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Influence of Indian Ocean dipole on rainfall variability and extremes over southern Africa

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सार – खराब मौसम की घटनाएँ जैसे बाढ़ और सूखा दक्षिण अफ्रीका (SA) के 8 देशों (बोत्सवाना, नामीबिया, दक्षिण अफ्रीका, लेसोथो, स्वाज़ीलैंड, मोज़ाम्बिक, ज़िम्बाब्वे, अंगोला और ज़ाम्बिया के कुछ हिस्सों) में सामान्य बात हैं। यह अध्ययन दक्षिण अफ्रीका में अक्टूबर-दिसंबर (OND) की वर्षा, हिंद महासागर द्विध्रुव (IOD) और दक्षिण अटलांटिक दोलन द्विध्रुव (SAOD) के बीच संबंधों की जांच करता है। आनुभविक दोलन फलन (EOF) तकनीक का उपयोग अक्तूबर-दिसम्बर (OND) तक की वर्षा की परिवर्तनशीलता की प्रमुख अवस्था को स्थापित करने के लिए किया जाता है, क्योंकि सहसंबंध विश्लेषण को IOD [द्विध्रुव मोड इंडेक्स (DMI)], SAOD इंडेक्स (SAODI) और OND वर्षा परिवर्तनशीलता सूचकांकों के बीच संबंध को निर्धारित करने के लिए लागू किया जाता है। परिणाम बताते हैं कि OND वर्षा की परिवर्तनशीलता की प्रमुख अवस्था दक्षिण अफ्रीका के ऊपर एक द्विध्रुवीय पैटर्न को प्रदर्शित करती है और एक सहसंबंध गुणांक के साथ क्षेत्र औसत OND वर्षा [वर्षा सूचकांक (RFI)] और DMI के बीच -0.3 के सहसंबंध गुणांक के साथ 95% के विश्वस्नीयता स्तर पर एक महत्वपूर्ण सहसंबंध मौजूद है। दक्षिण अफ्रीका में अक्तूबर-दिसम्बर तक की औसत वर्षा और हिंद महासागर द्विध्रुव (IOD) के सकारात्मक चरण के बीच का संबंध एक देश से दूसरे देश में बहुत भिन्न होता है। इसके अलावा दक्षिण अफ्रीका में अक्तूबर-दिसम्बर (SAOND) के शुष्क और आर्द्र के विश्लेषण से पता चलता है कि आर्द्रता वाले वर्षों में सतह के स्तर (850 hPa) पर अभिसरण और ऊपरी स्तर (200 hPa) में अपसरण हुआ है जिससे इस क्षेत्र में गति में वृद्धि होती है जबकि शुष्क वर्ष निम्न स्तर में अपसरण और ऊपरी स्तर में अभिसरण से जुड़े होते हैं जिससे गति अवरोही होती है। इस अध्ययन में किसी देश के मौसम पर IOD के प्रभाव का पता लगाने के लिए देश के स्तर पर और स्थानिक स्तर पर और आगे शोध की सिफारिश की गई है। इससे क्षेत्र में ऋतुनिष्ठ मौसम पूर्वानुमानों की गुणवत्ता में सुधार करने के लिए IOD घटनाओं के विकास की सटीक निगरानी में मदद मिलेगी।

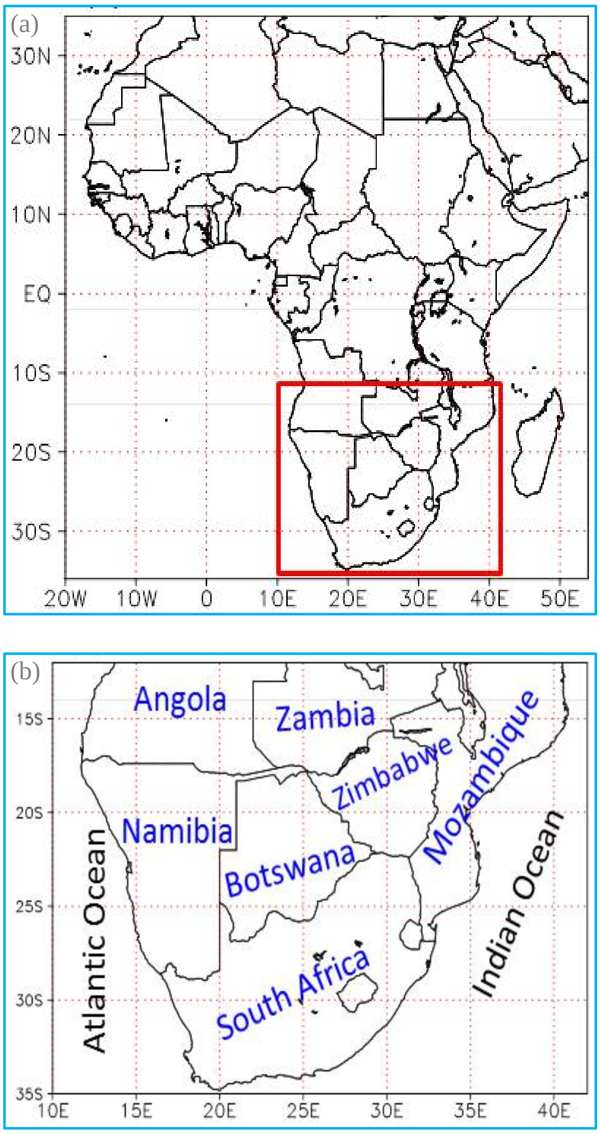
ABSTRACT. Extreme weather events; floods and droughts are common in southern Africa (SA) consisting of 8 countries (Botswana, Namibia, South Africa, Lesotho, Swaziland, Mozambique, Zimbabwe, parts of Angola and Zambia). This study examines the linkage between the SA October-December (OND) rainfall, the Indian Ocean Dipole (IOD) and the South Atlantic Oscillation Dipole (SAOD). Empirical Orthogonal Functions (EOF) technique is used to establish the dominant mode of variability of OND rainfall, as correlation analysis is applied to quantify the relationship between the indices; IOD [Dipole Mode Index (DMI)], SAOD Index (SAODI) and OND rainfall variability. Results show that the dominant mode of variability of OND rainfall exhibits a dipole pattern over SA and there exists a significant correlation at 95% confidence level between the area average OND rainfall (rainfall index (RFI)) and DMI, with a correlation coefficient of -0.3. The relationship between the mean SA OND rainfall and the positive phase of IOD varies greatly in space, ranging from one country to another. Further analysis of the dry and wet of SAOND rainfall years reveal that wet years are associated with convergence at surface level (850 hPa) and divergence at upper level (200 hPa), depicting rising motion in the region, whereas dry years are associated with divergence at low level and convergence at upper level, implying descending motion. The study recommends further research on a reduced spatial scale, for instance at a country level to ascertain the effect of IOD on individual country's weather. This will help in accurate monitoring of the evolution of IOD events to improve quality of seasonal weather forecasts in the region.

Key words – Drought, Flood, IOD, Rainfall, SAODI, Southern Africa.

1. Introduction

Climate and weather variability affect socio-economic sectors such as agriculture, transport, environment, ecosystem balances, food security, water services, health, energy supply, social order, public safety and societal development. Over southern Africa (SA), western and eastern Africa, rainfall is among the most important weather variables (Boyd *et al.*, 2013; Adhikari *et al.*, 2015), (as it drives rain fed agricultural systems (Washington & Downing, 1999; Jury, 2002; Funk & Brown, 2009; Shisanya *et al.*, 2011; Ongoma, 2013; Ogwang *et al.*, 2014). It is therefore, important to understand teleconnections - spatial patterns in the atmosphere that link and control weather. A good understanding of rainfall distribution and variability of a given region increases accuracy and reliability of weather forecasting, aimed at saving lives and minimizing destruction of property. However, spatiotemporal variability of rainfall over the entire continent is generally high owing to varied topographical features and maritime bodies on and around the continent (Ogwang *et al.*, 2014).

