (Table 1). There was an increase in the number of days with rain at three geographically proximate parks in the north west of the country (Namaqua, Richtersveld and Augrabies Falls). This was associated with a decrease in the number of CDDs and a decrease in the amount of rain per rainfall event, but no overall change in the average annual rainfall. Annual rainfall variability (calculated as a 20-year moving coefficient of variation) changed significantly in 13 parks. However, for some parks it is likely that short time series and missing data undermine the reliability of these trends (e.g. Mountain Zebra and Kalahari Gemsbok). Despite this, it appears that there are two geographically distinct patterns in rainfall variability for parks that have longer time series (Figure 5 and Table 1). Rainfall in parks in the western half of South Africa (from as far north as Kalahari Gemsbok and Richtersveld to the south and east at Agulhas and Garden Route) has become less variable. Rainfall in parks in the eastern part of the country is becoming more variable, most notably in Kruger and Mapungubwe. The only exception to this was Table Mountain where rainfall variability has increased over the last century. However, variability in this park appears to have been decreasing in the last 50 years, mirroring the trend identified in the other western parks (Figure 5).

4. Discussion

Lack of information on which to base management decisions in protected areas has been identified as a problem globally (Cook *et al.*, 2010). This is often particularly relevant in the context of local climate change information, especially because of the common mismatch between the international scale of the problem (and therefore studies regarding its general impacts and management), the predictions of statistically downscaled models, and local observations at the scale at which specific protected area management decisions need to be made (Wilbanks and Kates, 1999; Cash and Moser, 2000; Welch, 2005). Here we have shown the importance of ongoing collection of weather data to capture local variation in climate (Booth *et al.*, 2012) and to provide local change information valuable for management. Collecting weather data in parks that currently have no such information is critical to guide future management decisions. Capture of metadata describing observations of impact and verification of extreme events is also

