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Master of Science in Applied Marine Science

RAINFALL VARIABILITY CHARACTERISTICS OVER THE EAST AFRICAN COAST

**Thesis submitted in partial fulfillment of the requirements for a Master's Degree in
Applied Marine Science**

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Presented to University of Cape Town, Faculty of Science

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Dedication

To my beloved mother Mwanasiti Majambo, my adoring sisters Tima, Fatma and Rukia, thank you for the prayers and encouragement to take this step in my life

Declaration

"I know the meaning of Plagiarism and declare that all of the work in the document, save for that which is properly acknowledged, is my own"

Date and place: 05 September 2012

Signature:

Mombasa, Kenya

University of Cape Town

Acknowledgement

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I would like also to express my sincere gratitude to CORDIO East Africa for awarding me the scholarship to study and conduct this research work at the best University in Africa not forgetting additional financial support from Marine Biology Research Centre Postgraduate Bursary.

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Lastly my friends and fellow marine science colleagues, your smiles and jokes kept me going, thank you all.

Abstract

This study explores inter-annual rainfall variability over the East African coast region (Kenya and Tanzania) for the period 1980-2010 and focuses on dry and wet spell characteristics during the two rainy seasons. The atmospheric and ocean conditions associated with the rainfall variability are also considered. Extreme occurrences of rainfall variable can result in droughts and floods which in turn may lead to socioeconomic disruptions. East Africa is highly dependent and vulnerable to the amounts and timing of rainfall.

Anomalous rainfall is typically associated with low-level convergence of moisture emanating from the tropical western Indian Ocean and the Southeast Atlantic Ocean / Congo Basin. Four indices are identified and used in assessing the wet and dry spells characteristics. These indices provide useful information in understanding rainfall and they are also related to extreme weather events such as floods and droughts. A relatively robust relationship between either wet or dry spell frequencies with Niño 3.4 Sea Surface Temperature was found in October-November-December (OND) but a weak relationship existed in March-April-May (MAM). Relationships of wet or dry spell frequency and Indian Ocean Dipole (IOD) index were also explored to find that they exhibited a similar pattern to that observed with Niño 3.4 SST. The results provide evidence that wet and dry spell characteristics are related to large-scale climate modes and are influenced by regional atmospheric circulation patterns.

Key words: inter-annual rainfall variability, wet and dry spells, indices, ENSO, IOD

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Table 3: Descriptive summaries of the climatological values indices of the wet and dry spell characteristics of the MAM season with their respective standard deviation (*P* refers to pentad)

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Acronyms

MAM	March April May
CMAP	Climate Prediction Center Merged Analysis of Precipitation
ENSO	El Niño Southern Oscillation
FEWS	US Famine and Early Warning System
IOD	Indian Ocean Dipole
ITCZ	Inter-tropical Convergence Zone
KMD	Kenya Meteorological Department
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
OND	October November December
SST	Sea Surface Temperature
TMA	Tanzania Meteorological Agency

CHAPTER ONE: INTRODUCTION

Rainfall is a climatic factor of utmost significance in the East African countries, with extreme occurrences resulting in droughts and floods. These anomalous events are often associated with food, energy and water shortages, loss of life and property, and many other socioeconomic disruptions (Kabanda and Jury 1999). In these regions, rainfall is highly variable in space and time and because the economies of East African countries largely depend on rain-fed agriculture, it makes agricultural activities difficult. Most parts of East Africa tend to have two rainy seasons - the March-April-May (MAM) "Masika" long rains as the Inter Tropical Convergence Zone (ITCZ) moves northwards and the October-November-December (OND) "Vuli" short rains as the ITCZ retreats southwards. The two rainy seasons have been noted to be independent of each other with MAM experiencing greater precipitation compared to OND which also experiences a larger degree of inter-annual variability relative to climatology than typically in MAM (Hastenrath *et al.*, 1993). Indeje *et al.*, (2000) demonstrated that the most important rainfall variability throughout the short rains (OND) season is related to Sea Surface Temperature (SST) anomalies associated with El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) which are the dominant sources of inter-annual variability across the East Africa region.

The East African region is affected by ENSO events with above (below) average rain tending to occur during El Niño (La Niña) episodes (Ogallo, 1988; Reason *et al.*, 2000). For example, in 1997, the OND East African rains were in many areas 5–10 times the average, the highest in the century (World Meteorological Organization 1998), and this led to severe socioeconomic disruption. Several studies have investigated the relationship between the short rains and the ENSO. Nicholson *et al.*, (1997) found a strong connection between ENSO and rainfall over much of the African continent and suggested a linkage through ENSO-induced SST anomalies in the Indian Ocean, which, in turn, modulate inter-annual variability of rainfall over Africa. In addition to ENSO, the other large-scale mode important in shaping the regime's climate is the IOD (Saji *et al.*, 1999). The IOD is known to influence the region's rainfall pattern with several studies showing that the short rains correlate strongly with SST in the western Indian Ocean (Mutai *et al.*, 1998; Nicholson and Kim 1997; Ogallo 1988). These studies suggest that Indian

Ocean SST is a major contributor to the variability of the short rains. An atmospheric general circulation model study suggested that the Indian Ocean SST exerts a greater influence over the East African short rains than does the Pacific (Goddard and Graham 1999).

Regarding the atmospheric circulation, Camberlin and Wairoto (1997) did composite analysis of daily wind anomalies associated with dry and wet spells in Kenya and found significant relationships for the two main rainy seasons and that stronger than usual easterlies generally correspond to days with no or little rainfall over the country. Wet events occur when the wind flow exhibits an anomalous westerly component. Mutai and Ward (2000) observed that pulses of westerly anomaly winds tend to develop about five days before the corresponding rainfall event over the Horn of Africa region with strength of about 5m/s. These authors showed that before the rainfall event, anomalous near surface easterlies strengthen over the Indian Ocean giving the northeast and southeast trade winds a stronger onshore component. Thus, strengthening easterlies were associated with increased rainfall over parts of Great Horn of Africa.

For agricultural purposes, the consistency with which the basic minimum of required rainfall is received is more important than the total rainfall received over the duration. Crops are more likely to do well with uniformly spread light rains than with a few heavy rain events interrupted by dry periods (Usman and Reason 2004). Reason *et al.*, (2005) studied the inter-annual variability of dry spell frequencies, dry and wet spell characteristics and onset dates of the austral summer rainy season over the Limpopo region of northern South Africa. Summer dry spell frequency and onset date were related to ENSO via changes in regional circulation. Over Zambia, Hachigonta and Reason (2006) investigated the variability of dry and wet spell frequency during the core of the rainy season of December January February (DJF), and associated circulation anomalies. They found that the southern part of Zambia is frequently subjected to seasons with increased dry spell frequency, whereas northern Zambia typically has relatively few dry spells during the austral summer (DJF) rainy season. They suggested that the decrease in dry spells over the north was likely due to the position of the ITCZ, which is located over the area during the summer.

Kijazi and Reason (2005) examined the intra-seasonal rainfall variability responsible for short-term rainfall variability along the Tanzanian coast throughout ENSO years. They found that rainfall seasons tend to finish significantly later in wet years than in dry years, i.e. wet years tend to possess longer-than-average rainfall seasons and vice versa for dry years. They also found the onset and peak rainfall during El Niño years to be associated with an active convective zone over the equatorial western Indian Ocean with enhanced moisture convergence, thereby resulting in above average rainfall. Mapande and Reason (2005) studied the inter-annual rainfall variability over western Tanzania and found that wet/dry years are characterized by weaker/stronger equatorial westerlies over the western Indian Ocean that lead to less/more export of equatorial moisture away from East Africa. The atmospheric circulation associated with the 1998 to 2005 drought that affected the northeastern highlands of Tanzania during the short rainy season was related to westerly low-level moisture flux divergence and subsidence associated with an eastward shift of the Walker cell (Kijazi and Reason, 2009).

Generally, the national meteorological services forecast rainfall and temperature as probabilities of above, near and below average values for the season as a whole. These organizations provide information on how seasonal conditions are expected to vary from average for the next few months. However, many user groups desire more specific information such as the likely onset and cessation dates of the rainy season and the likelihood of more or less wet and dry spells than average within the season. A better understanding of the impacts of climate variability in the region is of paramount importance as it may assist to achieve food security as well as for policy formulation regarding agriculture, health and water resources.

It is because of this motivation that much research has been done to investigate African rainfall variability and its characteristics. Like many previous studies, rainfall variability and characteristics have been studied in this thesis using monthly or seasonal anomalies. One way of studying rainfall variability is to use indices that reflect the intensity of rainfall anomalies and the frequency of wet and dry spells during rainy season.

Rainfall characteristics such as onset and cessation of the rainy season and dry and wet spell frequencies are most important as subsistence farmers rely on this information to determine cultivation periods and planning. They also do not have access to reliable irrigation and are therefore vulnerable to anomalies in rainfall characteristics. To better understand the wet and dry spells characteristics, there is a need to investigate the link between these characteristics and circulation patterns that might influence their occurrence. Despite the importance of such rainfall variability for water resources, agriculture and the prevalence of diseases, relatively little work has been done on forecasting or early warnings.

With all this in mind, this work aims to explore the inter-annual rainfall variability over the coastal zone of East Africa. To achieve this aim in a way that addresses the needs of the user communities, the analysis will investigate the frequency of wet and dry spells during each rainy season and study linkages between these parameters and large scale SST and wind fields to see whether predictability might exist.

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CHAPTER TWO: DATA AND METHODS

The research presented here focuses on rainfall variability and analysis of wet and dry spells characteristics with associated atmospheric circulation.

2.1 Study area

The study focused on the coastal zone of East Africa (Kenya and Tanzania), where the local communities are dependent on fishing activities, subsistence farming and other extractive natural resource-based activities, which are highly vulnerable to rainfall variability within a changing climate.