The need for understanding the variability of rainfall helps in planning adaptive options (Ogallo, 2010). Studies have indicated likelihood of an increase in frequency and intensity of extreme climate events, especially those related to precipitation (IPCC, 2013; SADC, 2010; Ongoma *et al.*, 2018). Many developing countries including the expansive SA region [Figs. 1(a&b)] are vulnerable to effects of the rainfall variability (Desanker & Magadza, 2001; Hudson & Jones, 2002; Davis-Reddy & Vincent, 2017). This is explained by their over reliance on rain driven agricultural practices that are not immune to climate sensitivity. The SA region experiences uni-modal rainfall regime; with heaviest rainfall coinciding with the southern hemisphere summer; December - February (Harou *et al.*, 2006).



Figs. 1(a&b). (a) Map of Africa showing the area of study (red rectangle) and (b) countries within the study area (Botswana, Namibia, South Africa, Lesotho, Swaziland, Mozambique, Zimbabwe and parts of Angola and Zambia)

Among the synoptic and localized systems that control or influence weather in this region include the Inter-Tropical Convergence Zone (ITCZ); this is a zone of large-scale low pressure characterized with deep convection, Hadley cell circulation, convergence on the surface and divergence a aloft, resulting in strong vertical motions, that occasion deep clouds and associated heavy episodic precipitation. The ITCZ's seasonal north-south migration is in response to the apparent motion of the sun (Diallo *et al.*, 2014). The region with ITCZ is heated most due to high insolation; the air becomes less dense triggering upward motion and creating low pressure. It is associated with convergence of tropical easterlies from the northern and southern hemispheres that influence the rainfall seasonality across large swathes of Africa. Studies have focused more on understanding the influence of local factors on climate and weather

(Nicholson, 1996, 2000). Among the common features affecting weather in Africa, include the influence of the Indian Ocean (IO) (Saji *et al*., 1999; Behera & Yamagata, 2001) and Pacific Ocean (PO) (Philippon *et al.*, 2012; Lakhraj-Govender & Grab, 2019).

Zonal temperature differences in the Pacific Ocean set up a circulation known as Southern Oscillation (SO). The intensity of SO is measured during Southern Oscillation Index (SOI). A positive SOI implies a La Niña event while the negative index is linked to El Niño condition. According to Rasmusson & Carpenter (1982), the El Niño and the Southern Oscillation are two characteristics of a one large ocean-atmosphere coupling event known as El Niño Southern Oscillation (ENSO). A number of studies concludes that southern African summer seasonal rainfall is significantly influenced by ENSO (Ropelewski & Halpert, 1989; Cook, 2000, 2001; Gaughan *et al.*, 2016; Hoell *et al.*, 2017; Pomposi *et al.*, 2018). La Niña (El Niño) is generally associated with anomalously wet (dry) conditions over southern Africa and dry (wet) conditions over East Africa (Hoell *et al.*, 2017).

The IO forms a significant warm water pool on earth and its coupling with the atmosphere plays an active role in influencing climate on both local and global scales (Schott *et al*., 2009). Several studies focus on the Indian ocean response to ENSO (Cadet, 1985; Lindesay, 1988; Nicholson & Kim, 1997; Reason *et al.*, 2000; Hoell *et al.*, 2017), the monsoons (Shukla & Misra, 1977; Rao & Goswami, 1988) and variability of the Atlantic Ocean (Reason & Mulenga, 1999; Reason, 2001; Behera & Yamagata, 2001; Rouault *et al.*, 2003).

According to the past studies (Richard *et al.*, 2000; Reason & Rouault, 2006; Diallo *et al.*, 2014), the systems controlling the weather and the forcing factors behind climate variability over SA are varied and complex in nature. Saji *et al.* (1999) reported occurrence of different IO rainfall events during 1958 to 1998; - termed IO dipole (IOD) mode events. According to Saji *et al.* (1999), the strength of IOD is measured by dipole mode index (DMI) that is computed as the difference in the SST anomalies between the tropical western Indian Ocean (50° E - 70° E, 10° S - 10° N) and the tropical southeastern Indian Ocean (90° E - 110° E, 10° S - 0°). A zonal mode of variability of the IOD influences rainfall variability over many parts of Africa. Further studies (Clark *et al*., 2003; Black *et al*., 2003) revealed that a positive IOD is associated with an increase in rainfall in eastern and southern Africa.

The positive phase of the IOD is associated with the westward shift of convective zone over the eastern IO, thus alternating warm sea surface temperatures (SSTs) to the east and cool SSTs to the west result in wet and dry spells respectively over SA. Over the western SA, on average, the Atlantic Ocean anticyclone shifts only about 6° latitudes between seasons with significant semi-annual oscillation in position (Reason *et al*., 2006). The seasonal fluctuations in the anticyclone drive changes in the surface winds and hence SSTs, particularly in the upwelling zones along the west coast of SA such as Namibian coast during winter months. These oceans act as sources of low-level moisture and have high influence on the climate of SA both at global, synoptic and seasonal time scales.

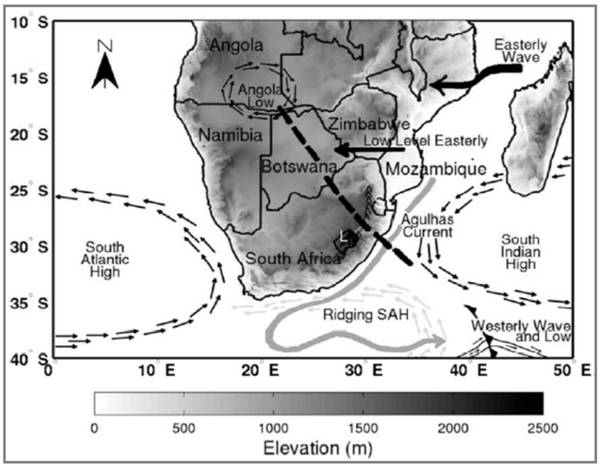


Fig. 2. Main weather and climate features over SA during a typical summer time. The dark broad dashed diagonal line represents mean position of the ITCZ associated with convective bands normally associated with what is referred to as the interior trough and the cold front over the Indian Ocean (*Source* : Blamey & Reason, 2013)

In a study on the influence of the IOD mode on precipitation over the Seychelles, Harou *et al.* (2006) revealed that the December-February (DJF) DMI is significantly correlated to cooler SSTs off Sumatra and a zonal wind anomaly in the IO. These correlations are much stronger during the months of September-November (SON), the peak months for the IOD. The study further showed a three-month time lag relationship between SSTs and precipitation in some parts of Seychelles indicating a good potential for its applicability as seasonal forecasting predictor. These findings are supported by a number of studies (Washington *et al*., 2003; Washington & Preston, 2006). These studies which relied on both observational and idealized modeling results that showed anomalous SSTs gradients during the early austral summer in the southwest IO are the most important pattern controlling SA rainfall variability (Zinke *et al*., 2009; Neukom *et al*., 2014). Fig. 2 shows some of the systems controlling weather & climate features over SA during summer period.

As noted by Gaughan *et al*. (2016), a lot of studies not only in southern Africa but across Africa have given more attention to ENSO as compared to Indian Ocean Dipole (IOD). That is why this study investigates the influence of the IOD on rainfall variability and extreme weather events over SA.

The effect of IOD on the SA OND rainfall is examined in this study, alongside the circulation anomalies associated with extreme events of rainfall. The OND season is chosen because IOD is a seasonally phase-locked phenomenon that initiates in May, peaks in October and decays by December (Owiti *et al*., 2008). The understanding of the influence of IOD on rainfall variability, with the associated circulations during extreme weather events; dry and wet years will greatly help improve the quality of seasonal forecasts. This is necessary, especially in the current evolving state of climate, variability and change.

The remaining parts of this work are organized as follows: Section 2 contains data and methodology, Section 3 gives the results and discussion, while the conclusion of the study is presented in Section 4.

