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ARTICLE INFO

Citation:
Jimmy R, Govender P, Bencherif H, Moodley KM (2019) TREND-RUN model application of surface temperature and its implications for South African forestry using local weather services data. Reforesta 7: 50-72.
DOI: http://dx.doi.org/10.21750/REFOR.7.05.67

Editor: Vladan Ivetić, Serbia
Received: 2019-06-06
Accepted: 2019-06-24
Published: 2019-06-28

Abstract

Temperature can directly and indirectly impact the livelihood of inhabitants of a country and the natural environment as a whole. The surface temperature trend approximations for South Africa (SA) were calculated using a linear-regression fitting model. The model was adapted at The University of Reunion Island and was referred to as the Trend-Run model. The geophysical signal of the model was split into a sum of oscillations, which was used to clarify most of its variability. The trend values were calculated from the residual terms as a linear function. The model used atmospheric oscillations, which included Annual (AO), Semi-Annual (SAO), Quasi-Biennial Oscillations (QBO), El Niño-Southern Oscillation (ENSO), the 11-years solar cycle-Sun Spot Number (SSN) and Indian Ocean Dipole (IOD). The South African Weather Service (SAWS) data were used for the study. Data sets over a 31-year period, from March 1980 to December 2011, were used to measure the validity of the Trend-Run model, to determine the contribution and effect of this particular oscillation, and the validity of the model. The Trend-Run model showed very high applicability to the surface temperatures in all provinces across the SA region under investigation. High coefficient of determination values between (0.70-0.91) were recorded for surface temperatures across all provinces in the country with minor variations. The AO, ENSO and SAO were the highest contributing forcings in the model, thereby showing their high relevance to the success of this model in the study area. The temperature increases are expected to negatively impact on the biomes of SA, including the forest biome. Selected tree species of *Acacia*, *Eucalyptus* and *Pinus* could be impacted negatively with rising temperatures, which would negatively impact on the forestry industry in SA. As expected, the model did obtain a high success rate that ranged from 70% to 91% in the areas under study, however, there was still room for improvement by the possible inclusion of additional atmospheric forcings to the model that maybe be applicable to the weather and forestry distribution in SA.

Keywords

Atmosphere measurements; Simulation; Atmospheric forces; Oscillations; Acacia; Pinus; Eucalyptus; Surface temperature

Contents

1 Introduction

Africa is one of the most susceptible continents to climate variability, a situation that is intensified by the interaction of 'numerous stresses' that arise at a variety of levels and with little adaptive capability (IPCC 2007a). Southern Africa is considered as one of the most susceptible regions in Africa (IPCC 2007b). Increases in temperature have the potential to actively impact human health across the continent, since it is generally anticipated that, as the planet heats, climate variability will intensify (Garland et al. 2015). Variations in the occurrence of unforgiving life-threatening climate events and the variability of weather configurations were predicted to have substantial challenges for biotic and abiotic factors (Lewis and King 2017). Future cumulative occurrences of heat stress, drought and flooding instances were predicted, and these were projected to have detrimental effects, especially from variations in mean temperature. Climate system warming can result in very large corresponding changes in climate extremes.

General Circulate Models (GCMs), which make use of the recognized fundamental standards of physics, are often used to interpret weather adjustments and worldwide warming (IPCC 2007c). These studies indicated that anthropogenic forcing was the major contributor to climatic modifications over the last century (Scafetta 2010). However, these results are questionable because the GCM simulations failed to reproduce the oscillations observed in the climate phenomena at different scales on the ground since 1850 (Scafetta 2010). It was maintained that climatic oscillations articulate at multiple time scales with astronomical cycles (Scafetta 2010). The existing GCMs of the climate therefore do not embrace vital astronomical forcings (Scafetta 2010). Subsequently, climate changes due to natural causes may still be severely underestimated (Scafetta 2010). Past developments in climatic variables are of interest in a variety of educational disciplines and financial sectors; alongside ecology, agriculture, forestry and water aid management. Several studies have investigated climatic developments in South Africa, primarily focusing on station data of temperature as well as diverse indices derived from those portions (IPCC 2007c). The greatest limitation to such studies of historic climate is the provision of lengthy-term meteorological station observations that have sufficient coverage to give a justifiable illustration of weather in a vicinity. South Africa has a strong network of rainfall and temperature recording stations compared to most countries in the southern hemisphere, which makes it possible to investigate developments and variability over several decades. However, it is often difficult to get clear signals of long-term adjustment because of large variability across a range of spatial and temporal scales (DEA 2013). Many researchers in atmospheric science have recently been studying climatic trends over extensive terms (IPCC 2007c) but the physical mechanisms and characteristics have not yet been clearly established; including the current climate models. The linear-regression fitting model (hereafter referred to as Trend-Run) was applied using the selected data sets to calculate the relevant values and temperature trends at selected regions (Sivakumar et al. 2017). The Trend-Run is a statistical model that was adapted at The University of Reunion Island for temperature trend approximations in the southern subtropical upper troposphere and lower stratosphere (UT-LS) region (Bencherif et al. 2006).

The intergovernmental panel on climate change (IPCC) found that global temperatures have been increasing by a rate of 1.5°C per decade, which is very concerning for abiotic and biotic factors on the earth (IPCC 2018). Hugues and Balling (1996) showed a maximum temperature increase of 0.11°C per decade between 1960 and 1990. There was also a significant increase in temperature over three weather stations in the Limpopo province of South Africa between 1960 and 2003 (Kruger and Shongwe 2004). A model simulation study by Engelbrecht (2005) showed an escalation in temperature in South Africa of 1 to 3°C and 1 to 2°C in summer and winter, respectively.

Temperature and its variability can influence numerous processes in the hydrological cycle, such as rainfall, which is a vital resource for agricultural and forestry practices in a country. The forest biome overlaps with a number of bioregional programmes for provinces such as the Cape, KwaZulu-Natal (KZN) and Mpumalanga (DWAF 2005). Two of these regions were identified by Conservation International as global biodiversity regions with high levels of endemism (DWAF 2005). A wide range of climatic conditions and variations in topography and vegetation exists in SA and this gives rise to broad vegetation zones. It has been projected that South Africa's biodiversity will be adversely affected by climate change in the medium- to long-term (DEA 2015a). It is against this background that creating a conducive environment adaptation of climate change is recognized as a crucial area of intervention by the Government of South Africa. As such, expanded opportunities now exist to think more broadly about climate change responses in these areas, including different responses for different biomes (DEA 2015b). The SA bioclimate showed that warming and trends in aridification are strong enough to decrease the area of the country's biomes to between 38 and 55% of their current combined surface area; especially in the western, central and northern parts of the country where the largest losses can be expected (Rutherford et al. 2000). The areas studied in SA had high levels of terrestrial and aquatic biodiversity; the Cape and KwaZulu-Natal Provinces had some of the highest biodiversity of plants in the world and high levels of endemism. Along the eastern seaboard of SA, there are high levels of aquatic biodiversity, which play an important role in the economy of the associated towns and cities (de Moor and Day 2013). Forestry research has demonstrated that South African forests have the largest biodiversity of any temperate forested region in the world (Silander 2001). The national biodiversity importance of South African forests is not always recognized nor given the appropriate attention. The forested areas in SA has been up to seven times richer in species than any other forested area in the Southern Hemisphere, even though these forests cover a much larger surface area. When the number of plant species (occurring within each of the six biomes in SA) are correlated to the total area covered by each biome, this results in the forest biome having the highest concentration of species (3,000 species in approximately 5,052 km^2, as opposed to the next highest, fynbos with 7,500 species on 76,744 km^2) (DWAF 2005). Trend investigations of temperature and interrelated variables are critical in the creation of future climatic settings and management practices (Jain and Kumar 2012). Throughout Africa, rainfall and vegetation are known to resonate with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), coupled with ocean-atmosphere phenomena. However, the regional-scale repercussions of surface temperature changeability for photosynthesis in Africa have not received motivated consideration, especially IOD. The first possibility for the IOD is created by a feedback joined with ocean-atmosphere monsoon and tropical circulation (Saji et al. 1999). The second possibility considers the IOD as part of an Indo-Pacific ENSO (Behera and Yamagata 2003). According to Owiti et al. (2008), some of east Africa's extreme rainfall conditions were related to the negative and positive phases of the IOD. This kind of climate information could assist to progress monitoring, prediction and early warning of extreme rainfall events and reduce adverse impacts of climate extremes over east Africa. A more recent study has established that the IOD is now acknowledged as a foremost climatic influence and should be considered in the southern Indian Ocean (Morioka et al. 2010). However, it must be stressed that these studies have not addressed any quantitative influence of the diverse atmospheric forces in the values of the temperature trend. Therefore, the aim of the present study was to determine whether the Trend-Run model was applicable to the surface temperature over SA in general. Our objectives were: (1) to assess the performance of the model on the surface temperature using historical data sets from the South African Weather Service (SAWS) stations from all provinces for the period from March 1980 to December 2011; (2) to assess the weighted relevance of atmospheric forcings on the model in various regions of the country; and (3) to determine the decadal trend values and compare them to the literature and possible effects of selected commercial forest species in SA.

