The Atlantic-Indian Ocean Dipole and Its Influence on East African Seasonal Rainfall

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ABSTRACT

This study has used principal component analysis, composite analysis and correlation analysis to establish the sea surface temperature modes that could represent the combined influence of the Atlantic and Indian Oceans on the seasonal rainfall over East Africa. The results from principal component analysis indicated that sixteen, sixteen, fifteen, and fourteen modes, accounting for about 93%, 94%, 93%, and 93% of the total seasonal sea surface temperature variance, were significant for the December-February, March-May, June-August and September-December periods, respectively. Most of the first four modes represented sea surface temperature variability associated with the individual oceans such as basin wide warming/cooling associated with El Niño/ Southern Oscillation, inter-hemispheric SST variability over the Atlantic Ocean, and Indian Ocean Dipole. The decadal and inter-decadal variability were observed with the time coefficients associated with the modes.

The results from correlation analysis indicated that the mode representing Atlantic-Indian Ocean Dipole together with the associated gradient has significant relationships with rainfall for March-May and September- December periods. The gradient mode accounted for the highest rainfall variance with September-December rainfall. The use of the gradient mode improved the values of correlation compared to those observed with the sea surface temperatures of the centres used to develop the mode indicating the ability of the gradient modes to improve relationships with rainfall.

The results from composite analysis indicated that the gradient associated with the mode delineated the March-May and September-December rainfall associated with its opposite phases. The opposite phases of the mode were associated with opposite patterns of seasonal rainfall and wind currents confirming that the observed relationships are realistic.

These results have documented a mode together with the associated gradient that can be used to represent the combined influence of the Indian and Atlantic oceans on the rainfall over the region, and improve the monitoring and prediction of seasonal rainfall over the region. However, more studies need to be done to understand further the dynamics of this mode and its association with rainfall over the region.

1. 0 INTRODUCTION

The Atlantic and Indian oceans are major sources of moisture for the East African region. The oceans do not influence the regional climate independently but in some integrated manner through the interactions associated with the oceanic and atmospheric circulations (Wolter 1987). The El Niño/ Southern Oscillation (ENSO) and Walker circulation (Chervin and Druyan 1984), and the Great Ocean Conveyor(GOC) (Gross 1972; Saenko et al. 2002) are some examples of the atmospheric and oceanic processes that may be associated with the combined influence of the global oceans on global climate. The low-level circulation patterns associated with the above-normal rainfall over the region is dominated by easterly inflow from the Indian Ocean and westerly inflow from the Congo tropical rain forest into the positive rainfall region (Anyah and Semazzi 2006; Schreck and Semazzi 2004). Goddard and Graham(1999) observed significant influence of the Indian Ocean on seasonal rainfall over the region. Okoola(1996) observed that the cooling over the eastern Atlantic Ocean together with the warming over the Indian Ocean are associated with enhanced rainfall over the region.

The GOC transports warm and low salinity water from the tropical Pacific and Indian oceans round South Africa to north Atlantic near Iceland (Burroughs 1999). The GOC and the associated currents influence the global climate patterns through ocean-atmosphere interactions and any change in the path or strength of the GOC may influence the climate around the world (Burroughs 1999; Dong and Kelly 2004; Stouffer et al. 2007). The amount of heat transported around by atmospheric and oceanic currents plays an important role in determining the mean climate of any region on earth (Shukla 1991; Wunsch and Heimbach 2006) and the ocean waves have significant influence on Sea Surface Temperatures (SST) (Hashizume et al. 2003; Jochum et al. 2007; Qiao et al 2004; Valsala and Ikeda 2007 ; Zang and Gottschalk 2002).

Most studies in the region established the major Principal Component Analysis modes associated with the influence of the Atlantic and Indian Oceans as independent fields(Omondi 2005 ; Owiti 2005). Such approaches may not reveal the modes representing the combined influence of the two oceans on the rainfall over the region. In this study the two oceans are analysed as a single SST field to establish their combined influence on the seasonal rainfall over the region and develop an index that would be used as a for regional rainfall.

This study recognizes that the SST gradient modes together with the associated pressure gradients have a strong influence on the atmospheric and oceanic circulation(Barry and Chorley 1968; Lindzen and Nigam 1987; Shukla 1991). The SST gradient modes influence the Walker circulation together with the intensities of the individual cells(Lindzen and Nigam 1987). The temperature gradients and the associated pressure gradients are key factors in determining pressure gradients, wind patterns, moisture transport, moisture convergence and divergence patterns, and many other regional circulation patterns that determine rainfall anomalies (Goddard et al 2000; Lindzen and Nigam 1987). In developing the SST gradient mode to represent the influence of the two oceans in climate prediction models, it is assumed that horizontal atmospheric motions in response to meridional and zonal temperature gradients, which are stronger than the vertical motions(Byers 1959), would account for most of the influence of the general circulation on seasonal rainfall over the region. These assumptions are motivated by the findings of the previous studies, which have shown that meridional and zonal gradients have the highest influence on the general circulation in the tropics (Lindzen and Nigam 1987; Ward 1998). A more detailed discussion of the properties of SST gradient modes that motivated this study is presented in Nyakwada(2009). The SST index is based on the centres of major PCA mode representing their combined variability.

The methods and data used in this study are presented in Chapter two. Chapter three presents the results from this study. The conclusions from this study are presented in Chapter 4.

2.0 DATA AND METHODOLOGY

2.1 Data Sources

The data used in this study are rainfall from 59 stations, distributed over East Africa, available at the IGAD Climate Prediction and Application Centre (ICPAC) formerly known as the Drought Monitoring Centre (DMC), Nairobi obtained from the Kenya Meteorological Department (KMD), Tanzania Meteorological Agency (TMA) and Uganda Meteorological Department (UMD) for the period 1960-2006. The homogeneous climate zones used in this study are those developed over the years by ICPAC through pre-season capacity building workshops from principal component analysis (PCA) using the same data(ICPAC 1999). The same zones are used for operational purposes and capacity building workshops at ICPAC (ICPAC. 1999). Many recent studies including Nyakwada(2009), Komutunga (2006); Njau (2006); Omondi (2005) and Owiti (2005) used the same homogenous zones in order to reduce the number of rainfall stations used in examining teleconnections between regional rainfall and global scale circulation variables.

The other data used are the SST for 10° x 10°

latitude/longitude grid points and NCEP /NCAR reanalysis wind for the period 1960-2006. The wind data are on 2.5° x 2.5° latitude/longitude grid points

2.2 Methodology

The methods used in this study included principal component analysis (PCA), Correlation Analysis and composite analysis. Principal Component analysis (PCA) is a frequently used multivariate technique in atmospheric sciences to reduce data sets while retaining maximum variability contained in the original data, establish similarities in spatial and temporal climate variability, and identify the dominant modes of variability in statistical fields (Barnston and Livezy 1987; Wilks 2006; von Storch and Zwiers 1999). Kaiser criterion (Kaiser 1959; 1960) and Scree test(Craddock and Flood 1969; Craddock and Flintoff 1970) were used to establish significant PCA modes. The PCA was used to establish the major modes of variability that dominate SST for the combined oceans. The core centres of the modes representing opposite phases of SST variability are used to develop the SST gradient modes associated with the combined influence of the two oceans.

The correlation analysis is used to quantify the relationships between rainfall, and SST PCA and gradient modes representing a combined influence of the Atlantic and Indian Oceans. The Student t - test was used to determine the significance of the values of correlation(Wannacott and Wannacott 1985).