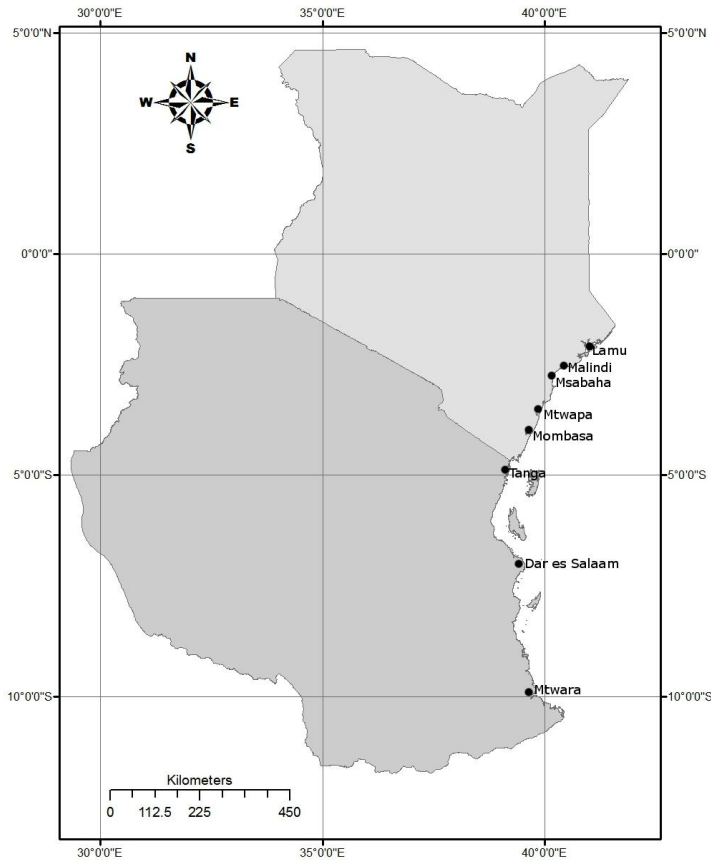


Figure 1: Schematic distribution of meteorological station along the East African coast (Kenya and Tanzania) used for studying wet (dry) spell characteristics. Filled in black circles represents the rainfall stations

2.2 Data

2.2.1 Station data

Rain-gauge measurement is the traditional and oldest method of monitoring rainfall since the instrumental age began. In this study, we consider daily rainfall data records from three stations (Tanga, Dar-Salaam and Mtwara; Figure 1) within the period 1980 – 2010, obtained from the Tanzania Meteorological Agency (TMA). Also monthly rainfall data records were obtained from the Kenya Meteorological Department (KMD). The monthly records were sourced from 5 stations (Lamu, Malindi, Msabaha, Mtwapa and Mombasa; Figure 1). Unfortunately KMD would not release daily data so satellite derived rainfall data was used for the Kenyan coast.

2.2.2 Satellite data

Because of practical observational limitations, station data suffers from numerous gaps in space and time and are not always readily accessible. Satellite data can be used to address some of these problems. The Climate Prediction Center merged analysis of gauge and satellite derived precipitation (CMAP) pentad gridded rainfall data (Xie and Arkin, 1997) updated to 2008 was used. The CMAP data analyzed here merges various satellite estimates (infra-red, special sensor Microwave Imager, Advanced Microwave Sounding Unit) only with spatial resolution of $2.5^{\circ} \times 2.5^{\circ}$. The dataset is composed of yearly files where each year file consists of 73 fields of pentad precipitation.

2.2.3 ENSO and IOD index classification

2.2.3.1 Niño 3.4 index

Niño 3.4 is one ENSO index, and represents SST anomalies in the equatorial Pacific. It is calculated by taking the average SST anomalies over $5^{\circ} \text{ N} - 5^{\circ} \text{ S}$, $170^{\circ} \text{ W} - 120^{\circ} \text{ W}$. The SST anomalies are computed from HadISST data set of Met Office Hadley Centre (Rayner *et al.*, 1996). This index has been extensively used in many climate diagnostic studies.

2.2.3.2 Indian Ocean Dipole (IOD)

The IOD, also sometimes referred to as the Indian Ocean Dipole zonal mode (IODZM) is a major climatic mode found in the tropical Indian Ocean. Its strength is measured through the

IOD index, which has been commonly expressed in terms of several variables including sea level pressure, outgoing long-wave radiation and SST. In this study, the SST index definition of Saji *et al.*, (1999) is used, which is based on the difference in SST 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°). The IOD index data for 1980-2010 was extracted from: http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi_HadISST.txt

2.2.2.3 Spatial coherence

The spatial and temporal associations of wet and the dry spell rainfall frequency with SSTs in the tropical Indo-Pacific region are computed only for the available rainfall data period from 1980-2010 for Tanzania and 1980-2008 for Kenya. HadISST global data are used to calculate the spatial coherence between the Indo-Pacific SSTs and the wet and dry spell frequencies. Spatial correlations of the zonal winds at surface level with wet and dry spell frequency were also calculated and composites of atmospheric circulation anomalies constructed for both rainy seasons show the atmospheric circulation mechanisms. The spatial correlation plots were calculated using the KNMI Climate Explorer analysis tool (<http://climexp.knmi.nl/>)

2.2.2.4 Circulation anomalies

The NCEP-NCAR re-analysis project that began in 1991 produces daily atmospheric and surface fields considered being an optimal estimate of the evolving state of the atmosphere (Kalnay et al., 1996). Zonal winds at the surface, omega (or pressure tendency) at the 500hPa level, and the velocity potential were constructed for both rainy seasons to consider the anomalous atmospheric circulation patterns and the associated rainfall characteristics.

2.3 Methods

For each rainy season (OND and MAM), standardized rainfall anomalies are used to assess the intensity of rainfall anomalies in East Africa similar to previous studies by Mapande and Reason (2005) and Kijazi and Reason (2005). Anomalously wet and dry seasons were chosen using a criterion of a standardized departure of at least above 0.9 or below -0.9. Daily station rainfall data were then grouped into 5-day means (pentads) to reduce noise associated with day-day variability before being subjected to statistical analysis. The grouping was performed

on non-overlapping 5-day means starting at pentad 1 for each year (1–5 January) and ending at pentad 73 (27–31 December). Pentad 12 contained an additional day to include February 29 in the case of a leap year.

To determine the wet and dry spell frequencies, the definitions of Usman and Reason (2004) were used. The authors defined a dry spell to exist for any pentad where rainfall was less than 5 mm which is similar to that used by the US Aid Famine and Early Warning System (FEWS) (4.85 mm). A wet spell was defined as a pentad with at least 10 mm of rain. Due to lack of available daily station data in Kenya, pentad satellite data from CMAP were used. The satellite data were averaged over 2.50-0.00°S, 37.50-40.00°E to represent the north area and 5.00-2.50°S, 37.50-40.00°E to represent the south area. Correlation analysis between satellite data and station data were performed for comparison to determine if satellite data is really representative of surface observation. If the comparison is robust, then the satellite data can be used to address gaps in station data.

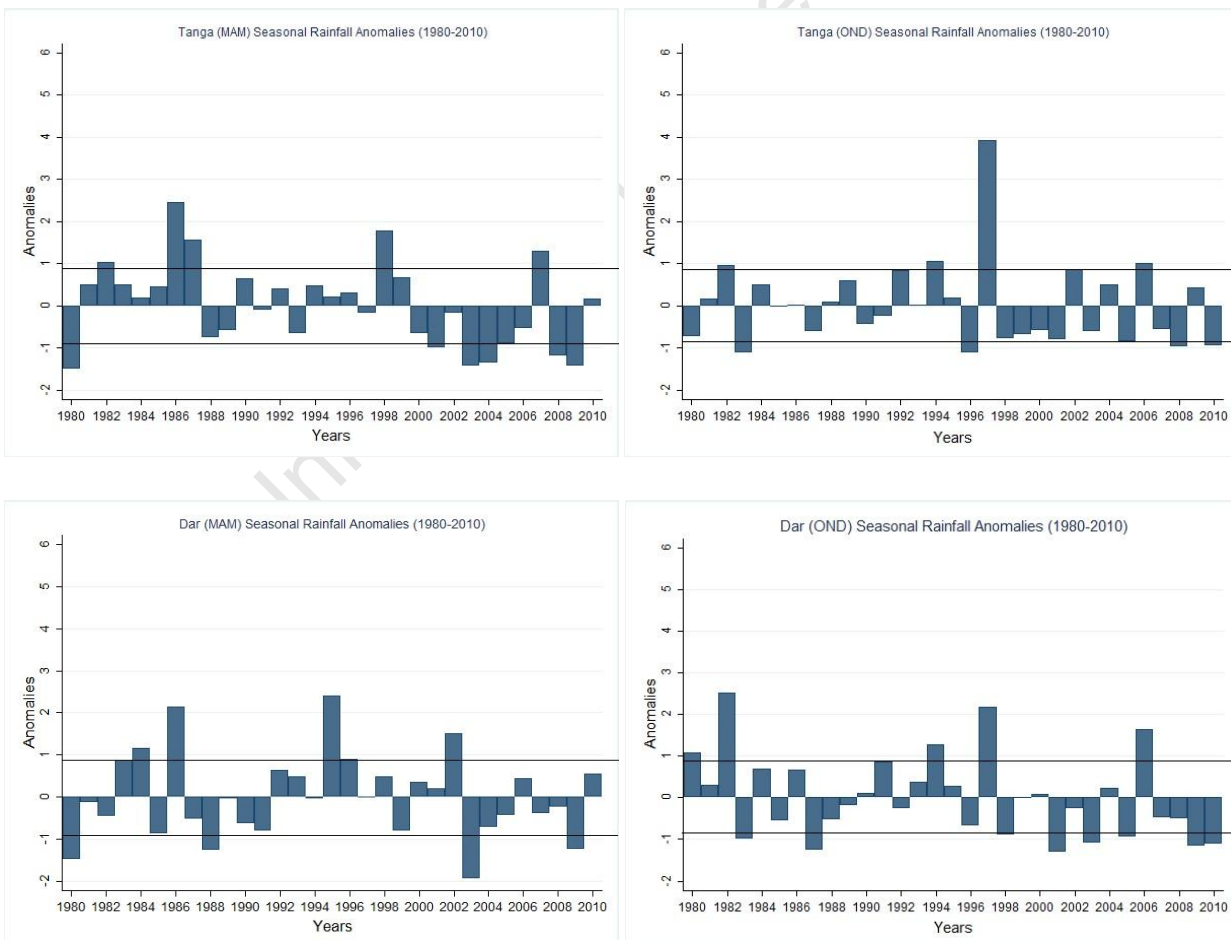
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CHAPTER THREE: RESULTS

3.1 Inter-annual rainfall variability

The region of study herein has a bimodal type of rainfall (the rainfall seasons are OND and MAM) and these two seasons are independent of one another. Three rainfall stations from Tanzania (Tanga, Dar and Mtwara) and five stations from Kenya (Lamu, Malindi, Msabaha, Mtwapa and Mombasa) (Figure 1) were used to analyze inter-annual variability over the region which supports a relatively large and poverty stricken rural subsistence population who are vulnerable to the effects of changing climate, especially rainfall variability. Figures 2 and 3 plot standardized departures in OND and MAM seasons from 1980-2010 for each station.

