Southern Africa winter temperature shifts and their link to the Southern Annular Mode

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Abstract The main characteristics of spatial and temporal variability of the winter (June–August) observed surface air minimum temperature (SAMT) of southern Africa (Africa south of the equator) were examined from 1960 to 2011. The empirical orthogonal function (EOF) analysis was used to extract the dominant mode of SAMT variability. Statistically significant shifts were detected in both the index derived from the spatially averaged regional SAMT and its EOF1 time coefficients. These discontinuities displayed a sharp rise followed by an abrupt drop during the periods around 1988 and 2007 respectively. The years corresponded to change points in the Southern Annular Mode index where the 1988 significant alteration to a relatively more positive index polarity was followed by a sudden weakening during the latter shift. The development of the warm phase coincided with the decoupling of SAM from SAMT. This occurred when the strengthening of the western ridge of the Mascarene High appeared to be coupled to the creation of anomalously low pressure systems over Angola and the region pole-ward of South Africa. In this epoch, the meridional wind over southern Africa reversed to become predominantly northerly and hence was symptomatic of warm temperature advection from the lower latitudes. However the post 2007 era, though still of indeterminate length, is characterized by a partial return to the pre-1988 circulation conditions. This implies that the impacts of SAM’s epochal alterations have implications not only for the current climate, but also for the interpretation of climate change over southern Africa.

Keywords Southern Africa minimum temperatures · Southern Annular Mode · Mascarene High · Shifts

1 Introduction

Complications emanating from increased surface air temperatures (SAT) in southern Africa are emerging as serious threats and can have impacts that are comparable to those resulting from deficits in rainfall. Of late a pressure buildup of the Mascarene High (MH, Xue et al. 2003), one of the dominant controls of southern African climate (Tyson and Preston-Whyte 2000) has been tied to the unprecedented shift in the Southern Annular Mode (SAM) towards a more positive phase (Gillet et al. 2006). These shifts in the extratropical features which dominate the southern hemisphere, warrant better understanding in relation to their impact on the regional climate, especially the SAT.

Southern Africa has been observed to have warmed by 2 °C in the last century (Collins 2011). 1985–1995 was the warmest and driest decade on record displaying an average increasing SAT of more than 0.5 °C (Arntzen et al. 1996). January 2000 was one of the driest Januaries on record with accompanying high temperatures of over 40 °C which fueled extensive fires along the coast in the Western Cape Province (IFFN 2000). Southern Africa’s soft fruit industry is not spared as it suffered from a 1 °C temperature rise in the last 30 years. In addition regional farmers reported rising temperatures which impeded
from sufficient winter resting, while fruit was becoming sunburned during ripening season (http://news.softpedia.com/newsLinkTo/41077). Paradoxically, future water scarcity aggravated by increased evaporation will increase water demand for human consumption, further cutting water amounts for an increasingly necessitated agriculture in this already largely water stressed region. With the SAT increase, malaria prone regions have expanded and winter wheat production especially in South Africa’s Cape Province’s and Zimbabwe has been negatively affected (One-World 2010). Thus as increasing evidence grows on temperature controls of important physiological processes in the region’s flora and fauna, the topic of climate change specifically related to temperature, becomes imperative. Studying the behaviour of minimum SAT in particular, is key for the region as it determines frost occurrences and winter wheat production which significantly affects agricultural production. In addition, it sets the lower tolerance limit for the spread of malaria, a disease with the highest year round mortality rate over southern Africa (Grimwade et al. 2004).

Southern Africa’s SAT exhibits strong seasonality, with distinct seasonal variations that are tied to the semianual cycle of the two semi-permanent subtropical high pressure systems. Of the two anticyclones which sandwich southern Africa, the South Atlantic Anticyclone and the South Indian Anticyclone, the latter also known as the MH has more influence due to its southeastward location. This position enables the high pressure system to control the sub-region’s southeast trade winds typically through the associated continental and ridging anticyclones. Thus it is during the cooler seasons of winter when the MH is at its most westward and equatorward position that leads to the development of more robust cold south-easterlies. This results in more temperate control of the region during the winter season. Therefore it is expected that the low frequency modulation of the minimum temperature, during winter should be influenced mainly by the atmospheric circulation systems which originate from the southern hemisphere extratropics. Recently, Manatsa et al. (2013a) noted that the interannual variability of the MH is characterized by zonal displacements which are believed to be related to the SAM variability (Xue et al. 2003). In fact the origins of the southeast trade winds are predominantly the extratropics, one of the major component regions which define the SAM.