2 Material and methods

2.1 Study sites and population of data

This study was performed on monthly averages of surface temperature from selected meteorological stations in the nine provinces of South Africa; covering the period of March 1980 to December 2011 (Figure 1). The chosen study sites had a complete dataset and were continuous (with no gaps in the datasets). The 29 weather stations were selected because they ranged from a 100 km to 300 km apart as shown in Figure 1. The data was obtained from the South African Weather Service (SAWS) in Pretoria, South Africa. The data was screened from the stations and the raw data went through quality checks to evade syntax errors, ensure internal reliability, remove extreme outliers and exhibit spatial coherency. The obtained daily data-sets were averaged over a month and weather stations with incomplete data sets were excluded from the study. Due to the consistent nature of data obtained from the selected station (directly from a designated official at SAWS), the data sets were considered to be of good value and satisfactory for the study. The data was arranged in 12 month blocks for a total period of approximately 31 years for surface maximum temperature for each station. This followed the parameter set by the World Meteorological Organization (WMO) as the period for averaging these variables (30 years) (WMO 2017). The geographical coverage of stations used in this study is shown in Figure 1.1.

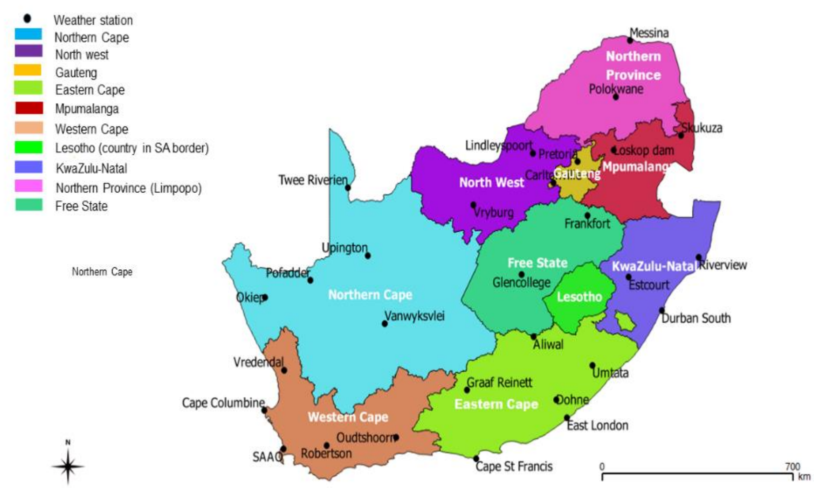

Figure 1.1 Geographical location of the 29 weather stations used in this study in all provinces of South Africa.

2.2 Trend-Run model

Trend-Run is an algebraic model that was modified and used at The University of Reunion Island for temperature trend estimates in the southern subtropical upper troposphere-lower stratosphere (UTLS) (Bencherif et al. 2006). The model was based on the principle of breaking down the variations of a time series signal (in our case, Temperature) Y (t) into the sum of the different parameters that describe the variations of Y (t):

$$Y(t) = c_1\,SAO(t) + c_2\,AO(t) + c_3\,QBO(t) + c_4\,ENSO(t) + c_5\,SSN(t) + c_6\,IOD(t) + \varepsilon$$

Where, ε represented the residual term and $c_{i\ (i = 1\ to\ 6)}$ represented the various considered atmospheric force coefficients. Once the coefficients $c_{i\ (i = 1\ to\ 6)}$ were calculated, the analogous parameters were detached in the model and the least-square method was applied to minimize the sum of the residual squares and to determine the parameter coefficients c_i. The trend was parameterised as linear and regarded as: $Trend(t) = \alpha_0 + \alpha_1 t$, where t denoted the time series, α_0 was a constant, α_1 was the slope of Trend (t) line that estimated the trend over the time scale. The former version of the model utilised only the main oscillations, such as: annual and semi-annual oscillations (AO and SAO, respectively), QBO (quasi-bi-annual oscillation), ENSO (El-Niño-Southern Oscillation), and the 11-years solar cycle-Sun Spot Number (SSN). AO and SAO were considered to be mean seasonal cycles. The model further used South Oscillation Index to parameterize the QBO (Randel and Cobb 1994; Li et al. 2008) and the ENSO cycles, respectively. The SAO in the tropical region above 35 000 m above sea level was the strongest mode of annual variability. This SAO was initially detected in temperature and zonal wind in the data recorded in the 1960s (Reed and

Rogers 1962; Reed 1966). The amplitude of the SAO usually declines with an increase in latitude, however, it can recuperate in the subtropics, which is dependent on the altitude. The IOD resemble the inter-variability existing in the Indian Ocean, with an east-west dipole in the sea surface temperature (SST) anomalies of the basin. One of the mechanisms responsible for the IOD is that the eastern Indian Ocean can become abnormally cold, anomalous winds blow from east to west along the equator and south eastward of the coast of Sumatra causing a thermocline and a mixed layer lift up in which the atmospheric convection gets inhibited during certain years (Saji et al. 1999; Morioka et al. 2010). This coupled ocean-atmospheric phenomenon in which convection, winds, SST and thermocline actively take part in, is known as the IOD. The IOD is commonly measured by an index called the dipole mode index (DMI), which is defined as the SST anomaly difference between the western (50°E-70°E, 10°S-10°N) and eastern (90°E-110°E, 10°S-Equator) tropical Indian Ocean (Sivakumar et al. 2017). In order to consider the IOD in the Trend-Run model, we used DMI from the Japanese agency for marine - earth science and technology (http://www.jamstec.go.jp/frsgc/research/d1/iod/dmi.html). The coefficient of determination (R^2) is a vital coefficient to recognize since it affords total information about the capability of the regression model to explain variance in the result. The decadal trend values in degrees Celsius were also calculated to see if there was any change in the temperature increase or decrease over time. For more information about the use Trend-Run model and forcing parametrisation, the reader may refer to the works published by Bencherif et al. (2006) and Bègue et al. (2010).

3 Result and discussion

Climate change effects are uncertain in southern Africa (Fairbanks and Scholes 1999). The commercial forestry industry in South Africa is sensitive to global warming since only 1.5% of the country, under present climatic conditions, is appropriate for tree crops (Fairbanks and Scholes 1999). Additionally, the relatively extended time frame between planting and yield (rotation) renders tree plantations more susceptible to any environmental adjustment. The potential effects of climate change were modelled on pines and eucalypts as the main tree species in South Africa by Warburton and Schulze (2008). Different climate prediction models all indicated that there is a temperature increase over the forestry constituencies of the country (Warburton and Schulze 2008). Predictions regarding rainfall are more divergent; a rise in precipitation seems more probable in forestry areas in the eastern part of the country (Warburton and Schulze 2008). Probable climate change possibilities to determine their potential effects on the forest industry found that declining rainfall with rising temperature was detrimental to forest growth, whereas rainfall increases offset all adverse impacts of temperature (Warburton and Schulze 2008). This simultaneously increased the optimal growing conditions for the total area under both pines and eucalyptus (Warburton and Schulze 2008). Long-term and regional outlooks of forest ecology, biogeography and conservation management are important considerations in SA because of its high levels of biotic and abiotic diversity (ISRIC 2013). The altitudinal and latitudinal distribution of forests and vegetation types display substantial sensitivity to climate change (ISRIC 2013). Forest preservation in the long-term requires reserves in areas with good climate allowing for viable forest management strategies (Eeley et al. 1999). Climate change make forests most vulnerable to climate change and extremes in the regeneration phase and it is imperative to take projections of climate change into consideration in future reforestation programs (Ivetic and Devetaković 2016). As new regions turn out to be climatically appropriate for forestry, the geographical location of the industry to match areas of optimum potential should be shifted to the new favourable regions (Kiker 2000). Heat and drought resistant hybrids could be developed by genetic engineering to offset the danger of climate change (Kiker 2000). According to Jewitt et al. (2015), the future climate developments encourages an understanding of the series and degree of climate change impacts. The incorporation of habitat loss and climate change into a framework that can be developed to inform appropriate conservation actions, mitigate climate change impacts on biodiversity and facilitate dynamic conservation planning in South Africa.