Composite analysis, which is a simple method used to study atmospheric processes influencing specific phenomena, was used to establish relationships that could not be revealed by the correlation method. The method was also used to infer the physical processes that may be associated with the observed relationships. The first step of the method involves the choice of a basis for developing composites. The second step involves the selection of the cases that meet a specific category of the decided base. The selected cases are then averaged to set a mean pattern of the element in response to the behaviour of the selected base (Drbohlav et al. 2007; Kayano et al. 2007; Nobre and Shukla 1996; Krishnamurthy and Shukla 2007; Maloney and Shaman 2008). This approach was used in this study. The SST gradient mode associated with the PCA modes representing the combined influence of the Atlantic and Indian Oceans formed the basis for composite analysis.

3.0 RESULTS AND DISCUSSIONS

3.1 Principal Component Analysis

A total of one hundred 10° x 10° latitude/longitude SST grid points were used to represent the two oceans. It should be noted that, since the total sum of eigenvalues was one hundred, the portion of the variance accounted for by the PC modes was equal to the eigenvalue associated with each mode in agreement with the equation used to calculate the variance accounted for by the PC modes(Murakami 1980). The PCA results are presented for the December-February (DJF), March-May (MAM), June-August (JJA) and September-November (SON) periods.

The SST for the period December-February (DJF) season are often used to predict the MAM seasonal rainfall over the region. The MAM seasonal rainfall remains the most difficult to predict. The understanding of the modes that dominate SST variability when the oceans operate as a single field would help reduce the number of predictors. Figure 1 and Table 1 indicate that sixteen PCA modes, accounting for about 93% of the total DJF SST variance, were significant for the DJF SSTs. The first four modes accounted for about 61% of the total SST variance. The first, second, third and fourth mode accounted for about 36%, 10%, 8% and 7% of the total SST variance, respectively. The large number of significant PCA modes and the low variance that they explain may be a reflection of the complexity of the shared Indian and Atlantic oceans SST variances. Each of the oceans has its own circulation systems, but some persistence in anomaly patterns are common during some periods and seasons, especially during major ENSO years (Chambers et al. 1999; Colberg and Reason 2004; Terray and Dominiak 2005). Only the spatial and temporal characteristics of the first three modes that accounted for most of the variance are discussed.

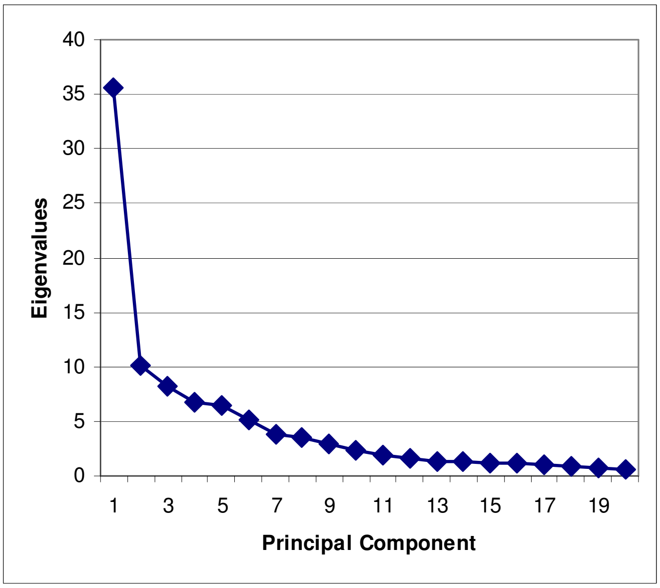


Figure 1: Results of Scree test for principal component analysis of December-February sea surface temperatures for the combined Indian-Atlantic Ocean

Table 1: The significant principal component analysis modes of December-February sea surface temperatures for the combined Indian-Atlantic Ocean and the associated variance

PCA Mode Number	Eigenvalues	% of Total Variance	Cumulative % of Total Variance
1	35.61	35.61	35.61
2	10.08	10.08	45.69
3	8.25	8.25	53.94
4	6.71	6.71	60.65
5	6.47	6.47	67.12
6	5.13	5.13	72.25
7	3.80	3.80	76.05
8	3.47	3.47	79.52
9	2.88	2.88	82.40
10	2.33	2.33	84.73
11	1.90	1.90	86.63
12	1.56	1.56	88.19
13	1.36	1.36	89.55
14	1.27	1.27	90.82
15	1.16	1.16	91.98
16	1.10	1.10	93.08
17	0.96		

Figure 2 gives the spatial patterns of the loadings of the modes observed with DJF SST for the combined Indian-Atlantic Ocean. Figure 2a indicates that the first mode had high loadings of the same sign in both oceans similar to the first modes observed with the SST of individual oceans (Nyakwada 2009; Omondi 2005). This mode represents basin wide warm-

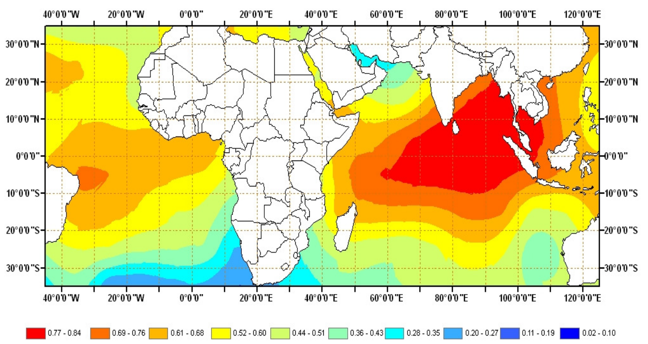


Figure 2a:The spatial patterns of the loadings of the first PCA mode observed with the December-February SST for the joint Indian-Atlantic Ocean

The second PCA mode of the DJF SST (Figure 2b) was similar to the second PCA mode for the Atlantic Ocean representing inter-hemispheric SST variability (Nyakwada 2009; Omondi 2005). The third mode (Figure 2c) represented meridional and zonal SST variability similar to the third mode for the Atlantic Ocean(Nyakwada 2009).

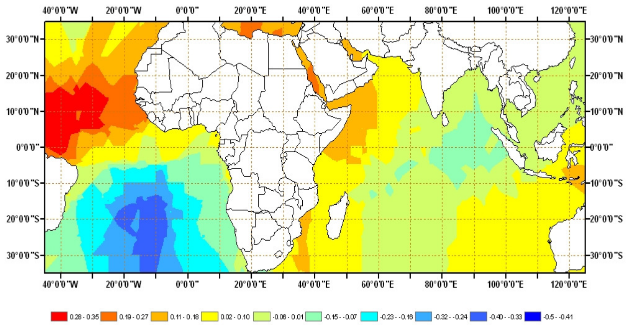


Figure 2b: The spatial patterns of the loadings of the second PCA mode observed with the December-February SST for the joint Indian-Atlantic Ocean.

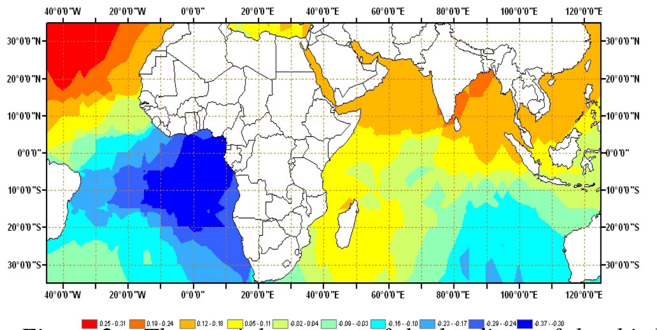


Figure 2c: The spatial patterns of the loadings of the third PCA mode observed with the December-February SST for the joint Indian-Atlantic Ocean.

The temporal characteristics of the modes observed with the DJF SST (Figure 3) indicated that they represented inter-decadal and decadal variability. Decadal and multidecadal variability associated with the variation of thermohaline circulation have been observed in the Atlantic Ocean (Latif et al. 2006). The first mode represented a trend similar to what was observed with the first DJF modes for the Indian and Atlantic Oceans (Nyakwada 2009). The years of large positive and negative values of the time coefficients correspond to some of the major wet and dry years over parts of central, eastern and western Africa associated with ENSO and inter-hemispheric SST gradient in the Atlantic (Nicholson and Entekhabi 1987; Nicholson and Kim 1997; Schreck and Semazzi 2004; Wu et. al. 2007).