SAM, also referred to as the Antarctic Oscillation or high-latitude mode, is considered the leading mode of circulation variability south of 20°S on low frequencies (Fog et al. 1998). This climate mode is characterized by synchronous anomalies of opposite geopotential sign in the mid and high latitudes (Marshall 2003) and hence is essentially a measure of the pressure gradient between these two regions. However SAM influence extends well beyond these categories as it provides a means of coupling the Antarctic climate with that of lower latitudes allowing it to demonstrate a heavy presence reaching the tropics (Reason and Rouault 2005; Gillett et al. 2006; Karpechko et al. 2009; Kang et al. 2011; Kang and Polvani 2011; Manatsa et al. 2013a). Although SAM influence extents to the tropics, it is not always related to ENSO (Fogt and Bromwich 2006) the primary control of the tropical climate (Zhang et al. 1998). The association between SAM and ENSO is at its maximum during the peak ENSO related anomalies during austral summer. Therefore one may not expect ENSO to significantly affect SAT of southern Africa especially in the austral winter season when ENSO variability is at its lowest. In fact even in the warm season, Kruger and Shongwe (2004) could not establish any link of increases in summer temperatures to the occurrence of El Nino and La Nina events. Considering the apparent relatively high contribution of SAM to the Southern Hemisphere atmospheric circulation (Kang et al. 2011), it is natural to determine whether this significant influence extent to winter SAT of southern Africa. This aspect was not considered by Manatsa et al. (2013b) when they established a significant link between ozone depletion and the early summer SAT of southern Africa.

The importance of understanding relationships between the SAM and regional winter climate is underscored by the recent shift in the SAM towards a more positive phase, which is shown to contribute to observed long-term climate trends over the Southern Hemisphere (e.g. Thompson and Wallace 2000; Kushner et al. 2001). The MH’s mean state has not been spared and has displayed a significant pressure build up in the recent decades (Xue et al. 2003). Thus here we hypothesise that the recent strong positive signal of SAM on decadal time scales should play an important role in the low frequency modulation of winter SAT over southern Africa. This should have been achieved through modification of the mean sea level pressure of the MH which in turn regulates the strength and source regions of the southeast trade winds which affect southern Africa. Hence the main goal of this study is to objectively characterise the regional dominant spatial and temporal patterns of the mean SAMT over southern Africa and relate it to SAM.

1.1 Data and methods

1.1.1 Data

The main variable analysed in this study is the land only SAT. While the study of the long term trends of this variable is quite essential, there are difficulties in not only obtaining continuous long term data in both its spatial and temporal domain, but also in acquiring accurate meteorological and
climatological records in southern Africa. This is primarily
due to a lack of funding in the African countries, topogra-
phy which renders some places inaccessible and remote-
ness of areas. In some instances where quality data is avail-
able, it is not freely provided. This has led us to rely more
on data that we found to be freely available and mostly a
product of extrapolation from the station observations.
A station observation-based global land monthly mean
SAT dataset at 1° latitude–longitude resolution for the
period from 1885 to the present was developed recently by
the Berkeley Earth Surface Temperature Study. This data
set was constructed using temperature reports from 16 pre-
existing data archives and provides SAT anomalies rather
than the absolute quantities. The stations used are roughly
five times the stations found in the Global Historical Cli-
matology Network Monthly dataset, the dataset which has
been commonly used in most temperature research. How-
ever, Nicholson (2001) noted that weather stations first
emerged in the south of Africa, meaning that this region
should have reasonably long observation based records in
Africa. In this work we used data from 1960 as this is the
period when there has been substantial evolution of the
observing climate system over southern Africa (Peterson
et al. 1998). Details of the Berkeley dataset and the meth-
ology used in its construction are found in http://ber-
kereylearth.org/methodology. Because this dataset provides
anomaly temperature values only, the CRU minimum tem-
perature dataset, though of lower resolution, is also used
as a complement where actual approximated values aid in
clarification. The data are obtained from the CRU TS ver-
nion 3.22 data files available on http://badc.nerc.ac.uk/
browse/badc/cru/data/.
Climate data for process interpretation and comparative
purposes are drawn from the National Centers for Envi-
nronmental Prediction (NCEP)—National Center for Atmo-
spheric Research (NNR; Kalnay et al. 1996). Employing the NNR dataset in the current analysis
makes it easier to relate to the underlying physical pro-
cesses generated by the model which could be responsible
for the temperature variations. This is made possible by the
ability of reanalysis to diagnose regional scale atmospheric
conditions based on observations above the surface being
assimilated into a physically consistent atmospheric model.
In the NNR, wind and geopotential data that are mostly
analysed in this study are classified as B category variables.
This designation indicates that, although observational data
directly affect the value of the variable, the model also has
a very strong influence on the analysis value (Kalnay et al.
1996). Thus, since surface observations are not exclusively
used in the reanalysis, it is the reanalyzed surface data con-
figurations which extend higher into the atmosphere and
hence provides more consistent patterns relative to the sur-
face. Another important consideration was that, unlike the
Berkeley dataset which is land only, the NNR includes
the ocean data making it possible to determine the explained
variance of temperature relative to the geopotential and
wind locations that include the ocean. However, the inter-
pretation of the results from the NNR data analysis before
1988 (the pre satellite era), over the southern hemisphere
where conventional observations are sparse, should be done
with caution (Tennant 2004).