3.1 Model application and uncertainty

There is potential to improve the understanding of atmospheric interactions with the current data sets. In general, all data sets have some organized biases and reservations and their usefulness will depend on a particular application. Simplified representations of regional climate models in reality are often founded on insufficient input data and doubts in parameter values and reduced mathematical depiction of processes. Henceforth, caution must be applied when using any of these data sets. A vital science question that now arises is how predictive doubt can be recognized, quantified and eventually reduced for climate change modelling? Uncertainty evaluation is compelled by the need to contribute towards an accurate and/or optimum basis for decision making.

3.2 Trend-Run model efficiency

Table 2 depicts a summary of the values for the contribution coefficients for different forcings (SAO, AO, QBO, IOD, ENSO and SSN) expected to drive the most of surface temperature variability. The corresponding R^2 values are reported in Table 1. The model coefficient of determination for the Trend-Run model performed (on average) the highest (Vanwyksvlei-0.91, Oudshoorn-0.90) over the Northern Cape and Western Cape respectively; with the lowest R^2 values (Dohne-0.72, Umtata-0.70) being recorded in the Eastern Cape as compared to the rest of the country (Table 1). This was a significant finding as the model recorded both the highest and the lowest overall values in the provinces of the Cape. There was no relationship between the spatial distribution (geographical coordinates) and model performance (coefficient of determination values) in the study as the results were inconsistently randomly distributed throughout the country as illustrated and demonstrated in Figure 1. and Table 1 respectively. However, the model was found to perform efficiently; this was based on the high coefficient of determination values, which ranged from 0.7 to 0.91 in this study (Table 1). These results showed that the model is highly applicable in all provinces across South Africa.

Table 1. The corresponding values for the coefficient of determination (R^2) and geographical coordinates for the 29 weather stations in all nine provinces (Northern Cape-NC, Western Cape-WC, Eastern Cape-EC, KwaZulu-Natal-KZN, Free State-FS, North West-NW, Mpumalanga-MP, Limpopo-LP and Gauteng-GT) for surface temperature over South Africa.

Meteorological Station name (Province)	Latitude Decimal degrees	Longitude Decimal degrees	R^2
Vanwyksvlei (NC)	-30.35	21.82	0.91
Oudtshoorn (WC)	-33.60	22.20	0.90
Aliwal (EC)	-30.72	26.72	0.89
Okiep (NC)	-29.60	17.88	0.89
Graaf Reinett (EC)	-32.25	24.53	0.89
Glencollege (FS)	-28.95	26.33	0.88
Vredendal (WC)	-31.67	18.50	0.88
Upington (NC)	-28.40	21.27	0.87
Durban South (KZN)	-29.97	30.95	0.87
Twee Riverien (NC)	-32.03	20.52	0.87
South African Astronomical Observatory - SAAO (WC)	-33.93	18.48	0.86
Carltonville (GT)	-26.33	27.38	0.84
Pretoria (GT)	-25.73	28.18	0.84
Cape Columbine (WC)	-32.83	17.86	0.84
Polokwane (LP)	-23.87	29.45	0.83
Estcourt (KZN)	-29.02	29.87	0.81
Vryburg (NW)	-26.95	24.75	0.81
Robertson (WC)	-33.83	19.90	0.81
East London (EC)	-33.03	27.83	0.81
Riverview (KZN)	-28.45	32.18	0.80
Lindleyspoort (NW)	-25.48	26.70	0.80
Messina (LP)	-22.27	29.90	0.78
Cape St Francis (EC)	-34.20	24.83	0.77
Loskop dam (MP)	-25.40	29.37	0.77
Frankfort (FS)	-27.27	28.50	0.76
Skukuza (MP)	-24.98	31.60	0.75
Pofadder (NC)	-29.12	19.38	0.75
Dohne (EC)	-32.52	27.47	0.72
Umtata (EC)	-31.53	28.67	0.70

The lengthy-time period oscillations observed for each wind and temperature consisting of annual, semi-annual, and quasi-biennial oscillations (AO, SAO, and QBO), are important functions in this dynamic vicinity (Mayr et al. 2010). The SAO is a vital oscillation, particularly around the equator and peaks at the stratosphere and mesosphere (Remsberg et al. 2002). The forcing mechanism of SAO is beneficial for generating knowledge of the numerous functions inside the meridional structure and the seasonal march of the SAO. Since the sun crosses the equator twice a year, the SAO can be generated via motion advection from summer time to the winter hemisphere (Holton and Wehrbein 1980). The results of the coefficient values in Table 2 allows one to deduce that the AO was a dominant factor (~52% in average) and this was followed by the ENSO (~11% in average). The highest SSN contributions over SA in this study was recorded in the Western Cape at (Table 2), indicating that it has a little contribution to the temperature variability across the country; with the exception of the Eastern and Western Cape Provinces. There was scientific agreement that only a trivial part of current climate change could be attributed to the solar cycle (IPCC, 2013). However, this reason did not appear to be applicable to certain areas of the Cape. For all the study sites the AO is a dominant forcing. Its contribution is within 35%-65% and, as one may expect, it is increasing southward as illustrated in Figure 1.2 and Table 2. With regards to the SAO, its contribution is less than the ENSO one. The SAO contribution is found to be quasi-constant (about 8,8% ±2,5% (Table 2) in average) for all locations. In fact, the ENSO forcing appears as the 2nd important one, and shows more variability across the country (Figure 1.3) than the SAO (ENSO averaged contribution is about 11.22% ±5,6% (Table 2). In fact, ENSO is known to drive regional climate variability and may have impact on agriculture and forestry. Figure 1.3 illustrates how the ENSO contributions increase northward and eastward. The North-East SA provinces seem to be the most exposed to ENSO effects.

Table 2. Contribution (in percentages) of SAO, AO, QBO, IOD, ENSO and SSN (11-year solar cycle) and decadal trend values, as obtained by the linear regression Trend-Run model at 29 weather stations in all provinces of South Africa for surface temperature: Northern Cape-NC, Western Cape-WC, Eastern Cape-EC, KwaZulu-Natal-KZN, Free State-FS, North West-NW, Mpumalanga-MP, Limpopo-LP and Gauteng-GT.

Station name and Province	Temperature						
	SAO (%)	**AO (%)**	**QBO (%)**	**IOD (%)**	**SOI (%)**	**SSN (%)**	**Trend (°C/decade)**
Pretoria (GT)	13.75	48.81	1.26	5.57	12.28	2.54	0.84
Twee Riveren (NC)	8.89	61.51	0.02	2.99	11.29	2.30	0.77
Oudtshoorn (WC)	9.36	69.34	3.29	0.39	4.54	2.55	0.60
Vredendal (WC)	10.34	57.84	1.60	9.53	3.98	4.25	0.59
Messina (LP)	8.83	35.88	2.64	4.95	20.42	5.48	0.57
Skukuza (MP)	7.67	36.10	2.74	5.39	20.82	2.11	0.49
Upington (NC)	6.41	57.33	1.05	3.52	12.84	0.25	0.48
Polokwane (LP)	12.26	41.35	2.45	4.29	19.41	3.21	0.43
Robertson (WC)	3.57	54.18	1.34	2.49	8.93	10.12	0.38
Dohne (EC)	7.78	44.86	3.00	2.98	10.05	3.17	0.37
Carltonville (GT)	12.25	44.57	2.66	3.62	16.42	4.02	0.35
Aliwal (EC)	8.24	64.17	0.55	0.88	10.30	5.02	0.33
Pofadder (NC)	4.26	51.56	0.94	3.77	9.46	5.07	0.33
Umtata(EC)	9.33	42.09	0.25	4.63	10.70	2.93	0.31
East London (EC)	7.44	56.30	1.25	2.82	8.78	4.03	0.26
South African Astronomical Observatory - SAAO (WC)	5.48	67.96	0.83	3.16	0.41	8.01	0.24
Riverview (KZN)	6.34	42.63	1.32	4.75	17.54	6.98	0.23
Graaf Reinett (EC)	6.63	66.94	1.09	0.25	12.51	1.15	0.18
Cape Columbine (WC)	6.66	65.60	1.90	2.31	0.42	7.05	0.18
Frankfort (FS)	11.11	41.94	0.53	3.38	18.07	0.67	0.15
Estcourt (KZN)	10.93	51.16	0.80	3.50	11.42	3.55	0.13
Glencollege (FS)	9.01	60.26	0.25	2.70	9.82	5.89	0.12
Durban South (KZN)	6.40	59.27	0.14	8.16	9.89	3.27	0.11
Vryburg (NW)	8.47	50.74	2.34	1.68	10.10	7.60	0.07
Vanwyksvlei (NC)	7.27	65.52	0.09	6.45	9.55	1.79	0.07
Cape St Francis (EC)	11.28	43.69	0.65	8.32	12.76	0.54	0.07
Loskop dam (MP)	13.47	34.21	4.97	5.56	14.91	3.47	0.06
Okiep (NC)	10.81	64.14	2.02	8.09	0.71	2.81	-0.25
Lindleyspoort (NW)	9.87	34.72	3.26	10.35	17.14	4.13	-0.38

