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Temporal Changes in Minimum and Maximum Temperatures at Selected Locations of Southern Africa

Walter Mupangwa [1,*], Lovemore Chipindu [2], Bongani Ncube [3], Siyabusa Mkuhlani [4], Nascimento Nhantumbo [5], Esther Masvaya [1], Amos Ngwira [6], Mokhele Moeletsi [7], Isaiah Nyagumbo [2] and Feyera Liben [8]

[1] Faculty of Erath and Environmental Sciences, Marondera University of Agricultural Sciences and Technology, Marondera P.O. Box 35, Zimbabwe; enmasvaya@muast.ac.zw
[2] International Maize and Wheat Improvement Centre, Mount Pleasant, Harare P.O. Box MP 163, Zimbabwe; l.chipindu@cgiar.org (L.C.); i.nyagumbo@cgiar.org (I.N.)
[3] Centre for Water and Sanitation Research, Faculty of Engineering and the Built Environment, Cape Peninsula University of Technology, Bellville, Cape Town 7535, South Africa; ncubeb@cput.ac.za
[4] International Institute for Tropical Agriculture (IITA) c/o ICIPE, Nairobi P.O. Box 30772-00100, Kenya; s.mkuhlani@cgiar.org
[5] Divisão de Agricultura, Instituto Superior Politécnico de Manica, Campus de Matsinho, Chimoio P.O. Box 417, Mozambique
[6] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Chitedze Research Station, Lilongwe P.O. Box 1096, Malawi; a.ngwira@cgiar.org
[7] Agricultural Research Council, Institute for Soil, Climate and Water, Pretoria 0001, South Africa; moeletsim@arc.agric.za
[8] Ethiopian Institute of Agricultural Research, Addis Ababa P.O. Box 2003, Ethiopia; feyeraliben@yahoo.com
* Correspondence: mupangwa@yahoo.com or mupangwawt@gmail.com or wmupangwa@muast.ac.zw

Abstract: Agriculture is threatened by ever increasing temperatures and this trend is predicted to continue for the near and distant future. The negative impact of rising temperatures on agri-food systems is also compounded by the erratic and highly variable rainfall in most parts of southern Africa. Minimum and maximum temperatures' variability and trend analysis were undertaken using daily time series data derived from 23 meteorological stations spread across Malawi, Mozambique, South Africa and Zimbabwe. The modified Mann–Kendall and Theil–Sen slope models were used to assess temperature trends and their magnitudes. Temperature varied with location and minimum temperature was more variable than maximum temperature. Semi-arid regions had higher variation in minimum temperature compared to humid and coastal environments. The results showed an upward trend in minimum (0.01–0.83 °C over a 33–38 year period) and maximum (0.01–0.09 °C over a 38–57 year period) temperatures at 9 and15 locations, respectively. A downward trend in minimum temperature (0.03–0.20 °C over 38–41 years) occurred in South Africa at two locations and Dedza (Malawi), while a non-significant decline in maximum temperature (0.01 °C over 54 years) occurred at one location in coastal dry sub-humid Mozambique. The results confirm the increase in temperature over 33–79 years, and highlight the importance of including temperature when designing climate change adaption and mitigation strategies in southern Africa and similar environments.

Keywords: climate change; global warming; heat stress; smallholder agriculture; temperature variability

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1. Introduction

1.1. Temperature Trends

Agriculture is a key economic sector in southern Africa and is under threat from climate variability and change. Consequently, close to one third of the rural population in southern Africa is at risk of food shortages and loss of livelihood [1–3] due to climate variability and change. In Africa, decadal temperature increases of 0.32 °C were observed before 2010 [4], while Ref. [5] reported a significant increase in air temperature between 1979 and 2010. Temperature trend analyses conducted between 2004 and 2017 have indicated temperature increases of 0.2 °C in South Africa between 1960 and 2003 [6] and 0.16 °C per decade in semi-arid parts of Zimbabwe between 1967 and 2015 [7]. In South Africa, temperature variability of 0.18 °C in winter and 0.09 °C in summer were observed for the period 1950–1999 under semi-arid conditions using a decade time step [8]. Globally, there has been a general increase in night and daytime temperatures [9], and [10] reports increases of 1.1 °C from 1850–1900 to 2010–2019. Specifically, there has been a decrease in cold days and nights in most parts of southern Africa [11]. In southern Africa, air temperature is projected to increase over the coming decades [6] with the projected changes varying from no change to 3.5 °C by 2050 [12]. Globally, mean annual temperature has increased by 0.85 °C since 1880 [13], while general increases in the night and daytime temperatures have also been observed [4].

1.2. Impact of Day and Night Time Temperatures

Maximum temperatures during crop growth and development have a significant impact on the final yield outcomes [14]. Temperature interaction with other weather elements and their impacts on crop yield also needs more exploration [15]. Temperatures beyond the threshold for major food security cereals and legumes are detrimental, particularly during the pollination and grain filling growth stages [16,17]. Daytime temperatures of >35 °C often limit growth and the overall productivity of cereals and legumes that require optimum temperatures of 25 to 33 °C [14,16,17]. Temperatures above optimum levels for cereals and legumes may shorten the duration of grain filling, resulting in low crop yields [15]. Ref. [18] observed a notable negative correlation between daytime maximum temperature during grain filling and yields of maize (*Zea may* L.) and soybean (*Glycine max* (L.) Merr). High temperatures (>35 °C) at the pollination stage of maize plants reduce pollen viability, which negatively impacts kernel set resulting in reduced yields [19]. A daytime temperature of >25 °C reduces the growth rate and pod formation of legumes such as cowpea, common bean, soybean and groundnut [20]. For pigeon pea, a decrease in night temperatures affects pod set [21], resulting in low yields. Drought has a critical and negative impact on grape yields at the farm scale and this can be attributed to high temperatures during summer and winter [22]. Agronomic management practices that reduce crop exposure to high temperature are, therefore, critical to complement genetic improvements targeted at dealing with heat stress [15].

High daytime temperature promotes more soil evaporation, which could lead to increased soil water deficits [23]. This introduces stress in crop plants under rainfed cropping systems, particularly during sensitive growth stages such as flowering. Soil water losses of 1.5–4 mm per day can occur from bare soil in the sub-humid and semi-arid environments of southern Africa [23]. There is evidence that climate-change-induced temperature and soil moisture changes can result in varying effects on the diversity, distribution and abundance of soil microfauna, most of the effects being negative [24]. Soil microbial activity which is critical for organic matter build-up and nutrient cycling might be reduced due to increased soil temperature [25,26]. This in turn has negative impacts on plant growth conditions. At a watershed level, extreme daytime temperature drives rapid depletion of soil moisture through an increase in evapotranspiration and augmenting water supplies through rainwater harvesting is paramount for agricultural systems in dry areas [27]. Water losses of up to 40% due to evaporation can occur from large water bodies during periods of extreme daytime temperature [28,29] and this will continue to have negative impacts on irrigated agriculture and livestock water supply.

Minimum temperatures are also critical for crop growth and development [30]. In southern Africa, projected trends indicate an increase in minimum temperatures, with notable variation depending on location [8,12]. Minimum temperatures are projected to increase more rapidly than maximum temperatures in the United States of America [31]. The southern Africa region is one of the hotspots for the projected general warming, characterized by increase in average day and night temperatures [32]. This will in turn affect production of field and horticultural crops, as well as fruits, in the different agro-ecological regions of southern Africa. High nighttime temperatures can be more detrimental than daytime temperature, especially on temperate crops. Respiration rate increases with increase in nighttime temperatures and this results in rapid depletion of stored sugars in the plants, thus reducing the final crop yield [15,33]. An increase in minimum temperatures will influence horticultural crops negatively or positively depending on species but will be detrimental to fruit production [16,34]. In field crops, increasing minimum temperatures potentially promote early senescence, which in turn shortens the grain filling period, resulting in low yields [16]. In fruit production, chilling hours required to trigger flowering might not be met in the face of increasing nighttime temperatures [35,36], while in both fruit and vegetables increasing temperatures result in high vulnerabilities during reproductive stages and, an increase in insect pest attacks and disease prevalence [36].

Daytime temperature extremes reduce livestock productivity, quality of livestock and shelf-life of products [37]. Under heat stress and water temperatures above 21 °C, animals take less feed and water [37]. This reduces growth and the overall productivity of the animal. With increasing daytime temperatures new adaptation and mitigation strategies for livestock management need to be formulated in southern Africa. Prioritizing climate smart livestock production technologies is imperative in the face of a changing climate [38]. Livestock management strategies should include diseases and pest prevention practices, in addition to the provision of adequate feed during the dry season. Inclusion of forage crops in the cropping systems, as well as integration of agroforestry into farming systems, could be key in tackling livestock production challenges induced by climate change and variability [39]. Similarly, in aquaculture fish are facing changing climate dangers due to the alterations in their habitats [36].

Temperatures in southern Africa are already conducive for emerging crop pests such as the fall armyworm (*Spodoptera frugiperda* (Smith)), and further increases in temperature will worsen pest and disease management on smallholder farms [40]. In livestock systems, high temperatures promote increased infestation of pests such as ticks [41]. Studies conducted by [42,43] revealed that increased ambient temperature promotes the proliferation of storage pests in traditional granaries used on smallholder farms, resulting in high grain losses.