2 Methods
2.1 Shift detection methods

The work is primarily based on the coinciding shifts in
the SAM and SAMT of southern Africa to assert linkages
between the two. Basically we employed two methods to
detect abrupt changes in long-term time series, the manu-
ally performed cumulative sum (CUSUM, Buishand 1982;
Lanzante 1996) and the Excel add-in “Sequential Regime
Shift Detection version 3.2” (SRSD) (http://www.bering-
climate.noaa.gov; Rodionov (2004, 2006) techniques. With
abrupt changes we mean a sudden stepwise change in the
time series. The CUSUM technique consists of plotting the
cumulative sum of standardized values over time whereby
each individual value is subtracted from the mean of the
time series. This results in a new time series of residuals
which are used for the calculation of the cumulative sum
(Sr), as follows: each data point yr (corresponding to time t,
from 1 to n) is added to the preceding data point according
to the equation: Sr = \sum_{r=1}^{n} yr. When plotted these values
allow one to determine t when the change occurred (Ibanez
et al. 1993). Hence changes in the average level of the pro-
cess are reflected as changes in the slope of the plot. For
successive values equal to t, the slope will be horizontal,
and for successive values lower than t, the slope will be
negative and proportional, and vice versa. This approach
to detect change points performs well and is relatively easy
to implement (Breaker 2007). The use of cumulative vari-
ables in the analysis of climate problems derives from the
idea that certain climate driven quantities respond not only
to the instantaneous climate, but to the accumulated effects
of the climate variables over the period of time. Thus this
method enables the shift process to be considered holisti-
cally, being composed of sequenced and linked events
rather than seasonal events that are independent.
In the second method the existence of regime shifts in the
mean and variance were tested using the SRSD which is a
sequential data processing technique. The SRSD is easy to
use and many time series can be analyzed simultaneously
using yearly mean values. The technique assumes no a priori
of when the abrupt change should occur, but the time
series must be continuous. In the algorithm, the procedure

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for detecting regime shifts in the variance is similar to the
time-varying spatial patterns that explain most of the vari-
ance in the data. This technique did not only assist in iden-
tifying the spatial homogeneity of the climate variables, it
also enabled the dominant lower frequency patterns to be
extracted. However the basic result of this technique is a
decomposition of climate anomalies into EOF modes of
decreasing explained covariance. The significance of the
separation of the neighboring EOFs, is determined using
the North et al. (1982) criterion. Each mode is character-
ized by a singular vector describing the spatial pattern of
weights (loadings) for the winter variables and a series
of expansion coefficients describing the weighting of
the mode in the temporal domain. In this way, the spatial
amplitude of the EOF modes indicates the spatial distri-
bution of the intensity of specific processes, while the tem-
poral amplitude of the principal components (PCs) indicates
the time that a particular process is important. Hence the
combined spatiotemporal variability is obtained by multi-
plying the spatial and temporal amplitudes of each mode.
Unlike similar research which further apply rotated EOFs
(e.g. Kawamura and Ryouichi 1994; Cheng et al. 1995), in
this study we did not rotate the EOFs so that we preserve the
dominant individual sources of variation in the data which
can otherwise be lost in the process of rotation. In this way
the method did not only assist in the identification of the
spatial temporal variability of the climate variable of inter-
est, but also facilitated linking them to sources of the vari-
ability. However, it has to be noted that the EOF analysis is
dependent on the domain size and location with maximum
loadings coinciding with the highest variability of the mode
within the selected area.

2.3 Surface air minimum temperature (SAMT) index

The area averaged SAMT was extracted from the region
depicted in the box region (10°S–26°S; 18°E–35°E) in
Fig. 1a. The demarcation of the box was determined by the
region of maximum spatial loadings of SAMT shown in
Fig. 3a. We used this geographical location of high load-
ings as the basis for averaging the SAMT from the Berke-
ley minimum temperature dataset that represents the tem-
poral variability of the actual observed values for southern
Africa. The selection of the JJA period emanated from the
winter months with the largest anomalies that are illustrated
in the Fig. 1b. This period is when the controlling signal
is expected to be at its maximum. The mean for the study
period was removed from the averaged SAMT in the boxed
region to obtain the SAMT index thereby retaining its units.