The PCA of MAM SST indicated that sixteen PCA modes, accounting for about 94% of the total SST variance, were significant. The first four modes accounted for 68% of the total SST variance compared to 61% for DJF. The first, second, third and fourth modes accounted for about 39%, 13%, 10%

and 6% of the total SST variance, respectively and their spatial and temporal characteristics were similar to those of the modes observed with DJF SSTs, which represented the PCA modes observed with the Individual oceans. The only differences were the levels of the explained variances and areas dominated by specific modes.

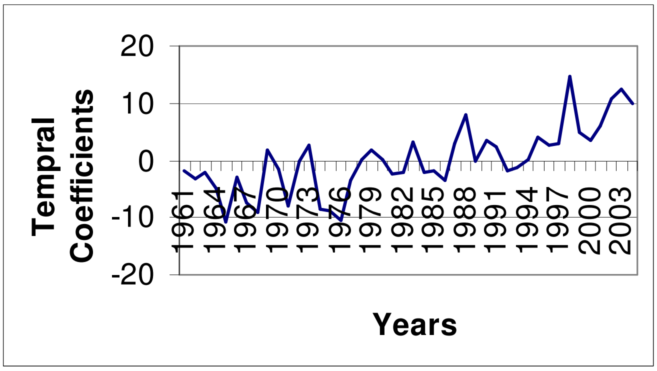


Figure 3a: The graphical plot of the time coefficients of the first joint Indian- Atlantic Ocean SST PC mode for December-February.

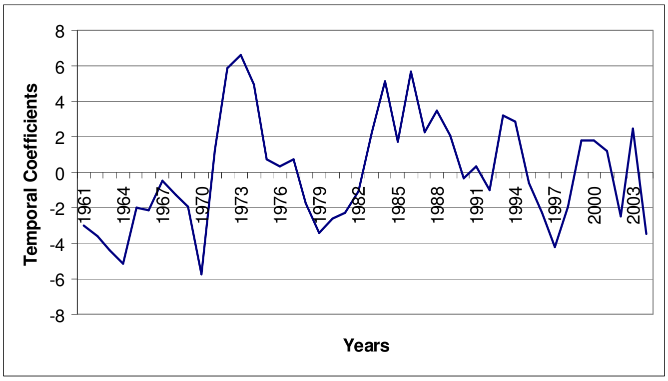


Figure 3b: The graphical plot of the time coefficients of the second joint Indian- Atlantic Ocean SST PCA mode for December-February.

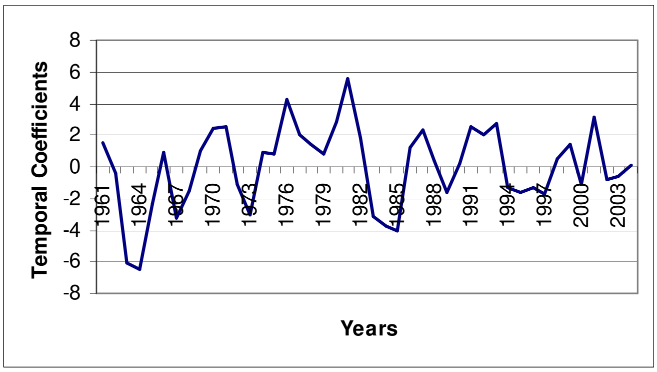


Figure 3c: The graphical plot of the time coefficients of the third joint Indian- Atlantic Ocean SST PC mode for December-January-February

The period JJA is often used to predict the October-December (OND) seasonal rainfall over the region. The OND rainfall season is the most studied due to high potential of its predictability (Behera et al. 2005; Black et al. 2003; Omondi 2005; Owiti 2005). The PCA for this season indicated that fifteen PCA modes, accounting for about 93% of the total JJA SST variance, were significant. The first four modes in this season accounted for about 64% of the total JJA SST variance. The first, second, third and fourth mode accounted for about 37%, 13%, 8% and 6% of the total JJA SST variance, respectively. The spatial and temporal characteristics of the first and third PCA modes were similar to those observed with DJF and MAM SST, and represented SST variability in the individual Indian and Atlantic Oceans. The second mode was, however, unique for the season and represent a dipole with a positive pole in the western Indian Ocean located in the region (20°N-20°S, 40°E-90°E) and a negative pole over the eastern Atlantic Ocean located in the region (10°N-10°S, 40°W-20°E)(Figure 4). This dipole, which shall be referred to as Atlantic-Indian Ocean Dipole (AIOD), may be associated with the atmospheric and oceanic circulations linking the two oceans resulting from the Great Ocean Conveyor and the Walker cell across the continent of Africa linking the Western Indian Ocean and the Congo Basin (Hastenrath and Polzin 2004; Tanaka et al. 2004; Wang 2002). El Niño/La Nina have been associated with the cooling /warming off the western coast of Southern Africa and in the Gulf of Guinea during the period February –July (Frankignoul and Kestenare 2005) and warming/cooling in the western Indian Ocean (Chambers et al. 1999; Kug and Kang 2006; Kug et al. 2007). The opposite phases in the cooling/warming of the Atlantic/Indian Oceans have been associated with wet conditions over the region (Okoola 1996) resulting from the convergence of moist air masses from the Congo basin and Indian Ocean over the region ((Anyah and Semazzi 2006). Figure 4 indicates further a less prominent negative pole over the eastern Indian Ocean located in the region (0°-20°S, 100°E-130°E), which is often used to represent the eastern pole of the Indian Ocean Dipole mode (Behera et al. 2005; Saji et al. 1999). The less prominence of the eastern pole over the Indian Ocean in this season may imply that when the two oceans interact, the dipole linking the Atlantic and Indian Ocean is stronger than IOD.

Figure 5 gives graphical plot of the time coefficients associated with this unique second PCA mode observed with the JJA SST. Figure 5 indicates that large positive time coefficients were observed in the years 1962-1966, 1968, 1971-1975, 1984-1986, 1988, 1989, 1996 and 1998-2000. The large negative coefficients were observed in the years 1961, 1967, 1970, 1972, 1976-1983, 1987, 1990-1992, 1994, 1997, 2002 and 2003. Some of these years have been associated with ENSO and IOD events as defined by Behera et al.(2005); Owiti (2005); and Saji et al. (1999) among many other authors. It can be observed that most of the extreme wet/dry conditions over the region associated with El Nino/La Nina and positive/negative IOD correspond to negative/positive coefficients of this mode. The capability of this mode to separate the dry and wet years by JJA season makes it a more powerful tool than the classical IOD that has a maximum influence in SON as was observed for the PCA of the Individual oceans (Nyakwada 2009). This is the first time this mode (AIOD), which has useful linkage with regional rainfall, is documented. The centres over the western Indian Ocean (5°N-5°S, 40°E-60°E) and Eastern Atlantic Ocean(5°N-5°S, 10°W-10°E) were used to develop an SST gradient mode to represent the influence of this mode on rainfall over the region. .