2. Data and methodology

2.1. *Data*

Reanalyzed precipitation (rainfall) dataset used in this study is from the Global Precipitation Climatology Centre (GPCC) monthly precipitation dataset. The latest version of the data spans from 1901 to 2018. It is calculated from the global station data (Schneider *et al*., 2013). GPCC Precipitation data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at https://psl.noaa.gov/data/gridded/data.gpcc.html. This data is used because the African rain-gauge observed data has many spatial and temporal discontinuities over large sections of Africa (Schreck & Semazzi, 2004).

Meridional and zonal winds, temperature and relative humidity used to determine moisture transport are the ERA-interim data, gridded at a horizontal resolution of 0.75° (Dee *et al*., 2011). The South Atlantic Ocean Dipole (SAOD) is the mechanism of warming of the surface waters off the coasts of west/central Equatorial Africa associated with concurrent cooling of similar magnitude off the Argentina-Uruguay-Brazillian coasts. These SST patterns are coupled to the atmospheric circulation field and regional climates. A simple measure of the dipole; the SAOD Index (SAODI), is defined by differencing the domain-averaged normalized SST anomaly (SSTA) of the two centers of intense warming and cooling associated with the SAOD, given by Eqn. 1.

$$\mathrm{SAODI} = (\mathrm{SSTA})_{\mathrm{NEP}} - (\mathrm{SSTA})_{\mathrm{SWP}} \qquad (1)$$

where, the square brackets indicate domain averages, the subscripts show the two regions over which the SSTA averages are computed. These domains are described by their locations in the South Atlantic Ocean as the northeast pole (NEP : 10° E - 20° W, 0° - 15° S) and the southwest pole (SWP : 10° - 40° W, 25° S - 40° S) (Nnamchi *et al*., 2011; Nnamchi & Li, 2011).

2.2. *Methodology*

Empirical Orthogonal Functions (EOF) analysis is used in this study to investigate the dominant modes of variability of the OND rainfall over the region. The data used is normalized in order to prevent areas (and seasons) of maximum variance from dominating the eigenvectors (Walsh & Mostek, 1980). The standardized rainfall anomaly Z is computed as expressed in Eqn. 2.

$$Z = \frac{X - \overline{X}}{S_d} \qquad (2)$$

where, X is the observed OND rainfall, $\overline{X}$ is the long term mean OND rainfall and S_d is the OND rainfall standard deviation. The value of Z provides immediate information about the significance of a particular deviation from the mean (Kabanda & Jury, 1999).

Composite analysis is used in this study to show dominant features and patterns in rainfall during dry and wet years. It involves identifying and averaging one or more categories of fields of a variable selected according to their association with key conditions. Results of the composites are then used to generate hypotheses for patterns which may be associated with the individual scenarios (Folland, 1983). According to Washington & Preston (2006), a comprehensive understanding of atmospheric mechanisms over SA can be derived from composite analysis for both dry and wet years. In this study, the key conditions for the composite analysis are wet/flood years and dry/drought years, where the composites for wet and dry years were separately done, especially for wind, divergence and convergence. This is mainly to detect the circulation anomalies associated with wet/dry events over the region. The composite years were chosen based on the standard deviation (SD) of the area average rainfall, where the years with SD ≥ 1 and ≤ -1 implies wet and dry years, respectively as used in related studies (Tan *et al*., 2014; Ogwang *et al*., 2015). A number

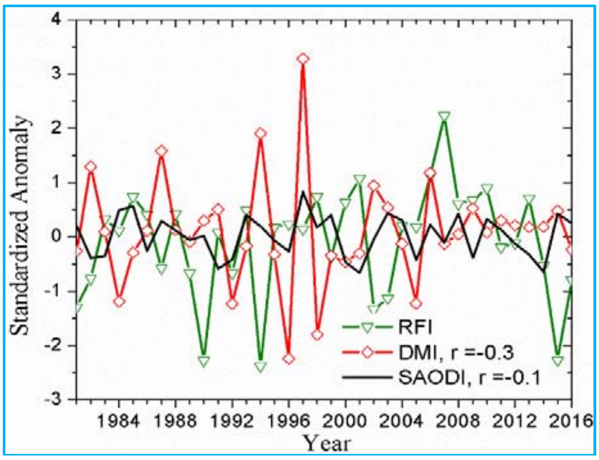


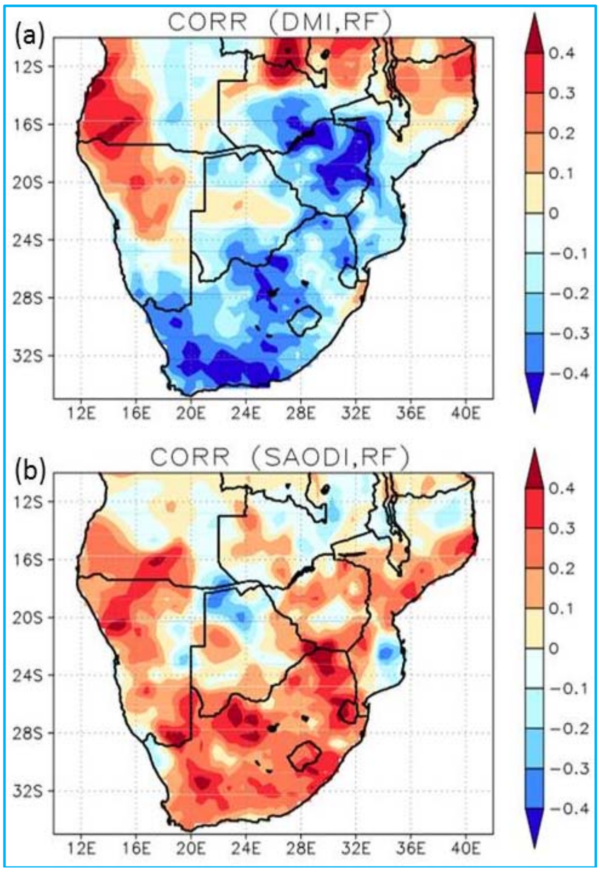
Fig. 3. The inter-annual variability of the area average rainfall (RFI) over southern Africa, the Dipole Mode Index (DMI) and the South Atlantic Ocean Dipole Index (SAODI). The correlation coefficient between RFI and DMI = -0.3 and that between SAODI & RFI = - 0.1, for 1981 - 2016

of authors, including Okoola (1999); Ogwang *et al.* (2012, 2015) and Ngarukiyimana *et al*. (2018) have successfully used composite methods in their analyses over different parts of the African continent.

Pearson correlation analysis reveals the relationship between pairs of variables (Wilks, 2006). In this study, correlation analysis is aimed at quantifying/displaying the relationship between SAODI/DMI and OND rainfall over southern Africa. Partial correlation between rainfall and IOD is performed to control the influence of ENSO on the rainfall. The significance of the correlation is tested using *t* test statistic, at 95% confidence level.