1.3. Purpose of Study

Household food security is under threat in the coming decades due to ongoing global warming. This threat is higher in southern Africa's rainfed agricultural systems. Therefore, generating timely information on all key elements of the weather that drive productivity of rainfed farming in the region is critical to improve decision making and agricultural risk management at farm, landscape, regional and national levels. This is also important to fine tune extension messages, research agendas and agriculture policy making. Nevertheless, more emphasis has been placed on analysing rainfall patterns and their impact on agriculture particularly for rainfed systems [44–46]. However, temperature is emerging as an important weather element that needs to be considered when designing adaptation and mitigation strategies against climate change [14]. Therefore, more research is needed to build a clear understanding of how minimum and maximum temperatures have changed over the years in Southern Africa. This will aid targeted research design to critically understand/assess the impacts of temperature dynamics on crop growth and farm productivity in Sub-Saharan Africa.

This study was guided by the following research questions: (i) How did minimum and maximum temperatures vary between 1947 and 2019 in southern Africa? (ii) What have the minimum and maximum temperature trends been between 1947 and 2019? (iii) What are the magnitudes of changes in minimum and maximum temperature between 1947 and 2019, at the selected locations in southern Africa? The specific objectives were to (i) assess the degree of minimum and maximum temperature variation, (ii) analyse the trends in minimum and maximum temperatures, (iii) evaluate the magnitude of change in minimum and maximum temperatures between 1947 and 2019 in selected locations of southern Africa and (iv) explore some of the implications of the temperature changes for agriculture and water resource management in southern Africa.

2. Materials and Methods

2.1. Description of Study Sites

Measured temperature data from 23 meteorological stations located in regions of contrasting climate regimes in Malawi, Zimbabwe, Mozambique and South Africa were used for this study (Figure 1). The geographical characteristics of the sites are summarized in Table 1. Based on agro-ecological characteristics (rainfall, temperature and altitude), the selected locations in Malawi, Mozambique, South Africa and Zimbabwe were placed into arid, semi-arid, sub-humid, dry sub-humid, coastal dry sub-humid and coastal regions (Table 1). Malawi experiences a sub-tropical climate with a minimum temperature averaging 17–22 °C in semi-arid lowlands, and 6–17 °C in the sub-humid highlands. The maximum temperature averages 27–32 °C in semi-arid lowlands and 23–30 °C in sub-humid highlands [47]. Mozambique experiences tropical to sub-tropical climatic patterns. Generally, temperatures are warmer along the Indian Ocean coast than further inland. Minimum and maximum temperatures average 16–24 °C and 26–32 °C, respectively, along the coast. Further inland, minimum and maximum temperatures average 12–20 °C and 22–36 °C, respectively [48,49]. South Africa experiences a wider range of climatic regimes than the other three countries used in this study, due to multiple different agro-ecologies. These climate patterns include arid, semi-arid, sub-tropical and Mediterranean. Minimum and maximum temperatures in coastal areas average 10–19 °C and 18–24 °C, respectively. Under arid to semi-arid conditions, minimum and maximum temperatures average 3–22 °C and 20–34 °C, respectively. Under Mediterranean conditions, minimum and maximum temperatures average 7–16 °C and 18–27 °C [50]. Climatic patterns of Zimbabwe are close to those experienced in Malawi and inland Mozambique. Semi-arid parts of Zimbabwe experience minimum temperatures of 6–23 °C and maximum temperatures of 26–35 °C on average. Highland areas experience a minimum of 7–16 °C and maximum of 13–29 °C [45,51].

2.2. Data Source and Quality

Daily minimum and maximum temperatures data were derived from 23 meteorological stations located in four countries and spread across different agro-ecological regions of Malawi, Mozambique, South Africa and Zimbabwe. The choice of these meteorological stations was based on the availability of long-term records of daily minimum and maximum temperature data, and completeness of the data sets. The length of available daily minimum and maximum temperature data varied from country to country and station to station. Meteorological stations with at least 20 years of measured temperature data were considered for the analyses as such length can produce a credible statistical analysis output. The temperature data were checked for quality using the RHtestV3 package in RClimDex 1.1 program [52] and the process involved identifying missing data, outliers and errors in the data set. The quality checks on the temperature time series data focused on identifying duplicate data and outliers, as well as spatial and temporal inconsistencies in the data sets from the different locations. Furthermore, the boxplots were used to display a clear summary of the maximum and minimum temperature time series data as they can expose the existence of extreme events (outliers) and handle large data easily.

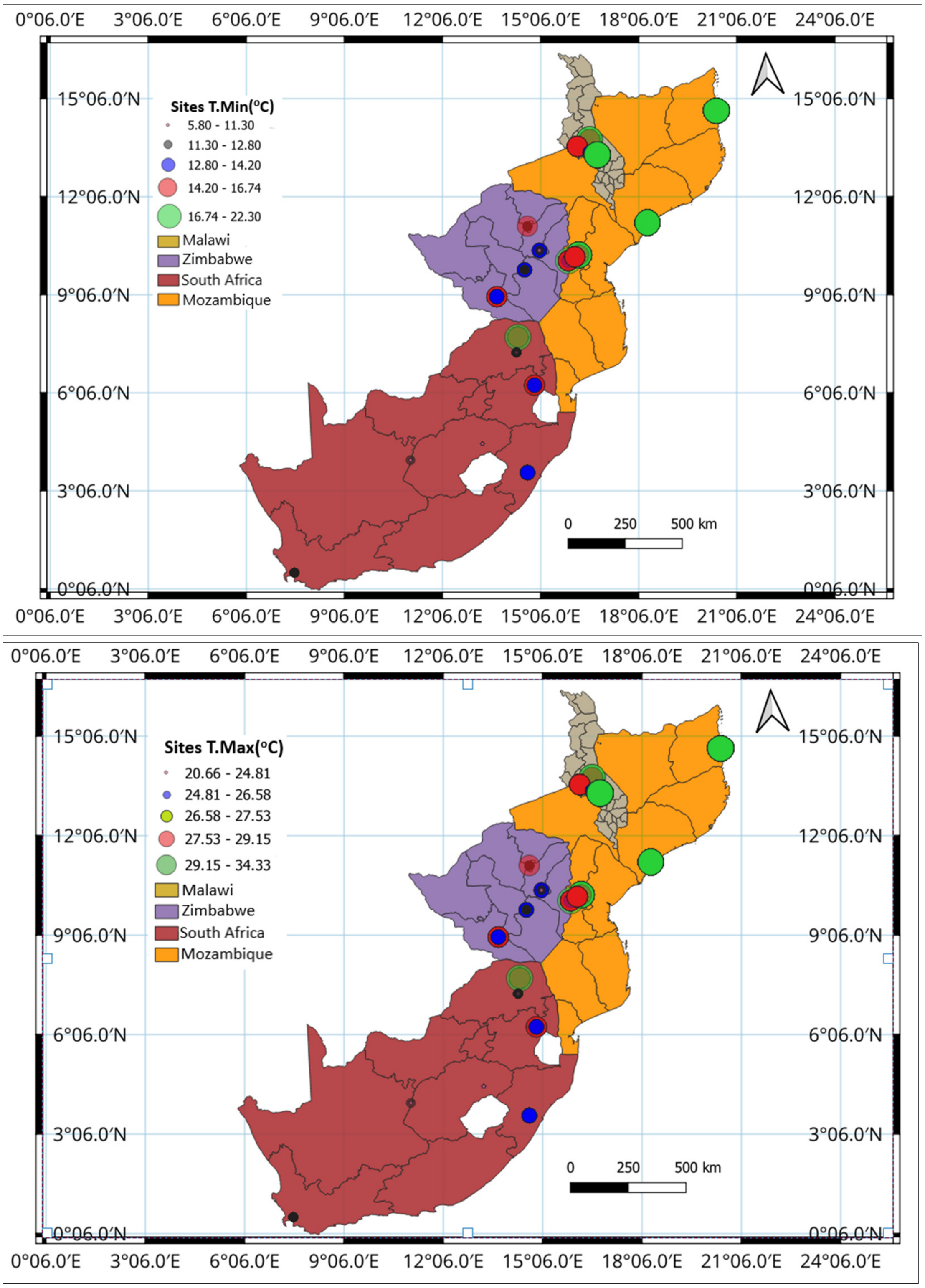

Figure 1. Maps of part of southern Africa showing average minimum and maximum temperatures of the meteorological stations used in the study.

Table 1. Location-related information of the meteorological stations and time period of the temperature data sets used in the study in the four southern African countries.