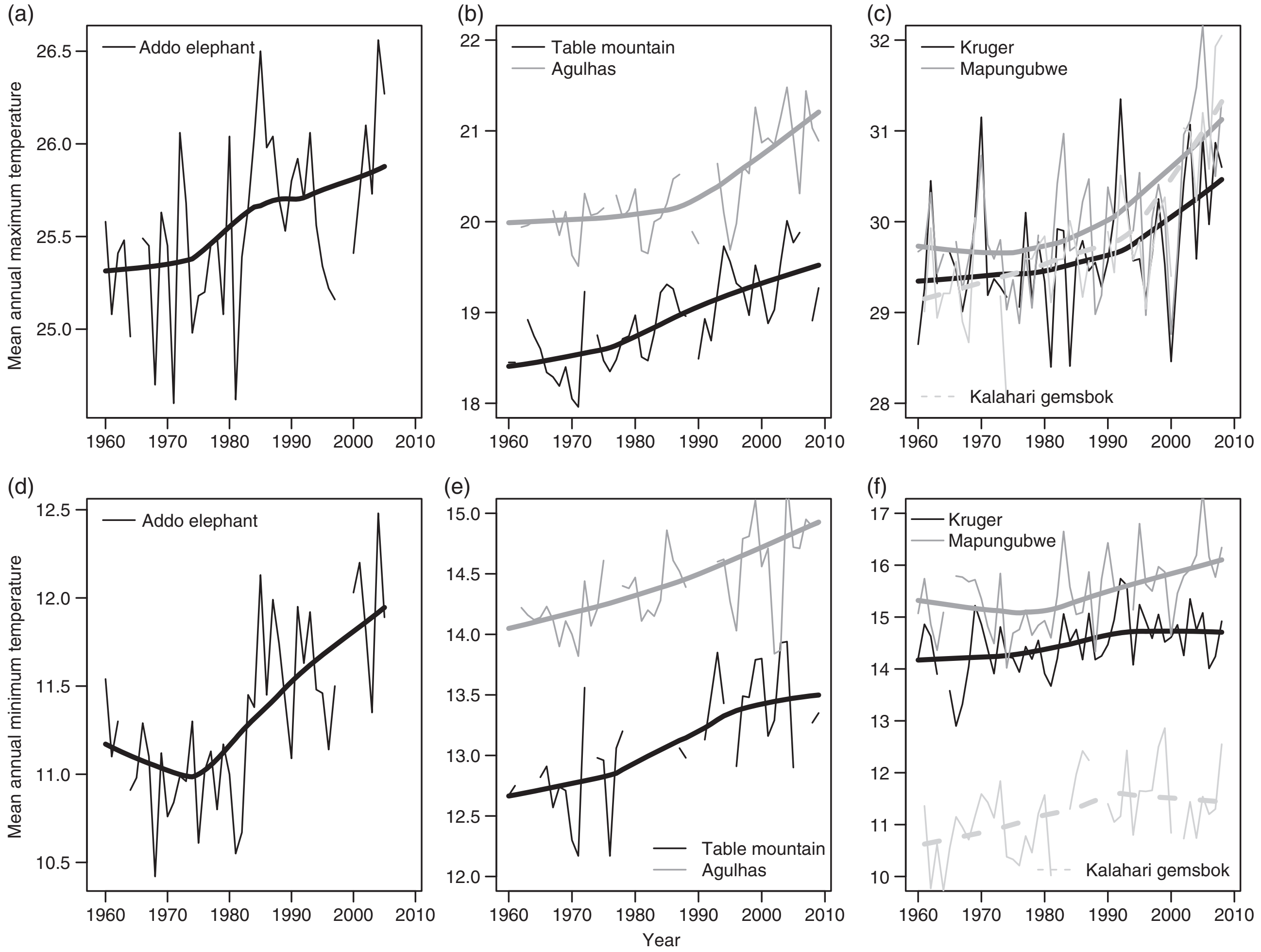

Figure 2. LOWESS trends in annual (a–c) mean maximum temperature and (d–f) mean minimum temperature for all parks with 50 years of data (see Figure S4 in Appendix S1, for results from all parks with >20 years of data). Parks included one aseasonal park (left column), two winter rainfall parks in the south-west of South Africa (middle column) and three summer rainfall parks, one in the north-west of South Africa and two in the north-east of the country (right column).

increasingly important and will assist greatly in future data analyses.

4.1. Temperature

Data were generally better for the coastal parks and the older parks in the north of the country, with very little data available for parks in the central and interior regions of South Africa. Because of the sparse data in some areas, as well as differences in the length of available data between parks, it was not possible to draw conclusions about temperature changes for the entire network of parks. There were however some broad patterns that largely reflect what has been found for South Africa generally (Hulme *et al.*, 2001; Kruger and Shongwe, 2004; New *et al.*, 2006, MacKellar *et al.*, 2014). We found an increase in mean minimum and maximum temperatures in nearly all parks with 30 or more years of data ($n = 9$). Exceptions included Augrabies Falls, where only mean minimum temperature increased and Golden Gate Highlands, where no significant changes were detected. Rates of temperature change varied across the country, but reflected an average change of over 1 °C for mean minimum (1.03 °C ± 0.08SE) and maximum temperatures (1.22 °C ± 0.17SE) since 1960 for the six parks with data spanning this time period.

These temperature changes are generally in keeping with global trends. For example, an inflection point in temperature anomalies is clear at the start of the 1980s globally (Hansen *et al.*, 2006) and for many of the parks (Figure 2). Extreme high temperature anomalies are now also becoming more common globally (Hansen *et al.*, 2012). The changes we detected also align with regional findings and predictions for the area. A compilation of the latest research results by South Africa's Department of Environmental Affairs (hereafter referred to as the DEA study; DEA, 2013b), predicts the north-east of the country (subtropical summer rainfall zone) to experience the highest warming by 2100, with increases up to 6 °C predicted using conformal-cubic atmospheric models (CCAM) under the A2 scenario (DEA, 2013b). This corresponds with increases in the most northerly park in SANParks, Mapungubwe, in which one of the highest rates of temperature increase over 50 years (0.025 °C year^{-1}) was observed. This rate of change equates to an increase of

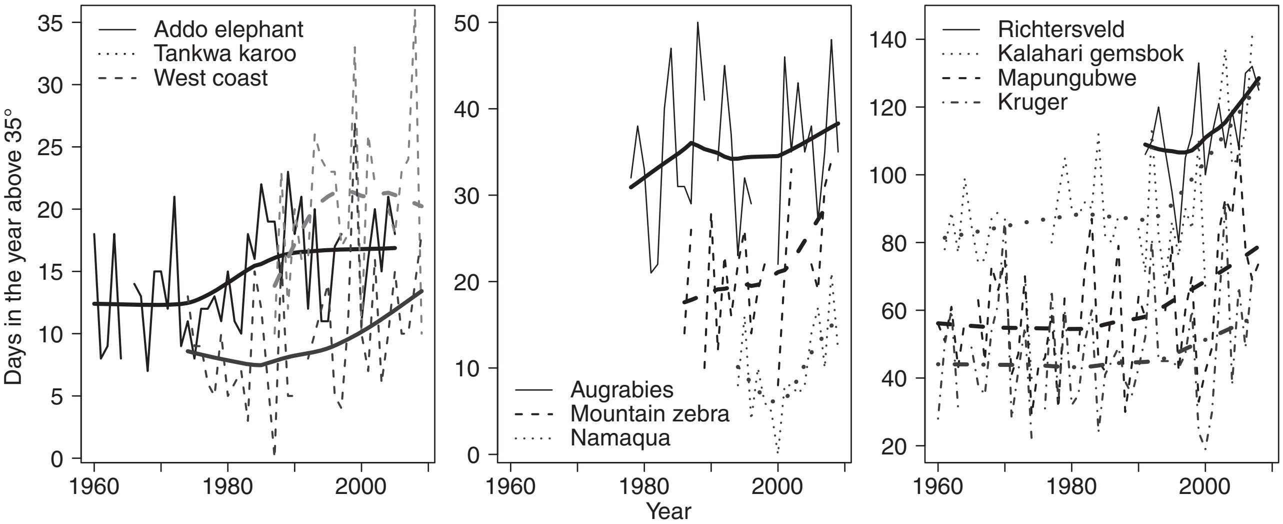

Figure 3. Change in the number of days in a year above 35 °C in parks where this threshold is relevant (*y*-axis scale differs regionally).