3.1.2 Tanzania



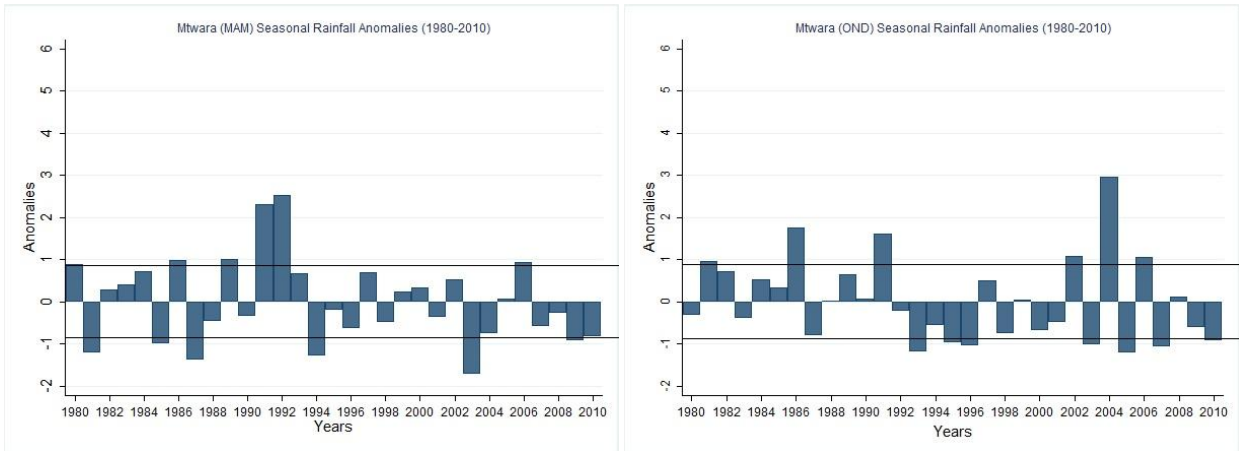
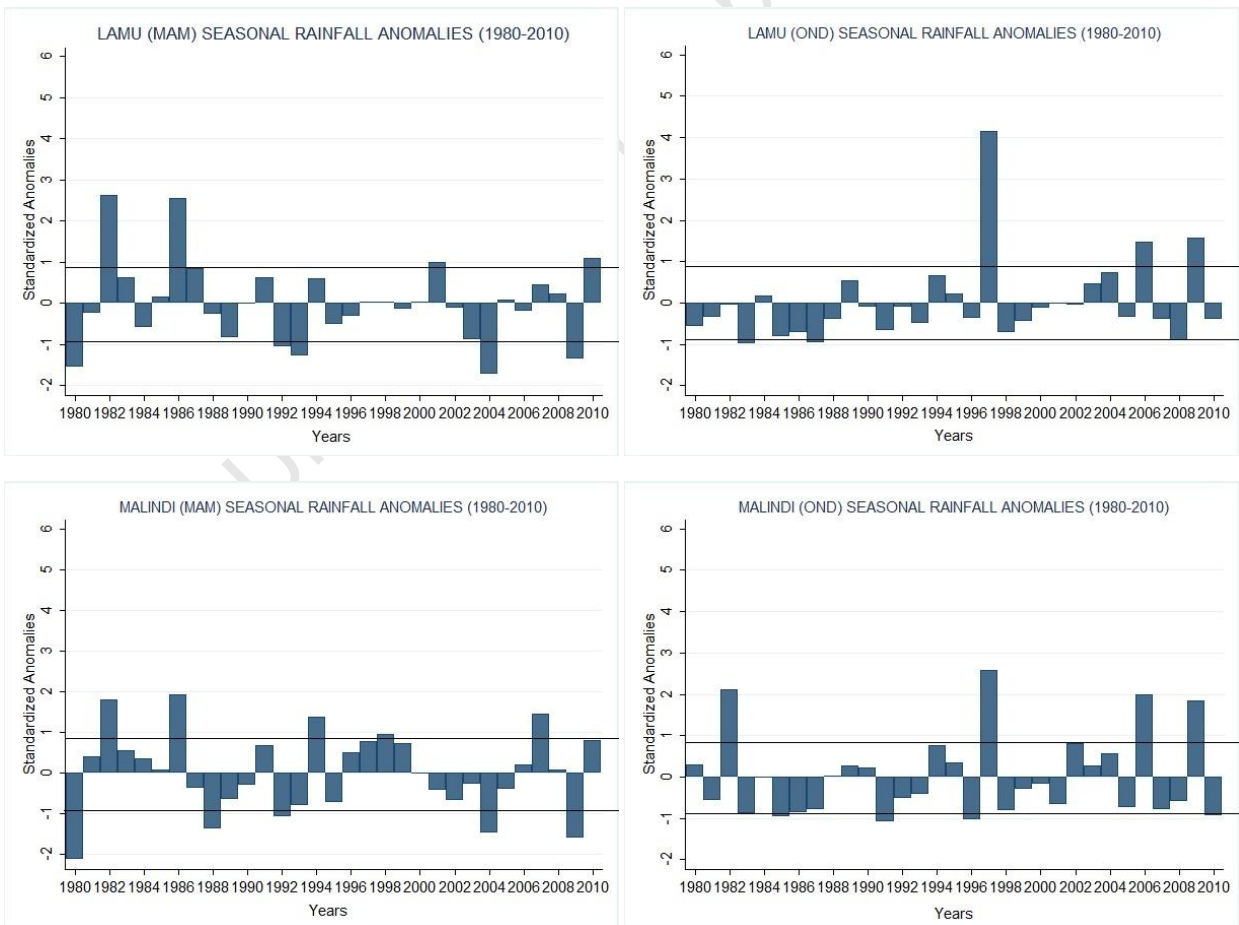


Figure 2: Plots of standardized rainfall anomalies of station data in Tanzania for the two rainfall seasons (MAM and OND) from 1980-2010. The thick black line shows +0.9 and -0.9 mark for anomalously wet and dry periods.

3.1.3 Kenya



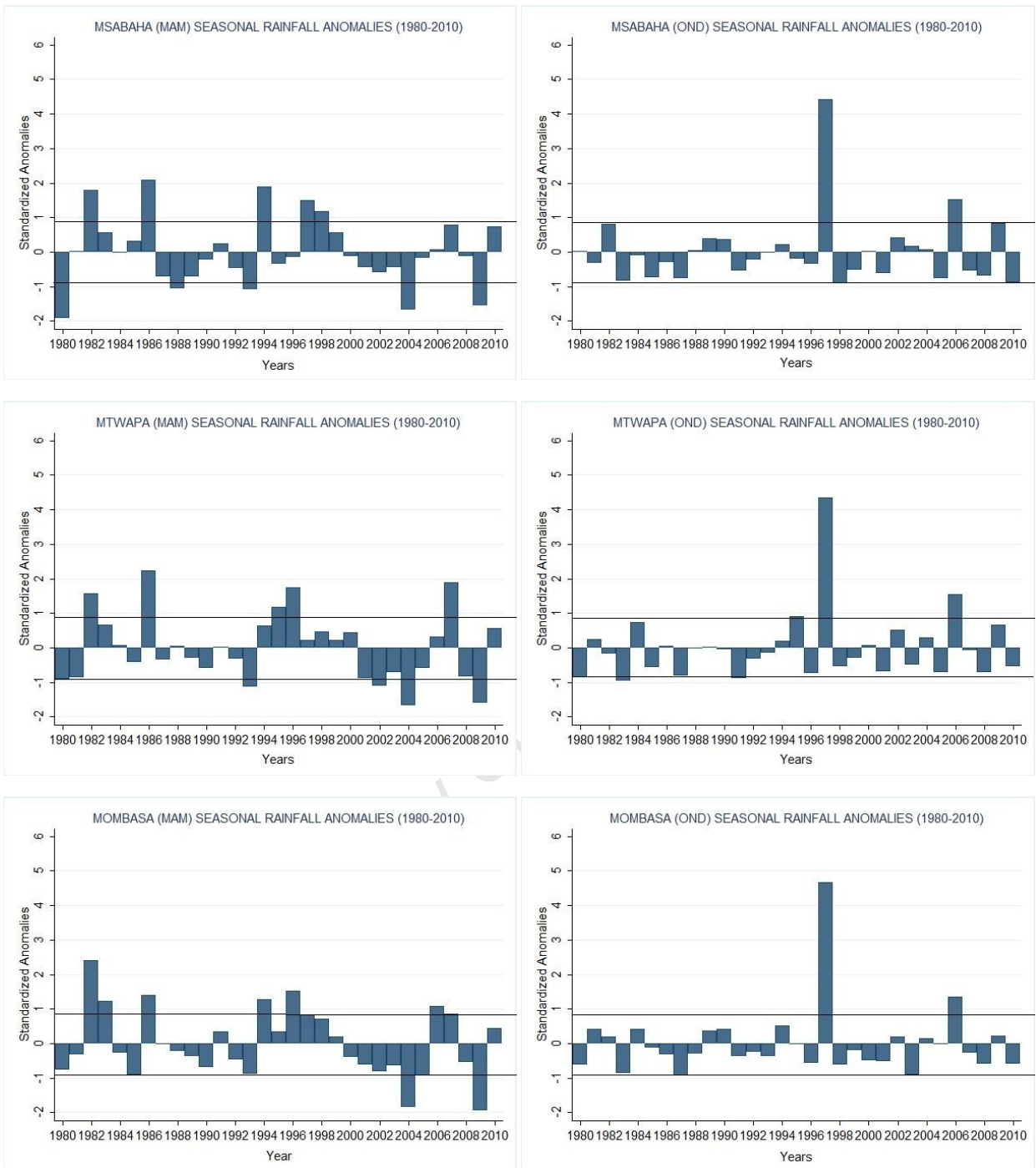


Figure 3: Plots of standardized rainfall anomalies of station data in Kenya for the two rainfall seasons (MAM and OND) from 1980-2010. The thick black line shows +0.9 and -0.9 mark for anomalously wet and dry periods.