Country	Location	District	Latitude (°)	Longitude (°)	Altitude (m)	Agro-Ecology	Period	Years
Malawi	Chitala	Salima	−13.68	34.25	606	Semi-arid	1947–1999	52
	Chitedze	Lilongwe	−13.98	33.64	1100	Dry sub-humid	1980–2013	33
	Dedza	Dedza	−14.32	34.25	1632	Dry sub-humid	1958–1999	41
	Golomoti	Dedza	−14.44	34.60	578	Dry sub-humid	1985–2019	34
	Kandeu	Ntcheu	−14.44	34.59	916	Dry sub-humid	1979–2019	40
Mozambique	Chimoio	Chimoio	−19.25	33.43	693	Sub-humid	1951–2015	64
	Pemba	Pemba	−12.59	40.52	70	Coastal, dry sub-humid	1951–2005	54
	Quelimane	Quelimane	−17.86	36.87	5	Coastal, dry sub-humid	1951–2008	57
	Rotanda	Sussundenga	−19.50	32.92	1020	Moist sub-humid	1991–2013	22
	Sussundenga	Sussundenga	−19.33	33.24	550	Sub-humid	1969–2005	36
South Africa	Bethlehem	Thabo Mofutsanyane	−28.16	28.29	1631	Humid Sub-tropical	1940–2019	79
	Kimberley	Frances Baard	−28.77	24.76	1198	Semi-arid	1980–2018	38
	Levubu	Vhembe	−23.08	30.28	706	Humid Sub-tropical	1980–2004	24
	Nelspruit	Ehlanzeni	−25.45	30.96	660	Humid Sub-tropical	1980–2018	38
	Pietermaritzburg	uMgungundlovu	−29.67	30.40	775	Humid Sub-tropical	1980–2018	38
	Polokwane	Capricorn	−23.82	30.17	749	Semi-arid	1980–2018	38
	Stellenbosch	Cape Winelands	−33.93	18.85	116	Humid Sub-tropical	1980–2018	38
	Upington	ZF Mgcawu	−28.40	21.27	836	Arid	1980–2018	38
	Vryburg	Dr Ruth Segomotsi Mompati	−26.47	20.62	879	Semi-arid	1980–2018	38
Zimbabwe	Harare	Harare	−17.72	31.02	1475	Sub-humid	1961–2001	40
	Marondera	Marondera	−18.93	31.54	1658	Sub-humid	1951–2000	49
	Masvingo	Masvingo	−19.83	30.77	1064	Dry sub-humid	1951–2001	50
	West Nicholson	Gwanda	−21.06	29.36	864	Semi-arid	1961–2001	40

2.3. Analyses of Minimum and Maximum Temperatures

2.3.1. Homogeneity Test

The Mann–Whitney–Pettitt test is a non-parametric test, and it was applied in this study in order to handle abrupt changes in the mean of the distribution of temperature changes. This test allows the detection of a single shift at an unknown point in time. Minimum and maximum temperature data for each meteorological station were subjected to a test for homogeneity using the Mann–Whitney–Pettitt test [53] at a 5% significance level. The null hypothesis (H_0—homogenous) assumes uniform trends, whilst the alternative hypotheses (H_a—heterogenous) assumes that the trends were composed of diverse parts.

2.3.2. Modified Mann–Kendall (MMK) Test

Previous observations of weather elements such as temperature influence time series data, and when the data is not random, the power of the non-parametric Mann–Kendall test is also highly influenced by serially correlated data. The Modified Mann–Kendall (MMK) test is a variance correction approach which addresses the issue of serial correlation in trend analysis. Data are initially detrended and the effective sample size is calculated using the ranks of significant serial correlation coefficients which are then used to correct the inflated (or deflated) variance of the test statistic. In this study, the MMK test was conducted in R (version 4.2.2) [54] using the modified MK package (version 1.6) as follows:

MMKh ($X_{1,\ldots,n}$, ci = 0.95) where *mmkh* is the command to compute the modified Mann–Kendall test, X is the station, 1 . . . , n is the number of stations for both minimum and maximum temperatures. The test results give corrected Zc, the Z statistic after variance correction; a new *p*-value after variance correction; N/N*, the effective sample size; the original Z, the original Mann–Kendall Z statistic; old *p*-value, the original Mann–Kendall *p*-value; Tau, Mann–Kendall's Tau; Sen's Slope, Sen's slope; old variance, the old variance before variance correction; and new variance, the variance after correction (Supplementary Tables S1 and S2).

To illustrate the spatial changes in minimum and maximum temperatures over time, maps were drawn representing the districts where the meteorological stations are located. The maps were drawn focusing mainly on the 1980–2004 period which was common at most locations.

2.3.3. Theil–Sen Slope Estimator

The Theil–Sen slope test was performed to examine the magnitude of the slope for minimum and maximum temperature changes. Given a set of pairs of years in a data series in this study, the slopes between all pairs of years were calculated. The Theil–Sen estimate of the slope is the median of all these slopes. The Theil–Sen estimator procedure was selected for this study because it gives accurate confidence intervals even with data that are not normally distributed, and it can handle outliers. The test was performed in R version 4.2.2 using the Trend package [54]. The test computes slope using Theil–Sen's method which calculates a set of linear slopes followed by a median of the slopes as follows:

$$d_k = (X_j - X_i)/(j - i) \tag{1}$$

for ($1 \leq i < j \leq n$), where d is the slope, X denotes the variable, and i and j are indices. As a result, the Theil–Sen slope (b_{Sen}) is given by

$$b_{Sen} = \text{med}(d_k) \tag{2}$$

where "med" is the empirical median function.

3. Results

3.1. Descriptive Statistics of Minimum and Maximum Temperatures

Descriptive statistical analyses performed on the minimum and maximum temperatures across the different locations in the four countries are summarized in Tables 2 and 3. In Malawi, maximum temperature ranged from 22 °C to 43 °C in the lowland semi-arid Chitala location. In mid- and high-altitude locations, maximum temperature ranged from 11.9 °C to 41.4 °C. The minimum temperature ranged from 0.9 °C to 29 °C over the study period. The smallest and largest minimum temperature ranges were recorded at dry sub-humid Golomoti (18.7 °C) and Chitedze (7.80 °C), respectively. In Mozambique, maximum temperature ranged from 2.1 °C to 43.9 °C, and the smallest range was recorded in Cabo Delgado (Pemba), along the northern Mozambique costal channel. Minimum temperature ranged between 1.5 °C and 29.6 °C with the smallest range also being experienced in the northern Mozambique costal line in Cabo Delgado province (Table 3). Maximum temperature ranged from −0.1 °C to 47.8 °C in South Africa with the semi-arid Vryburg location having the largest temperature range. Minimum temperature ranged from −13 °C at humid sub-tropical Bethlehem to 30.7 °C at semi-arid Vryburg. As observed with maximum temperature, the largest minimum temperature range was also recorded at semi-arid Vryburg. In Zimbabwe, the maximum temperature ranged from 2.6 to 42.4 °C with semi-arid West Nicholson having the largest range of minimum temperature (39 °C). Minimum temperature ranged from −4.6 to 26.3 °C and West Nicholson experienced the highest temperature (29.2 °C).

Table 2. Descriptive statistics for maximum temperatures measured at each of the meteorological stations in the four countries.

Location	N	Mean	SD	Min	Max	Range	Skewness	Kurtosis
Chitala	19,150	31.01	2.96	22.0	43.0	21.0	0.44	0.29
Chitedze	12,228	27.15	3.00	15.7	41.4	25.7	0.32	0.79
Dedza	15,113	22.99	2.78	11.9	30.3	18.4	−0.40	0.07
Golomoti	12,569	27.65	3.16	18.4	38.1	19.7	0.46	−0.27
Kandeu	14,761	27.58	3.20	15.5	38.1	22.5	0.35	−0.23
Chimoio	23,495	26.81	4.02	2.1	40.6	38.5	−0.48	2.08
Pemba	20,089	29.77	1.69	18.7	37.5	18.8	−0.14	−0.02
Quelimane	21,185	30.2	3.06	19.7	43.9	24.2	0.16	0.00
Rotanda	8187	27.45	3.95	2.8	42.1	39.3	0.03	0.57
Sussundenga	13,149	27.72	3.59	14.2	41.0	26.8	−0.03	0.02
Bethlehem	14,245	22.56	5.12	−0.1	36.3	36.4	−0.31	−0.29
Kimberley	14,245	26.85	6.26	6.7	43.1	36.4	−0.29	−0.58
Levubu	8887	26.36	4.48	8.4	41.9	33.5	−0.15	0.09
Nelspruit	14,245	27.3	4.57	9.5	42.6	33.1	−0.14	−0.21
Pietermaritzburg	14,245	24.34	5.31	7.0	41.9	34.9	0.02	−0.24
Polokwane	14,245	27.16	4.85	11.3	43.3	32.0	−0.09	−0.32
Stellenbosch	14,245	23.74	5.83	9.5	43.1	33.6	0.18	−0.67
Upington	14,245	29.23	6.65	7.5	45.2	37.7	−0.35	−0.59
Vryburg	14,245	30.53	6.55	6.8	47.8	41.0	−0.37	−0.48
Harare	14,334	25.24	3.33	2.6	35.4	32.8	−0.33	0.18
Marondera	17,960	25.6	3.55	9.4	39.1	29.7	−0.17	0.28
Masvingo	18,447	26.33	4.63	9.2	39.1	29.9	−0.31	−0.16
West Nicholson	14,429	28.63	5.2	3.4	42.4	39.0	−0.26	−0.28

Table 3. Descriptive statistics for minimum temperatures measured at each of the meteorological stations in the four different countries.