3. Results and discussion

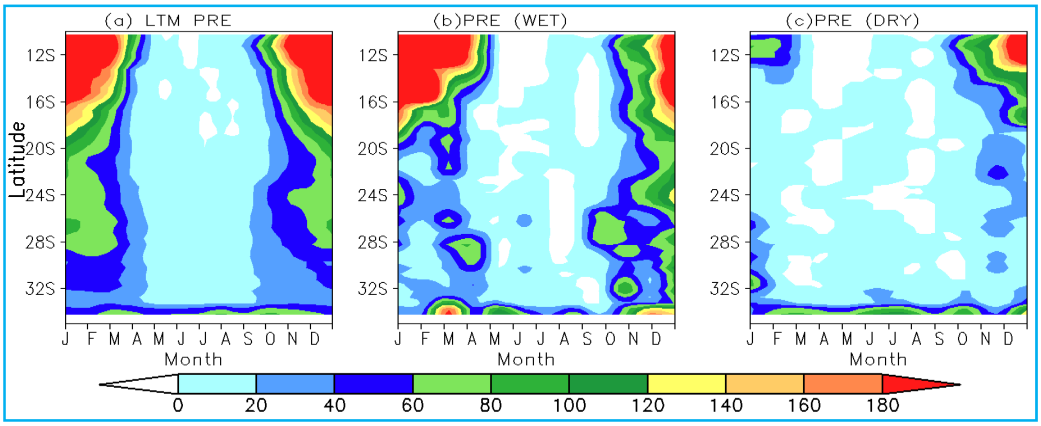
Analysis of the relationship between the SA area average OND rainfall (rainfall index, RFI) and the OND Dipole Mode Index (DMI)/South Atlantic Ocean Dipole Index (SAODI) is presented in Fig. 3. The results confirm that there exists a negative correlation of coefficient -0.3 between RFI and DMI at 90% confidence level. However, the relationship between SAODI and RFI exhibits a weak negative correlation. When the influence of ENSO is removed through partial correlation, the correlation coefficient between SA rainfall and IOD remains negative, -0.13. This implies that rainfall over Southern Africa is enhanced during the negative phase of IOD, which agrees with the positive correlation between RF and SOI [Figs. 4(a&b)]. In a related study over the Kavango-Zambezi Transfrontier Conservation Area, Gaughan *et al.* (2016) observed that El Niño (*i.e.*, negative SOI) and positive IOD events are significantly related to dry periods.



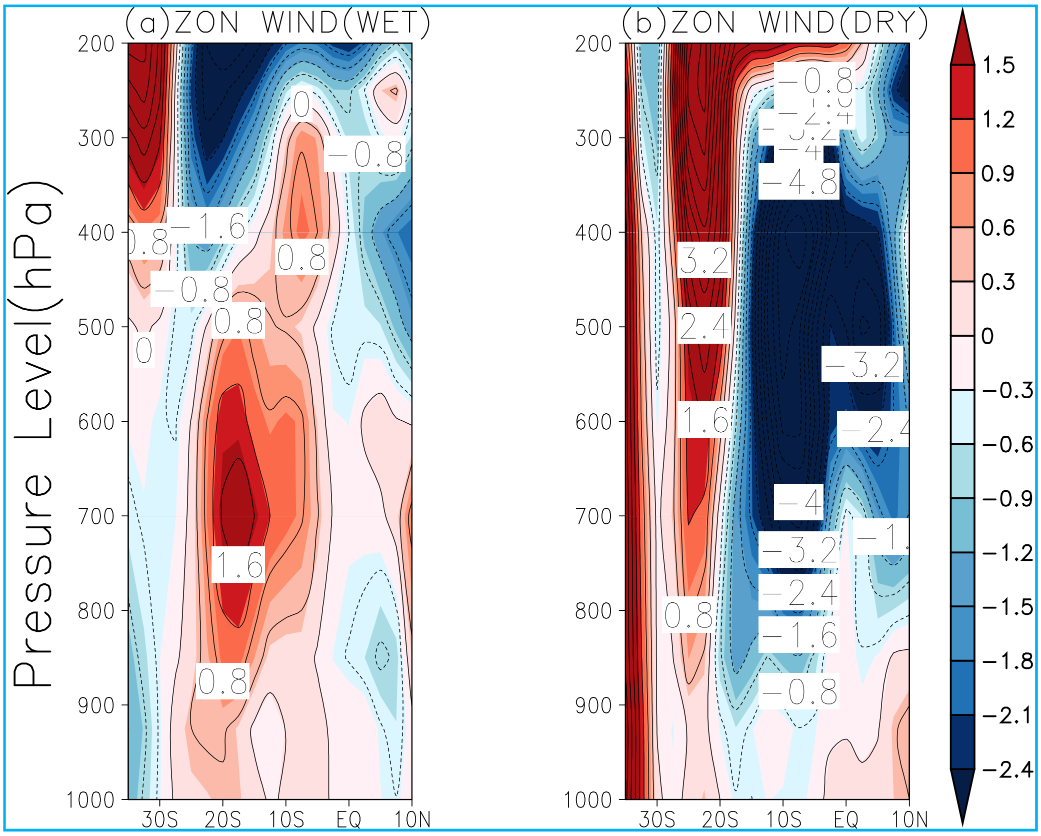
Figs. 4(a&b). Correlation map of (a) the Dipole Mode Index (DMI) and the grid point rainfall and (b) the South Atlantic Ocean Dipole Index (SAODI) and the grid point rainfall over southern Africa. The critical values for significant correlation coefficient are ±0.32

In order to understand the influence of the indices on OND rainfall over the countries/sub-regions within the study area, the study investigates the spatial correlation between DMI/SAODI and the grid point OND rainfall over the region [Figs. 4(a&b)].

Results reveal that there exists a significant negative correlation between DMI and the grid point OND rainfall over South Africa (especially southern parts of Western Cape and Eastern Cape provinces, North western parts of Free-State and northern parts of the North-West Provinces), Zimbabwe, northern tips both Lesotho and Swaziland and the southern regions of Mozambique and Zambia. Positive correlation is depicted in the western sectors of Namibia and Angola and the northern regions of Zambia, Malawi and Mozambique. SAODI exhibits a significant positive correlation with the grid point rainfall over the entire region, with exception of northern Botswana and southeastern Mozambique, which displays a string negative correlation.