2.4 Southern Annular Mode (SAM) index

Following Thompson and Wallace (2000), the SAM
index is derived from the standardized time coefficients
Fig. 1  a Selected area representing the dominant spatio-temporal variability of SAMT for southern Africa during winter (JJA) period. b Spatially averaged monthly SAMT for the region derived from the CRU minimum temperature dataset. The analysis is for the duration from 1960 to 2011.

Fig. 2  a The EOF1 of the geopotential values at the 700 hPa level and b its PC1 temporal manifestation representing SAM index (bars) with the superimposed associated cumulative index (solid line). The analysis is for OND averaged monthly values during the period 1960 to 2011. Both the EOF1 and the SAM index should be multiplied by −1.

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of the EOF1 at the 700 hPa geopotential height monthly anomalies south of 20°S. This index explains the order of ~34% of the total variance in the geopotential height. It can be noted from Fig. 2a, b that this annular mode is characterized by meridional shifts in atmospheric mass between the Polar Regions and the middle latitudes. This enables the pressure pattern associated with SAM to assume a nearly annular pattern with a large low pressure anomaly centered over the South Pole and a ring of high pressure anomalies at mid-latitudes. Hence by convention, the high index polarity of the annular mode is defined as lower than normal pressure over the Polar Regions. However, the usefulness of the Antarctic analysis in the NNR before the satellite era (pre-1979) has been questioned by Marshall (2002). For this reason, the pre-1979 values of the index are included for completeness, but should be used only after reading Marshall (2002). The EOF1 and its temporal manifestation are presented in Fig. 2a, b respectively. However, the interpretation of Fig. 2 should be reversed (multiplied by −1) so as to conform with the standard SAM definition where the positive SAM has relatively suppressed geopotential values.
over the Antarctica. For comparative purposes with the reanalysis derived SAM index, we used the SAM index constructed from observed data by Marshall (2003) and downloaded from http://www.nerc-bas.ac.uk/icd/gjma/sam.html. He calculated the SAM index as a normalized difference between the zonal mean SLP at 40°S and 65°S using SLP from 12 stations, 6 each along the respective latitudes from 1957. The correlation between BAS SAM index and SAM 700 hPa PC1 (hereafter simply referred to as SAM index) is 0.841 with p value <0.0001.

The temporal associations are computed using 10-year overlapping segment correlations and their significances are determined against a 10,000 sample Monte Carlo (Dwass 1957) at 90 % confidence level. The 10 year window width has been selected because it is of a strategic compromise. This segment length is long enough to estimate relationships of decadal variability whilst not too long to ‘dilute’ the sought for transitions. At the same time, the segment length is long enough to avoid capturing transitions that are of no decadal significance (Manatsa and Behera 2013). Unless stated throughout the analysis, correlations are considered to be statistically significant at the 95 % confidence level or higher. Significance of the correlations is determined by a two tailed student’s t test. The trends were computed using an ordinary least squares regression method. The degree of significance of the slope of their best-fit linear trends was determined to be significant at the 10 % level. We considered this parametric technique as the appropriate and more robust methodology because the mean SAM anomalies are assumed to be normally distributed (e.g. Christy et al. 2009).

The analysis is for the JJA winter period. The focus on this particular period is not only because it coincides with the winter season but is associated with the maximum regional temperature impacts from the MH driven south-east trade winds. However, we use the 850 hPa geopotential height rather than the sea level pressure to partially alleviate the ambiguities introduced by the reduction to sea level over the predominantly high terrain of southern Africa. In this regard the atmospheric circulation analysis was also performed at 850 hPa. All dataset analyses are considered over the same period, from 1960 to 2011 and where necessary, are detrended before any statistical operation is applied. Where the detrending procedure is done, it was to ensure that the outcome of statistical operations done, like that of the correlation analysis may not be attributed in part to the common linear trend resulting from global warming. Because the climatic time series used in this study consist of 3-monthly (JJA) values per year, as expected no robust autocorrelation on time series is found. Therefore we considered the impact of autocorrelation of the time series in significant t test hypothesis testing as unimportant.

### Table 1 Results of SAMT EOF analysis for the monthly averaged JJA period from 1960 to 2011

<table>
<thead>
<tr>
<th>No.</th>
<th>Eigenvalue</th>
<th>Explained var (%)</th>
<th>Cumulative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>103.5</td>
<td>64.1</td>
<td>64.1</td>
</tr>
<tr>
<td>2.</td>
<td>28.1</td>
<td>11.8</td>
<td>75.9</td>
</tr>
<tr>
<td>3.</td>
<td>16.7</td>
<td>8.4</td>
<td>84.3</td>
</tr>
<tr>
<td>4.</td>
<td>11.2</td>
<td>4.1</td>
<td>88.4</td>
</tr>
</tbody>
</table>

A scree plot was used as the cut off criterion to determine the significant modes.