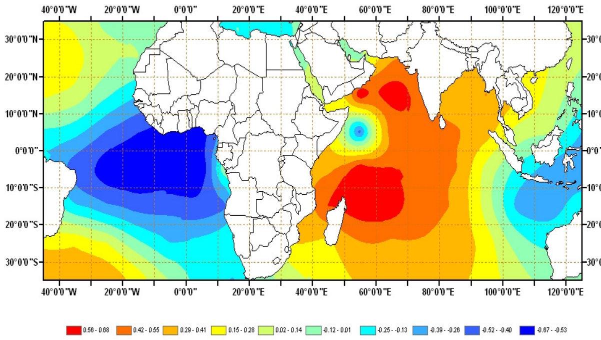


Figure 4: The spatial patterns of the loadings of the second principal component analysis mode of June-August sea surface temperatures for the combined Indian-Atlantic Oceans representing Atlantic-Indian Ocean Dipole

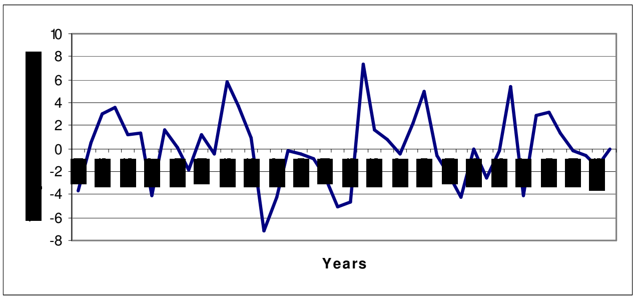


Figure 5:The graphical plot of the time coefficients of the second principal component analysis mode of June-August sea surface temperatures for the combined Indian-Atlantic Oceans representing the Atlantic-Indian Ocean Dipole

The PCA of SON indicated that fourteen modes accounting for 93 % of SST variance were significant. The PCA modes observed in DJF, MAM, and JJA were still discernable in SON. The extensively documented Indian Ocean Dipole was the second mode in SON SST and accounted for 11.53% of SST variance. These results indicate that IOD reaches its peak in a combined ocean field in SON compared to AIOD which has the peak in JJA.

3.2 Correlation Analysis

3.2.1 Correlation with the PCA Mode

The correlation analysis is used to quantify the relationships between the SST modes and rainfall. The correlation analysis is also used to assess the potential to improve the relationships between regional rainfall and SST based predictors. The results for correlation analysis of rainfall and PCA modes are presented for the September-December period that showed the highest relationships with the PCA mode representing the AIOD. The results from t-test indicated that a correlation of 0.25 was significant. Figure 6 indicates that the mode representing AIOD had significant negative correlation with rainfall over most parts of the region. The largest value of correlation of 0.41, indicating that the mode accounted for about 16.81% of SOND rainfall variance, was observed over the northern parts of Kenya and Uganda. These results indicate that this mode could be used to predict the rainfall for the season. However, the variance accounted for by the mode is relatively low necessitating the need to establish related indices that could provide more powerful tools for predicting rainfall over the region.

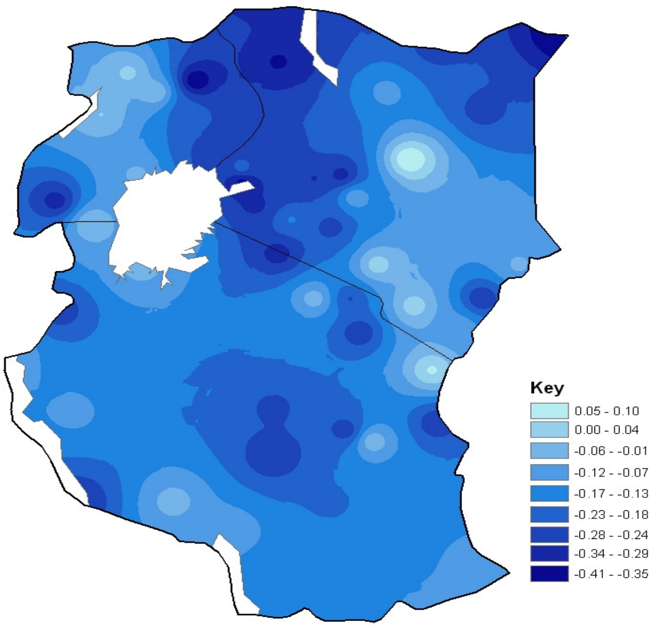


Figure 6: The spatial patterns of the values of correlation between September-December rainfall and June-August Principal Component Analysis mode representing the Atlantic-Indian Ocean Dipole.

3.2.2 Correlation with the Sea Surface Temperature Gradient Mode Associated with the Atlantic-Indian Ocean Dipole

The results from correlation analysis are presented for the core centres used to compute the SST gradient mode and for the related gradient mode to establish improvements in relationships when the gradient modes are used. Figures 7a and 7b give the spatial patterns of the values of correlations between SOND rainfall and the July SST representing the centres over the equatorial western Indian and eastern Atlantic Ocean used to compute the SST Gradient mode. Figure 7a indicates that SOND rainfall over the northern parts of the region was negatively correlated to the July SST over the eastern equatorial Atlantic Ocean. The largest value of correlation was 0.39 indicating that the July SST over the eastern equatorial Atlantic Ocean accounted for about 15.21% of SOND rainfall variance.

Figure 7b indicates that SOND rainfall was positively correlated to the July SST for the centre over the equatorial western Indian Ocean. The largest value of correlation was 0.54 indicating that the SST over this centre for the month of July accounted for about 29.16% of SOND rainfall variance.

Figure 7c indicates marked improvements in the values of correlation when SST gradient mode computed from the two centres is used. Figure 7c indicates that SOND rainfall over most parts of the region was significantly and negatively correlated to the SST gradient mode associated with AIOD for the month of July. The highest value of correlation of 0.63 indicated that the SSTG mode accounted for about 39.69% of SOND rainfall variance which is higher than the variance accounted for by the PCA mode and SST for the core centres of the PCA. The lowest correlations were concentrated in the coastal region. The Atlantic Ocean influences rainfall over the region through moisture incursions by the westerly wind currents over the western parts of the region (Anyah and Semazzi 2006; Indeje and Semazzi 2000;

The improvement in relationships when the gradient mode are used as indicated in Figures 7a-7c confirm the advantages this SST gradient mode could have in the prediction of seasonal rainfall over the grid point SSTs. The results also indicate the AIOD has significant influence on rainfall over the region.

The negative/positive correlation observed with the SST over the equatorial eastern Atlantic / western Indian Ocean is reaffirms the existence of the dipole observed in the second JJA PCA mode (Figure 4). The influence of this mode on the rainfall over the region may be in cognizance of the fact that the oceans and the atmosphere act as a single field through the associated wind and water currents (Shukla 1991; Stouffer et al 2007; Wunsch and Heimbach 2006).

The negative relationships observed with the gradient associated with AIOD indicate that the warming /cooling over the equatorial western Indian /eastern Atlantic Ocean favour enhanced SOND seasonal rainfall over most parts of the region in agreement with the observations of Nicholson and Entekhabi (1987); and Okoola (1996). This pattern of SST variations is likely to influence the Walker circulation cell linking the western Indian Ocean and the Congo Basin. The negative values of the SST gradient could be associated with the warm equatorial western Indian Ocean and a relatively cold equatorial eastern Atlantic Ocean that would imply the reverse of the Walker circulation favouring enhanced influx of moisture into the region from the Congo Basin and Indian Ocean as has been observed for wet years (Anyah and Semazzi 2006; Indeje and Semazzi 2000, Schreck and Semazzi

