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

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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

(637)
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 unimodal rainfall regime; with heaviest rainfall coinciding with the southern hemisphere summer; December - February (Harou *et al.*, 2006).

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 Rasmussen & 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.

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.

**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: Blaemy & Reason, 2013)
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 coast of west/central Equatorial Africa associated with concurrent cooling of similar magnitude off the Argentina-Uruguay-Brazilian 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.

\[
SAODI = (\text{SSTA})_{\text{NEP}} - (\text{SSTA})_{\text{SWP}}
\]  

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.

\[
Z = \frac{X - \overline{X}}{S_d}
\]

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 \( \geq 1 \) and \( \leq -1 \) 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

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.

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.
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 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
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Figs. 7(a-d). Mean anomaly of OND velocity potential (×10⁶ m² 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 m² s⁻¹ (for 850 hPa) and 0.1 × 10⁶ m² 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.

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) |

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
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.
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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