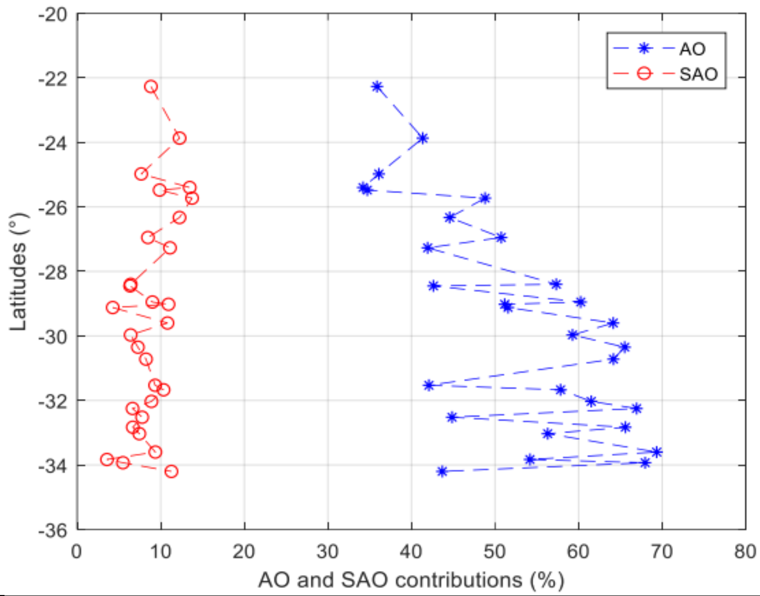

Figure 1.2 Annual Oscillation (AO) increasing southwards in the country.

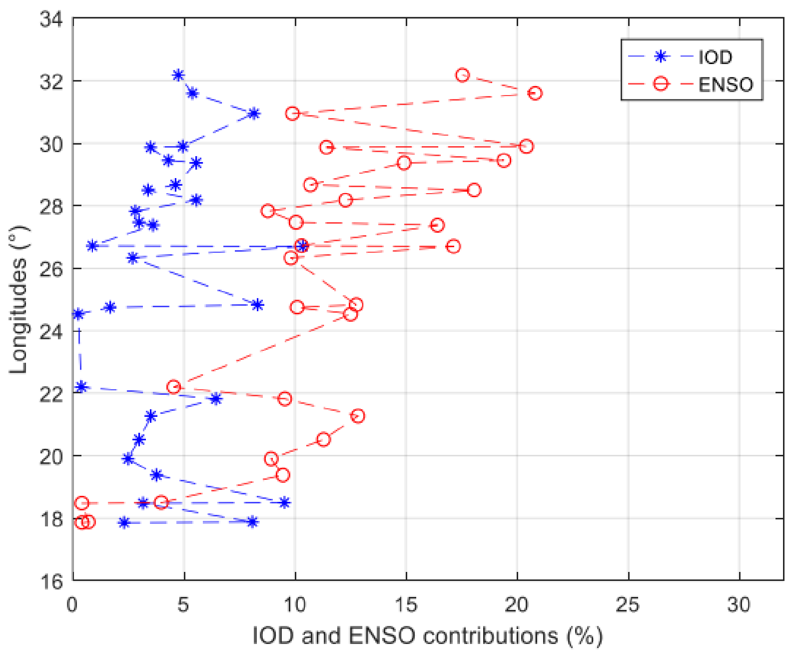

Figure 1.3 ENSO (El-Nino Southern Oscillation showing high variability as it increases across the country.

The highest SAO contributions were found in Gauteng and Limpopo (Table 2). The QBO had little or no effect on the model performance as seen from the AO and SAO contributions (Table 2).

3.3 The possible impact of the decadal trend values on commercial forestry species in South Africa

The decadal trend values calculated by the Trend-Run model ranged between -3.8°C and 0.84°C per decade throughout the country (Table 2). Coastal stations and inland stations did not create a distinctive pattern in the decadal trend distribution throughout the country (Figure 1.4). Some weather stations under investigation along the coasts (Eastern and Western Cape) and interior part (Mpumalanga, Limpopo, Northern Cape and Gauteng) of SA had decadal trend values (Table 2) congruent to the work by Spear et al. (2015), who found increases in temperature of approximately 0.4 to 1.4°C along the coasts and certain areas of central South Africa (Figure 1.4). These current increases in the temperature trends could also have dire consequences such as increased evaporation during drier periods, which can subsequently impact the quantity of available drinking water, water resources and agriculture (Prokić 2018). During the 20th century, the presence of breaks in global and hemispheric temperatures have been deliberated extensively in the climate literature. However, this was not always formally studied using the time series properties set by the World Meteorological Organization (WMO) (IPCC 2013). The long time periods associated with decisions developed in the forestry industry and the timing and the magnitude of global warming will need to develop strategies for adaptation (Bennett and Kruger 2013). These strategies will vary with area and time frames (Bennett and Kruger, 2013). Whilst the indigenous forests in SA provide aesthetic and conservation values, they arguably do not contribute as much to the economy as the commercial forestry sector, which introduced exotic tree species for timber in the early 19th century (van der Zel 1995; Bennett and Kruger, 2013). A number of non-invasive species were introduced more than a century ago in SA (Forsyth et al. 2004), and there is no scientific literature to demonstrate the invasiveness in SA by eucalypt hybrid clones. Subsequently, the eucalypt tree is a good option for land use that could assist in the rendering of ecosystem services such as animal shelter on farms and pollination services (De Lange et al. 2013; Harper et al. 2017).

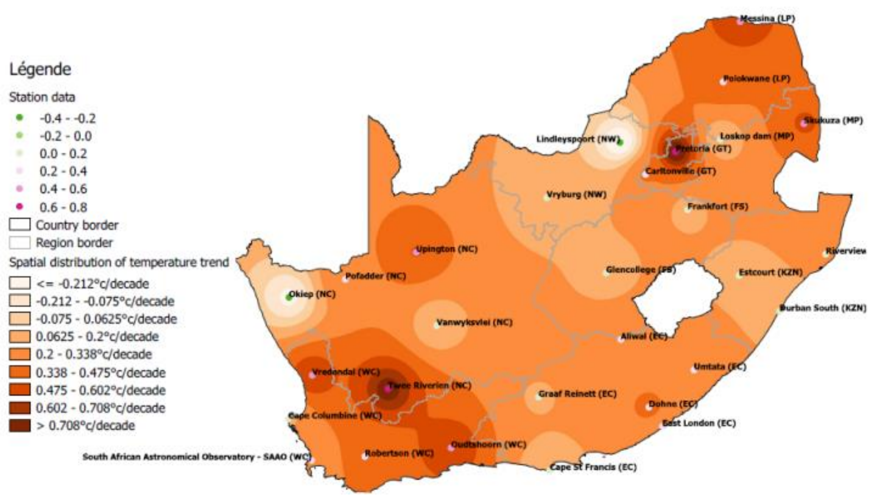

Figure 1.4 °C per decade (March 1980-December 2011) distribution across all weather stations and provinces in SA.