Location	N	Mean	SD	Min	Max	Range	Skewness	Kurtosis
Chitala	19,150	15.03	3.82	4.0	29.0	25.0	0.37	−0.19
Chitedze	12,228	14.56	3.73	0.9	28.7	27.8	−0.45	−0.88
Dedza	15,113	13.33	2.97	0.9	22.1	21.2	−0.64	−0.19
Golomoti	12,569	18.06	3.39	7.97	26.7	18.7	−0.38	−0.95
Kandeu	14,761	17.34	3.80	2.89	26.7	23.8	−0.47	−0.44
Chimoio	23,495	16.24	3.42	2.1	25.9	23.8	−0.36	−0.69
Pemba	20,089	21.6	2.34	12	28.7	16.7	−0.49	−0.43
Quelimane	21,185	20.15	3.46	8.3	29.6	21.3	−0.4	−0.86
Rotanda	8187	15.35	3.69	2.3	24.8	22.5	−0.44	−0.61
Sussundenga	13,149	15.5	4.17	1.5	25.0	23.5	−0.48	−0.62
Bethlehem	14,245	6.81	6.33	−13	20.2	33.2	−0.37	−1.03
Kimberley	14,245	9.87	6.63	−7.9	26.4	34.3	−0.27	−0.99
Levubu	8887	15.32	3.71	0.0	25.8	25.8	−0.28	−0.41
Nelspruit	14,245	13.71	5.07	−10.8	24.9	35.7	−0.43	−0.86
Pietermaritzburg	14,245	13.06	3.93	−2.6	25.4	28.0	−0.27	−0.49
Polokwane	14,245	14.46	4.38	0.6	23.9	23.3	−0.36	−0.76
Stellenbosch	14,245	11.36	3.87	1.0	23.6	22.6	0.02	−0.50
Upington	14,245	11.48	7.03	−6.5	29.6	36.1	−0.17	−0.94
Vryburg	14,245	11.77	7.65	−9.0	30.7	39.7	−0.25	−1.02
Harare	14,336	11.72	4.42	−2.1	21.4	23.5	−0.5	−0.85
Marondera	17,960	12.22	4.23	−4.6	23.7	28.3	−0.47	−0.75
Masvingo	18,447	12.4	5.12	−4.6	23.7	28.3	−0.47	−0.82
West Nicholson	14,429	13.23	5.8	−2.9	26.3	29.2	−0.43	−0.89

The relatively higher standard deviation (up to 7.65 °C) of daily minimum temperature confirms higher variation in minimum than maximum temperature at most of the locations (Tables 2 and 3). In Malawi, a higher variation in minimum temperature was observed at four of the five locations with a standard deviation of at least 3 °C. Chitala experienced higher variation in minimum temperature than maximum temperature. The high-altitude upland Dedza location experienced more variations in maximum than minimum temperature over the study period. In Mozambique, minimum temperature exhibited higher variation than maximum temperature at all locations. The lowest minimum and maximum temperature variation were experienced in Central Mozambique's costal Quelimane location in Zambezia. However, the combined highest minimum and maximum temperature variation in Mozambique was recorded in Chimoio, a central Mozambique mid-altitude zone. Overall, the highest variation in maximum temperature was recorded in Chimoio and Rotanda, both in central Mozambique mid- and high-altitude inland regions. Six of the nine locations experienced higher variation in minimum than the maximum temperature in South Africa. The highest variation (10.8 °C) in minimum temperature was observed at the semi-arid Upington location in western South Africa. The highest variation in maximum temperature was experienced at the Polokwane location in the Limpopo province. As observed in the other countries, the minimum temperature varied more than the maximum temperature at the locations in Zimbabwe. Sub-humid Harare had the highest variation in minimum temperature and the lowest variation in maximum temperature in Zimbabwe (Tables 2 and 3).

3.2. Trends in Maximum and Minimum Temperatures

The upward or downward direction, or lack of trends in maximum and minimum temperatures were location specific and also varied from country to country. In Malawi, three and four of the five locations, experienced significant upward trends in both maximum and minimum temperatures, respectively (Figure 2, Table 4). In contrast, Dedza experienced a significant decreasing trend in minimum temperature. In Mozambique, Chimoio and Sussundenga experienced increasing minimum temperature trends (Figure 3, Table 4) between 1951 and 2015. The inland locations registered the highest trend increase in minimum temperature. Maximum temperature increased significantly in the Zambezia coastal line (Quelimane) between 1951 and 2008. In South Africa, trends were location specific and three locations (Bethlehem, Nelspruit, Polokwane) experienced significant increase in minimum temperature (Figure 4, Table 4). Two locations from arid and semi-arid sub-tropics (Kimberley, Upington) exhibited decreasing trends in minimum temperature. Eight of the nine locations in South Africa experienced an upward trend in maximum temperature (Table 4). In Zimbabwe, West Nicholson experienced an increase in minimum temperature while the high-altitude sub-humid Harare experienced no change in both minimum and maximum temperatures between 1961 and 2001 (Figure 5). Three locations in Zimbabwe (Marondera, Masvingo, West Nicholson) experienced a significant increase in maximum temperature.

Based on the Theil–Sen slope estimator, 15 out of the 23 locations exhibited significantly increasing maximum temperature (Table 4). Maximum temperature increased by 0.01–0.09 °C over a 34–79 year period across the 15 locations. Overall, locations in South Africa experienced a higher increase in maximum temperature compared to stations from other countries. Nine locations experienced a significant increase in minimum temperature, ranging from 0.01 °C at Sussundenga and Nelspruit to 0.83 °C at Chitedze over a 33–38 year period. At semi-arid locations, a significant increase in maximum temperature (0.03–0.09 °C over 30–40 years) was detected at four of the five locations while a significant increase (0.02 °C over 38–40 years) in minimum temperature was experienced at two locations. In the humid and sub-humid locations, a significant increase in maximum temperature of 0.01–0.09 °C occurred at 8 of the 16 locations over a 38–57 year period. Four locations experienced an upward but insignificant trend, while one location had a significant downward trend in the humid and sub-humid agro-ecologies of southern Africa over the same period.

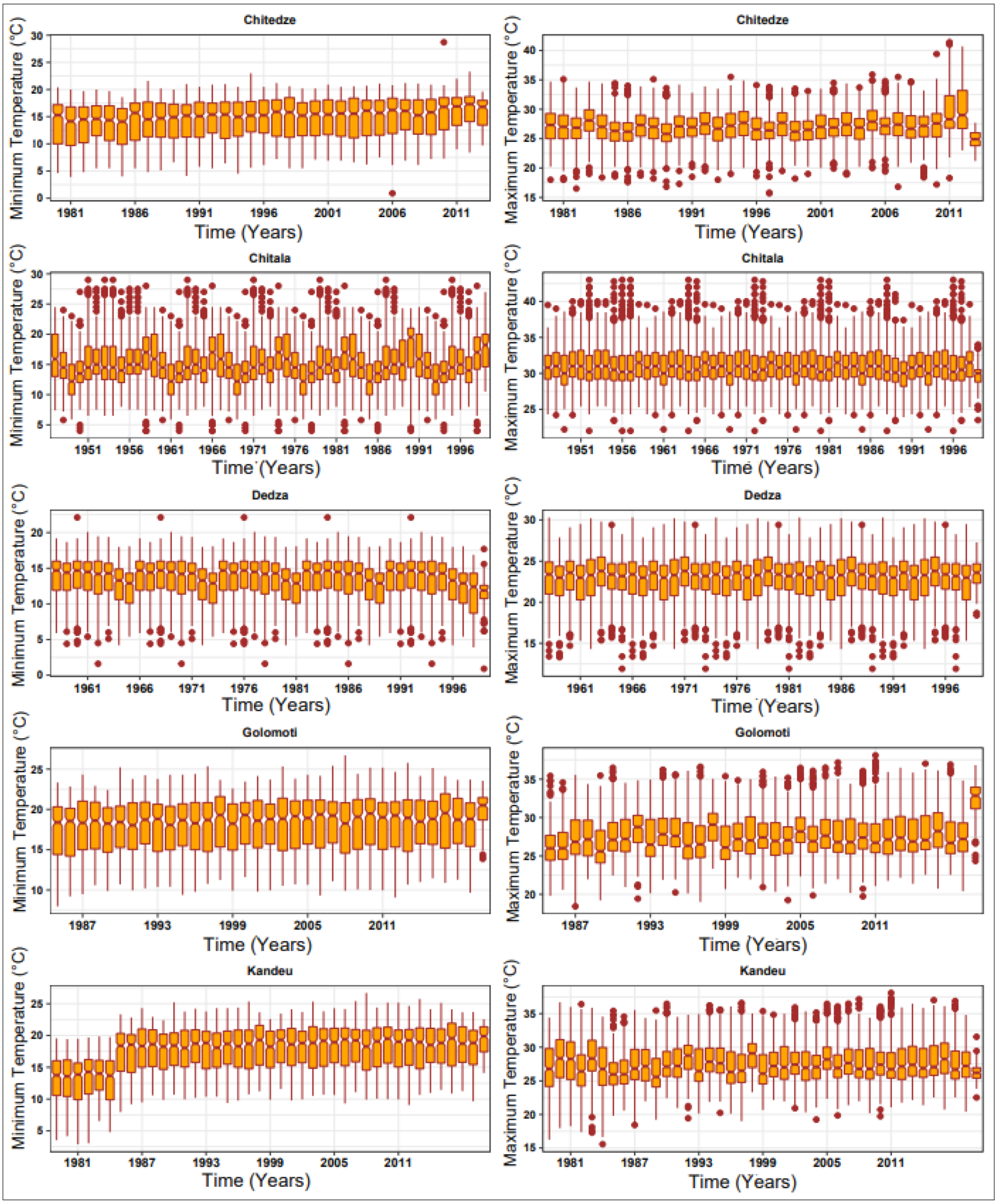

Figure 2. Minimum and maximum temperature trends at five locations in Malawi over varying periods between 1947 and 2019.