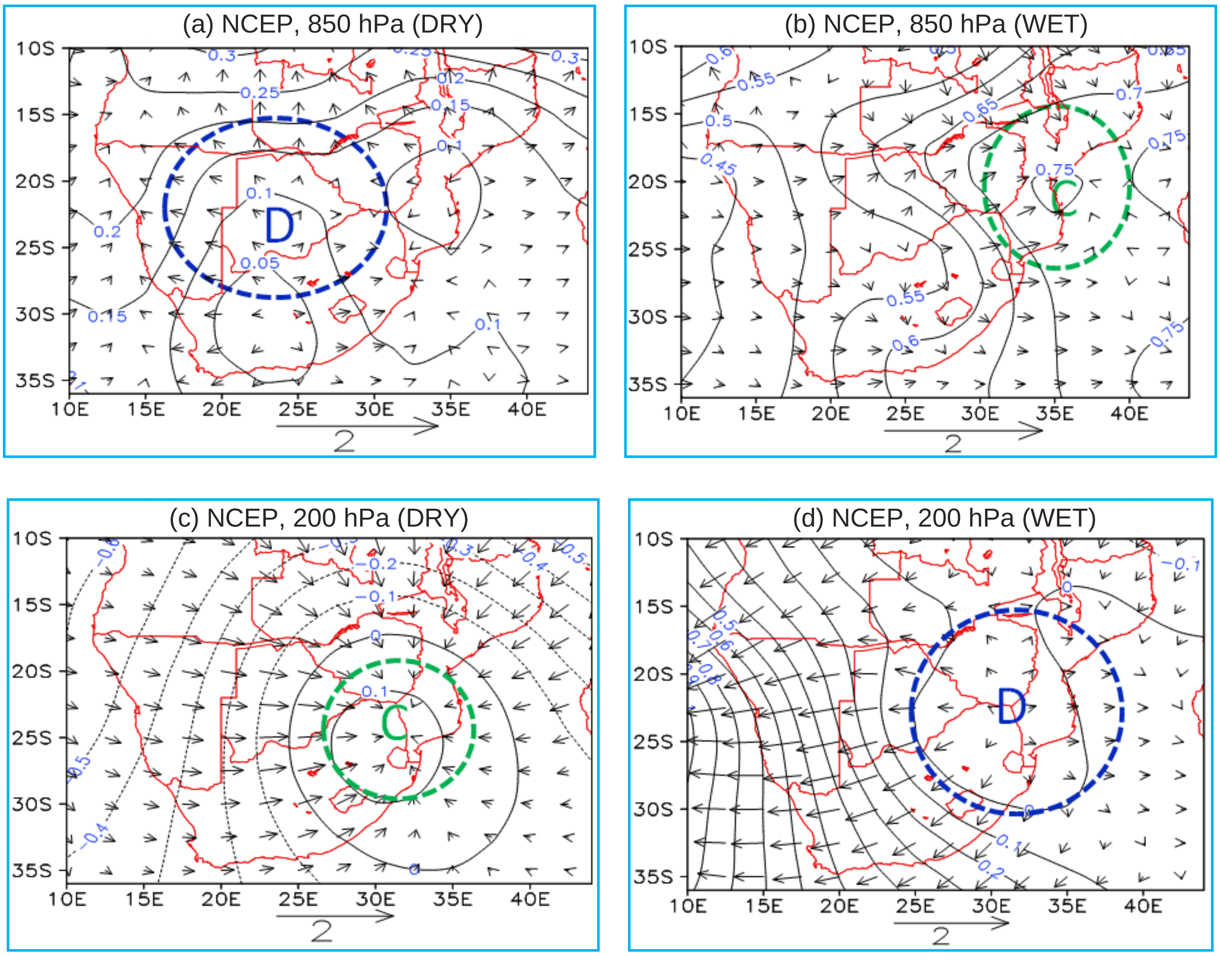


Figs. 5(a-c). A display of rainfall in mm (a) The mean seasonal cycle of rainfall (LTM) over the period 1981-2010, at longitude 24° E (b) The observed rainfall during the wet years and (c) The observed rainfall during the dry years



Figs. 6(a&b). Vertical cross section of the mean zonal wind anomaly (ms^{-1}) averaged over longitudes 10° E - 42° E for (a) wet years (2001, 2006 and 2007) and (b) dry years (1981, 1990, 1994, 2002, 2003)

Composite analysis was deployed, where the composite years were chosen based on the standard deviation (SD) of the area average rainfall. Using the chosen criteria, the years 2001, 2006 and 2007 were chosen as a wet years, while 1981, 1990, 1994, 2002 and 2003 were taken as dry years. Table 1 reveals that in the composite dry years, the mean OND rainfall was reduced by about 20%, with respect to the long term mean of OND rainfall, whereas for wet years, rainfall amount was enhanced by about 18%. These years are considered for



Figs. 7(a-d). Mean anomaly of OND velocity potential (×106 $m^2 s^{-1}$) / divergent (or convergent) wind (a) for dry years at 850 hPa, (b) for wet years at 850 hPa, (c) for the dry years at 200 hPa and (d) for wet years at 200 hPa. Contours represent velocity potential and are at 0.05 × 106 $m^2 s^{-1}$ (for 850 hPa) and 0.1 × 106 $m^2 s^{-1}$ (for 200 hPa) intervals. Vectors show divergence/convergence of wind

further analyses in order to understand the prevailing circulation anomalies during flood and drought events in the region, in regard to winds, divergence and convergence at low and upper levels.

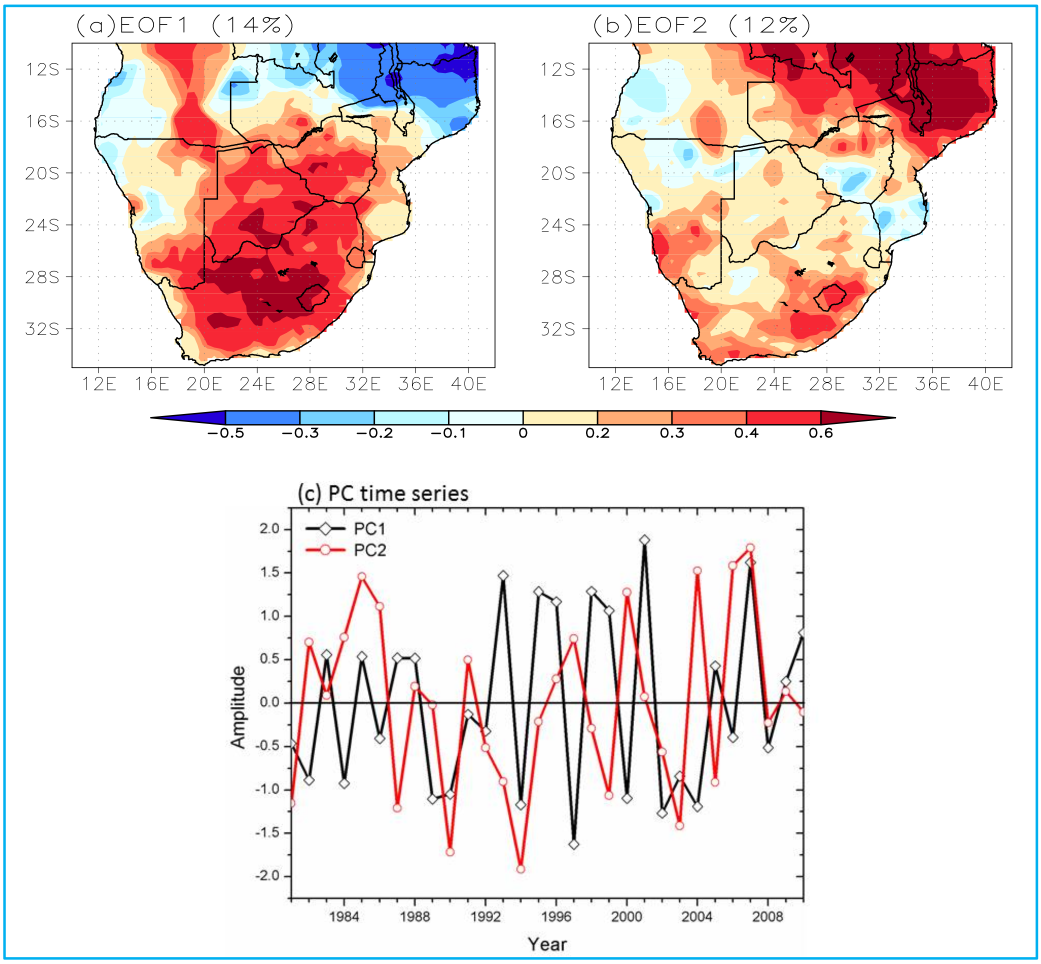
Figs. 5(a-c) shows that during the wet years [Fig. 5(b)], rainfall was well distributed between October to March over latitudes 35° S - 10° S, with the maximum amounts recorded between 20° S and 10° S [which also captures the LTM, Fig. 5(a)]. During dry years [Fig. 5(c)], the latitudinal distribution of rainfall was far less than normal over all the months.

Analysis of the vertical cross section of the mean zonal wind [Figs. 6(a&b)] reveals that during wet years, strong winds dominate at low level, particularly between latitudes 30° S - 5° S, whereas the upper level is characterized by weak winds (between 30° S - 10° N) and strong westerly winds (latitudes lower than 35° S). Dry years on the other hand are dominated by weak easterly winds, especially between latitudes 20° S - 10° N from low level to upper level, as opposed to the region between latitudes 30° S - 20° S which experiences strong westerly

TABLE 1

The mean OND rainfall (RF* in mm), averaged over longitude 10° E - 42° E and latitude 35° S - 10° S. LTM is the long term mean OND rainfall over the period 1981-2010. WET and DRY are the mean OND rainfall amounts during the composite wet years and dry years, respectively. PC* is the percentage change, computed with respect to LTM

Event	RF* (mm)	PC* (%)
LTM	67	-
WET	84	18 (Increase)
DRY	49	20 (Decrease)



Figs. 8(a-c). (a) The first EOF spatial mode, EOF1 (explains 14% of the total variance) of the mean OND rainfall (b) The second EOF spatial mode, EOF2 (explains 12% of the total variance) of the mean OND rainfall and (c) The first (PC1) and second (PC2) EOF time series corresponding to EOF1 and EOF2

winds from low level to upper level. In the wet years, increased (enhanced) vertical wind shear is dominant in the middle and upper levels [Fig. 6(a)]. Strong winds in the upper troposphere relative to the lower troposphere leads to pressure differences between the two levels that enhances convection, leading to increased rainfall. An opposite pattern of the vertical wind shear is observed in dry years. This point out the significant role played by the vertical wind shear in rainfall bearing systems over southern Africa.