1.25 °C during roughly the same time used as a base period for the DEA study (1971–2005). For the northwest arid summer-rainfall region temperature increases could reach 5.5 °C by 2100, with models under less conservative scenarios (RCP8.5) predicting up to 7.5 °C, encompassing a range never before experienced in this semi-desert region (DEA, 2013b). This dramatic increase is already evidenced by a change of almost 2 °C in mean maximum temperature since 1960 at the Kalahari Gemsbok station and 1.2 °C since 1990 for Richtersveld (Table 1), suggesting that local temperature changes may be more closely aligned with the more extreme temperature models.

Temperature increases for the southwest and south-central regions have been predicted to be slightly lower (up to 4–5 °C by 2100; DEA, 2013b) than northern regions, although we detected changes at some of the southwestern stations that were as large as those at northern stations (e.g. changes in mean maximum temperature at Table Mountain and Agulhas stations). Overall, the changes already experienced in a number of the national parks already match or exceed the changes predicted in the near-future (2035) scenarios used in the DEA reports. This suggests that the scenarios used for government planning purposes may be too conservative and regular revision in the light of actual measured changes is advised.

Similar to other studies, we found that absolute minimum temperatures have increased faster than absolute maxima, evidenced by the fact that West Coast was the only national park where a significant increase in absolute annual maximum temperature was recorded. However, we found no difference in the rate of increase in mean maximum temperatures compared to mean minimum temperatures, although faster rates of increase in minimum temperatures are routinely reported globally (Karl *et al.*, 1993; Hartmann *et al.,* 2013). In contrast however, studies in Southern Africa and India have found faster rates of increase in mean maximum temperatures (Kumar *et al.*, 1994; New *et al.*, 2006; Kothawale *et al.*, 2012). The global perspective of greater increases in minimum temperature may result from a bias in reporting towards changes in North America and Europe (Felton *et al.*, 2009), although a difference in metrics used makes it difficult to compare results directly.

4.2. Rainfall

Trends in rainfall were more variable than trends in temperature and many of the data series were too short (given natural cycles, Tyson *et al.*, 1975; Figure S5 in Appendix S1) to expect the identification of meaningful trends. However, some interesting patterns appeared to be emerging in the data. For both the southwest and south-central regions of South Africa, drying over the next century is predicted by regional climate change models, but predictions are more severe for the southwest (Engelbrecht *et al.*, 2011; Malherbe *et al.*, 2013). Our findings of decreasing rainfall for three parks in the south and south west of the country are in line with this prediction, although we did not detect a drying trend in Table Mountain, the most south-westerly park.

We detected an increase in rainfall at one station (Mokala, central South Africa), albeit with more year-on-year variation, which is in line with predictions of an increase in rainfall for this region by the CCAM downscaled ocean atmosphere general circulation model (OAGCM) under the A2 scenario (Engelbrecht *et al.*, 2009). Annual rainfall showed a tendency to become more variable in stations to the east of the country and less variable in stations to the west (Figure 5). The former change is predicted as a result of oceanic-atmospheric anomalies in the southwest Indian Ocean (Fauchereau *et al.*, 2003; Engelbrecht *et al.*, 2009). The explanation of less variability in rainfall to the west of the country is less clear, although predictions for this region potentially include more summer (out of season) rainfall and less winter rainfall, which may lead to more consistent year on year totals, although drying is still predicted for the region