### 3 Results

#### 3.1 SAMT characteristics over southern Africa

The results of the EOF analysis for the SAMT over southern Africa (south of the equator) are presented in Table 1. It can be noted that the SAMT EOF1 explains more than 64 % of the minimum temperature variability over southern Africa. Even the application of the North et al. (1982) criterion demonstrates that this dominant mode is a robust signal which is not interfered with by its neighbors. Figure 3 shows the spatial pattern of SAMT EOF1. The related loadings display positive values throughout indicating variability that is unidirectional over the region implying an in-phase oscillation of the whole sub region around a steady-state mean. The highest spatial loading, though centrally located, display a southeast-northwest orientation which extend from the southwest Indian Ocean (SWIO) right across through southeast South Africa to northwest Angola. This indicates land modifications of minimum temperatures that are principally connected to the SWIO. Because of the displayed strong and coherent spatial SAMT variability over the sub region, the EOF1 time series can be used to represent the dominant temporal variability of the SAT of the whole of the southern African region. We then used the spatial loadings greater than 0.75 to demarcate the box presented in Fig. 1a to construct an area averaged SAM index. However the other three modes in Table 1, explaining the SAMT variability over southern Africa displayed spatial patterns which were too complex to be related reasonably well to any known physical processes occurring in the sub region and hence we did not discuss them further in this paper.

We suggest that the dominance of the decadal signal in SAMT PC1 (figure not shown) and SAMT index (Fig. 4a) hints at the existence of shifts. In fact we note that the temporal manifestation of SAMT index and its corresponding cumulative index in Fig. 4a display three regimes, whereby predominantly negative values sandwich an epoch of warmer conditions. The cumulative graph conspicuously fix these periods of SAMT discontinuities as 1988 and
3.2 Connection of SAMT variability with the Mascarene High (MH)

Although SAMT modification from the land is quite apparent due to the robust coherence of the spatial loadings over the subcontinent demonstrated in Fig. 3, there is a reasonable indication that the SAMT of the region is strongly tied to extratropical influences. The cool south easterlies that are driven by the MH related western ridge of high pressure have the propensity to significantly regulate the temperature of southern Africa (Tyson and Preston-Whyte 2000). However the strength and the magnitude of temperature advection of these trade winds depends on the position and strength of this subtropical high pressure system. To ascertain this supposition, we extracted the dominant mode of pressure variability which we consider to be strongly tied to the western ridge of the MH. We deliberately excluded the whole of the MH from the EOF domain of analysis as it is mostly the western portion of this pressure system which predominantly steers the south easterlies that affect southern Africa. Table 3 demonstrates the results of the SLP EOF analysis including the explained variance of each of the first four modes whose cut off criterion is determined based on the scree-test (Cattell 1966). The EOF1 explains more than 39% of the SLP variability of the selected sub region which is almost twice the value of its neighbor. This demonstrates that the EOF1 is a robust and largely independent mode which we confirmed using the North et al. (1982) criterion.

The spatial dimension of EOF1 SLP is presented in Fig. 5a. It can be noted from this figure that this paramount mode of SLP variability extends a ridge north westwards over the sub region which is bound to interfere with the characteristics of the prevailing southeast trade winds from the Indian Ocean. The correlation between SLP PC1 and the SAMT PC1 yields the value of 0.62 which has a p value <0.0000 and hence implying a strong coupling between the two. The manner in which this coupling is realized is presented in Fig. 5b with the aid of a scatter plot for the pre and post 1988 epochs together with the relationship for the entire analysis period. It is noted that the MH western ridge is strongly positively linked to SAMT PC1 with p values <0.0000 irrespective of the period considered. This implies that the MH western ridge variability consistently and in a unidirectional way, influences the winter minimum temperatures of southern Africa. This finding corroborates our earlier results presented in Figs. 6 and 7 which demonstrate that a relatively weak western ridge may develop in tandem with an anomalous low pressure system south of Madagascar, coinciding with the strengthening of the Angola Low. The coupling of these oppositely signed pressure systems results in the strengthening of the south easterlies with the net effect of lowering SAMT. The reverse occurs with the
Fig. 4  
(a) The temporal manifestation of the 15-year variance of the SAMT index with its cumulative index superimposed (solid line). The broken line indicates the identified regime shifts in the mean using the Rodionov Technique. 
(b) The SAMT index running 15-year variance with values at the end of the segment. The analysis is for monthly values averaged during the JJA period from 1960 to 2011 derived from the Tmin Berkeley dataset.

strengthening of the western ridge. Consequently, it is the post 1988 SAM related strengthening of the MH western ridge which could have resulted in the simultaneous warming of minimum temperatures of southern Africa. The relative cooling of the sub region within the recent decade could have resulted from the 2006 SAM related weakening of the ridge. The observation that this SLP PC1 mode is reasonably tied to the dynamic processes related to SAMT change suggests that the MH which is controls the decadal variations in the related trade winds (Tyson and Preston-Whyte 2000) should be directly involved.