Further investigation of the velocity potential and divergent/convergent winds [Figs. 7(a-d)] show that during wet years [Fig. 7(b)], there is a notable convergence at low level (850 hPa), centered between 33° - 36° E and 25° S - 15° S), which enhances moisture influx into the study area, as anomalous winds flow into the centre (labeled C).

At the upper level [200 hPa, Fig. 7(d)], there is a widespread divergence over the region (labeled D), which may be associated with the observed convergence at low level. This therefore implies an ascending motion in the region during wet years. On the other hand, during dry years, there is a notable divergence at low level [Fig. 7(a), labeled D] and convergence at upper level [Fig. 7(c), labeled C], depicting descending motion.

The spatial component [Fig. 8(a)] of the first eigenvectors (EOF1) of the mean OND seasonal rainfall exhibits more or less a dipole mode (pattern) of variability, with strong positive loadings to the southern sector of the region and strong negative loadings in the northern sector. The second eigenvectors (EOF2) shows the strongest positive loadings to the northeast and southeastern sectors, whereas weak negative loadings are observed in the central region [Fig. 8(b)]. The principal

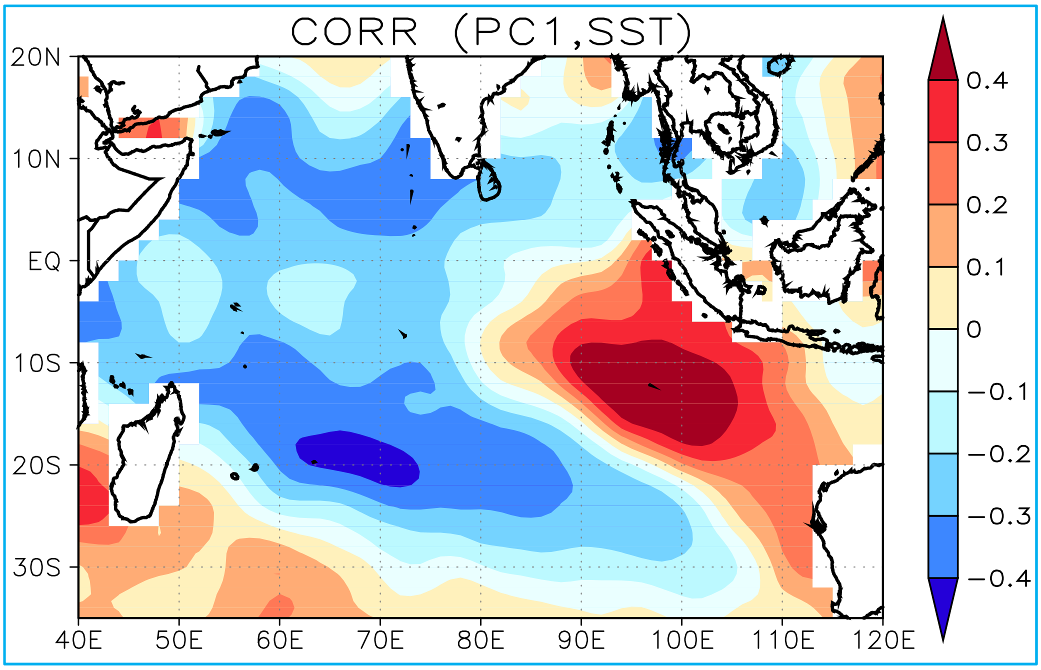


Fig. 9. Correlation map between PC1 of the mean OND rainfall over southern Africa and the grid point sea surface temperature (SST) over the Indian Ocean. The critical values for significant correlation coefficient are ±0.32

component (PC) time series corresponding to EOF1 (PC1) and EOF2 (PC2) are shown in Fig. 8(c).

Further analysis of the relationship between PC1 and the mean OND grid point SST (Fig. 9) shows that there exists a significant positive correlation with the tropical southeastern IOD sub-region (90° E - 110° E, 10° S - 0°) and significant negative correlation with the western IOD sub-region (50° E - 70° E, 10° S - 10° N). This implies that SA OND rainfall exhibits a positive relationship with the negative phase of IOD events and *vice versa* is true.

4. Conclusions and recommendation

Accurate rainfall forecasting is very important especially in areas such as southern Africa that are very vulnerable to rainfall variability and change. The regions vulnerability is population growth that is mainly reliant of rain fed agriculture. Rainfall variability has significant influence on crop growth consequently affecting food security. Thus, there is need to have a good understanding of how different factors influence rainfall variability over the region. This study investigates how DMI influences rainfall variability in southern Africa, with an aim of using it as a predictor for rainfall forecasts in the region.

The study affirms that that there exists a significant negative correlation between DMI and the grid point OND rainfall over South Africa (especially southern parts of Western Cape and Eastern Cape provinces, North western parts of Free-State and northern parts of the North-West Provinces), Zimbabwe, northern tips both Lesotho and Swaziland and the southern regions of Mozambique and Zambia. A positive correlation is depicted in the western sectors of Namibia and Angola and the northern regions of Zambia, Malawi and Mozambique. SAODI however exhibits a significant positive correlation with the grid point rainfall over the entire region, with exception of northern Botswana and southeastern Mozambique, which displays a strong negative correlation.

The dry year was characterized by convergence over the Indian Ocean, which inhibits moisture influx into the study area, as anomalous winds flow from the continent towards the Indian Ocean. Anomalous divergence is observed in the northeastern sector of the study area. At the upper level (200 hPa), there is a widespread convergence over the region. This convergence is associated with the observed divergence at low level, which implies a descending motion in the region during the dry year.

The wet year on the other hand is characterized by divergence over the Indian Ocean (between 35° E - 44° E and 36° S - 30° S), which enhances moisture influx into the study area, as anomalous winds flow from the Indian

Ocean into the continent. There is a widespread anomalous convergence in the northeastern sector of the study area. At upper level (200 hPa), there was an extensive divergence over the region, which may be associated with the observed convergence at low level, depicting ascending motion in the region during the wet year. Convergence at low level leads to vertical stretching, whereas divergence at low level results in vertical shrinking which suppresses convection due to subsidence (Barry & Chorley, 2003).

The relationship between the mean SA OND rainfall and the positive phase of IOD varies greatly in space, ranging from country to another. The study recommends further research in the region, carried out at a higher spatial resolution, for instance at individual country level to ascertain the effect of IOD on its weather. This will help in accurate monitoring of the evolution of IOD events which will help improve the quality of seasonal rainfall forecast.

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References

Adhikari, U., Nejadhashemi, A. P. and Woznicki, S. A., 2015, “Climate change and eastern Africa : A review of impact on major crops”, *Food and Energy Security*, **4**, 2, 110-132. https://doi.org/10.1002/ fes3.61.

Barry, R. G. and Chorley, R. J., 2003, “Atmosphere, weather and climate”, 8th Edn., Routledge, London, p462.

Behera, S. K. and Yamagata, T., 2001, “Subtropical SST dipole events in the southern Indian Ocean”, *Geophysical Research Letters*, **28**, 2, 327-330. https://doi.org/10.1029/2000GL011451.

Black, E., Slingo, J. and Sperber, K. R., 2003, “An observational study of the relationship between excessively strong short rains in coastal East Africa and Indian Ocean SST”, *Monthly Weather Review*, **131**, 1, 74-94. http://dx.doi.org/10.1175/1520-0493 (2003)131<0074:AOSOTR>2.0.CO;2.

Blamey, R. C. and Reason, C. J. C., 2013, “The Role of Mesoscale convective complexes in Southern Africa summer rainfall”, *Journal of Climate*, **26**, 5, 1654-1668. https://doi.org/10.1175/JCLI-D-12-00239.1.

Boyd, E., Cornforth, R. J., Lamb, P. J., Tarhule, A., Lélé, M. I. and Brouder, A., 2013, “Building resilience to face recurring environmental crisis in African Sahel”, *Nature Climate Change*, **3**, 631-637. https://doi.org/10.1038/nclimate1856.