In Malawi, trends detected at Chitala and Chitedze were not significant for both maximum and minimum temperatures (Table 4). Only Dedza experienced a significant decrease in minimum temperature. The Pemba station in the northern Mozambique coastal province of Cabo Delgado experienced a decrease in maximum temperature over 54 years, although this change was not significant. Overall, South African locations had higher magnitudes of minimum temperature increase compared with locations in the other three countries. For minimum temperature, seven locations had positive but insignificant trends, while five had negative trends that were also not statistically significant. Six and three locations experienced insignificant positive and negative maximum temperature trends, respectively. Six locations experienced no change in minimum temperature between 1951 and 2018. Six locations also experienced no change in maximum temperature between 1947 and 2013 (Table 4).

Table 4. Sen slope of minimum and maximum temperature trends at meteorological stations in each country.

Country	Location	Minimum		Maximum		Period
		Sen's Slope	*p*-Value	Sen's Slope	*p*-Value	
Malawi	Chitala	0.07	0.55	0.00	0.50	1947–1999
	Chitedze	0.83	0.00 ***	0.02	0.08	1980–2013
	Dedza	−0.20	0.01 ***	0.00	0.88	1958–1999
	Golomoti	0.55	0.00 ***	0.03	0.01 ***	1985–2019
	Kandeu	0.66	0.00 ***	0.01	0.12	1979–2019
Mozambique	Chimoio	0.02	0.00 ***	0.01	0.11	1951–2015
	Pemba	−0.01	0.71	−0.01	0.16	1951–2005
	Quelimane	0.00	0.48	0.01	0.03 ***	1951–2008
	Rotanda	0.00	0.43	0.00	0.93	1991–2013
	Sussundenga	0.01	0.00 ***	0.00	0.51	1969–2005
South Africa	Bethlehem	0.02	0.00 ***	0.04	0.04 ***	1940–2019
	Kimberley	−0.03	0.00 ***	0.04	0.00 ***	1980–2018
	Levubu	0.00	0.64	0.00	0.11	1980–2004
	Nelspruit	0.01	0.02 ***	0.04	0.00 ***	1980–2018
	Pietermaritzburg	0.00	0.84	0.04	0.00 ***	1980–2018
	Polokwane	0.02	0.00 ***	0.09	0.03 ***	1980–2018
	Stellenbosch	0.03	0.07	0.07	0.00 ***	1980–2018
	Upington	−0.08	0.01 ***	0.06	0.00 ***	1980–2018
	Vryburg	0.02	0.13	0.08	0.00 ***	1980–2018
Zimbabwe	Harare	0.00	0.74	0.00	0.86	1961–2001
	Marondera	0.01	0.34	0.02	0.03 ***	1951–2000
	Masvingo	0.00	0.76	0.01	0.02 ***	1951–2001
	West Nicholson	0.02	0.03 ***	0.03	0.00 ***	1961–2001

*** = significant at <0.001.

In Malawi, two districts hosting the meteorological stations warmed between 1980 and 2004 based on maximum temperature (Figure 6). Based on minimum temperature, three districts warmed while Salima experienced cooling and warming cycles. In Mozambique, warming was more pronounced in the coastal districts (Pemba and Quelimane) with Pemba consistently warming based on both maximum and minimum temperatures (Figure 7). Inland districts (Chimoio and Sussundenga) experienced warming and cooling cycles between 1980 and 2004. Maximum temperature shows that Pietermaritzburg, Polokwane and Vryburg warmed between 1980 and 2004 (Figure 8). Based on minimum temperature, five locations experienced warming and cooling cycles in South Africa. In Zimbabwe, the Gwanda and Marondera districts experienced cooling and warming cycles based on maximum temperature, while all districts experienced warming and cooling based on minimum temperature (Figure 9).

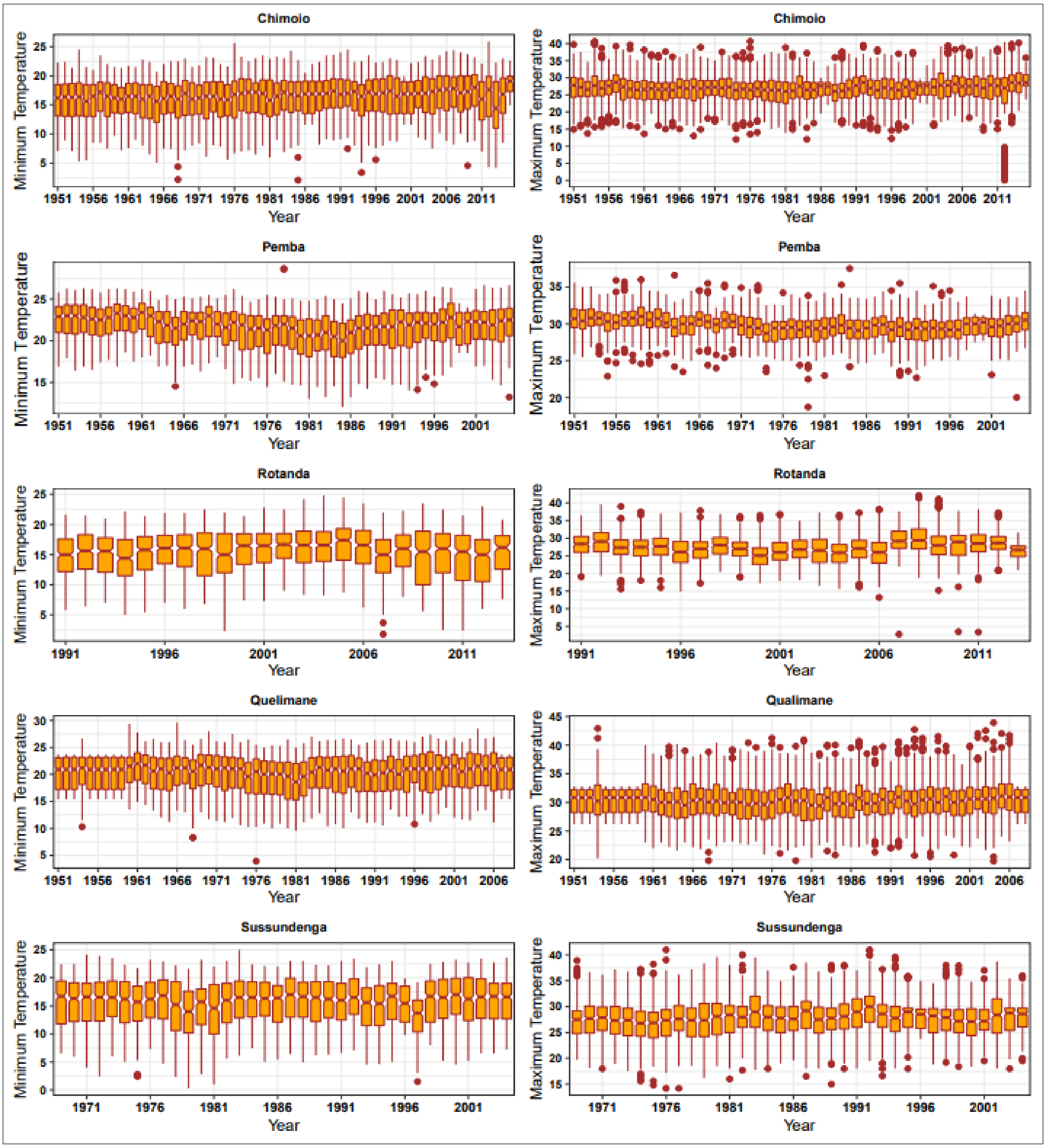

Figure 3. Minimum and maximum temperature trends at five locations in Mozambique over varying periods between 1951 and 2014.