3.3 Linking the SAMT to SAM variability

In the process of exploring the causality behind SAMT variability, it is important to determine whether the observed temperature shifts are sporadically generated by random local atmospheric fluctuations or connected to global
Table 2 Results of Rodionov Regime Shift Detector for monthly averaged JJA SAMT during the period from 1960 to 2011

<table>
<thead>
<tr>
<th>Shift year</th>
<th>Duration before shift (years)</th>
<th>Mean after/ before shift</th>
<th>RSI</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>29</td>
<td>0.398/–0.234</td>
<td>0.1998</td>
<td>&lt;0.0000</td>
</tr>
<tr>
<td>2006</td>
<td>17</td>
<td>–0.0891/0.383</td>
<td>–0.2526</td>
<td>0.0127</td>
</tr>
</tbody>
</table>

RSI: regime shift index; mean: equal-weighed arithmetic means of the regimes using the Huber’s weight function with the parameter = 2; p value: Significance level of the difference between the mean values of the neighboring regimes based on the Student’s two-tailed t test with unequal variance (TTEST procedure in Excel). The target significance level = 0.1.

Table 3 Results of JJA monthly averaged SLP EOF analysis for the period 1960–2011

<table>
<thead>
<tr>
<th>No.</th>
<th>Eigenvalue</th>
<th>Explained var (%)</th>
<th>Cumulative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>884.0</td>
<td>39.3</td>
<td>39.3</td>
</tr>
<tr>
<td>2.</td>
<td>5374.3</td>
<td>23.8</td>
<td>63.1</td>
</tr>
<tr>
<td>3.</td>
<td>2311.8</td>
<td>10.2</td>
<td>73.3</td>
</tr>
<tr>
<td>4.</td>
<td>1391.8</td>
<td>10.2</td>
<td>79.5</td>
</tr>
</tbody>
</table>

climatic variations. The SAM is the most likely candidate to consider because of its influence on the MH (Xue et al. 2003) and hence the south easterlies in the SWIO (e.g. Thompson and Wallace 2000). In fact the variability of the Southern Hemispheric extratropical circulation is dominated by this large-scale annular mode. In Table 4a, the SRSD method confirms the existence of two statistically significant shifts in the mean of the SAM index which coincide with the observed turning points in the SAMT index. When the same technique is applied to detect shifts in the variance, only 2007 is confirmed as significant but with the period around 1988 interpreted as insignificant even at a lower 90% confidence level.

In any case, the observed SAM temporal characteristics implies a relatively strong negative meridional pressure gradient between the subtropical and the extratropical regions before the first shift which eventually reverses to yet relatively strong positive values before the second shift. This is consistent with the SAM variability which has predominantly become positive with a large low pressure anomaly centered over the Polar Cap and a ring of high pressure anomalies at mid-latitudes (Marshall 2003). Therefore it can be reasoned that the epochal intensification of the western flank of the MH is related to the SAM activity which has displayed more positive values in the recent decades. In fact this relationship between SAM and the MH is not novel, several literature on the SWIO have confirmed the existence of a strong coupling between the two (Xue et al. 2003). It has been observed that whenever the circulation low in the high southern latitudes deepens the MH will be intensified (Xue et al. 2003; Manatsa et al. 2013b).

Therefore there is now reasonable ground to assume that the SAMT of southern Africa is related to SAM variability. Hence the coincidence of the two shift years for the SAM and SAMT indices suggests a sound association between the two.

Fig. 5 a The EOF1 of the SWIO monthly SLP variability and b the scatter plot between the MH PC1 and SAMT over southern Africa but decomposed to show epochal manifestation in the associations. In the inset are the regression equations with colors corresponding to the epoch. The analysis is for JJA during the period from 1960 to 2011 and the data has been detrended to partially remove linear relationships attributable to global warming.
Fig. 6 Monthly averaged geopotential values of the JJA composite mean difference maps between 1988–2011 and 1960–1987 epochs for a 925 hPa geopotential height anomalies (m) and b 850 hPa level vector wind (m/s). The data is derived from the NCEP/NCEP reanalysis dataset from 1960 to 2011.