The Australian *Acacia mearnsii* and the fast growing *Eucalyptus grandis* were introduced to supply wood for the country (Scott and Gush 2017). *Acacia mearnsii*, which is known as black wattle, is well researched in SA and of the locally grown commercial hardwoods, is the most drought resistant. It requires a mean annual temperature (MAT) of 16-19°C for its growth (Schulze and Davis 2014). The tree is grown optimally in the regions of KZN, Eastern Cape and Mpumalanga in SA (Schulze and Davis 2014). The climatically prime area for *A. mearnsii* production is in KwaZulu-

Natal and southern Mpumalanga under the present climate conditions. As the temperature increases and rainfall is decreased, the climatically optimal production areas are expected to decrease and also reduce tree growth (Warburton and Schulze 2008). However, if the temperatures increase with rainfall, then the tree growth will be increased subsequently (Warburton and Schulze 2008). The same prediction but with greater variation was predicted for the Eastern Cape. However, the climatically optimum area for *A. mearnsii* in Mpumalanga increases when the temperature increased by 1°C and 2°C; perhaps due to the decrease in frost occurrence (Warburton and Schulze 2008). The Trend Run Model in this study has demonstrated a range of temperature increases between 0.06°C per decade and 0.49°C per decade, which could result in a decrease in *Acacia* occurrence should the rainfall be decreased by climatic conditions during that time period.

Eucalyptus dunnii is a fast growing tree for the paper and pulp industry in SA. *Eucalyptus dunnii* is disease prone and susceptible to defoliating insects when the mean annual temperatures (MAT) are greater than 19°C, and especially under drought conditions. Eucalyptus GC (*grandis* x *camaldulensis*) is a hybrid for warmer climates but is very vulnerable to frost and snow damage (Schulze and Davis 2016). The climatically optimum distribution range for GC is along the east coast of SA, which extends approximately 100 km inland to the warmer parts of Swaziland and Mpumalanga. *Eucalyptus* GC seems to be a strong hybrid consideration in future climate change scenarios. *Eucalyptus* GU (*grandis* x *urophylla*), like the *Eucalyptus* GC hybrid flourishes in warm climates with MATs > 17°C, however, GC develops optimally at high precipitation with MAPs in excess of 950 mm (Schulze and Davis 2016). The Trend run model showed a high of 0.49°C per decade increase and these hybrids of *Eucalyptus* have a greater chance of survival and will be beneficial for the forestry industry. During MATs lower than 17°C, frost damage can occur and even snow damage when the MAT is less than 16°C. *Eucalyptus macarthurii* is tolerant to frost (except when young) and can produce commercially sustainable harvests with moderately low risk on negligible sites. *Eucalyptus macarthurii* requires a MAP > 800 mm for optimum growth and when the MAT is approximately 15.5°C. Although *E. macarthurii* thrives optimally under a wide range of rainfall patterns, they are susceptible to high temperatures where conditions are dry. The increase of 0.37°C per decade could eventually detrimentally impact the growth of *E. macarthurii;* its optimum climatic belt being the KZN interior, the Eastern Cape and Mpumalanga. It is predicted that during the climatic conditions between 2045 and 2065, this species will shift further into the interior into the eastern Free State and northern areas of the Eastern Cape (Schulze and Davis 2016).

A variety of eucalypts are grown on a short rotation (8-12 years) and some species of *Pinus* are grown over longer rotations for sawlog timber (Scott and Gush 2017). The Western Cape semi-arid zone could experience more inconsistent rainfall patterns and future drier condition. Under these conditions, even regions in the wetter portion of what is now classified as the semi-arid zone could be earmarked for planting with *E. gomphocephala*, as it has shown itself to be very resilient to the summer drought (du Toit et al. 2017). It was found that frost limited the growth and distribution of *E. grandis*, which prevented its invasion of native vegetation. However, the predicted decrease in the incidences of frost because of increased winter temperatures could result in *E. grandis* becoming more invasive (Musengi and Archibald 2017).

Pinus elliottii is the most robust pine species in South Africa (Schulze and Davis 2016). It produces a durable and relatively hard timber but its marketability is limited by its high resin content. It is also the most resistant of the pine species to attacks by *Sphaeropsis sapinea* following hail damage (Schulze and Davis 2016). Its wide tolerance range to both temperature and precipitation, has enabled *P. elliottii* to cover an extensively large area from the Eastern Cape through KZN, western Swaziland, Mpumalanga, and broadening from the coast to far inland. The least tolerant is *Pinus patula*; it requires MATs > 13°C. Following hail damage*, P. patula* is very vulnerable to *Sphaeropsis sapinea* but the least susceptible to snow damage. It grows from the north eastern areas of the Eastern Cape through KZN, Free State and into Mpumalanga. *P. patula* is expected to be suitable for climates during the periods between 2081 and 2100. *Pinus taeda* is the most challenging pine species in terms of climate and soil requirements. Although it can grow in low temperatures, it is sensitive to drought*. P. taeda* maybe more resistant to hail but is most susceptible to snow damage. *Pinus taeda* grows along the north coast of the Eastern Cape, large extents of KwaZulu Natal and in certain parts of Mpumalanga. Its climatically optimum areas will increase between the years 2045 and 2065 (Schulze and Davis 2016). *Pinus taeda* is expected to be more adaptable to climate change during the periods from 2080 to 2100, with possible shifts into the interior of SA, southwards into Lesotho and certain areas of the Eastern Cape (Schulze and Davis 2016). *Pinus* hybrids are recognised as being more robust to potential increasing temperatures and changing rainfall regimes than the pure *Pinus* species (Warburton and Schulze 2008). The climatically optimal areas within KwaZulu-Natal were predicted to decrease with increasing temperatures, while areas climatically optimal for *Pinus* species/hybrids in the Eastern Cape and Mpumalanga were expected to expand under conditions of increasing temperatures (Warburton and Schulze 2008). Hence the highest recorded temperatures by the Trend run model of 0.84°C per decade (Table 2) might not negatively impact the *Pinus* hybrids, however, this will also be concurrently rainfall dependant (Warburton and Schulze 2008).

In Figure 2 (a, b, c), the measured values were congruent with the simulated values, which demonstrated that the model would work in the KZN region. The trend values range for this province was between 0.11°C to 0.23°C (Table 2) per decade increase. The significance of this finding is that unlike agricultural crops, trees are harvested between 10 and 30 years hence such increases compounded over time can decrease forest growth and adversely affect production in KZN (DWAF 2005).

In Figure 3 (a, b), the measured and simulated values were in good agreement with each other. The decadal trend values for Messina and Polokwane in the Limpopo Province are 0.57°C/decade and 0.43°C/decade, respectively. These results were closely congruent to that of the DEA (2013) which stated a 0.6°C to 0.9°C (Table 2) increase in the Limpopo Province. The DEA (2015a) stated that such a trajectory of increase would detrimentally affect agriculture, forestry and aquatic ecosystems in this province by the year 2030. The trend values from our stations in the Limpopo (Messina and Polokwane) of 0.57°C and 0.43°C (Table 2), respectively, were not congruent with the results of Tshiala et al. (2011), who found that the catchments in the Limpopo Province of SA exhibited a rise of 0.12°C/decade in the mean annual temperature.