Table 1: Summary of the calculated anomalous wet and dry years with highlighted El-Niño (La-Niña) episodes and IOD events

MAM		OND	
Wet years	Dry years	Wet years	Dry years
1982 (El-Niño); positive IOD	1980 (neutral)	1982 (El-Niño); positive IOD	1983 (La-Niña)
1986 (El-Niño); positive IOD	1993 (neutral)	1997 (El-Niño); positive IOD	1987 (El-Niño+1);
1998 (El-Niño);	2003 (El-Niño+1)	2006 (El-Niño)	1996 (La-Niña+1)
2007 (El-Niño+1)	2004 (El-Niño)	2009 (El-Niño)	1998 (La-Niña); negative IOD
	2009 (La-Niña+1)		2005 (La-Niña); negative IOD
			2010 (La-Niña)

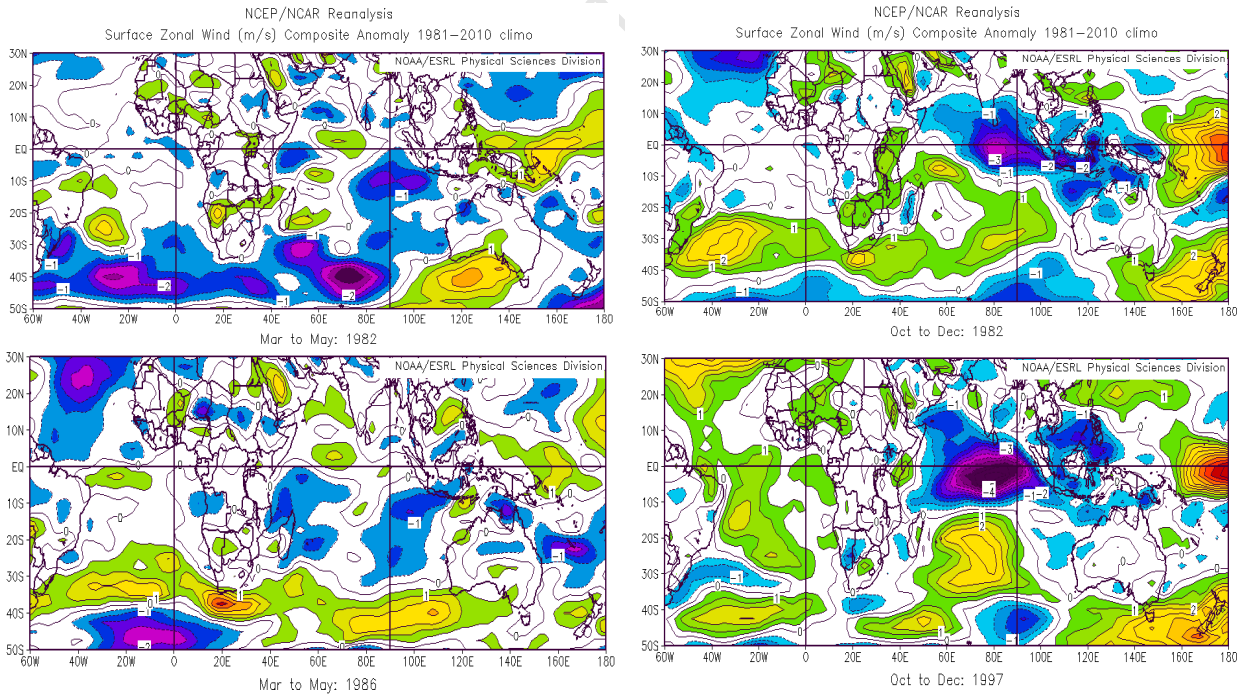
The 30 year time series of standardized OND and MAM anomalies show substantial inter-annual variability at each station. Of the identified extreme wet and dry OND seasons, it is seen that most of the wettest (driest) seasons occurred during El-Niño (La-Niña) events and IOD events. Based on the Niño 3.4 index (Table 1), El-Niño (La-Niña) events during 1980-2010 are; 1982/3, 1986/7, 1991/2, 1997/8, 2002/03 (1988/9, 1995/6, 1998/9, 1999/2000, 2005/06, 2007/08) while using the IOD index, positive (negative) IOD events are 1982/3, 1986/7, 1997/8 (1998/9). Anomalous wet and dry years for OND season were chosen from standardized anomalies above 0.9 and below -0.9. Because we are looking at multiple stations, anomalous wet and dry years were chosen when more than 50% of the stations from Tanzania and Kenya attain the 0.9 (wet) and -0.9 (dry) criterion. By this criterion, most of the wettest (driest) seasons correspond to El-Niño (La-Niña) events but only 1982, 1986 and 1997 for the wettest seasons and 1998 and 2005 for the driest seasons correspond to positive and negative IOD events respectively. It needs to be appreciated that most of the above average rainfall in the region during OND corresponds to El-Niño events while below average rainfall corresponds to La-Niña. As a result, the impression from figures 2 and 3 is that the ENSO impact over the coast of East Africa is linear in the sense that the wet OND/ El-Niño ENSO relationship (dry OND / La-Niña) appears to be robust.

3.2 Circulation patterns

To assess regional circulation anomalies associated with anomalously wet and dry seasons, composite anomaly circulation plots for zonal surface wind, velocity potential and omega at 500hpa were constructed corresponding to ENSO and neutral years. NCEP-NCAR reanalysis data were used for analysis of the atmospheric circulation patterns associate with anomalously wet and dry seasons. The velocity potential is useful in inferring changes in the large-scale vertical circulation and the Walker cell while omega indicates relative uplift/subsidence in the atmosphere.

The anomalous wet and dry seasons are chosen from the station rainfall time series while the ENSO and neutral years are chosen from the Niño 3.4 index time series. Figure 4 and 5 show circulation patterns of individual anomalously wet and dry seasons during ENSO and neutral years. Figure 6 show composite plots of velocity potential at lower level and figure 7 show composite plots of omega at 500hpa during ENSO events.

3.2.1 Surface zonal winds during ENSO events



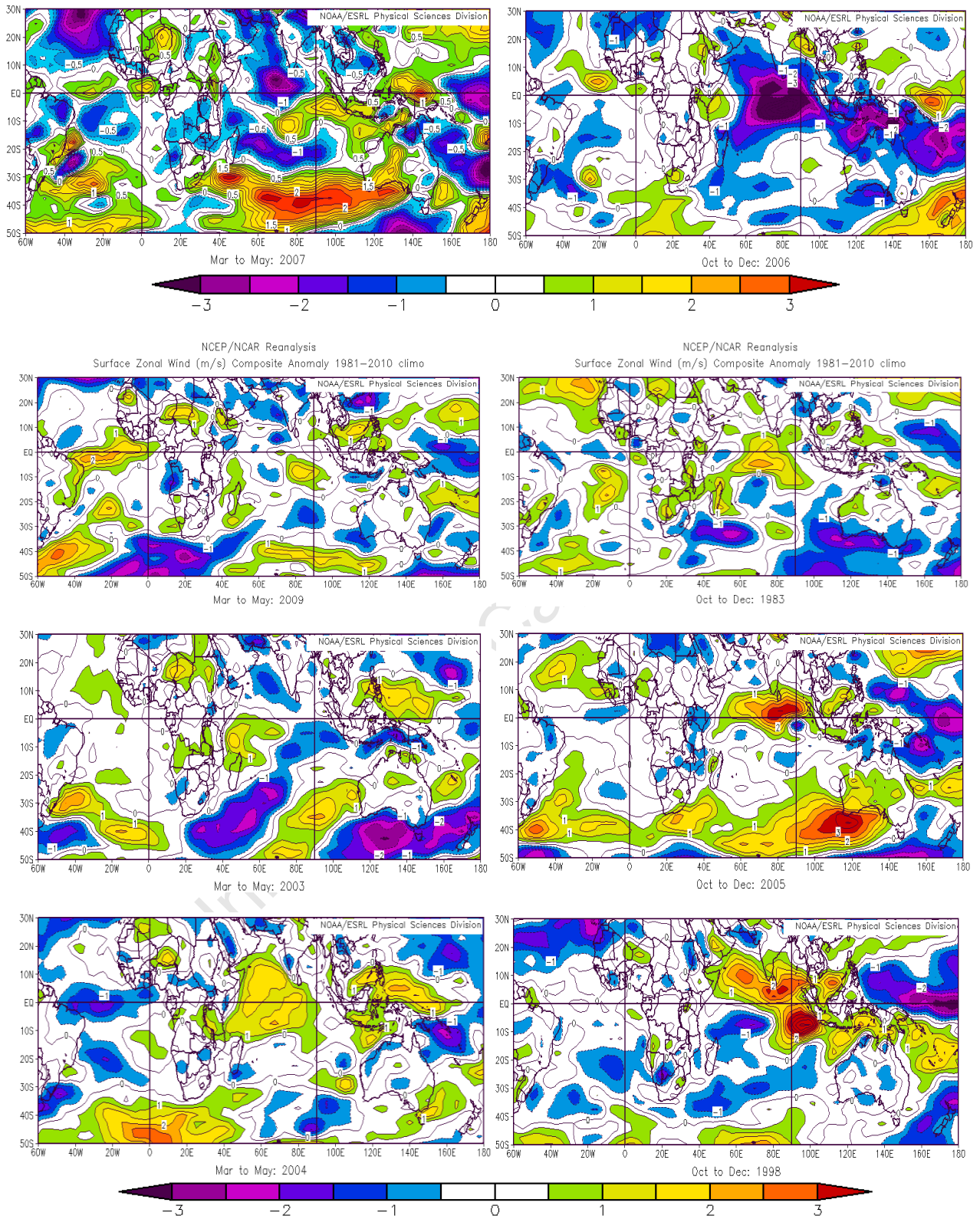


Figure 4: Surface zonal winds anomaly (m/s) (negative implies enhanced easterlies) for anomalously wet seasons during ENSO events. Upper plots (wet seasons) lower plots (dry season)