Cadet, D., 1985, “The Southern Oscillation over the Indian Ocean”, *Journal of Climatology*, **5**, 2, 189-212. https://doi.org/10.1002/ joc.3370050206.

Clark, C., Webster, P. and Cole, J., 2003, “Interdecadal variability of the relationship between the Indian Ocean zonal mode and East African coastal rainfall anomalies”, *Journal of Climate*, **16**, 3, 548-554. http://dx.doi.org/10.1175/1520-0442(2003)016<0548: IVOTRB>2.0.CO;2.

Cook, K. H., 2000, “The South Indian Convergence Zone and Interannual rainfall variability over southern Africa”, *Journal of Climate*, **13**, 21, 3789-3804. http://dx.doi.org/10.1175/1520-0442(2000)013<3789:TSICZA>2.0.CO;2.

Cook, K. H., 2001, “A Southern Hemisphere wave response to ENSO with implications for southern Africa rainfall”, *Journal of Atmospheric Science*, **58**, 15, 2146-2162. http://dx.doi.org/ 10.1175/1520-0469(2001)058<2146: ASHWRT>2.0.CO;2

Davis-Reddy, C. L. and Vincent, K. 2017, “Climate Risk and Vulnerability : A Handbook for Southern Africa (2nd Edn.)”, CSIR, Pretoria, South Africa.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli. P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A., Van de Berg. L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S., Hersbach, H., Holm, E. V., Isaksen, L., Kallberg, P., Koehler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J. N. and Vitart, F., 2011, “The ERA-Interim reanalysis : Configuration and performance of the data assimilation system”, *Quarterly Journal of Royal Meteorological Society*, **137**, 656, 553-597. https://doi.org/ 10.1002/qj.828.

Desanker, P. and Magadza, C., 2001, “Africa. Climate Change 2001: Impacts, Adaptation and Vulnerability”, J. McCarthy *et al.,* Eds., Cambridge University Press, 489-531.

Diallo, I., Giorgi, F., Sukumaran, S., Stordal, F. and Giuliani, G., 2014, “Evaluation of RegCM4 driven by CAM4 over Southern Africa : Mean climatology, interannual variability and daily extremes of wet season temperature and precipitation”, *Theoretical and Applied Climatology*, **121**, 3-4, 749-766, https://doi.org/ 10.1007/s00704-014-1260-6.

Folland, C. K., 1983, “Regional-Scale Interannual variability of climate, a north-west European perspective”, *Meteorology Magazine*, **112**, 163-183.

Funk, C. and Brown, M. E., 2009, “Declining global per capita agricultural production and warming oceans threaten food security”, *Food Security*, **1**, 3 271-289. https://doi.org/ 10.1007/s12571-009-0026-y.

Gaughan, A. E., Staub, C. G., Hoell, A., Weaver, A. and Waylen, P. R., 2016, “Inter and Intra-annual precipitation variability and associated relationships to ENSO and the IOD in southern Africa”, *International Journal of Climatology*, **36**, 1643-1656. https://doi.org/10.1002/joc.4448.

Harou, P. A., Lajoie, F. R., Knivetona, R. D. and Frogley, R. M., 2006, “The Influence of the Indian Ocean Dipole Mode on Precipitation over the Seychelles”, *International Journal of Climatology*, **26**, 1, 45-54. http://dx.doi.org/10.1002/joc.1239.

Hoell, A., Funk, C., Zinke, J. and Harrison, L., 2017, “Modulation of the Southern Africa precipitation responseto the El Niño Southern Oscillation by the subtropical Indian Ocean Dipole”, *Climate Dynamics*, **48**, 7-8, 2529-2540. https://doi.org/10.1007/s00382-016-3220-6.

Hudson, D. and Jones, R., 2002, “Simulations of present-day and future climate over southern Africa using HadAM3H”, Meteorological Office, Hadley Centre for Climate Prediction and Research, Tech. Note 38, p3.

IPCC, 2013, “Summary for Policymakers. In : Climate Change 2013 : The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change”, [Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, S.

Jury, M. R., 2002, “Economic impacts of climate variability in South Africa and development of resource prediction models”, *Journal of Applied Meteorology*, **41**, 1, 46-55. http://dx.doi.org/10.1175/1520-0450(2002)041<0046 : EIOCVI >2.0.CO;2.

Kabanda, T. A. and Jury, M. R., 1999, “Inter-annual variability of short rains over northern Tanzania”, *Climate Research*, **13**, 231-241.

Lakhraj Govender, R. and Grab, S. W., 2019, “Assessing the impact of El Niño-Southern Oscillation on South African temperatures during austral summer”, *International Journal of Climatology,* **39**, 1, 143-156. https://doi.org/10.1002/joc.5791.

Lindesay, J. A., 1988, “South African rainfall, the southern oscillation and a southern hemisphere semi-annual cycle”, *Journal of Climatology*, **8**, 1, 17-30. https://doi.org/10.1002/joc.3370080103.

Neukom, R., Nash, D. J., Endfield, G. H., Grab, S. W., Grove, C. A., Kelso, C., Vogel, C. H. and Zinke, J., 2014, “Multi-proxy summer and winter precipitation reconstruction for southern Africa over the last 200 years”, *Climate Dynamics*, **42**, 9-10, 2713-2726. http://dx.doi.org/10.1007/s00382-013-1886-6.

Ngarukiyimana, J. P., Fu, Y., Yang, Y., Ogwang, B. A., Ongoma, V. and Ntwali, D., 2018, “Dominant atmospheric circulation patterns associated with abnormal rainfall events over Rwanda, East Africa”, *International Journal of Climatology*, **38**, 1, 187-202. https://doi.org/10.1002/joc.5169.

Nicholson, S. E. and Kim, J., 1997, “The relationship of the El Niño-Southern Oscillation to African Rainfall”, *International Journal of Climatology*, **17**, 2, 117-135. https://doi.org/10.1002/(SICI)1097-0088(199702)17:2<117::AID-JOC84>3.0.CO;2-O.

Nicholson, S. E., 1996, “A review of climate dynamics and climate variability in eastern Africa. The Limnology, Climatology and Paleoclimatology of the Eastern African Lakes”, Gordon and Breach, New York, 25-56.

Nicholson, S. E., 2000, “The nature of rainfall variability over Africa on time scales of decades to millennia”, *Global Planetary Change*, **26**, 1-3, 137-158. http://dx.doi.org/10.1016/S0921-8181(00)00040-0.

Nnamchi, C. H. and Li, J., 2011, “Influence of the South Atlantic Ocean Dipole on West African Summer Precipitation”, *Journal of Climate*, **24**, 4, 1184-1197. http://dx.doi.org/10.1175/ 2010JCLI3668.1.

Nnamchi, C. H., Li, J. and Anyadike, N. C. R., 2011, “Does a dipole mode really exist in the South Atlantic Ocean?”, *Journal of Geophysical Research*, **116**, D15104. https://doi.org/10.1029/2010JD015579.

Ogallo, L., 2010, “The mainstreaming of climate change and variability information into planning and policy development for Africa”, *Procedia Environmental Sciences*, **1**, 405-410. https://doi.org/10.1016/j.proenv.2010.09.028.

Ogwang, B. A., Chen, H., Li, X. and Gao, C., 2014, “The influence of Topography on East African October to December climate : Sensitivity experiments with RegCM4”, *Advances in Meteorology*, 143917. http://dx.doi.org/10.1155/2014/ 143917.

Ogwang, B. A., Chen, H., Tan, G., Ongoma, V. and Ntwali, D., 2015, “Diagnosis of East African climate and the circulation mechanisms associated with extreme wet and dry events: a study based on RegCM4”, *Arabian Journal of Geosciences*, **8**, 12, 10255-10265. https://doi.org/10.1007/s12517-015-1949-6.