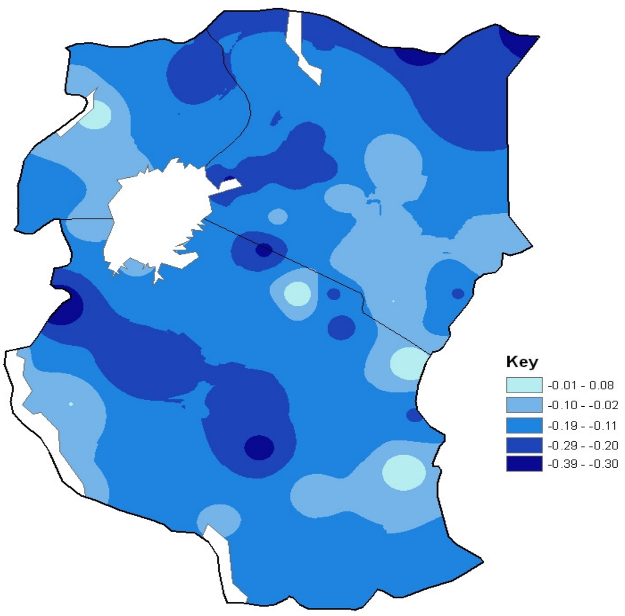


Figure 7a

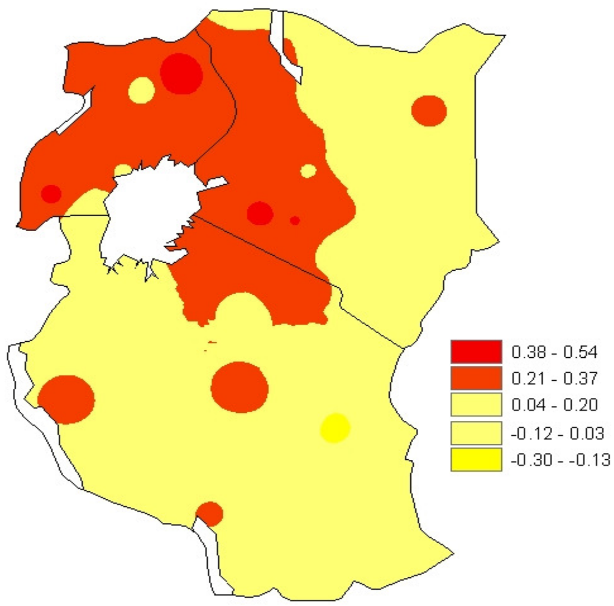


Figure 7b

Figure 7: The spatial patterns of correlation between September-December rainfall and the July sea surface temperatures for the centre in (a) the equatorial eastern Atlantic Ocean (b) the equatorial western Indian Ocean associated with the At-

These relationships also reveal the importance of the combined role of the Atlantic and Indian Ocean as influences seasonal rainfall over the region. The spatial patterns of the values of correlation also reveal that the responses of SOND rainfall over western parts of the region and Kenyan coast to the SST gradient mode associated with AIOD are in agreement with the responses of seasonal rainfall over the respective regions to SST variability. The improvements in the values of correlation between rainfall and SST based predictors when the SST gradient mode is used indicate that the use of this zonal SST gradient mode improves the relationships between SOND rainfall and SST based predictors compared to grid point SSTs.

The spatial patterns of the values of correlation observed between the SST gradient mode associated with AIOD together with the SST for the core centres and MAM rainfall are presented in Figures 8a-8d. The predictability for the MAM period has always proved difficult for most models and these difficulties have been referred to as spring predictability barrier (Annamalai et al. 2007; Barnston et al 1996; Korecha and Barnston 2007; Ogallo 1988) and predictability gap (Godfrey et al. 1995). The drop in the predictive skill in April has been attributed to weak organization of the tropical atmosphere in the month (Godfrey et al. 1995).

Figures 8a and 8b give the spatial patterns of the values of correlation observed between MAM rainfall and SST representing the centres over the western Indian Ocean and eastern Atlantic Oceans associated with the AIOD. Figure 8a indicates that MAM rainfall over parts of Lake Victoria Basin and northern coast was positively correlated to the March SST representing the centre over the western Indian Ocean. However, rainfall over southern Tanzania was negatively correlated to SST representing the centre over western Indian Ocean.

These results indicate that the response of MAM rainfall over parts of the region to SST over the equatorial western Indian Ocean was not uniform. The largest value of correlation observed with SST over the western Indian Ocean for the month of March was 0.51 indicating that they accounted for about 26.01% of the MAM rainfall variance.

Figure 8b indicates that MAM rainfall over parts of the region was negatively correlated to the March SST over the equatorial eastern Atlantic Ocean. The negative relationships observed between SST over the equatorial eastern Atlantic Ocean and MAM rainfall is in agreement with the findings of Nicholson and Entekhabi (1987); and Okoola (1996) among other authors.

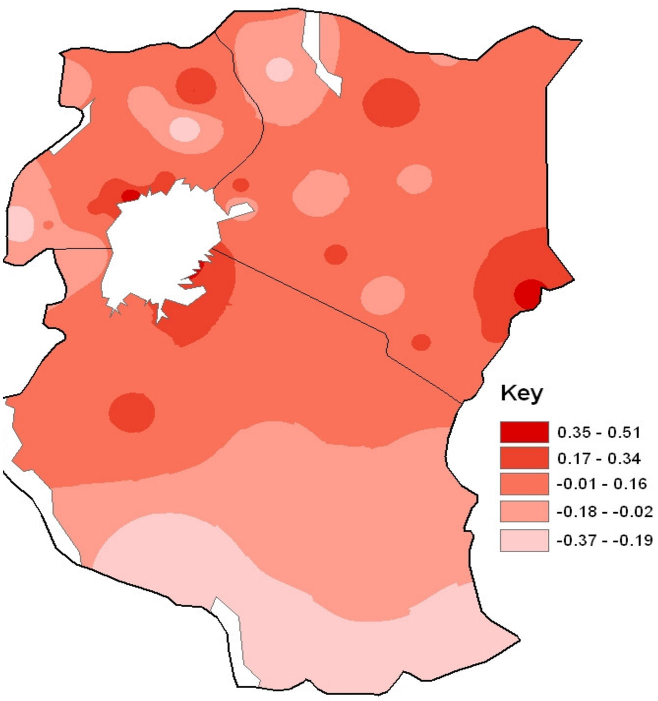


Figure 8a

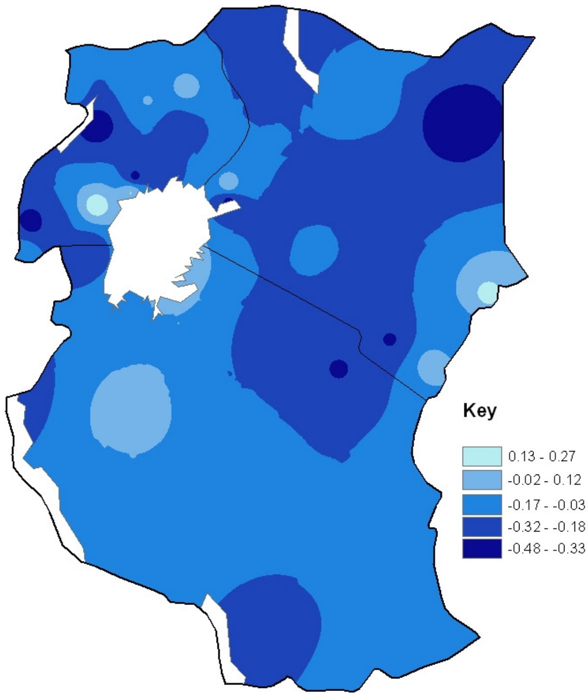


Figure 8b

Figure 8: The spatial patterns of the values of correlation between March-May rainfall and the March Sea surface temperature for the centre in the equatorial (a) western Indian (b) eastern Atlantic Ocean associated with the Atlantic-Indian Ocean Dipole.