An examination of surface zonal winds for anomalous wet OND seasons during El Niño shows that along the equator within the western Indian Ocean, there are strong easterly anomalies, extending from 40°E to 90°E. Convergence of the moist marine easterlies with the dry and continental westerlies along the East African coast results in instability of the atmosphere and therefore increased rainfall. During anomalous dry seasons, typically La Niña, westerlies are dominant over the western Indian Ocean. This circulation drives moist marine moisture away from the region and as a result dry conditions are experienced. A second source of moisture for the region is the tropical Atlantic Ocean where in some cases westerly anomalies in the Southeast Atlantic extending into Angola and Congo Basin oppose the increased easterly anomalies leading to moisture convergence near the Tanzania and Kenyan coasts extending out over the Indian Ocean.

3.2.2 Surface zonal winds during neutral events

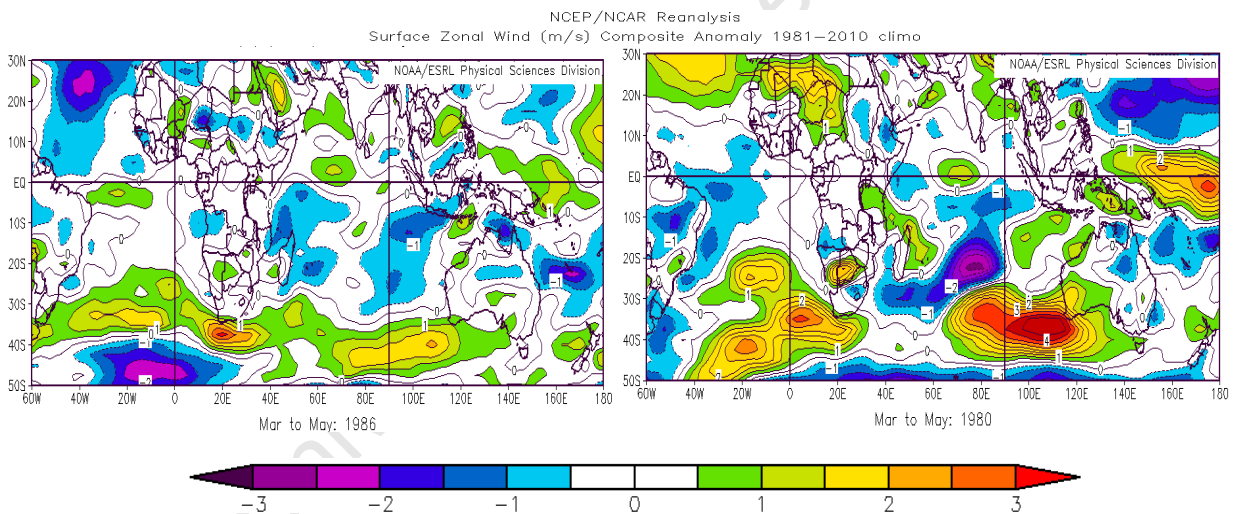


Figure 5: Surface zonal winds anomaly (m/s) for MAM rain season (negative implies enhanced easterlies) for anomalous wet and dry seasons during neutral years. Left hand plot (wet season), right hand plot (dry season)

An anomalous wet neutral MAM season occurred during 1986. In this case, easterly anomalies existed over the western tropical Indian Ocean from about 60°E to the East African coast while westerly anomalies existed over the Congo Basin. This pattern suggests increased moisture convergence over the coast. The neutral dry MAM season of 1980 showed westerly anomalies over the coastal ocean off Tanzania and Kenya implying advection of low level moisture away from the coastal land mass and hence reduced rainfall.

3.2.3 Velocity Potential during ENSO years

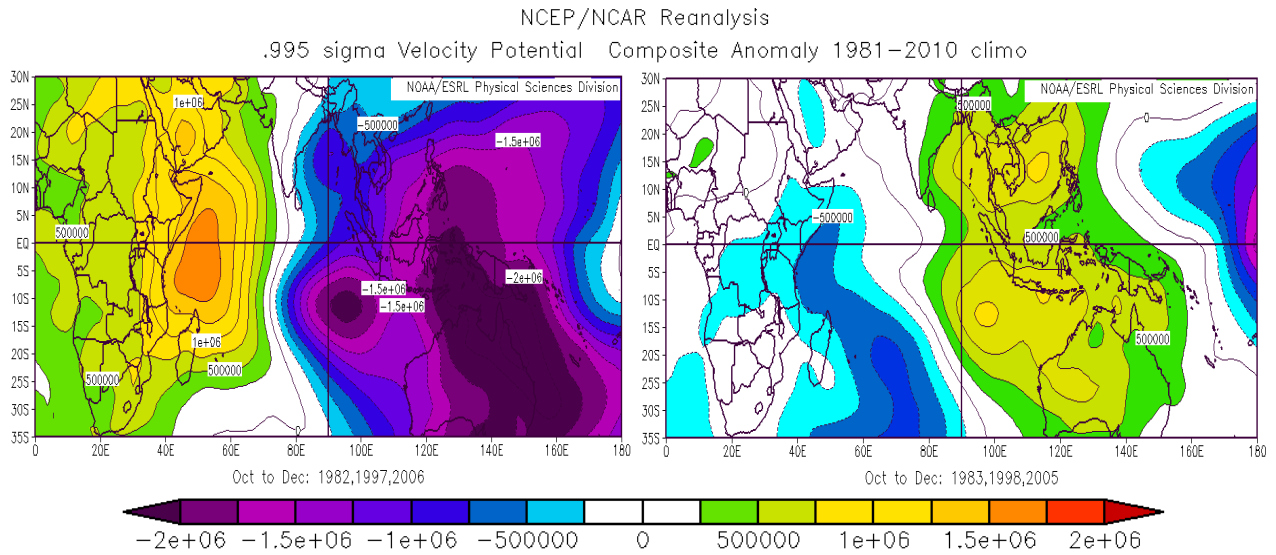


Figure 6: Composite lower level velocity potential anomaly during El-Niño and La-Niña years. Left panel (wet season) and right panel (dry season)

Plots of anomalies in lower level velocity potential (Figure 6) show eastward (westward) shift of the Walker circulation during OND with increased (decreased) low level convergence and hence uplift (sinking) over the western Indian Ocean consistent with increased (decreased) rainfall in the region.

3.2.4 Omega at 500ha

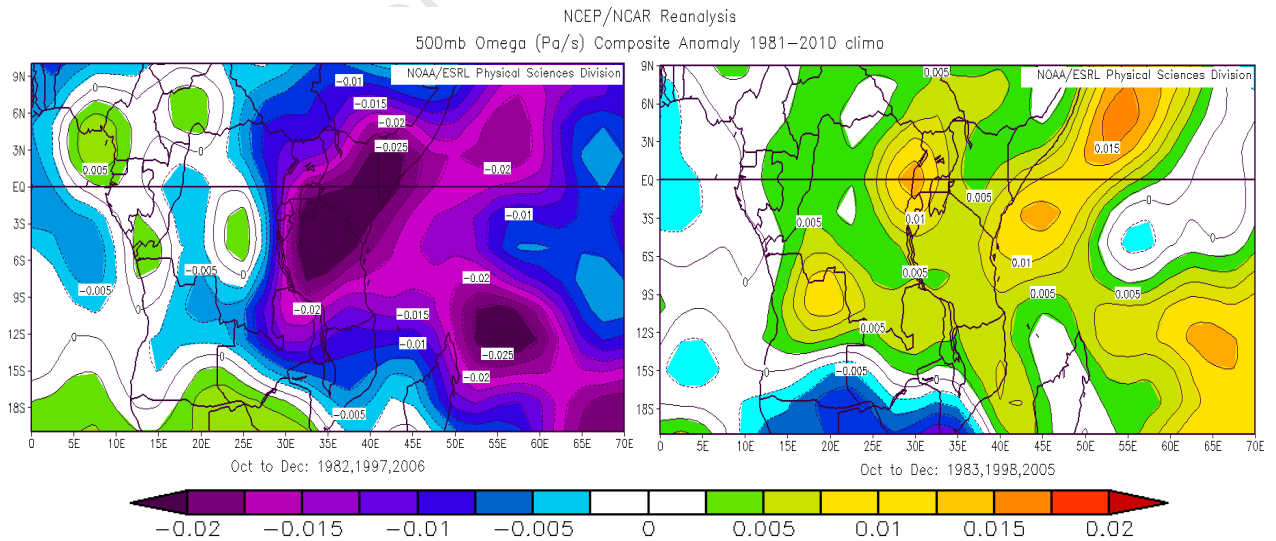


Figure 7: Composite omega anomaly (Pa/s) during El-Niño and La-Niña years. Left panel (wet season) and right panel (dry season).