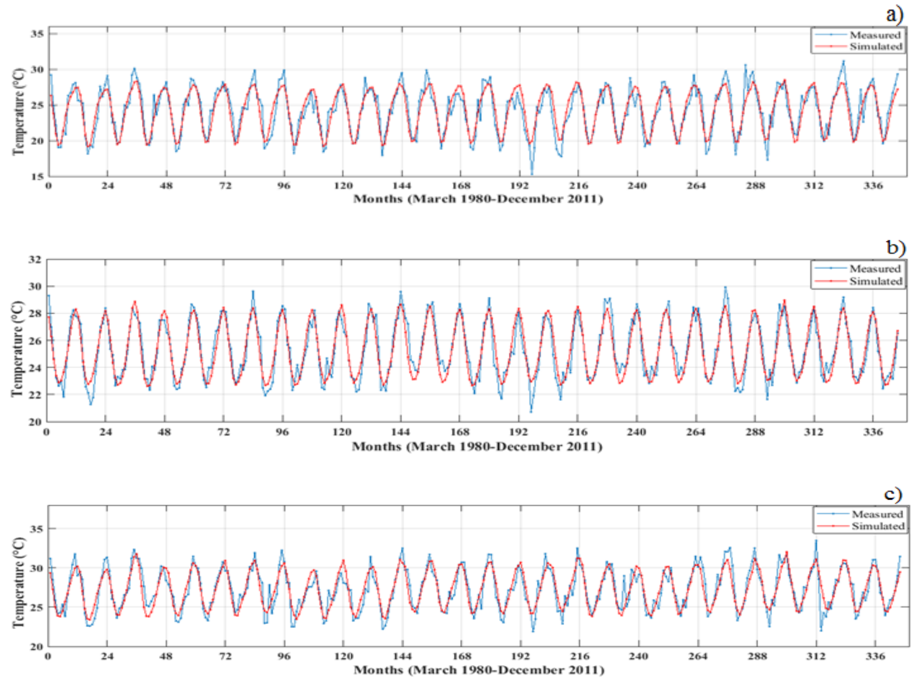

Figure 2. Temporal evolution of monthly surface temperature values as observed over KwaZulu-Natal weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Estcourt, b) Durban South and c) Riverview.

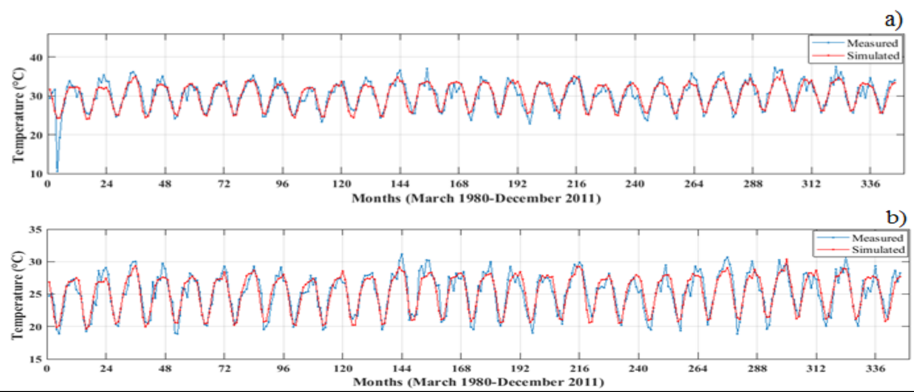

Figure 3. Temporal evolution of monthly surface temperature values as observed over Limpopo weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Messina and b) Polokwane.

In Figure 4 (a, b, c, d, e, f), the measured and simulated values were in good agreement with each other. The decadal trend values for Aliwal, Umtata, Graaf Reinett, Dohne, East London and Cape St Francis in the Eastern Cape were 0.33°C/decade, 0.31°C/decade, 0.18°C/decade, 0.26°C/decade and 0.07°C/decade (Table 2), respectively. The decadal trend increase was lower at the coastal area stations in the Eastern Cape, which is concurrent with the finding by the DEA (2013). The potential to expand the forestry plantations in the Eastern Cape is a high possibility with the increasing temperatures found in this study since species of *Pinus* are more robust to climate change than the other tree species (*Acacia* and *Eucalyptus*)

(Warburton and Schulze 2008). Henceforth, proactive forestry planning is imperative for this industry (Warburton and Schulze 2008).

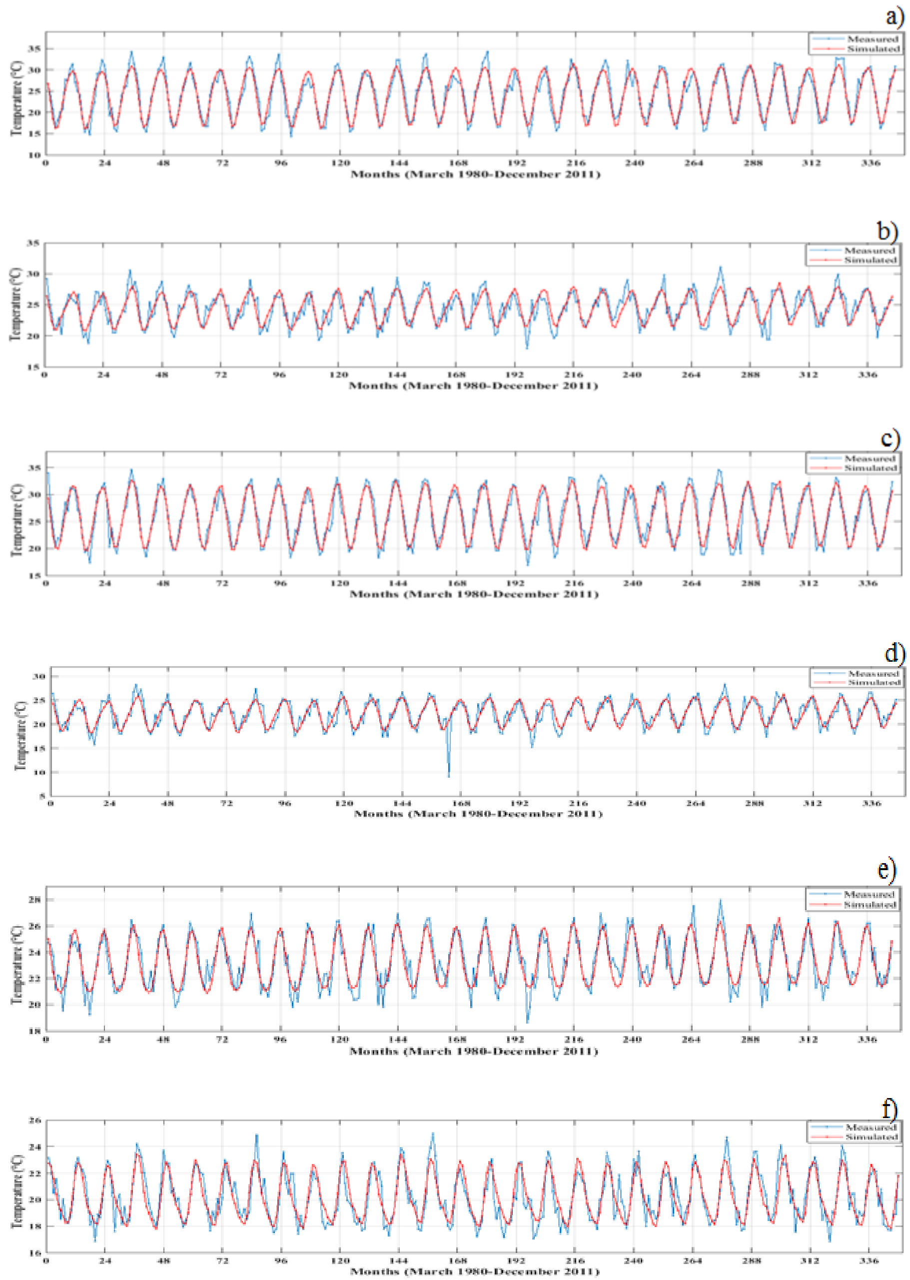

Figure 4. Temporal evolution of monthly surface temperature values as observed over Eastern Cape weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Aliwal, b) Umtata, c) Graaf Reinett, d) Dohne, e) East London and f) Cape St Francis.

In Figure 5 (a, b, c, d, e), the measured and simulated values were in good agreement with each other. The decadal trend values for Vredendal, Cape Columbine, South African Astronomical Observatory (SAAO), Oudshoorn and Robertson are 0.59°C/decade, 0.18°C/decade, 0.24°C/decade, 0.60°C/decade and 0.38°C/decade (Table 2), respectively. The increase in these temperatures at the current state could affect the high concentration of aquatic diversity and indigenous forests in the Cape region. Especially in the Western Cape regions, the occurrence and susceptibility of forests to fires have caused massive damage to the economy and forests in the regions because of these temperature increases (DEA 2013).