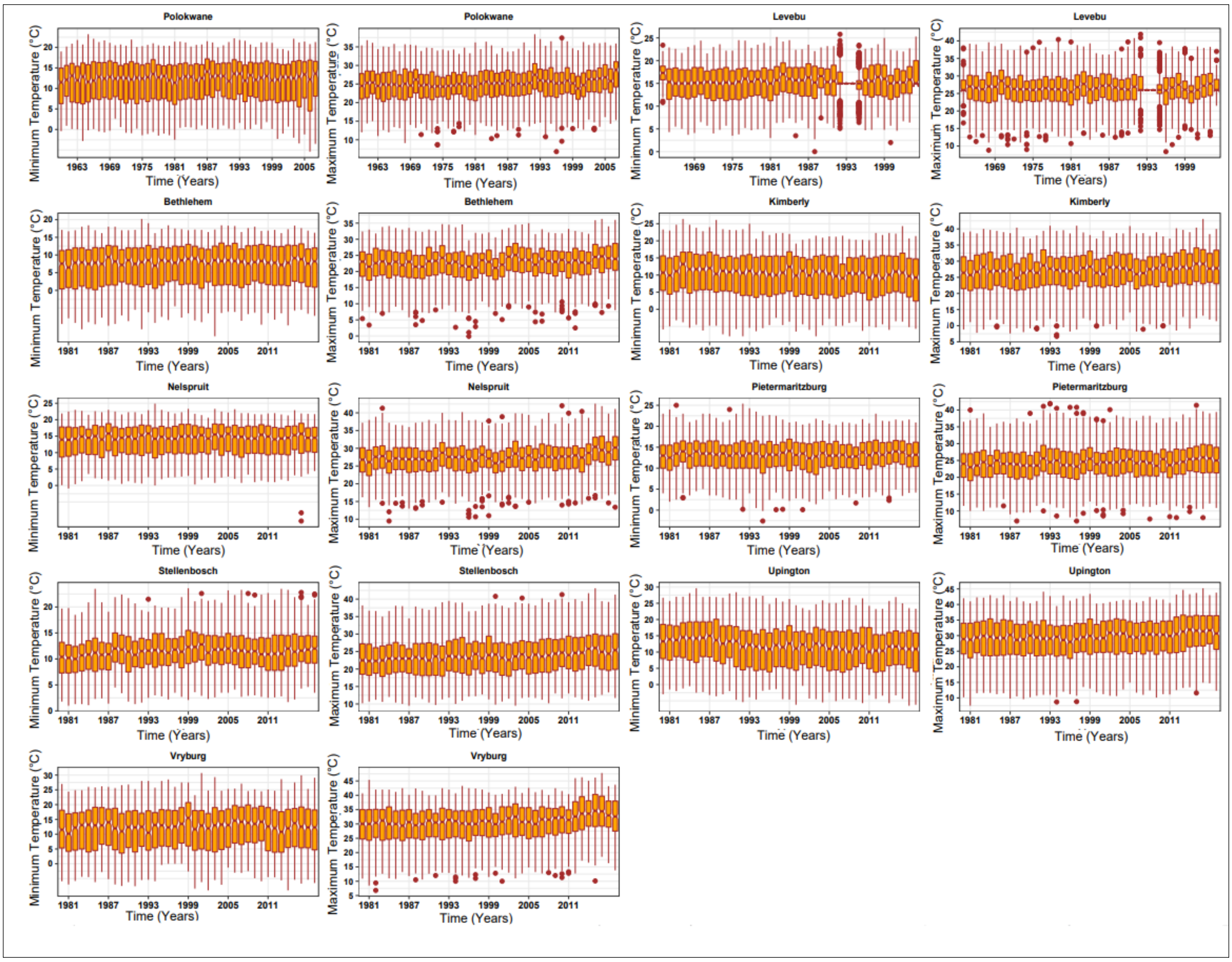

Figure 4. Minimum and maximum temperature trends at nine locations in South Africa over varying periods between 1960 and 2016.

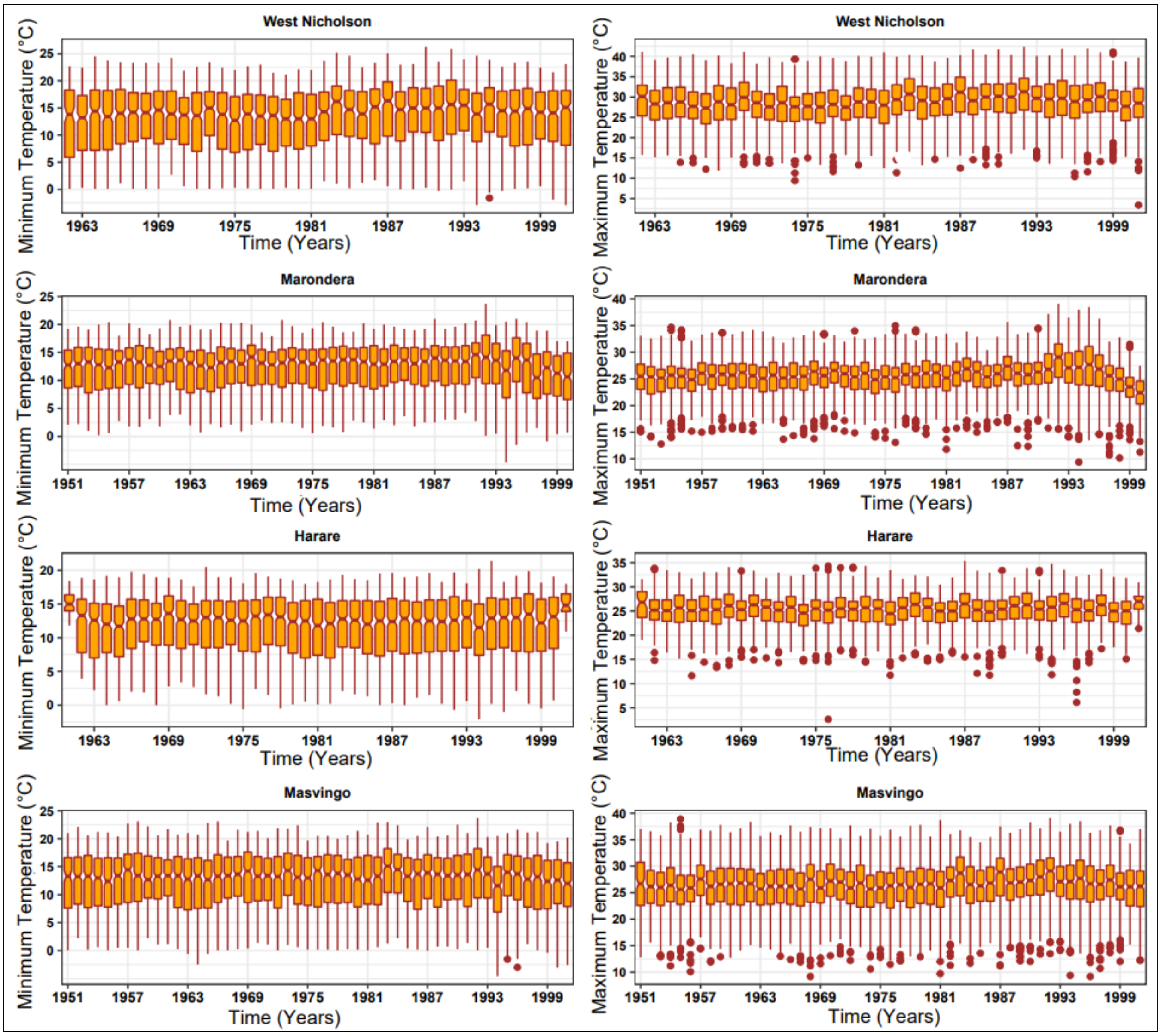

Figure 5. Minimum and maximum temperature trends at four locations in Zimbabwe over varying periods between 1951 and 2001.

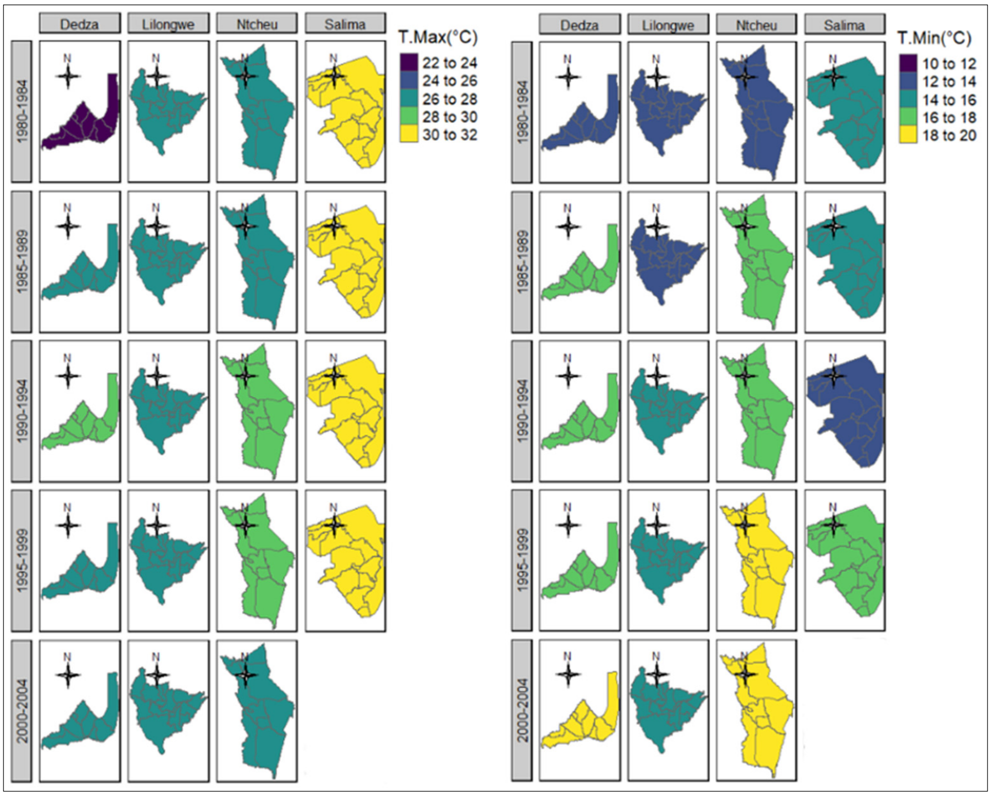

Figure 6. Temperature changes at 5-year intervals in the districts where meteorological stations are located in Malawi.