The omega composite anomaly plots at 500hPa for OND for wet El Niño and dry La Niña seasons (Figure 7) show strong relative uplift (sinking) present in the middle troposphere. Note that omega indicates the rate of change of pressure with time and therefore negative omega implies uplift which is favorable for increased rainfall and the reverse for positive omega anomalies. Enhanced upward (sinking) motion is found from the central Indian Ocean to the East African coast, with strongest values at the latter location. The area of rising motion likely results from a strong convergence between the northeasterly and the southeasterly trade winds.

3.4 Rainy season characteristics

The five rainfall indices were calculated from daily station data for the Tanzania sites while in Kenya, pentad satellite data from CMAP were used. Satellite data were averaged over 2.50-0.00°S, 37.50-40.00°E to represent northern stations in Kenya and over 5.00-2.50°S, 37.50-40.00°E to represent the southern stations. The analysis of wet and dry spell characteristics during OND and MAM seasons included seasonal mean rainfall, number of wet (dry) spells and the maximum number of consecutive wet (dry) spells.

Table 2: Descriptive summaries of the climatological values indices of the wet and dry spell characteristics of the OND season with their respective standard deviation (*P* refers to pentad)

Variables	Station (1980-2008)			CMAP (1980-2008)	
	Tanga	Dar	Mtwara	North	South
Seasonal Mean Rainfall (mm/day)	3.57±2.29	3.28±1.65	2.71±1.78	3.70±1.58	2.48±1.14
No. of Wet Spells ($P > 10\text{mm/pentad}$)	2.0±1.8	2.5±1.8	1.6±1.5	1.6±1.6	0.7±0.9
Number of Dry Spells ($P < 5\text{mm/pentad}$)	14.0±7.5	14.7±2.3	15.8±2.1	13.3±0.1	15.8±2.4
Max number of consecutive wet spells (<i>P</i>)	1.1±0.7	1.3±0.8	1.0±0.8	1.0±0.8	0.5±0.6
Max number of consecutive dry spells (<i>P</i>)	7.5±3.5	8.0±2.8	10.7±4.5	6.7±2.8	9.7±4.7

Table 3: Descriptive summaries of the climatological values indices for the wet and dry spell characteristics for MAM season with their respective standard deviation (P refers to pentad)

Variables	Station (1980-2008)			CMAP (1980-2008)	
	Tanga	Dar	Mtwara	North	South
Seasonal mean rainfall (mm/day)	6.54±2.06	6.17±1.70	4.74±1.65	3.34±1.06	3.07±0.91
Number of wet spells ($P>10\text{mm/pentad}$)	4.5±1.8	5.0±1.8	3.7±1.8	1.1±1.0	1.3±1.2
Number of dry spells ($P<5\text{mm/pentad}$)	11.7±1.0	10.8±2.3	12.2±2.3	14.9±1.7	14.9±1.7
Max number of consecutive wet spells (P)	2.4±1.1	2.3±1.1	3.7±1.8	0.7±0.6	0.8±0.6
Max number of consecutive dry spells (P)	5.8±2.1	4.6±1.9	5.8±0.8	7.5±2.3	7.5±2.3

Table 2 and 3 gives the summaries of the wet and dry spells characteristics for OND and MAM rainfall seasons. It can be seen that most of the stations show a similar seasonal mean rainfall of about 3mm/day for the OND season. This result changes for the MAM season as it is seen that the Tanzanian sites have a higher seasonal mean rainfall compared to the Kenyan sites. For the latter, the OND and MAM rainfall amounts are close in value. The number of wet spells received in OND does not vary much for both countries but this is different for the MAM season where the number of wet spells is higher for the Tanzania sites with at least 4 wet spells compared to only about 1 for both parts of coastal Kenya.

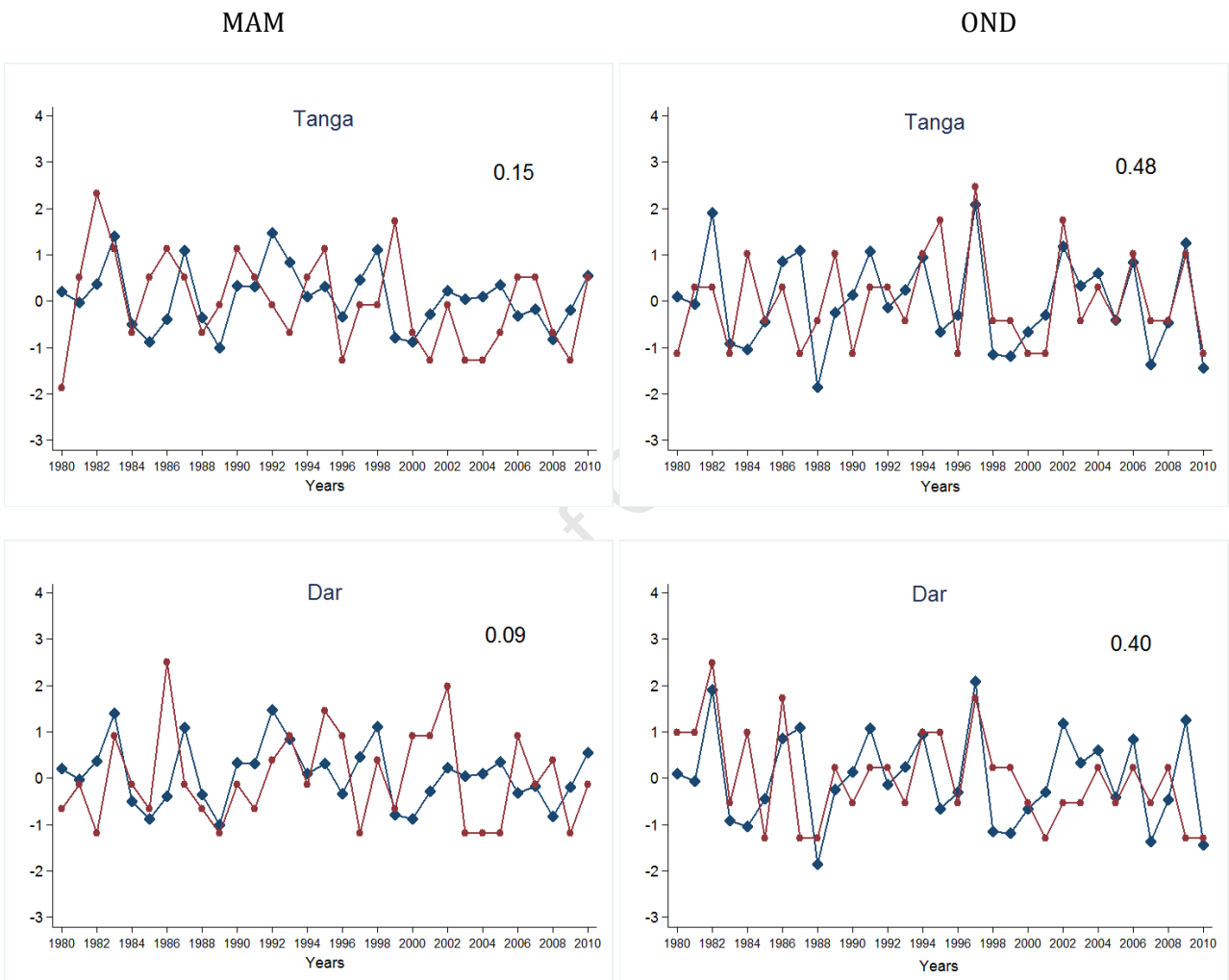
3.5 ENSO and IOD relationships

Dry spell frequencies and their inter-annual variability have been examined in southern Africa as a whole by Usman and Reason (2004), for Zambia by Hachigonta and Reason, (2006) and also investigated for the western Tanzania region by Mapande *et al.*, (2005). In each case, a relatively robust relationship existed between anomalies in this frequency and that in Niño 3.4 SST. Therefore to see whether this relationship also holds for the coastal regions of East Africa, Figures 8 and 9 plot the standardized wet and dry spell frequency with Niño 3.4 SST while Figures 10 and 11 plot the same with IOD index for Tanzanian stations. Figures 12 and

13 plot the standardized wet and dry spell frequency with Niño 3.4 SST while Figures 14 and 15 plots these frequencies with IOD index for Kenya.