Ogwang, B. A., Guirong, T. and Haishan, C., 2012, “Diagnosis of September - November Drought and the Associated Circulation Anomalies over Uganda”, *Pakistan Journal of Meteorology*, **9**, 11-24.

Okoola, R. E., 1999, “A diagnostic study of the East African monsoon circulation during the northern hemisphere spring season”, *International Journal of Climatology*, **19**, 2, 143-168. http://dx.doi.org/10.1002/(SICI)1097-0088(199902)19:2<143::AID-JOC342>3.3.CO;2-L.

Ongoma, V., 2013, “A review on the Effects of Climate Change on occurrence of Aflatoxin and its impacts on Food Security in Semi-Arid Areas of Kenya”, *International Journal of Agricultural Sciences Research*, **2**, 11, 307-311**.**

Ongoma, V., Chen, H., Gao, C., Nyongesa, A. M. and Polong, F., 2018, “Future changes in Climate extreme over Equatorial East Africa based on CMIP5 multimodel ensemble”, *Natural Hazards*, **90**, 2, 901-920. http://doi.org/10.1007/s11069-017-3079-9.

Owiti, Z., Ogallo, L. A. and Mutemi, J., 2008, “Linkages between the Indian Ocean Dipole and East African Rainfall Anomalies”, *Journal of Kenya Meteorological Society*, **2**, 3-17.

Philippon, N., Rouault, M., Richard, Y. and Favre, A., 2012, “The influence of ENSO on winter rainfall in South Africa”, *International Journal of Climatology*, **32**, 15, 2333-2347. https://doi.org/10.1002/joc.3403.

Pomposi, C., Funk, C., Shukla, S., Harrison, L. and Magadzire, T., 2018, “Distinguishing southern Africa precipitation response by strength of El Nĩno events and implications for decision-making”, *Environmental Research Letters*, **13**, 074015. https://doi.org/10.1088/1748-9326/aacc4c.

Rao, K. and Goswami, B., 1988, “Interannual variations of the sea-surface temperature over the Arabian Sea and the Indian Monsoon: a new perspective”, *Monthly Weather Review*, **116**, 3, 558-568. http://dx.doi.org/10.1175/1520-0493(1988)116<0558:IVOSST>2.0.CO;2.

Rasmusson, E. M. and Carpenter, T., 1982, “Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated With the Southern Oscillation/El Niño”, *Monthly Weather Review*, **110**, 5, 354-384. http://dx.doi.org/10.1175/1520-0493(1982)110< 0354:VITSST>2.0.CO;2.

Reason, C. J. C. and Mulenga, H. M., 1999, “Relationships between South African rainfall and SST anomalies in the South West

Indian Ocean", *International Journal of Climatology*, **19**, 15, 1651-1673. https://doi.org/10.1002/(SICI)1097-0088(199912)19:15<1651::AID-JOC439>3.0.CO;2-U.

Reason, C. J. C. and Rouault, M., 2002, "ENSO-like decadal patterns and South African rainfall", *Geophysical Research Letters*, **29**, 13, 161-164. https://doi.org/10.1029/2002GL014663.

Reason, C. J. C., 2001, "Subtropical Indian Ocean SST dipole events and southern African rainfall", *Geophysical Research Letters*, **28**, 11, 225-228. https://doi.org/10.1029/2000GL012735.

Reason, C. J. C., Allan, R. J., Lindesay, J. A. and Ansell, T. J., 2000, "ENSO and climatic signals across the Indian Ocean basin in the global context : Part I, Interannual composite patterns", *International Journal of Climatology*, **20**, 11, 1285-1327. https://doi.org/10.1002/1097-0088(200009)20:11<1285::AID-JOC536>3.0.CO;2-R.

Reason, C. J. C., Landman, W. and Tennant, W., 2006, "Seasonal to Decadal Prediction of Southern African Climate and its Links with Variability of the Atlantic Ocean", *Bulletin of the American Meteorological Society*, **87**, 7, 941-955. https://doi.org/10.1175/BAMS-87-7-941.

Richard, Y., Trzaska, S., Roucou, P. and Rouault, M., 2000, "Modification of the southern African rainfall variability/ENSO relationship since the late 1960s", *Climate Dynamics*, **16**, 12, 883-895. https://doi.org/10.1007/s003820000086.

Ropelewski, D. F. and Halpert, M. S., 1989, "Precipitation patterns associated with the high index phase of the Southern Oscillation", *Journal of Climate*, **2**, 268-284. http://dx.doi.org/10.1175/1520-0442(1989)002<0268:PPAWTH>2.0.CO;2.

Rouault, M., Florenchie, P., Fauchereau, N. and Reason, C. J. C., 2003, "Southeast tropical Atlantic warm events and southern African rainfall", *Geophysical Research Letters*, **30**, 5, 8009. https://doi.org/10.1029/2002GL014840.

SADC, 2010, "Southern Africa Framework of Sub regional Climate Change Programmes", 2011-2015, Gaborone, Botswana.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., 1999, "A dipole mode in the tropical Indian Ocean", *Nature*, **401**, 360-363. https://doi.org/10.1038/43854

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M. and Rudolf, B., 2013, "GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle", *Theoretical and Applied Climatology*, **115**, 1-2, 15-40. https://doi.org/10.1007/s00704-013-0860-x.

Schott, F., Xie, S. P. and McCreary, J. P. Jr., 2009, "Indian Ocean Circulation and Climate Variability", *Reviews of Geophysics*, **47**, 1, RG1002. https://doi.org/10.1029/2007RG000245.

Schreck, C. J. and Semazzi, F. H. M., 2004, "Variability of the recent climate of eastern Africa", *International Journal of Climatology*, **24**, 6, 681-701. https://doi.org/10.1002/joc.1019.

Shisanya, C. A., Recha, C. and Anyamba, A., 2011, "Rainfall Variability and Its Impact on Normalized Difference Vegetation Index in Arid and Semi-Arid Lands of Kenya", *International Journal of Geosciences*, **2**, 1, 36-47. http://dx.doi.org/10.4236/ijg.2011.21004.

Shukla, J. and Misra, M., 1977, "Relationships between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India", *Monthly Weather Review*, **105**, 8, 998-1002. http://dx.doi.org/10.1175/1520-0493(1977)105<0998:RBSSTA>2.0.CO;2.

Tan, G. R., Li, H., Ren, H. L. and Chen, H., 2014, "Quantifying synoptic eddy feedback onto the low-frequency flow associated with anomalous temperature events in January over China", *International Journal of Climatology*, **35**, 8, 1976-1983. https://doi.org/10.1002/joc.4135.

Walsh, J. E. and Mostek, A., 1980, "A Quantitative Analysis of Meteorological Anomaly patterns over the United States, 1900 - 1977", *Monthly Weather Review*, **108**, 5, 615-630. http://dx.doi.org/10.1175/1520-0493(1980)108<0615:AQAOMMA>2.0.CO;2.

Washington, R. and Preston, A., 2006, "Extreme wet years over southern Africa : Role of Indian Ocean sea surface temperatures", *Journal of Geophysical Research*, **111**, D15104. https://doi.org/10.1029/2005JD006724.

Washington, R., Preston, A. and Todd, M., 2003, "Sea surface temperature influences on African rainfall variability", *Bulletin of American Meteorological Society*, **84**, 899-900.

Washington, R. and Downing, T. E., 1999, "Seasonal forecasting of African rainfall : Prediction, responses and household food security", *The Geography Journal*, **165**, 3, 255-274. DOI:10.2307/ 3060442.

Wilks, S. D., 2006, "Statistical Methods in the Atmospheric Sciences", 2nd Edn., Academic Press, San Diego, p648.

Zinke, J., Pfeiffer, M., Timm, O., Dullo, W. C. and Brummer, G. J. A., 2009, "Western Indian Ocean marine and terrestrial records of climate variability : A review and new concepts on land-ocean interactions since AD 1660", *International Journal of Earth Sciences*, **98**, 115-133. http://dx.doi.org/10.1007/s00531-008-0365-5.