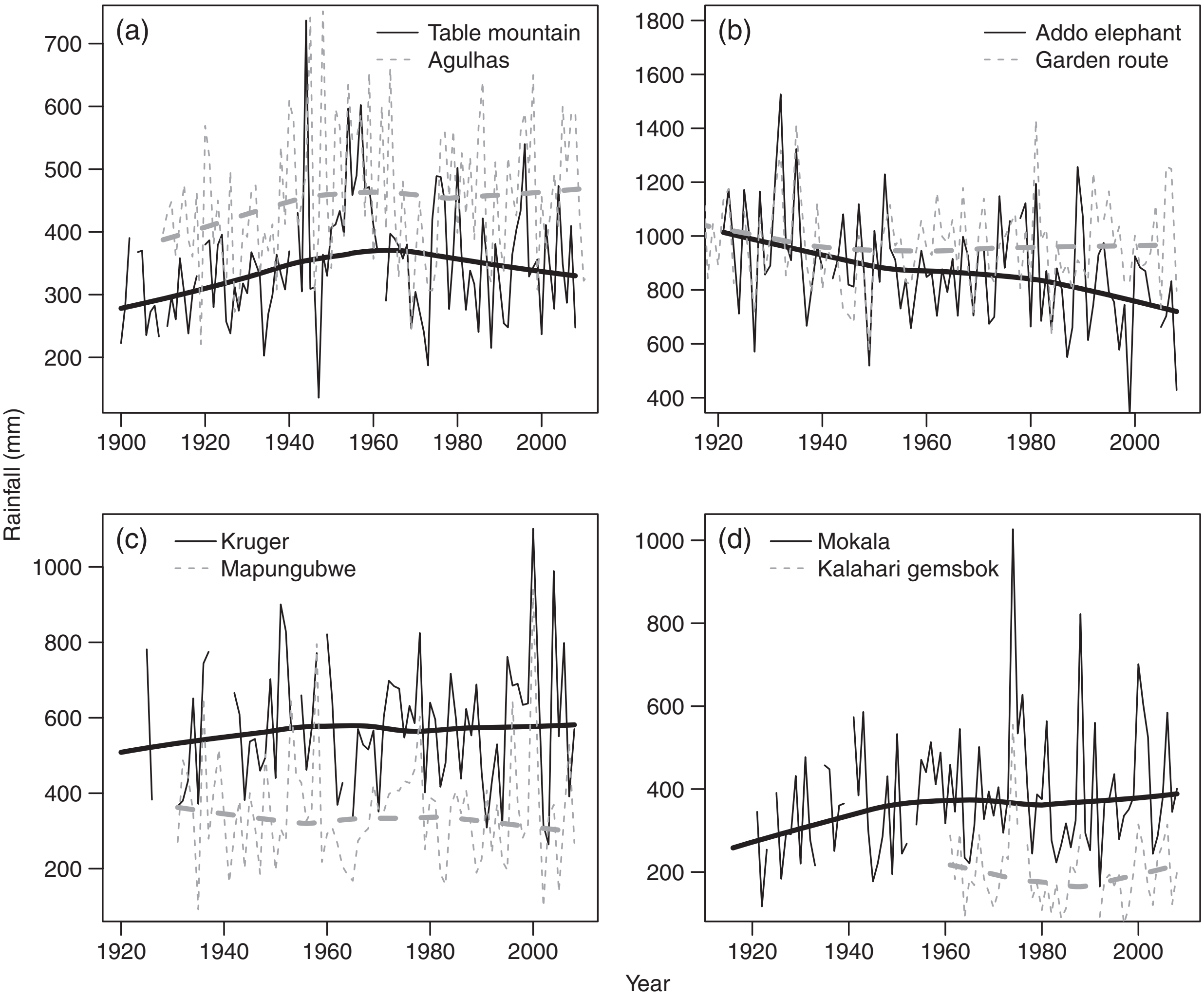

Figure 4. LOWESS trend in annual data for (a) two winter rainfall parks, (b) two aseasonal parks, (c) two summer rainfall parks and (d) two arid summer rainfall parks.

by the end of the century (DEA, 2013b; Engelbrecht *et al.*, 2009).

We also detected a trend towards increasing seasonality of rainfall for Kruger and Mapungubwe (see Appendix S1), with a longer dry period. Similar increases in seasonality were detected by Pettorelli et al. (2012) in Kruger and Kalahari Gemsbok using a satellite based index of annual seasonality. These changes were indicative of a decrease in net annual primary productivity which could have significant biodiversity impacts.

4.3. Potential biological and management implications

Much of the research on the biological impacts of climate change in South Africa has made use of bioclimatic envelope modelling to predict changes in the distribution of a wide variety of taxa (Erasmus *et al.*, 2002; Huntley and Barnard, 2012; Garcia *et al.*, 2014). There have however been very few experimental case studies to predict impacts on particular species or species groups (but see work by Cabral *et al.*, 2013; Cunningham *et al.*, 2013a; Foden *et al.*, 2007). In addition, many predictions have been made using climate models that have subsequently been updated and refined and their forecast impacts may therefore no longer be current. Interpreting the biological implications of the observed changes is therefore not straightforward, but in the next section we examine likely local implications of the changes we have detected given predictions that have been made.

4.3.1. *A warmer climate*

Several studies have considered the implications of future climate scenarios for particular southern African taxonomic groups, with emphasis on the biodiverse cape floristic and succulent karoo regions, savanna areas where large mammals are abundant and Important Bird Areas. The expected climatic changes under these future scenarios have not always been locally clear, although warming is a constant. For the majority of species some form of range change has been forecast, with particularly negative projections for localized, rare and endemic species, including, e.g. the Fynbos Proteaceae (Midgley *et al.*, 2002; Cabral *et al.*, 2013), a 41% reduction in endemic floral richness (Broennimann *et al.*, 2006), range