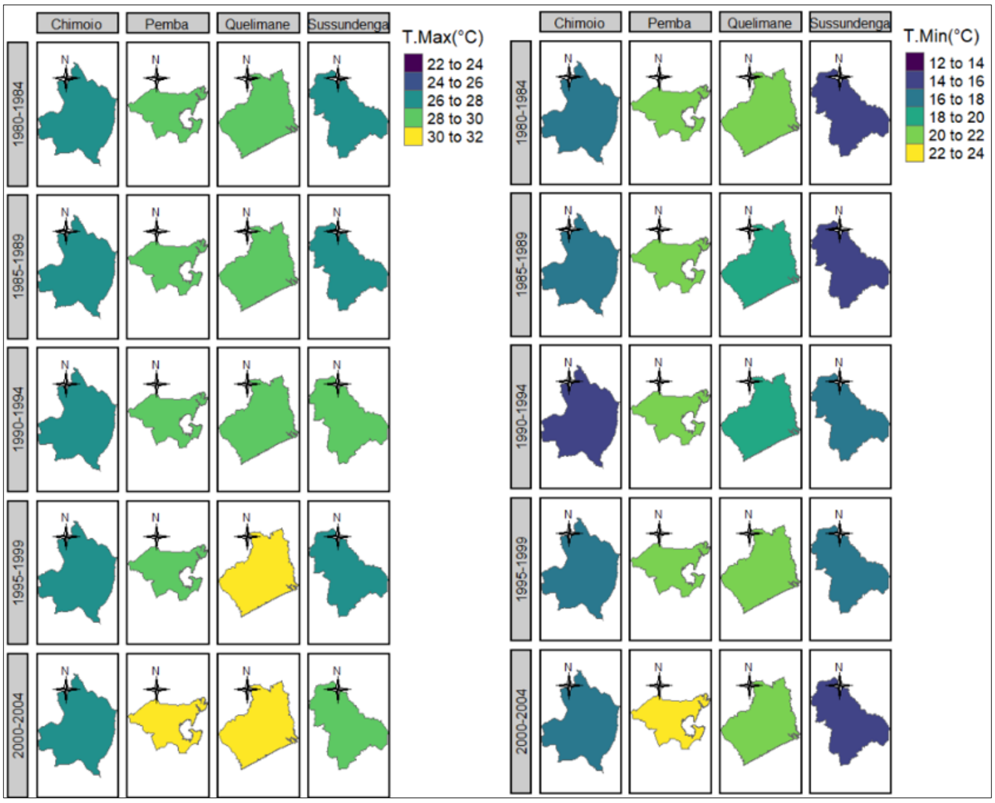

Figure 7. Temperature changes at 5-year intervals in the districts where meteorological stations are located in Mozambique.

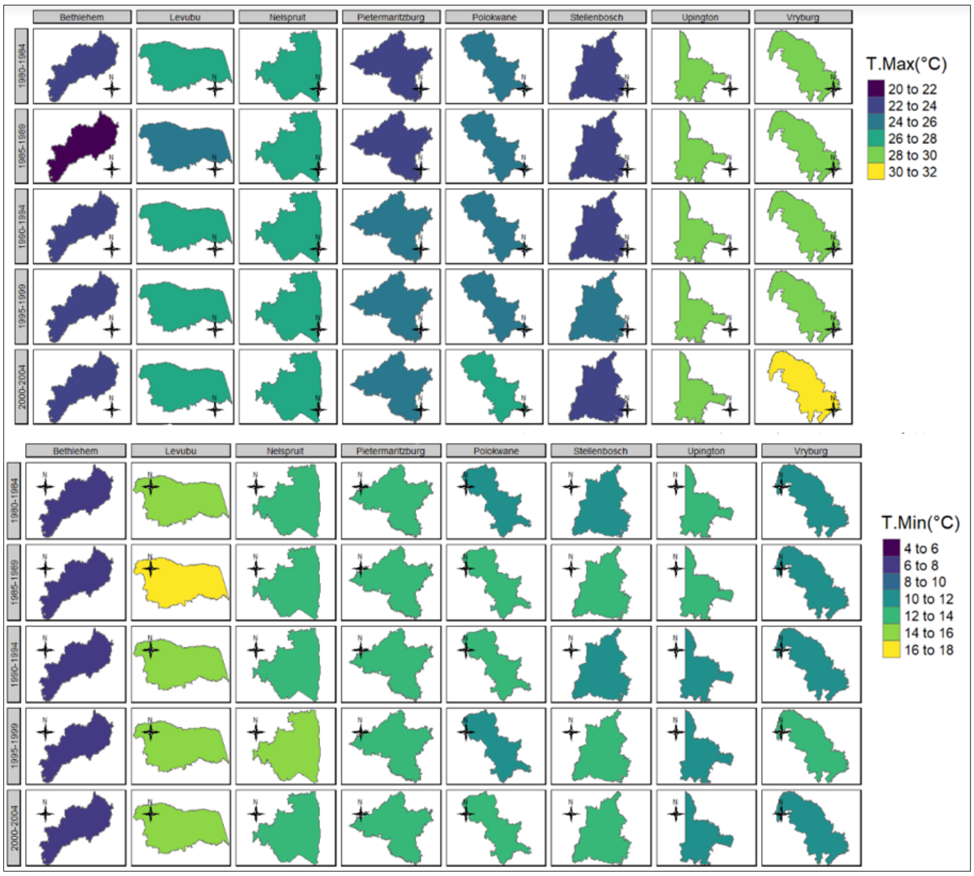

Figure 8. Temperature changes at 5-year intervals at the meteorological stations in South Africa.

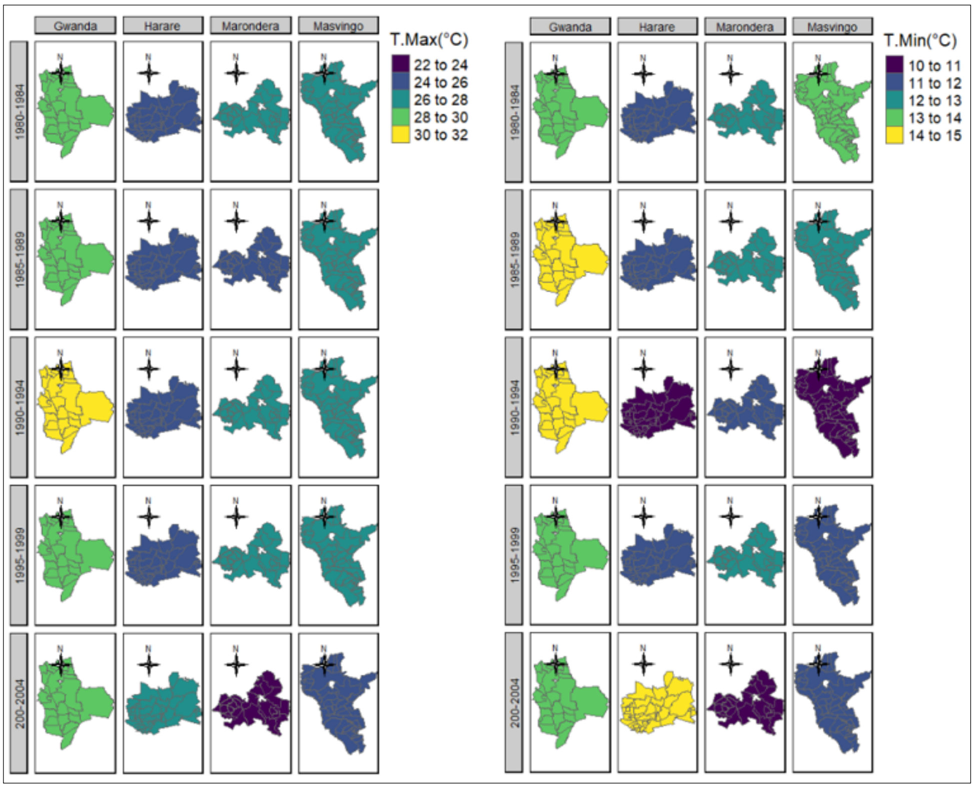

Figure 9. Temperature changes at 5-year intervals in the districts where meteorological stations are located in Zimbabwe.

4. Discussion

4.1. Temperature Variations and Trends

Changes in minimum and maximum temperatures occurred in different locations of southern Africa between 1947 and 2019. The patterns detected suggested the occurrence of peaks and troughs in temperature, highlighting the presence of extreme events over the years at all the locations. These temperature variations over time and scales are driven by various processes which include atmospheric and oceanic conditions (e.g., sea surface temperatures), land cover changes and locally based processes around a given location [55,56]. In this study, minimum temperature was more variable than maximum temperature at most locations. The results demonstrate that nighttime temperature increased more rapidly and it is more sensitive to warming than maximum temperatures because of the thinner boundary layer just above the ground [57]. Elsewhere, Ref. [58] used prediction models to assess temperature variations in the tropics and their results indicated higher variation in minimum than maximum temperatures. The highest variations in minimum temperatures were at the arid Upington and semi-arid Vryburg locations, and this introduces another challenge to such environments which already experience high daytime temperature and low and highly variable rainfall. Local conditions influencing minimum and maximum temperatures over time include location altitude, topography, land cover and atmospheric circulations [59]. This could explain the variations between locations observed in our results. Some locations experienced decreasing trends in both minimum and maximum temperatures, and this can be attributed to decadal variations in temperature at the same location, and a pattern which has previously been reported in other retrospective climate analyses studies in sub-Saharan Africa [5,60]. With the increasing minimum and maximum temperatures, inclusion of temperature when developing climate change adaptation and mitigation strategies and innovations in agricultural systems is imperative, particularly for regions identified as climate change hotspots such as southern Africa [61–63].