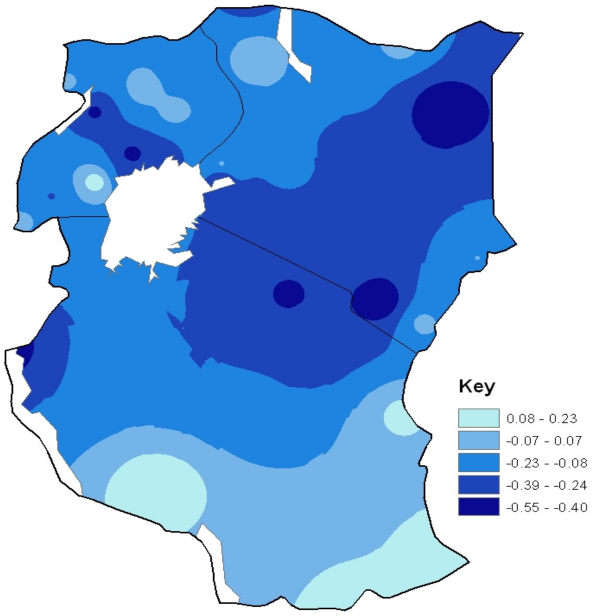


Figure 8c

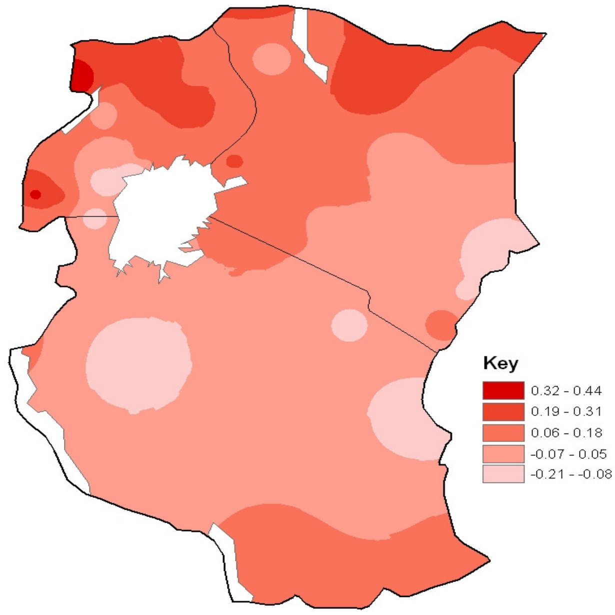


Figure 8d

Figure 8: The spatial patterns of correlation between March-May rainfall and the zonal sea surface temperature gradient mode associated with the Atlantic-Indian Ocean Dipole for (c) March (d) January.

These results indicate that MAM rainfall over parts of the region is likely to be enhanced by the cooling over the equatorial eastern Atlantic Ocean. The largest value of correlation observed with the SST over eastern Atlantic was 0.48 indicating that they accounted for about 23.04% of the MAM rainfall variance.

Figures 8c and 8d give the spatial patterns of the values of correlations between MAM rainfall and the SST gradient mode associated with AIOD. Figures 8a-8c indicate some improvement in the relationships when SST gradient mode is used compared to those observed with the SST representing individual centres. The MAM rainfall over most parts of the region is negatively correlated to the SST gradient mode for the month of March and the largest value of correlation was 0.56 indicating that this mode accounted for about 31.26% of MAM rainfall variance. Similar relationships were observed with the SST gradient mode for the months of February, April and May. However, Figure 8d indicates a change in the relationships in the month of January when this mode was positively correlated to MAM rainfall over parts of the region. Such changes in the sign of relationships need to be taken into consideration when using this mode as a tool for monitoring and advising on expected seasonal rainfall performance.

The peak relationships observed with SST gradient mode associated with AIOD were observed in the months of March and April suggesting that the inclusion of this SST gradient mode for these months may improve the skill in the prediction of MAM seasonal rainfall. This would require the prediction of SST for the months of March and April. It is possible to predict SSTs and the predicted SSTs may lead to improvements in the skills of the models (Mauget and Ko 2008).

3.3 Composite Analysis

The results from correlation analysis do not reveal the dynamics associated with the observed relationships. The composite analysis may reveal the physical basis and other forms of relationships not established with correlation analysis. The basis of composite analysis in this study was mapping mean rainfall, and wind anomalies for years of similar sea surface temperature gradient values for specific seasons. The categories for composite analysis are the extreme negative (EN) referring to values of SSTG <-s/2, moderate negative (MN) referring to values -s/2£ SSTG<0, moderate positive (MP) referring to 0< SSTG £ s/2 and extreme positive (EP) referring to SSTG >s/2. Only the results for extreme negative and positive phases of the SST gradient mode are presented.

3.3.1 September-December Rainfall

The years with similar categories for the gradient mode on which the composite analysis of SOND was based are given in Table 2.

Figures 9a and 9b give the spatial patterns of the values of the composites of SOND rainfall anomalies associated with the extreme negative and positive phases of the SST gradient associated with AIOD. The clear shifts in the signs of the rainfall anomalies map patterns for extremely positive and negative values of the gradient mode are quite evident. It can be observed from Figures 9a and 9b that the values of SOND rainfall composite anomalies associated with the positive/negative phases of SST gradient mode were negative/positive. This spatial pattern of the values of SOND rainfall composite anomalies indicates that the positive/negative phases of the SST gradient mode favour deficient/enhanced SOND rainfall over most parts of the region. This is in agreement with the negative correlation observed between the SST gradient mode and SOND rainfall. These results indicate that AIOD has significant influence on SOND rainfall over most parts of the region.

Table 2: The years during the period 1961 to 2006 associated with the various categories of the phases of the zonal sea surface temperature gradient modes.

GRADIENT	Extreme Negative	Extreme positive
	SSTG A£s/2	SSTG^{3}s/2
AIOD (July)	1961, 1962, 1967, 1972, 1975, 1976, 1983, 1982, 1992, 1997	1963, 1964, 1966, 1973, 1979, 1984, 1985, 1986, 1987, 1988, 1991, 1995, 1996 1998, 1999,

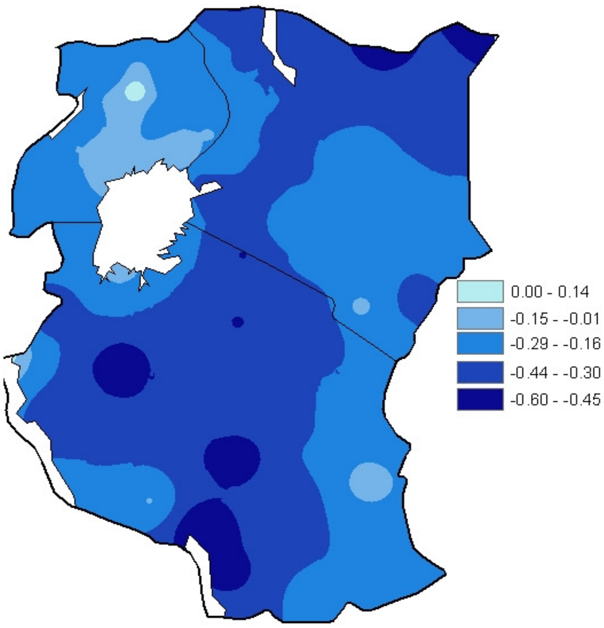
3.3.2 March-May Rainfall

The composite analysis of MAM rainfall was based on the years listed in Table 3 when the mode was extremely positive or negative.

Figures 10a and 10b give the spatial patterns of the values of composites of MAM rainfall anomalies associated with the extreme negative and positive categories of the SST gradient mode for the zero-lagged month of March. Figure 10a indicates that the MAM rainfall composites associated with the extreme negative values of the SST gradient mode for the month of March coinciding with season were

Table 3: The years during the period 1961 to 2006 associated with the various categories of the phases of the sea surface temperature gradient mode associated with Atlantic-Indian Ocean Dipole for the month of March.