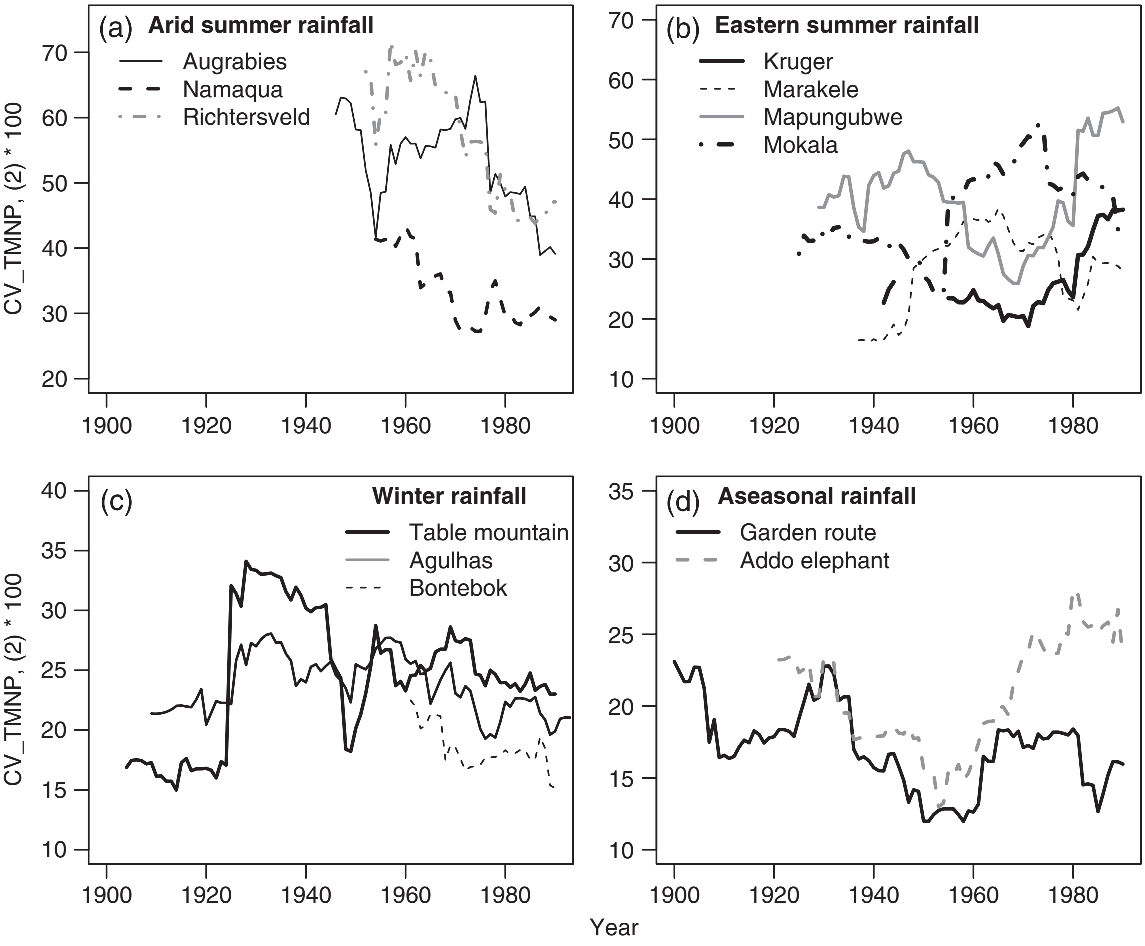

Figure 5. 20-year overlapping coefficient of variation of annual rainfall for parks in the (a) northwest, (b) northeast, (c) southwest and (d) south-central parts of South Africa.

reductions in several endemic chameleons (Houniet *et al.*, 2009), and frogs, especially those with specialized habitats (Botts *et al.*, 2013), bird species richness reductions of up to 40%, with dramatic species turnover in protected areas and losses in important bird areas (Coetzee *et al.*, 2009; Hockey *et al.*, 2011; Hole *et al.*, 2011; Huntley and Barnard, 2012) and range contractions in commercially important native species (Lötter and le Maitre, 2014). Heat waves in South Africa (with temperatures above 33–35 °C) have also been shown to likely induce fitness costs in birds, such as negatively impacting nestling growth and survival (Cunningham *et al.*, 2013a, 2013b).

The size of temperature increases identified in this study across national parks are often already more extreme than those included in future scenarios in the above studies (typically 1–2.5 °C, over the next 20–40 years). We therefore expect that species and ecosystems within parks have already begun experiencing climate-change-related impacts. Impacts are likely to be particularly dramatic where rapid warming is taking place in the northern parts of the country, especially in the Kalahari Gemsbok, Richtersveld and Mapungubwe, as well as in the southern parks where there is no potential for poleward range expansion. Although much of the protected area in the south-western region comprises mountainous terrain, the area available for colonization by species decreases with elevation as mountain peaks taper and low-lying areas are often fragmented or poorly connected, limiting opportunities for range expansion, while high altitude specialists are squeezed out (Hannah *et al.*, 2005). An additional concern in the florally diverse southwest is potential phenological mismatches between plants and their pollinators. Mean full bloom dates for apple and pear trees have been shown to have shifted forward between 1.6 and 4.2 days per decade over the last 35 years in the southwestern Cape, with temperature likely the main driver (Grab and Craparo, 2011). Experimental studies examining particular guilds of plants and pollinators are required to assess the potential impact on native assemblages.