Increasing maximum temperatures in sub-Saharan Africa (SSA) has been attributed to several factors including changes in sea surface temperatures (SSTs), reduced land cover due to deforestation, reduced evapotranspiration due to declining vegetative cover and greenhouse gas accumulation in the troposphere [5,64]. South Africa experienced a higher magnitude of maximum temperature increases than all the other countries used in the study. This could be due to the country being located between two oceans, the Atlantic and Indian, which control air movements and atmospheric circulations differently compared with other countries [65]. Additionally, the warming in South Africa (particularly daytime) is apparently enhanced by decreases in cloudiness, precipitation and soil moisture, which may be ultimately related to a southward shift in the extratropical storm track [10]. When both minimum and maximum temperature increased at some locations of southern Africa, the magnitude of maximum temperature increase was greater than that of minimum temperature. The interaction of atmospheric and SSTs from both oceans increases the complexity of identifying the drivers of such phenomena [66]. Identification of the current drivers of minimum and maximum temperature in addition to solar radiation at the local level is paramount for a better understanding of current trends and the designing of more robust and appropriate adaptation and mitigation measures for agricultural systems. Some locations experienced insignificant decreases in maximum temperature. The contrasting trends of increasing and decreasing temperature at some locations suggest that generalizing temperature trends across locations in the same region is inappropriate; therefore, adaptation and mitigation strategies should be tailored to specific localities. Additionally, the use of current trends complemented by future climate change projections is therefore important for designing adaptation and mitigation strategies in southern Africa. Additionally, coupling measured/observed and downscaled time series climate data could be ideal for future studies in order to achieve a more robust assessment of current temperature trends in future. This will unravel the decades or years that have experienced significant upward temperature changes. A study by [67] revealed more warming during June–August and September–November periods before the year 2000. Recent warming on the African continent has also been associated with the *El Niño* phenomenon [5] and its increased frequency of occurrence has impacted negatively on water resources and agriculture. The decrease in maximum temperature at Pemba, but not at Quelimane before 1980, confirms the spatial variations in changes taking place even when locations have the same general conditions.

4.2. Implications for Agriculture and Water Resource Management

Southern Africa is projected as a climate change hotspot for temperature increases and drying as is reported in some of the recent studies [61,68]. With the ongoing climate variation and change as also evidenced by temperature increases in this study, temperature increases will likely impact negatively and to varying degrees on different components of the agri-food systems as well as water and other natural resources in Southern Africa. Therefore, it is paramount to develop resilient agri-food systems in the region for the future. The changes in temperature in the study have proven to be mostly location specific and varying between locations. This is also confirmed in the 2018 IPCC Special Report on global warming [68]. Blanket interventions to reduce the impact of changing temperatures across the different agricultural sectors may, therefore, not be effective because components of the agricultural systems will be affected differently. There is a need for agro-ecology specific coping and adaptation options to improve the efficiency of adaption strategies [69].

4.2.1. Crop Production and Grain Storage

Both minimum and maximum temperatures can negatively influence crop production. An increase in minimum temperature promotes losses in the stored sugars in plants and negatively impacts the final crop yield [15,33]. With regards to the main food security cereals (maize, wheat, rice), increased minimum temperature can affect the critical grain yield determination stages leading to low yield [16,70]. Warming during the night will negatively affect fruit production and some horticultural crops [16,34]. Some fruit tree species require adequate chilling hours for flowering to commence and this requirement might not be met in the face of increasing minimum temperatures, which are usually experienced during the night [35,36]. Increasing maximum temperatures will introduce heat stress to the field and horticultural crops which were developed to deal with mainly drought, salinity and inherently low soil fertility stresses. The current risks presented by fall armyworm and locusts, as well as diseases such as maize leaf necrosis, are likely to be worsened by the general warming taking place in southern Africa. A study by [43] indicated that ambient temperature coupled with humidity significantly influences the effectiveness of grain storage technologies. With the increasing night and daytime temperature, grain damage is set to increase, especially in the traditional storage structures used by smallholder farmers in southern Africa. This will potentially lead to consequences of high storage loses and costs as well as low profitability.

4.2.2. Livestock Production

There are predictions of higher risks of undernutrition in communities that depend on dryland agriculture and livestock in southern Africa due to increased temperatures [68]. A 2013 review on climate change and livestock concluded that livestock production in Africa and southern Africa is vulnerable and at high risk of being severely affected by climate change [70]. Air temperature affects the productivity of ruminants and monogastric farm animals. The productivity of goats, sheep and cattle is drastically reduced by high daytime temperature as the animals undergo a body cooling process. Under heat stress animals take less feed and less water if the water temperature is above 21 °C [71]. This results in reduced growth and the overall productivity of the animal. In addition, sweating due to high ambient temperature promotes loss of body fluids from the animal and this upsets the overall functioning of the body. High daytime temperature and heat waves are more detrimental to large-bodied farm animals such as cattle, and farmers need to diversify livestock species in the face of the general warming being experienced and projected to increase in southern Africa, Africa and globally. Cattle exposed to long hours of heat stress reportedly produce beef of poor quality and shorter shelf-life, while milk yield and quality also decrease in dairy farming systems. In livestock systems, high temperature also promotes increased infestation of pests such as ticks [41]. Temperature increases are also likely to have negative impacts on the availability of livestock forage. Rangelands in the arid tropics have been projected to undergo a reduction in the length of growing period by more than 20% between 2000 and 2050 [72]. Even in cultivated pastures, there are likely to be challenges as a result of the increased demand for irrigation water due to high evapotranspiration rates.

4.2.3. Aquatic Animal and Plant Production

Aquatic life will be adversely affected by rising temperatures in the coming decades [36]. Warm water due to increasing temperature will hold less dissolved oxygen for aquatic animal species and less carbon dioxide for plant species [73]. In addition, high water temperatures might render some dissolved compounds poisonous to some aquatic animal and plant species [74]. Aquatic species tolerant to warm water will thrive, while those that are intolerant will become extinct. In the process, beneficial animals and plants will be lost due to the warming of the aquatic habitat. An increase in water temperatures might also promote higher growth rates of some animal and plant species [75], which will in turn increase demand for dissolved nutrients, oxygen and carbon dioxide. The supply of these resources might not meet the demand, leading to low productivity or even the death of some species. Consequently, food chains will be affected and altered in the aquatic habitat. For example, zooplanktons might grow faster than their food supply derived from *phytoplanktons*, triggering detrimental changes to the food web in the aquatic habitat [76].

4.2.4. Agricultural Water

The general warming of southern Africa and the rest of the world threatens reliable agricultural water supply. High temperatures and low precipitation are likely to result in the reduction of water availability for rainfed agriculture [32]. The challenge posed by increasing temperatures is being compounded by erratic rainfall [77], which has become highly variable between seasons and spatially in southern Africa and the rest of SSA. Climate models project decreases in annual precipitation for southern Africa to be by as much as 20% by the 2080s, and this will result in reduced water availability and crop yields [78]. High daytime temperature and evaporation coupled with erratic rainfall results in reduced surface water storage. It is projected that agricultural water supply will dwindle in semi-arid and sub-humid highland areas of southern Africa [79]. This will in turn affect crop productivity in irrigated systems and yields are projected to decline [80]. Integration of water harvesting techniques and soil moisture conservation with other climate change adaptation and mitigation strategies is critical on both small- and largescale farms in southern Africa. At the field level, soil moisture supply to crops is threatened by high evaporation due to increased daytime temperature and lack of soil cover [81]. At the watershed level, high soil evaporation due to high temperature and low land cover alters runoff patterns which are critical for the refilling of rivers and dams. Prevailing daytime temperature in southern Africa is already driving potential evapotranspiration rates of 5–10 mm day^{-1} in semi-arid and 3–4 mm day^{-1} in sub-humid highlands [81]. Catchment management strategies that facilitate river and groundwater recharge are, therefore, imperative for the future of sustainable irrigation systems.

5. Conclusions

Minimum and maximum temperatures were highly variable between 1947 and 2019 at some coastal, arid, semi-arid and sub-humid parts of southern Africa. Minimum temperature was more variable than maximum temperature under the ecological conditions of selected locations used in this study. The variation in minimum temperatures was higher under semi-arid conditions than in humid and coastal environments. Both minimum and maximum temperatures increased significantly at most of the locations between 1940 and

2019. Significant minimum temperature increases of 0.01–0.83 °C over a 33–38 year period occurred at nine locations of the southern African countries used in the study. Similarly, significant maximum temperature increases of 0.01–0.09 °C over a 38–57 year period at 15 locations also occurred at the same time. A significant decrease in minimum temperatures (0.03–0.20 °C over 38–41 years) occurred at two locations in South Africa and Dedza in Malawi, while a non-significant decline in maximum temperature (0.01 °C over 54 years) occurred at Pemba along the coast of the Indian Ocean.

There is evidence from various studies that southern Africa is vulnerable and at high risk of being severely affected by climate change due to temperature increase, and there are indications that the consequences for agriculture and food security are negative. Many of the studies are, however, part of global predictions with few studies looking at localized implications of temperature increase. The results of this study highlight the importance of including local temperature variations when designing climate change and variability adaption and mitigation strategies under the different agro-ecological conditions of southern Africa and similar environments. Future studies could focus on coupling measured/observed and downscaled time series climate data in order to achieve a more robust assessment of current and future temperature trends.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/cli11040084/s1, Table S1: Minimum Temperature Results of the original and modified tests. Table S2: Maximum Temperature results of the original and modified tests.

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