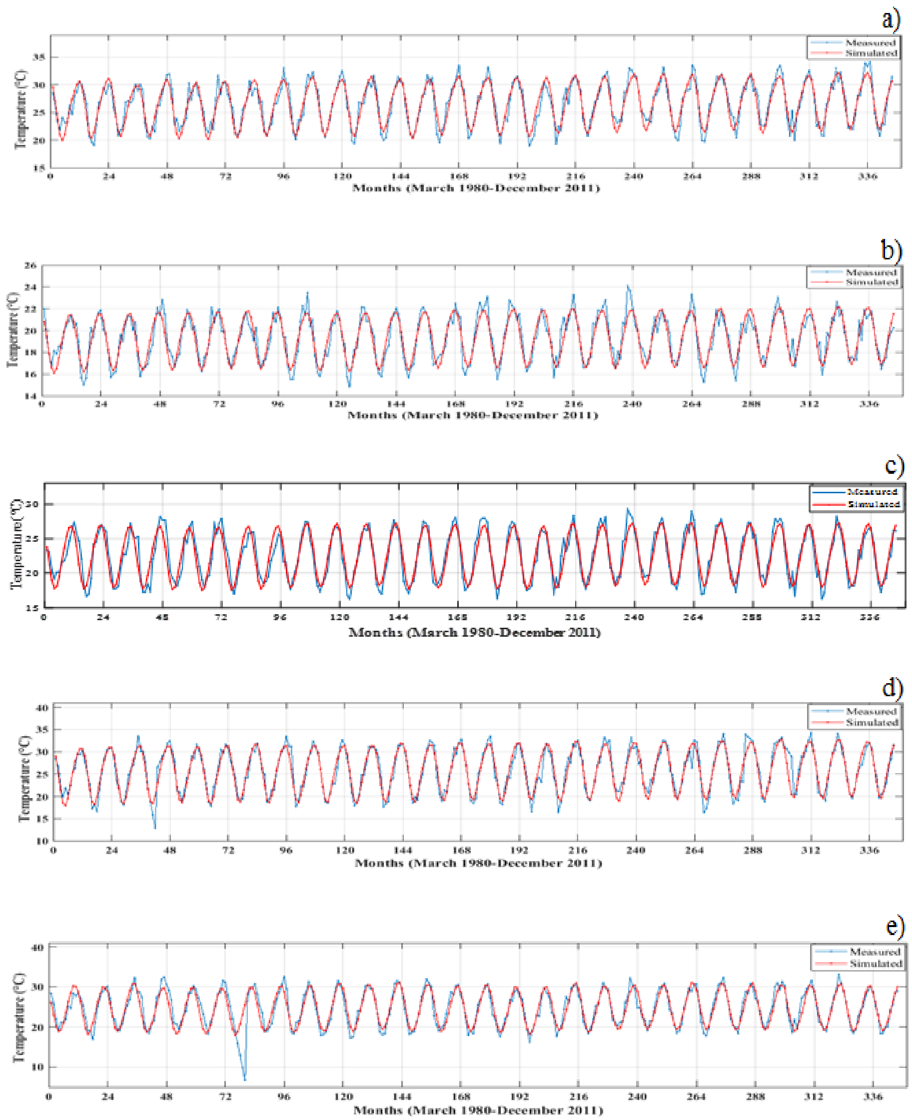

Figure 5. Temporal evolution of monthly surface temperature values as observed over Western Cape weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Vredendal, b) Cape Columbine, c) SAAO (South African Astronomical Observatory), d) Oudtshoorn and e) Robertson.

In Figure 6 (a, b, c, d, e), the measured and simulated values were in good agreement with each other. The decadal trend values for Twee Riveren, Upington, Pofadder, Okiep and Vanwykslvlei were 0.77°C/decade, 0.48°C/decade, 0.33°C/decade, -0.25°C/decade, 0.07°C/decade (Table 2), respectively. These increases were concurrent with the DEA (2013), which states that the high level of biodiversity and forestry in the Northern Cape will be detrimentally affected by such temperature increases).

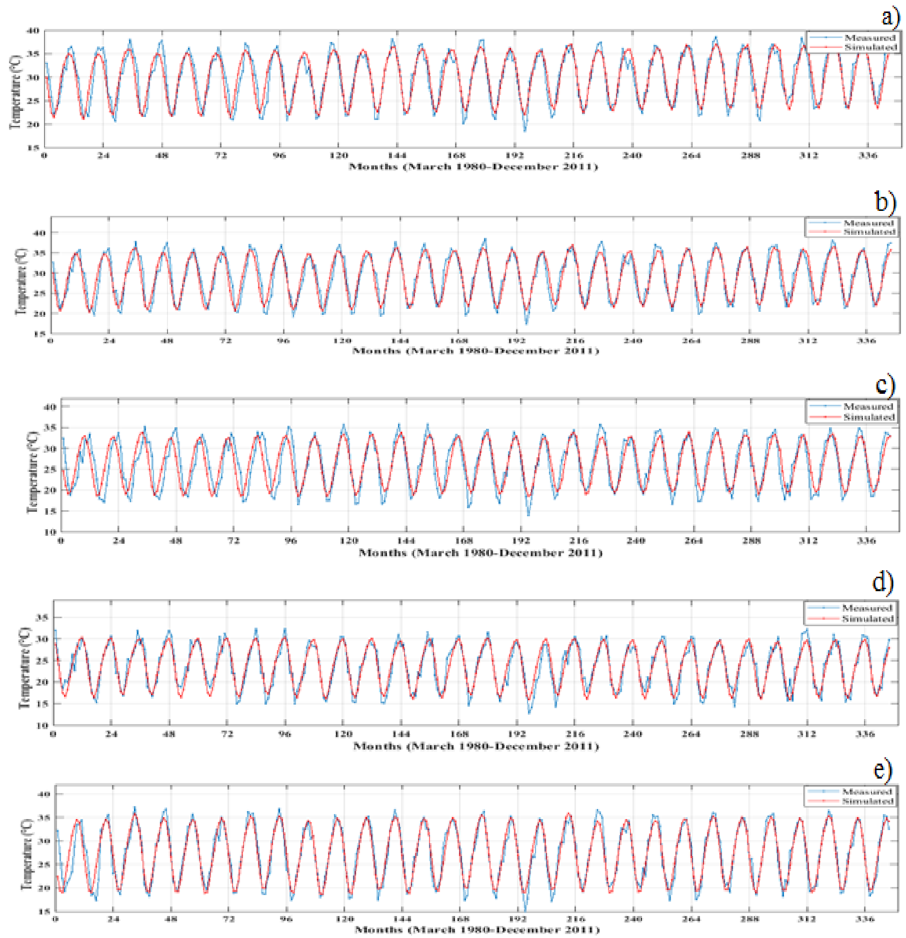

Figure 6. Temporal evolution of monthly surface temperature values as observed over Northern Cape weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Twee Riveren, b) Upington, c) Pofadder, d) Okiep and e) Vanwyksvlei.

In Figure 7 (a, b), the measured and simulated values were in good agreement with each other. The decadal trend values for Frankfort and Glencollege were 0.12°C/decade and 0.15°C/decade (Table 2), respectively. These results, however, did not support that in the Free State by Envirotech Solutions (2015), which stated that the temperatures could rise between 1 and 3°C (DEA 2015b). Their concern was that this increased heating over the interior could affect agricultural productivity in the Free State but we predict that the effect will be much lower. These projected changes are also expected to encourage tree growth and cause the expansion of the savanna biome into the already threatened grassland biome (DETEA 2014).

In Figure 8 (a, b), the measured and simulated values were in good agreement with each other. The decadal trend values for Lindleyspoort and Vryburg are -0.38°C/decade and 0.07°C/decade (Table 2), respectively. These results for the North West Province differed from those of the DEA (2015b), who predicted a temperature increase of around 1°C. Since this province plays a major role in stock and maize farming, this could negatively impact agriculture and the economy as a whole (DEA 2015b).

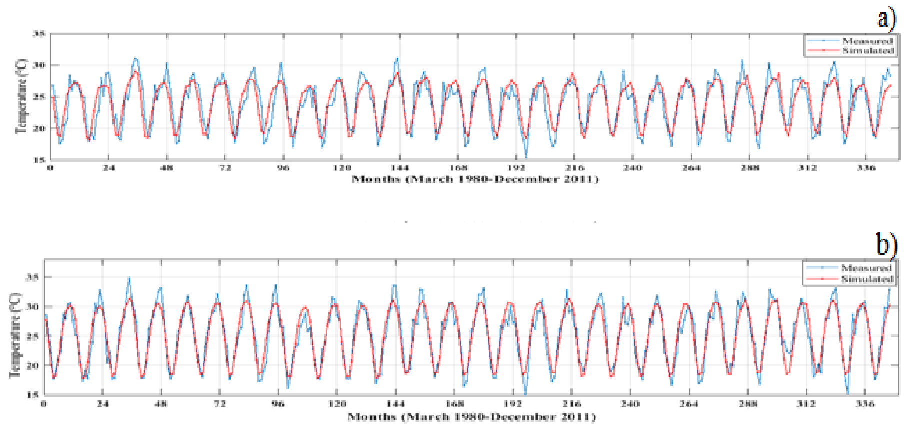

Figure 7. Temporal evolution of monthly surface temperature values as observed over Free State weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Frankfort and b) Glencollege.