The increase in frequency of hot extremes is likely to be a significant influence on many populations given that upper thermal limits appear to be tightly constrained across a range of taxa (Araújo *et al.*, 2013). The interaction between these hot extremes and water availability will also be important. For example, Foden *et al.* (2007) detected a decrease in *Aloe dichtoma* individuals in sites with increased evapotranspiration. Again, species that have limited room for range expansion, such as those naturally occurring at high altitudes or southerly coastal areas, are likely most at risk. Reductions in cold extremes such as in the Kalahari Gemsbok and Mokala are also important and could possibly result in range expansion of species previously restricted by cold winter temperatures (e.g. alien species that currently occur in low numbers in these parks; Spear *et al.*, 2013). Spread of aliens in a warmer climate is however not easy to predict without considering the implications of the interactions between rainfall and CO_2 fertilization, which is predicted to result in vegetation state shifts within the region (Higgins and Scheiter, 2012).

4.3.2. *A drier climate*

We detected drying in the southern Cape region. A decrease in extent of the forest biome has been predicted due to drying in this region (DEA, 2013a). A high proportion of the forest biome that remains in this region is currently protected, but it is likely that proportion of forest in relation to other biomes will begin to decrease in this area if drying continues, which could have implications for tourism in the region. The drying could also have implications for the Fynbos biome in this area. West *et al.* (2012) show that shallow-rooted, ansiohydric species (especially Ericaceae) are particularly vulnerable to drought, while Proteaceae seeds are vulnerable to drought after radical emergence (Mustart *et al.*, 2012). This means that the timing of fire (which stimulates Fynbos seed release and germination) in relation to droughts will be a particularly important determinant of biodiversity maintenance in the region.

Although we did not detect any absolute change in annual rainfall in the savanna regions (northern parts of South Africa), there were several indications of changing rainfall pattern, with increase in variability and likely increase in extreme wet and dry events. An increase in drought events in the region may lead to a decrease in shrubs (Tews and Jeltsch, 2004), which may counteract increases predicted by and being realized through CO_2 fertilization (Bond and Midgley, 2012), but will never the less undoubtedly impact on ecosystem function. Sedentary grazing herbivores and selective feeders have been identified as particularly vulnerable to droughts (Duncan *et al.*, 2012), as well as reduced dry-season rainfall (Seydack *et al.*, 2012) through the impacts on available forage. The trend of increasing seasonality in the eastern savanna parks with shorter rain seasons (Appendix S1) is therefore potentially cause for concern.

The changing rainfall pattern in the arid summer-rainfall region seen at Augrabies Falls and Richtersveld, with more rain days and smaller rainfall events may result in less water availability for plants and animals due to less water penetration and faster evaporation, despite constant annual totals. Although fog (which we have not considered) may play an important role in water availability, especially in the more coastal areas, the dramatic temperature increases observed in the region still make it likely that aridification impacts will begin to be observed.

4.3.3. *A wetter climate*

Although rainfall pattern and event size is likely to change in many parts of the country, there are generally few areas in South Africa where increased seasonal rainfall is expected (DEA, 2013b). Mokala (central South Africa, in the arid savanna region) was the only park where an increase in rainfall was detected. This increase in rainfall could be accompanied by an increase in shrubs (Tews and Jeltsch, 2004), which could exacerbate any predicted bush encroachment due to CO_2 fertilization, which is predicted to have particularly marked effects in savanna systems (Bond and Midgley, 2012).

4.4. Recommendations

Although parks cannot themselves alleviate climate change, adaptation will be important. A relevant, park-scale evidence base for current climate change trends is critical for appropriate and effective policy and management (Gillson *et al.*, 2013), as demonstrated by some local trends out of step with broader regional predictions. For example, this study has detected local trends that are quicker than those used in national studies on which policies are based, indicating that current policies and/or adaptation strategies may be too conservative. Critically, local information also allows for placement of specific values on the extent and rate of change rather than just general direction of trends provided by regional projections, which often make it difficult to take proactive local management decisions. The consequences for particular parks that do not have trend data or adequate weather stations are problematic, because lack of awareness generally means lack of action and absence of evidence means potentially inappropriate responses (Cook *et al.*, 2010). The gaps in weather information identified here should urgently be prioritized for new stations, while ongoing maintenance of stations currently operational will be extremely important, as will better coordination across monitoring systems (other than climate) to enable identification of climate change impacts and mechanisms (Mawdsley *et al.*, 2009; McGeoch *et al.*, 2011). In addition, Welch (2005) emphasizes the importance of leading by example, with informed staff, appropriate public awareness and ‘own house in order’ in terms of meeting national and international compliance targets and agreements (e.g. the Kyoto Protocol).