It appears from Figs. 2a and 4a that the most robust turning point in the SAM and SAMT extreme regimes could be both located around 1988. At the same time, it is intriguing to note that far afield; a climate shift towards warming was also noted in Western Europe in 1987/1988 that was related to the alterations in the North Atlantic Oscillation which,
Table 4 Results of Rodionov Regime shift Detection for the SAM index using monthly averaged geopotential values at 700 hPa level during JJA SAM for the period 1960 to 2011

<table>
<thead>
<tr>
<th>Shift year</th>
<th>Duration before shift (years)</th>
<th>Mean after/ before shift</th>
<th>RSI</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>1988</td>
<td>-9.814/0.223</td>
<td>-0.224</td>
<td>0.0014</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>-1.399/-9.814</td>
<td>0.905</td>
<td>0.0030</td>
</tr>
<tr>
<td>(b)</td>
<td>2007</td>
<td>12.418/112.330</td>
<td>-9.706</td>
<td>0.0436</td>
</tr>
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RSI: Regime Shift Index; mean: equal-weighted arithmetic means of the regimes using the Huber’s weight function with the parameter \( \tau = 2 \); \( p \): significance level of the difference between the mean values of the neighbouring regimes based on the Student’s two-tailed \( t \) test with unequal variance (TTEST procedure in Excel). The target significance level is 0.1.

similar to the SAM modifications, changed towards positive polarity (de Laat and Crok 2013). However, the causes and associated teleconnections appear to be radically different. As such several questions immediately come to the fore: that of the spatial coherence of the 1988 shift—
one large region over Europe and southern Africa or two regional shifts which are independent. In any case, this could be a coincidence or possibly a common mechanism which is yet to be identified.

Hence by considering 1988 to demarcate the relatively cool and warm epochs of southern Africa, we present in Fig. 6a, b the composite difference between these two epochs using the geopotential and vector wind field respectively. This allows for the identification of the major changes in the pressure and circulation patterns which occurred over the sub-region relative to this shift year. We note in Fig. 6a that the major transformation in the pressure anomalies was the simultaneous development of the low pressure anomaly system over Angola and an anomaly ridge of high pressure over southeast southern Africa. Figure 6b suggests that these pressure alterations are responsible for the continental circulation pattern which basically displays a dominant northerly anomaly component. Therefore the reversal of the wind direction to northerly could be responsible for the advection of relatively warmer low latitude temperatures to southern Africa. The recurved airflow from the lower latitudes around the anomalous low pressure which developed over Angola could have significantly displaced the airflow which had previously had a predominant extended southerly component over this area. And hence the shifts in the SAM could be attributed for the post-1988 changes to warmer minimum temperature conditions over southern Africa.

To determine how the SAM is possibly linked to SAMT temporal variability we expand the analysis to cover the whole of the southern hemisphere using composite analysis technique. In this method, we extracted from Fig. 4a, the ten highest extreme years for each of the positive and negative temperature anomalies. The years comprising the negative extremes are 1963, 1964, 1965, 1968, 1972, 1976, 1980, 1981, 1994 and 2011 whilst the positive extremes are composed of 1961, 1970, 1990, 1993, 1995, 1997, 1999, 2000, 2002 and 2005. By assuming symmetry in the impacts of these oppositely signed extreme events, we subtracted the former from latter event composite anomalies relative to the current World Meteorological Organization 1981–2010 standard climatology period. The temporal event distribution demonstrates that 80% of the extreme negative and positive events are concentrated in the period from 1963 to 1981 and 1990 to 2005 respectively.

The Southern Hemisphere spatial distribution of the mean difference geopotential anomaly composite between the negative and the positive SAMT extremes is presented in Fig. 7a. It can be noted that the pattern closely resembles the definition of the SAM given by Marshall (2003). The high latitude band consists of geopotential anomalies centered over the Antarctica and surrounded by reversed anomalies which basically form a midlatitude outer ring that is dominated by a zonal wavenumber three structure. The positive geopotential anomalies related to the MH and the oppositely signed significant anomalies connected to the polar cap are conspicuous over the southeast and southern regions of South Africa respectively. The reverse is implied during the negative composites. This suggests that the positive (negative) extreme temperature anomalies are related to the simultaneous intensification (weakening) of the MH and the corresponding weakening (intensification) of the polar cap geopotential values which are in sympathy with the SAM variability (Xue et al. 2003).