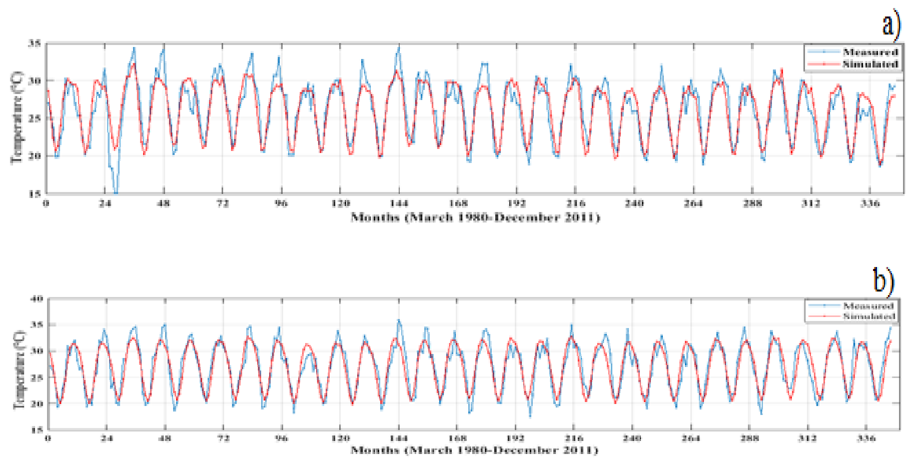

Figure 8. Temporal evolution of monthly surface temperature values as observed over North West weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the Trend-Run model (red line), a) Lindleyspoort and b) Vryburg.

In Figure 9 (a, b), the measured and simulated values were in good agreement with each other. The decadal trend values for Pretoria and Carltonville were 0.84°C/decade and 0.35°C/decade (Table 2), respectively. These were the highest calculated values for SA. This was congruent with the finding of up to 1°C/decade by the City of Tshwane (COT) report (2015), which stated that this increasing 'heat island effect' could be the result of the strong urbanization effect. As the rate of urbanisation increases, the species richness in plant diversity decreases. Since forests harbour a high level specialist species, this could most definitely render them vulnerable to extinction (Mellinger et al. 2018). Henceforth, this temperature increase as calculated by the trend run model can have dire consequences to species and forests health in the Gauteng region (Pretoria and Carltonville) should these decadal increases continue together with a high rate of urbanisation.

In Figure 10 (a, b), the measured and simulated values were in good agreement with each other. The decadal trend values for Skukuza and Loskop Dam were 0.49°C/decade and 0.06°C/decade (Table 2), respectively. This has high importance since Mpumalanga has the second highest quantity of commercially produced maize and the largest production area for forestry in the country (Maponya et al. 2013). At the weather station in Skukuza, a temperature increase of 0.49°C/decade was recorded by the Trend-Run model. This finding was congruent to the finding by Spear et al. (2015), where temperatures were expected to soar between 0.4°C and 1.5°C. The report by the City of Mbombela (COM) in 2017, demonstrated that the province could possibly see an increase in temperature by as much as 2°C by 2035 and 1 to 3°C by 2040, which could detrimentally affect the maize production and the forestry sector in Mpumalanga (Maponya et al. 2013). The challenge of temperature increases is exacerbated by the fact that temperature increases are expected to be higher over Mpumalanga and the other interior provinces of SA (DEA 2015a). The high level of congruency between the measured and the simulated values and high R^2 values from figures 2-10 and Table 1 respectively shows that the Trend model could have some application on the weather and used as a forestry management tool and for various other biomes across in SA.

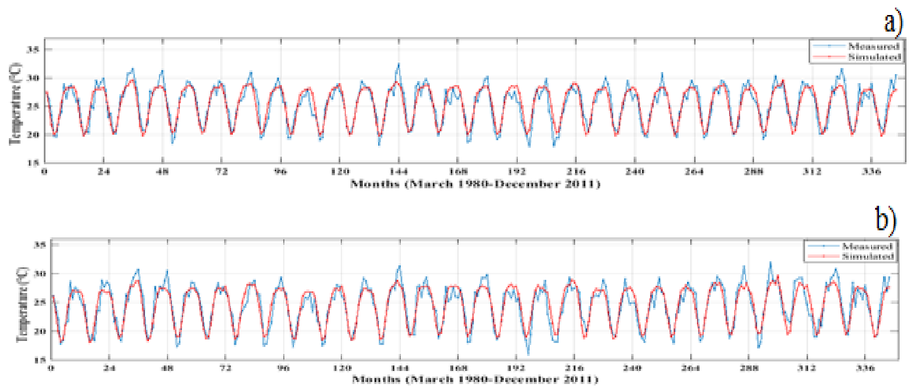

Figure 9. Temporal evolution of monthly surface temperature values as observed over Gauteng weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Pretoria and b) Carltonville.

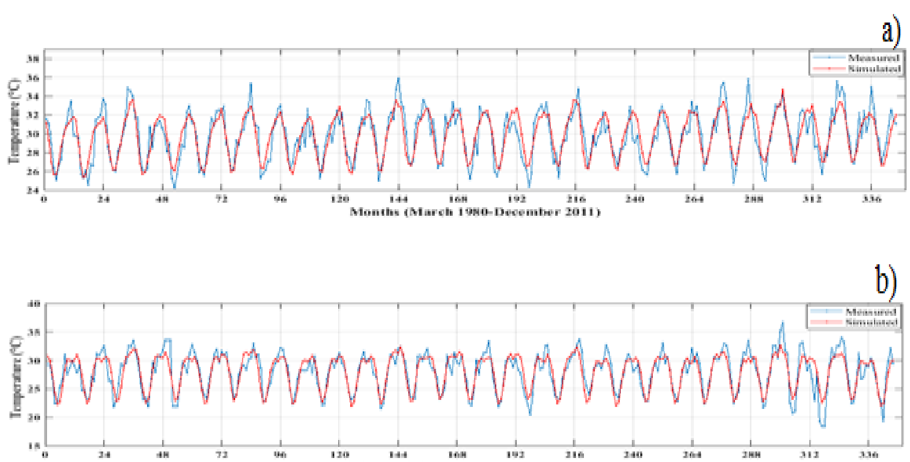

Figure 10. Temporal evolution of monthly surface temperature values as observed over Gauteng weather stations for the period from March 1980 to December 2011 (blue line), superimposed by the simulated Trend-Run model (red line), a) Skukuza and b) Loskop Dam.

4 Conclusion

The Trend-Run model efficiency was variable throughout the country but had consistently high coefficient of determination values for each station and in each province; overall the Trend-Run model performed very efficiently. The model outputs showed that the measured values were in strong agreement with the simulated values. The SAO, the AO and the ENSO played a vital role in model simulation in South Africa. The ENSO and AO produced the highest weighted contributed value to the model. The other contributions (from QBO, IOD and SSN forcings) to the variability of surface temperature were less significant. The trend values calculated by the Trend-Run model demonstrated a consistent rise in surface temperature across South Africa, which is alarming since the various biomes in SA will be detrimentally impacted by the warming effect in the country. The forestry industry is at risk because of the protracted period from planting to harvest. There were also possible negative implications for the aquatic biomes (fishing industry) in the Eastern Cape. Rising temperatures created the possibilities of changing biomes within the country, which would require proactive government intervention. The Trend-Run model can be very useful in monitoring the various biomes and has the capacity to be modified.

5 Acknowledgment

The authors would like to express their gratitude to Mrs Cindy van Schalkwyk for her valuable assistance with the data administration and technical assistance and the South African Weather Services for the data. Additionally, a sincere humble appreciation and gratitude to Dr Derian Echeverri-Molina.

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