The changes that have already taken place approximate the changes predicted in the next decades, providing strong evidence that directional shifts in climate have already occurred in parks over the last five decades. It is important to focus on projections, but it is perhaps more important to respond to evidence of changes that have already taken place and the conditions currently being experienced by individual parks and networks; informed by the sort of evidence we provide here. Focussing on the outcomes of this study, priorities for future research and monitoring include: (1) an assessment of the impacts of temperature increases in the Kalahari Gemsbok and Richtersveld as well as the impact that changing rainfall pattern may have in conjunction with this; (2) quantification of the impacts of drying on communities and climate change-sensitive species in the southern and coastal regions of the country; (3) experimental quantification of potential mismatches between Fynbos plants and pollinators as a result of increasing temperatures; (4) an assessment of disease-related risks under warmer conditions (e.g. Lyons *et al.*, 2013; Caminade *et al.*, 2014) with more frequent flood events (Appendix S1) in the lowveld and savanna regions; (5) impacts of changing climate on tourism (which impacts on revenue available for management), including not only human response to increased extreme hot days, but also impacts on infrastructure through more frequent flooding (which has for example caused significant damage to Kruger park tourist camps in multiple seasons in the past decade); and (6) finally, because climate change does not act alone and its impacts can be exacerbated by other change drivers, research and monitoring considering the combined impacts of climate change in concert with alien species (Spear *et al.*, 2013), harvesting of resources (van Wilgen *et al.*, 2013), disruption and pollution of freshwater systems (Nel *et al.*, 2007), land use change (Cabral *et al.*, 2013), and people's response to climate change, such as shifting agricultural activities (Estes *et al.*, 2014) are increasingly needed to inform landscape level conservation planning (Mawdsley *et al.*, 2009).

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APPENDIX

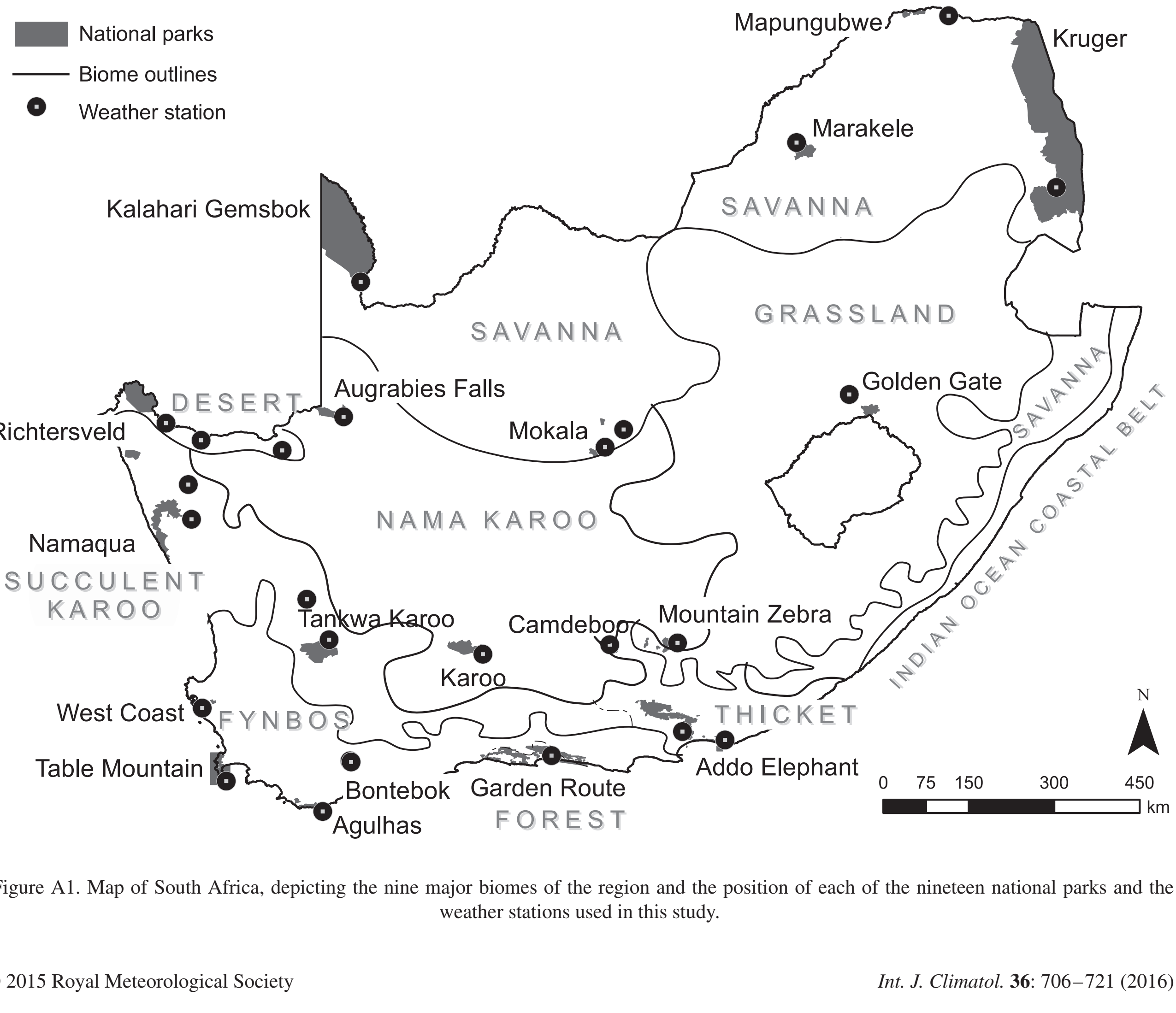

Figure A1. Map of South Africa, depicting the nine major biomes of the region and the position of each of the nineteen national parks and the weather stations used in this study.