The circulation patterns which are related to the negative and positive geopotential anomalies are presented in Fig. 7b, c respectively. The former composite anomalies are characterized by a weakened western ridge of the MH where an anomalous low pressure system steers airflow with intensified cold temperature advection from the Polar Regions. The latter demonstrates an intensified MH which controls a northerly flow over the southeast of southern Africa and a cyclonic flow to the south of the sub-region. This circulation pattern limits the southern extent of the southeasterly wind anomalies resulting in relatively reduced cooler temperature anomaly advection. Hence may explain why the cooler SAMT anomalies dominate the pre-1988 epoch while the latter era is characterized by positive minimum temperature anomalies.

The correlation between SAM and SAMT indices for the whole study period is 0.57 with a \( p \) value of 0.007. However, in order to eliminate the notion that SAM is consistently related to SAMT variability in the temporal scale, we present in Fig. 8, the 10-year running correlation
Fig. 8 Ten-year moving correlation coefficients between SAM and SAMT indices (solid line). Bars represent the corresponding p values. Values are at the end of the 10 year segments and the correlation coefficient values are to be multiplied by -1. The data are for monthly averaged JJA values for the period from 1960 to 2011.

coefficients between SAM and SAMT indices alongside their corresponding p values. It can be noted that the temporal relationship demonstrates a shift during the year 1988 when the significant linkages (p values > 0.1) suddenly collapsed to insignificance thereafter. However, another change in association can be envisaged as lower but dominantly insignificant p values were experienced as from 2006. This implies that the SAM related higher latitude sourced airflow for the sub-region gave way to airflow originating from the low latitudes after 1988, which is not significantly related to SAM variability. This is corroborated by Fig. 6b. Hence the decoupling of SAM from the regional circulation anomalies could explain the apparent post 1988 warming experienced over the sub-region.

4 Summary and conclusions

The influence of SAM on the SAMT variability is largely through its relatively strong association with the MH. It is this subtropical high which controls most of the meridional component of the trade winds that advect the extratropical influences located to the southeast of the sub-region in the SWIO. The periods around 1988 and 2006 have been identified as important shift points in SAM which is strongly coupled to the strength of the western ridge of the MH that extends onto the mainland of southern Africa. These years also coincide with the shift in the sub regional minimum temperature. Before 1988, the extension of the ridge inland was less pronounced and hence the resulting relatively steep meridional gradient influenced stronger trade winds which advected cooler SAMT over the sub region. Between 1988 and 2006, the meridional gradient weakened due to intensified western ridge coupled to the anomalous low pressure systems which developed over Angola and off the south coast of South Africa resulted in predominantly continental circulation. Consequently the southern African region was largely cut off from the temperate influence. In fact it is quite apparent however, that the shift to a warming trend detected from 1988 is related to the weakening of the meridional component of the south easterlies. In addition the southeast trade winds tended to advect less cool airflow over the subregion due to the development of a low pressure system to the south of the subcontinent during the 1988 to 2006 epoch. However from 2006, the relationship between SAM and SAMT was not all that robust, probably due to the characteristics of this last epoch whose length is still undetermined and relatively short.

The associated temporal SAMT changes seem to be dynamically consistent and indicate a possible link with epochal alterations in SAM. In fact we observed that the epochal modifications in SAM relative to the observed shift years are quasi-synchronous with changes in the meridional continental wind component that is predominantly controlled by the western flank of the MH. At the same time this flank in turn is coupled to the anomalous low pressure system over Angola and the anomalous pressure system which developed pole ward of South Africa. Since the SAMT time series are homogenized, the identified link with the continental meridional wind anomalies
should be physically strong. Moreover all the shift detection methods employed revealed similar results in the investigations of the SAM and SAMT indices. As such it is most likely that the proposed shifts in SAMT trends which have been related to SAM are real and not statistical artifacts. We conclude that changes in the circulation patterns south of the tropics may have produced or contributed to the changes in the southern African winter temperature. However, it is not clear whether the dynamics of the changes in the large-scale circulation mentioned in this study are due to natural fluctuation of the climate system or are determined by the external forcing. What is recognized is that anthropogenic emissions of carbon dioxide and other greenhouse gases have driven and will continue to drive widespread climate change at the Earth’s surface including that of southern Africa. In fact in the last epoch, SAM seems to have mitigated some of the longer-term increase in SAT across the sub region which was previously attributed to increasing greenhouse gases and other anthropogenic forcing (Shongwe et al. 2009). As such our results may suggest that the epochal alterations in the SAM, has implications not only for the current climate, but for the interpretation of climate change over southern Africa as well (Manatsa et al. 2013b). Finally, the fact that the links between changes in the large scale atmospheric circulation and southern SAMT have been determined statistically, imply that further dynamical studies is needed to appreciate better the physical mechanisms involved.

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