GRADIENT	Extreme Negative	Extreme Positive
	SSTG A£s/2	SSTG^{3}s/2
AIOD (March)	1961, 1962, 1968, 1970, 1972, 1978, 1981, 1990, 2001	1963, 1965, 1967, 1971, 1974, 1975, 1982, 1984, 1988, 1989, 1991, 1993, 1994, 1995, 1996, 1999, 2000, 2003, 2004, 2005,



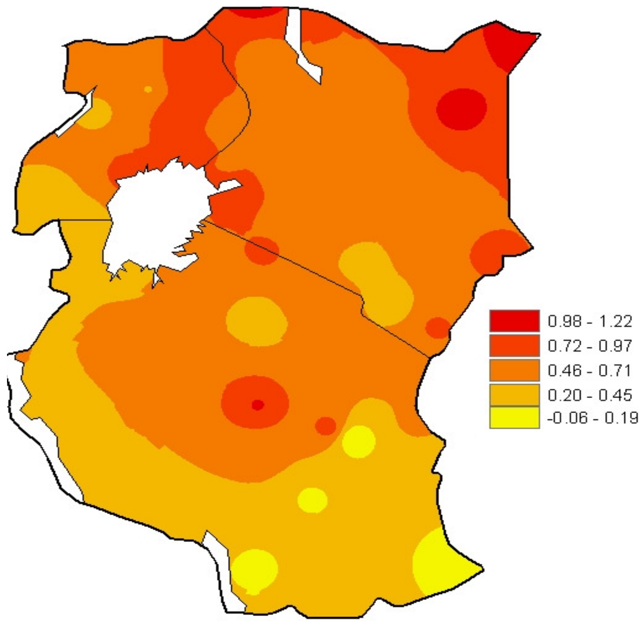


Figure 9a *Figure 9b*

Figure 9: The spatial patterns of the values of composite of September-December rainfall anomalies associated with extreme (a) negative (b) positive categories of sea surface temperature gradient mode based on Atlantic-Indian Ocean Dipole for the month of July.

positive over most parts of the region indicating that the extreme negative phase of this mode favour enhanced MAM rainfall over most parts of the region.

Figures 10b indicate that MAM rainfall associated with the extreme positive values of the SST gradient mode for the month of March coinciding with the season were negative over most parts of the region indicating that the extreme positive phase of this mode favour deficient MAM rainfall over most parts of the region. These results from composite analysis of MAM rainfall and the SST gradient mode for the zero-lagged month of March indicates further that the correlations observed between MAM rainfall and the SST gradient mode were realistic since the mode was able to delineate cases associated with each phase. These results also indicate that this SST gradient mode could be useful in the monitoring and prediction of MAM seasonal rainfall. However, since the peak relationship is achieved in the season, the use of this gradient requires that it be predicted.

The results of composite analysis of seasonal rainfall and the SST gradient mode have indicated significant linkages amongst some of the extreme phases of the SSTG mode and seasonal rainfall .The results confirmed that the observed relationships between the seasonal rainfall and SST gradient mode were realistic. The mode provides a useful tool for seasonal climate prediction.

3.3.3 Wind Composites

The wind currents represent the vehicles for the transport of moisture and dictate areas of convergence influenced by the strengths, tracks, sources and direction of wind currents. The pattern of the values of composite for wind would help in understanding the physical dynamics of the SSTG mode. The basis of the composite are the categories of the gradient as indicated in Table 2. Figures 11a and 11b give the spatial patterns of the SON zonal surface wind composite anomalies associated with the extreme positive and negative categories of the SST gradient mode, for the lagged month of July. Figure 11a indicates that the extreme negative values of the SST gradient mode are associated with westerly wind anomaly over the region 40°N-35°S, 20W-140E and easterly wind anomaly in equatorial central Indian Ocean. This pattern may favour enhanced rainfall over the region through the influence of the penetration of the Congo air-mass that interacts with enhanced dominant easterly wind current from the Indian Ocean. The largest values of the westerly and easterly anomalies were 0.6 and –1.4, respectively.

Figure 11b indicates that SON wind composite anomalies associated with the extreme positive values of the SST gradient mode for the lagged month of July were dominated with easterly wind anomalies, which would be associated with the acceleration of surface wind speeds and divergence. In the equatorial Indian Ocean, the easterly anomalies are replaced by westerly anomalies, which would be associated with the deceleration of the easterlies over the ocean and reduced moisture incursion into the region. The highest westerly anomaly was 1.2 and easterly anomaly was –0.8.

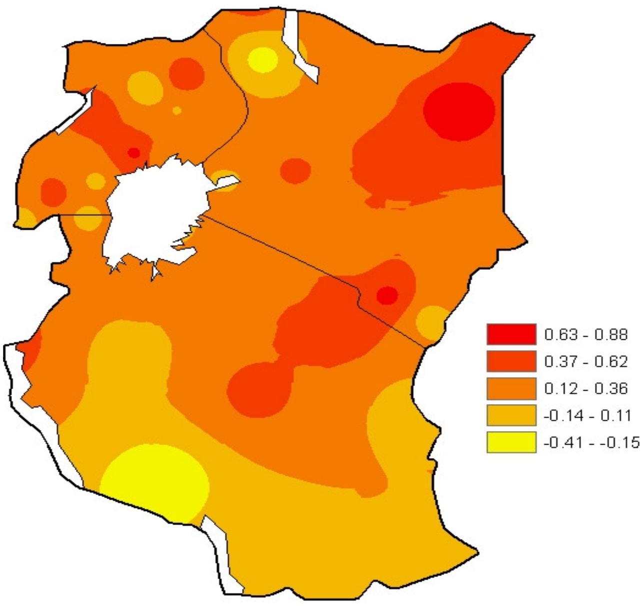


Figure 10a

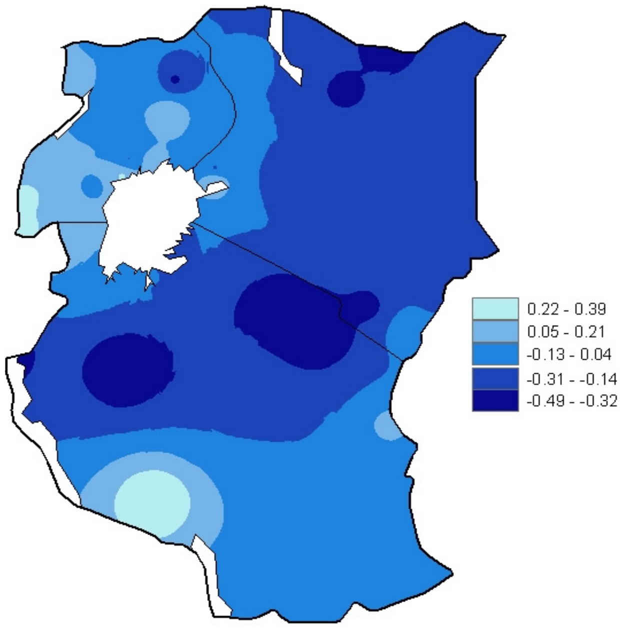


Figure 10b

Figure 10: The spatial patterns of the values of the composite of March-May rainfall anomalies associated with extreme (a) negative (b) positivecategories of zonal sea surface temperature gradient mode associated with the Atlantic-Indian Ocean Dipole for the month of March.

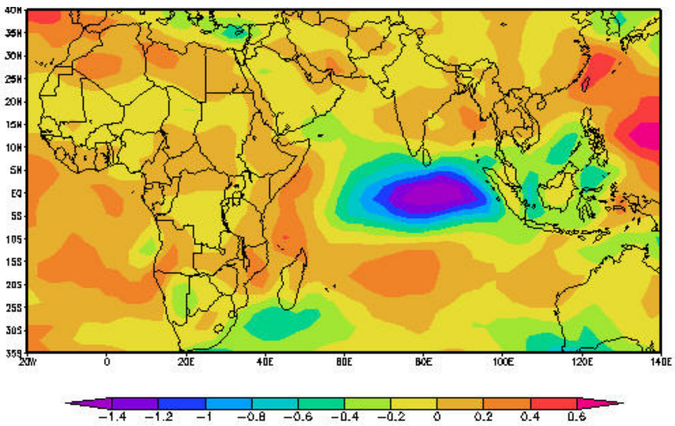


Figure 11a: The spatial patterns of surface zonal wind composites anomalies for the years when the zonal sea surface temperature gradient mode associated with the Atlantic-Indian Ocean Dipole for the month of July was extremely negative.