Table A1. Weather station information and time-span of data available for rainfall and temperature data at each station. Datasets with a high percentage of missing data are shown in grey.

				Rainfall			Temperature		
Park	Station name	Station number	GPS co-ordinates	Period	Duration (years)	Missing data (%)	Period	Duration (years)	Missing data (%)
Addo Elephant	AGR	0035334 3	25°41′24″E 33°33′43″S	1959–2009	51	0.35	1960–2009	50	7.7
Addo Elephant	Alexandria-bos	0036642 8	26°22′4″E 33°41′48″S	1919–2009	91	0.46	–	NA	NA
Agulhas	Cape Agulhas	0003020 4	20°0′38″E 34°49′40″S	1900–2009	110	0.14	1960–2009	50	2.0
Agulhas	Albertyn Farm		20°2′E 34°24′S	1909–2009	101	0	–	NA	NA
Augrabies Falls	Augrabies	0281760 1	20°25′54″E 28°39′36″S	1945–2009	65	0.52	–	NA	NA
Augrabies Falls	Pofadder	0247668A4	19°22′56″E 29°7′1″S	–	NA	NA	1978–2009	32	1.2
Bontebok	Swellendam	0008782 0	20°26′ 59″E 34°1′44″S	1900–2009	110	0.15	–	NA	NA
Bontebok	Bontebokpark	0008813 X	20°28′8″E 34°2′49″S	1961–2009	49	0.38	–	NA	NA
Camdeboo	Graaf-Reinet	0096072 5	24°32′35″E 32°11′35″S	1993–2009	17	4.57	–	NA	NA
Garden Route	Bloukrans-bos	0031237 5	23°37′50″E 33°56′45″S	1900–2009	110	0.37	–	NA	NA
Golden Gate Highlands	Bethlehem	0331585 9	28°19′38″E 28°15′19″S	1977–2009	33	2.16	1980–2009	30	1.5
Karoo	Beaufort Wes	0092081 5	22°33′′51″E 32°20′18″S	1993–2009	17	0.99	1993–2009	17	1.2
Kalahari Gemsbok	Twee Rivieren	0461208 4	20°36′46″E 26°27′57″S	1960–2009	50	0.83	1960–2009	50	2.6
Kruger	Skukuza	0596179 3	31°35′30″E 24°59′9″S	1920–2009	90	0.21	1960–2009	50	0.8
Mapungubwe	Messina-Macuville	0809706 X	29°54′8″E 22°15′32″S	1927–2009	83	0.06	1960–2009	50	4.8
Marakele	Hoopdal-pol	0630886 5	27°29′57″E 24°16′19″S	1937–2009	73	0.19	–	NA	NA
Mokala	Eureka	0257845 5	24°28′33″E 29°5′5″S	1914–2009	96	0.36	–	NA	NA
Mokala	Kimberley Wo	0290468A9	24°46′16″E 28°47′40″S	1991–2009	19	0.54	1991–2009	19	1.1
Mountain Zebra	Cradock-Mun	0098190B6	25°36′48″E 32°10′6″S	1985–2009	25	0.71	1985–2009	25	7.8
Namaqua	Springbok Wo	0214700B2	17°53′57″E 29°39′55″S	1990–2009	20	0.62	1990–2009	20	3.0
Namaqua	Kamieskroon	0185793A3	17°56′48″E 30°13′36″S	1953–2009	57	0.36	–	NA	NA
Richtersveld	Vioolsdrift	0276072 8	17°32′32″E 28°42′′14″S	1952–2009	58	0.17	–	NA	NA
Richtersveld	Henkries	0277178 3	18°5′39″E 28°58′14″S	1990–2009	20	1.05	1990–2009	20	1.4
Table Mountain	Cape Point	0004891 9	18°30′0″E 34°21′0″S	1900–2009	110	1.00	1960–2009	50	4.6
Table Mountain	Cape Town Slangkop	0004549 2	18°19′8″E 34°8′57″S	1996–2009	14	0.96	1996–2009	14	4.7
Tankwa Karoo	Agterkop	0087187 7	20°7′7.13″E 32°7′6.16″S	1986–2009	24	0.51	1986–2009	24	0.3
Tankwa Karoo	Calvinia Wo	0134479A3	19°46′′10″E 31°28′25″S	1933–2009	77	0.93	–	NA	NA
West Coast	Langebaanweg Wo	0061298 8	18°9′39″E 32°58′5″S	1973–2009	37	5.64	1973–2009	37	0.9

Supporting Information

The following supporting information is available as part of the online article:

Appendix S1. Methodological details and park specific results from analysis of temperature and rainfall data for national parks in South Africa.

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