3.5.1 Tanzania

3.5.1.1 Wet spell frequency with Niño 3.4 SST



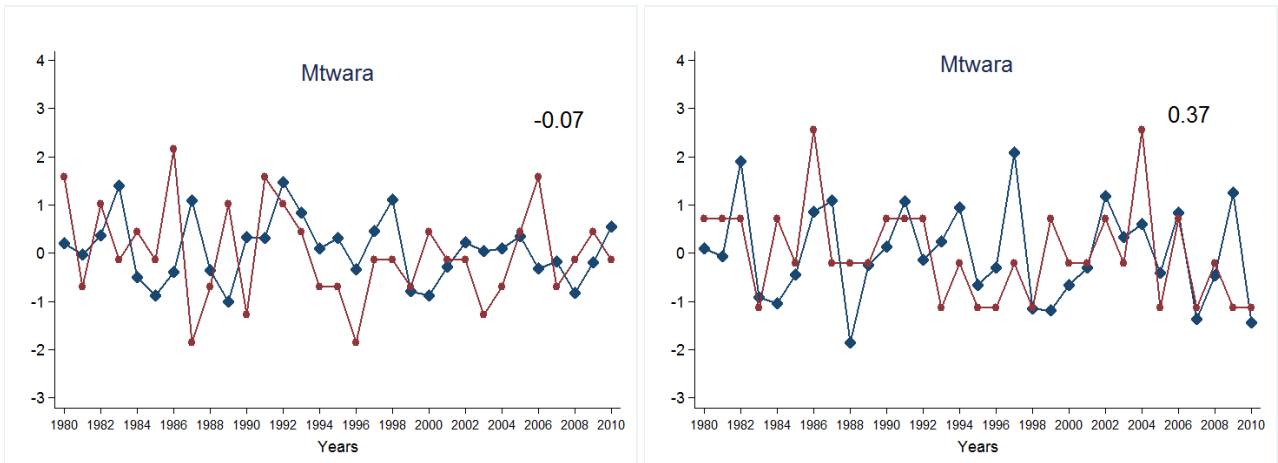
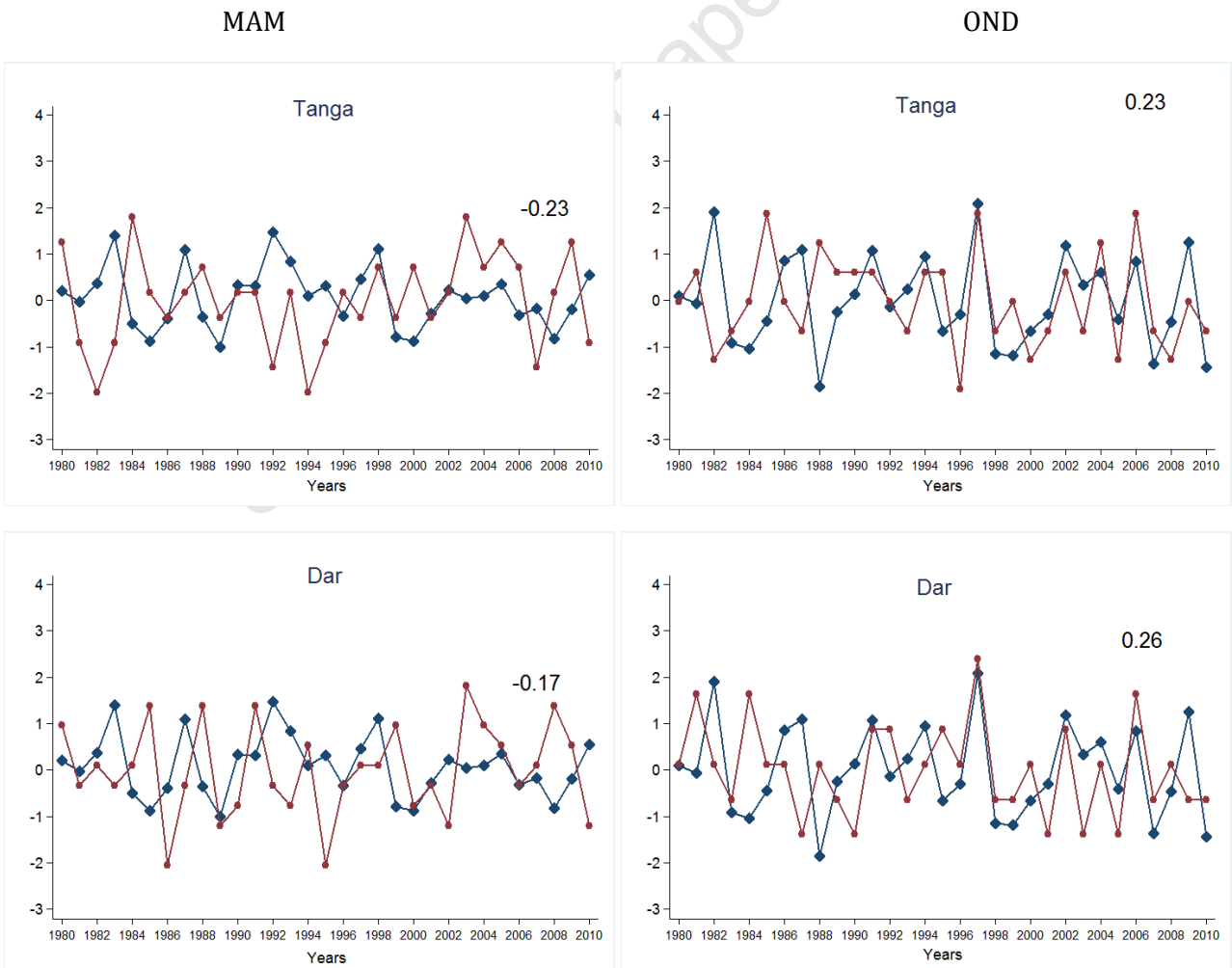


Figure 8: Anomalies in Niño 3.4 SST (blue) with standardized wet spell frequency (red) computed for Tanzania region with their respective Pearson correlation values.

3.5.1.2 Dry spell frequency with Niño 3.4 SST



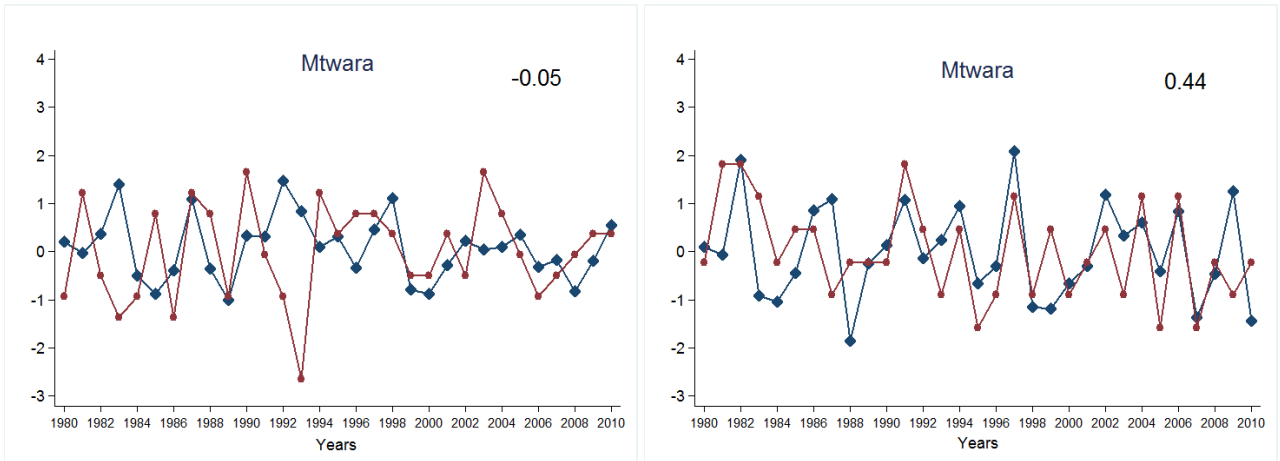


Figure 9: Anomalies in Niño 3.4 SST (blue) with standardized dry spell frequency (red) computed for Tanzania region with their respective Pearson correlation values.

Figure 8 shows that a relatively robust relationship exists between wet spell frequencies for Tanzania stations during the OND season with Niño 3.4 SST (correlation coefficient about 0.4) but this vanishes during MAM. Some inconsistencies in the OND relationship exist (e.g. 1983-84). The ENSO link with dry spell frequency is weaker than for the wet spell in OND. In MAM a weak negative correlation exists between the dry spell frequency and Niño 3.4 SST for two of the three stations.

3.5.1.3 IOD relationship with wet spell frequency

In addition to ENSO, modes of variability in the Indian Ocean such as the Indian Ocean Dipole Mode may also be related to wet (dry) spell frequencies over the region. The IOD-wet spell frequency link in OND is similar to that for ENSO and again weaker and inconsistent for MAM. For dry spell frequency, there is a relative robust positive link with IOD in OND. A weaker positive link exists in MAM at two of the stations

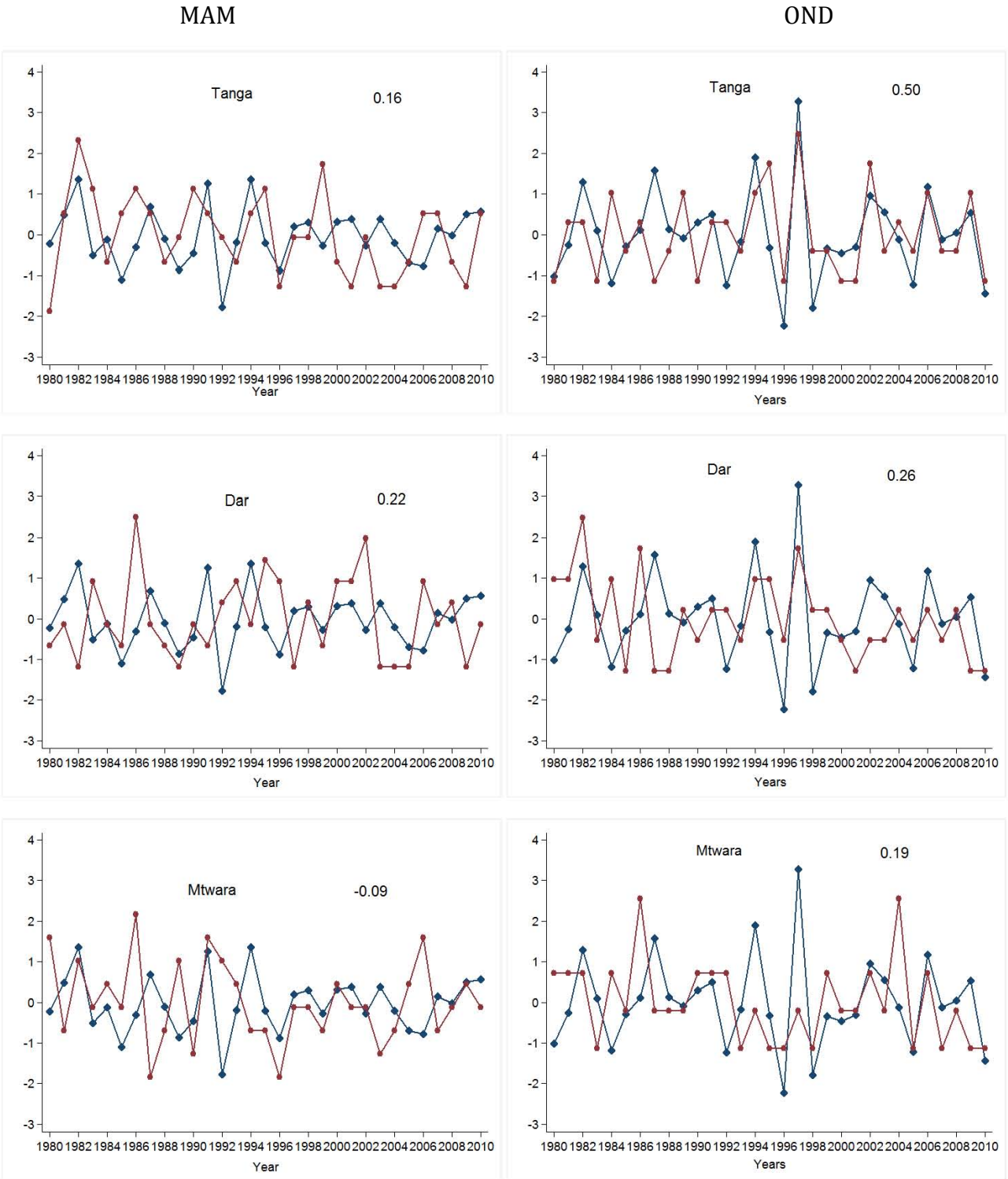


Figure 10: IOD index (blue) with standardized wet spell frequency anomalies (red) computed for Tanzania region the respective correlations calculated from Pearson correlation