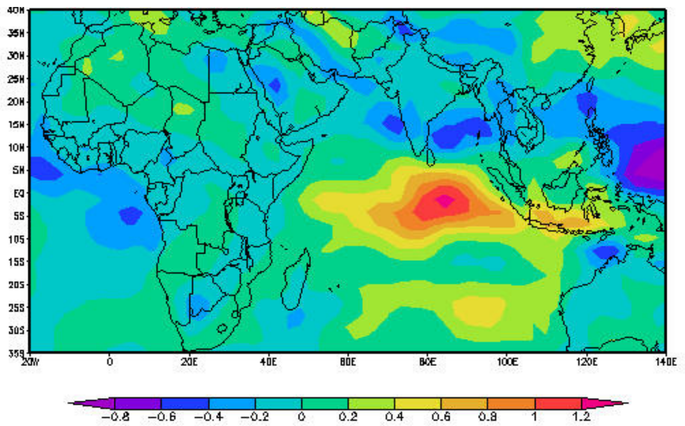


Figure 11b: The spatial patterns of surface zonal wind composites for the years when the zonal sea surface temperature gradient mode associated with the Atlantic-Indian Ocean Dipole for the month of July was extremely positive

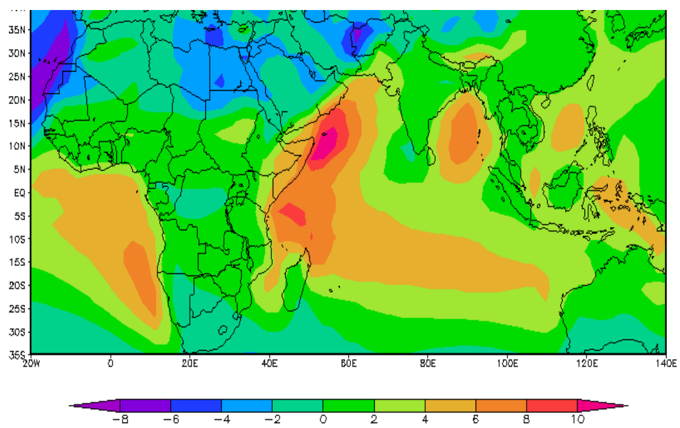


Figure 12a: The spatial patterns of surface meridional wind composites for the years when the zonal sea surface temperature gradient mode associated with the Atlantic-Indian Ocean Dipole mode for the month of July was extremely negative.

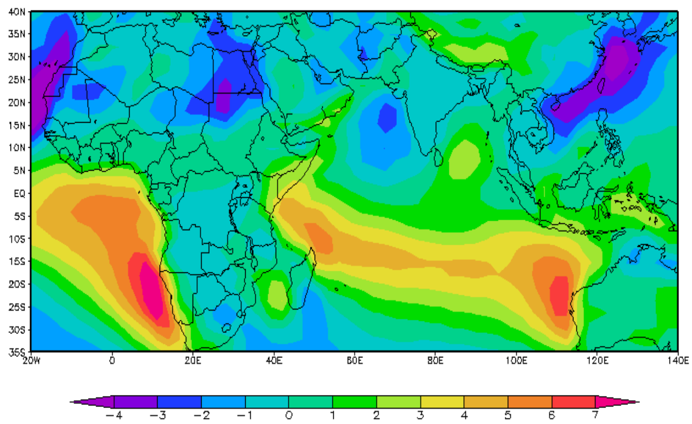


Figure 12b: The spatial patterns of surface meridional wind composites for the years when zonal sea surface gradient mode associated with Atlantic-Indian Ocean Dipole for the month of July was extremely positive.

These results indicate that the two extreme phases of the SST gradient mode for the month of July are associated with the opposite patterns of the SON wind composite anomalies confirming that the influence of the mode on rainfall may be associated with the changes in the wind currents, moisture transport and convergence. These results confirm that the AIOD has significant and realistic influence on the rainfall over the region. The SST gradient mode associated with AIOD would provide new and realistic tools for predicting seasonal rainfall over the region.

Figures 12a and 12b gives the spatial patterns of the SON meridional surface wind composite anomalies associated with the extreme negative and positive phases of the SST gradient mode for the lagged month of July. Figure 12a indicates that the extreme negative values of the SST gradient mode are associated with enhanced SON southerly surface winds over the southern and western Indian Ocean, and south-eastern Atlantic Ocean. These are the major sources of moisture for the region. The enhanced meridional component in these areas would lead to improvements in the moisture incursion. The largest positive anomaly was 10. A negative anomaly was observed over the northern Atlantic. The negative anomaly would imply enhanced northerly flow associated with the Azores high-pressure system. The largest negative anomaly was –8.

Figure 12b indicates that the values of SON meridional surface wind composite anomalies associated with the extreme positive phase of the SST gradient mode for the lagged month of July were generally weaker than those associated with the extreme negative phase especially over the western Indian Ocean and were positive over the southern Indian Ocean and southern Atlantic Ocean. A marked difference is observed over the western Indian Ocean where the positive anomalies observed with the negative phase are replaced with the negative anomalies. The largest positive anomaly was 7 compared to 10 observed with the negative phase of the SSTG mode. The negative anomalies were still observed over the northern Atlantic Ocean. The largest negative anomaly was –4 compared to –8 observed with the negative phase.

It should be observed that the anomalies were relatively weaker for the extreme positive phase compared to the negative phase of the mode. These results continue to indicate that the influence of AIOD on rainfall may be associated with the changes in the wind currents, moisture transport and convergence.

These results indicate that the influence of the SST gradient mode associated with AIOD is discernable from both the zonal and meridional surface wind currents and rainfall for both seasons. The mode was able to delineate the opposite phases of the zonal surface and meridional surface wind currents associated with opposite phases of the mode, and rainfall for both seasons. The results confirm further that the observed correlations between SOND rainfall and SST gradient modes are realistic and may be associated with the influence of the SSTG mode on atmospheric circulation, moisture transport and convergence. These results indicate further that the SSTG mode based on AIOD provide new and realistic tools for improving the prediction of seasonal rainfall over the region.

4.0 CONCLUSIONS

This study has established a mode that could be used to represent a combined influence of the Atlantic and Indian Oceans. The Atlantic-Indian Ocean Dipole (AIOD), which is documented for the first time, has significant influence on regional rainfall for both seasons. The sea surface temperature gradient mode associated with the AIOD had significant relationships with both March-May and September-December rainfall. The mode, however, accounted for the highest rainfall variance with the September-December rainfall.

Results from composite analysis of rainfall and wind confirmed significant linkages between the AIOD and rainfall through the influence on wind currents with the negative phase of the mode favouring enhanced rainfall during both MAM and SOND seasons. The SST gradient mode associated with AIOD effectively delineated rainfall and wind associated with the opposite phases of the mode. The extreme positive and negative phases of the SST modes influenced both the zonal and meridional wind circulation. For example the extremely negative phase of the SSTG mode associated with AIOD corresponded to mainly westerly wind anomaly with an easterly wind anomaly over the eastern Indian Ocean together with a southerly anomaly in the Indian and Southern Atlantic phase of the same mode was associated with mainly easterly wind anomaly with a westerly wind anomaly over the eastern and central Indian Ocean together with a relatively weaker southerly wind anomaly over the Indian and southern Atlantic Ocean. These wind patterns favour opposite rainfall performance confirming that the relationships observed with AIOD together with the associated SST gradient mode are realistic.

These results provide a useful tool that could be included in the monitoring and prediction of both MAM and SOND rainfall season

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