3.5.1.4 IOD relationship with dry spell frequency

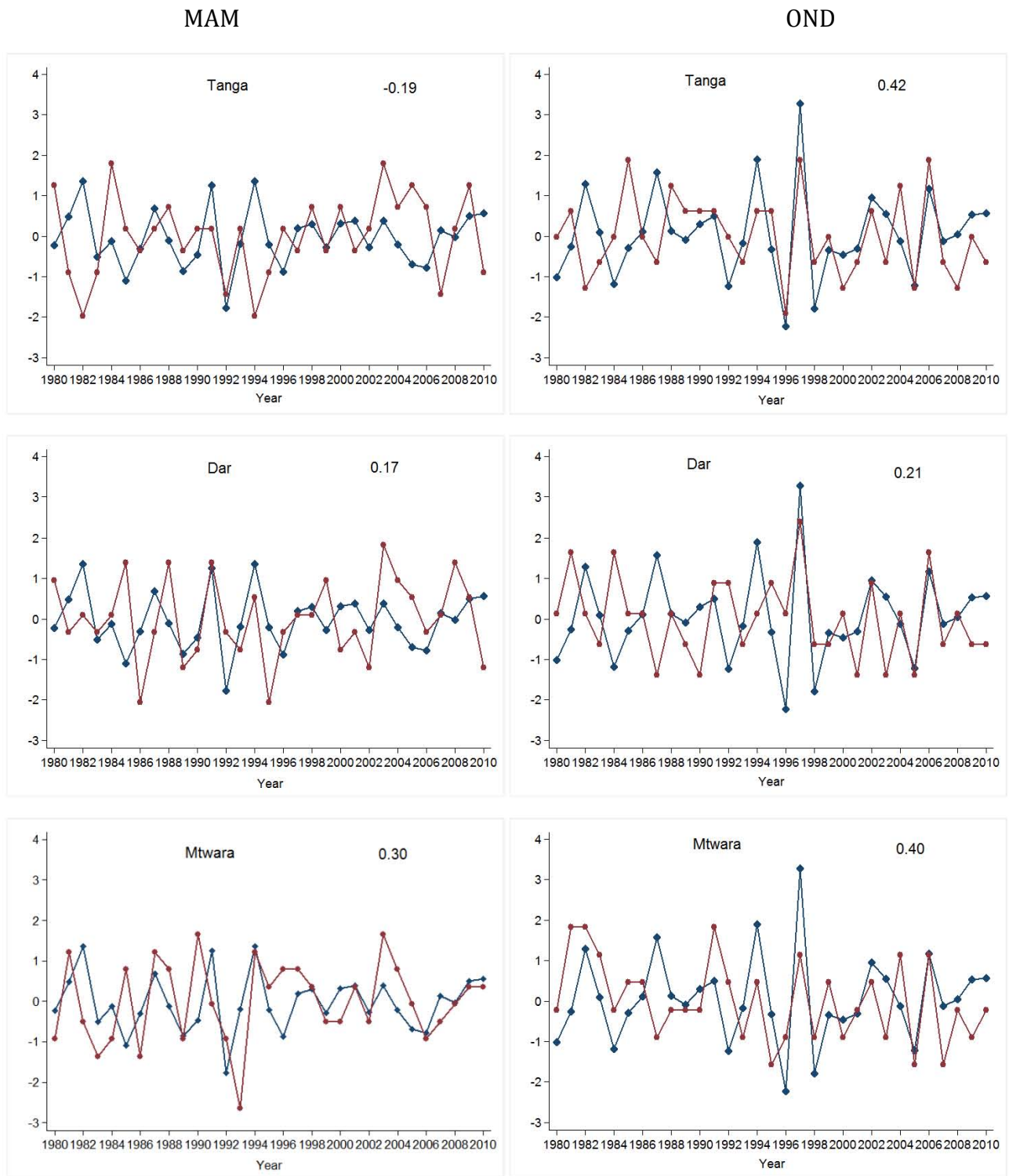


Figure 11: IOD index (blue) with standardized dry spell frequency anomalies (red) computed for Tanzania region with their respective Pearson correlation values.

3.5.2 Kenya

For the Kenya region, the relationship between standardized wet (dry) spell frequencies with Niño 3.4 SST is plotted in figures 12 and 13. The figures show a relatively robust positive relationship exists between wet spell frequencies for Kenyan stations during the OND season with Niño 3.4 SST which becomes weak and negative for MAM. For dry spell frequency, weaker inverse relationships exist with Niño 3.4 SST.

3.5.2.1 Wet spell frequency with Niño 3.4 SST

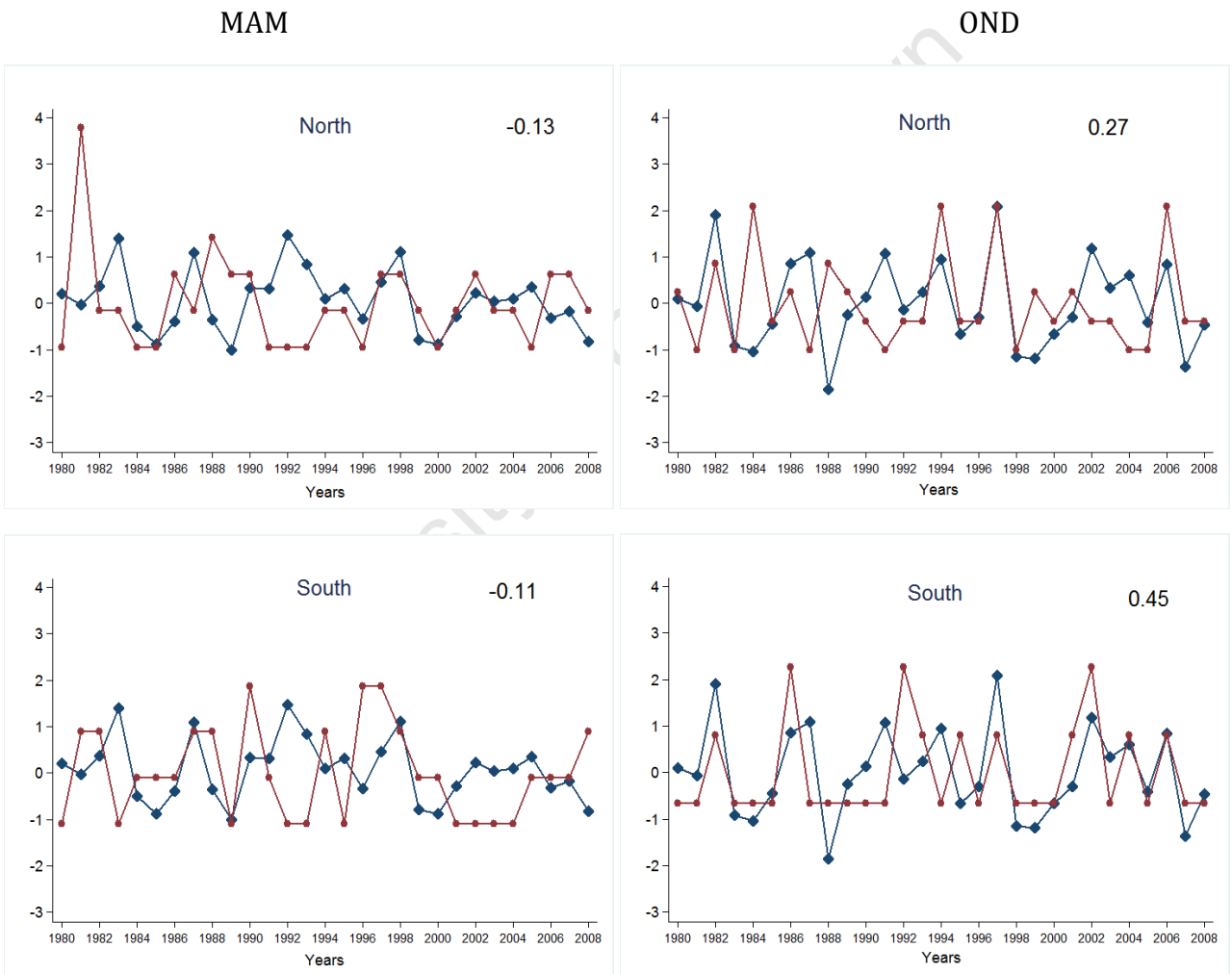


Figure 12: Niño 3.4 SST (blue) with standardized wet spell frequency anomalies (red) computed for Kenya region with their respective Pearson correlation values.

3.5.2.2 Dry spell frequency with Niño 3.4 SST

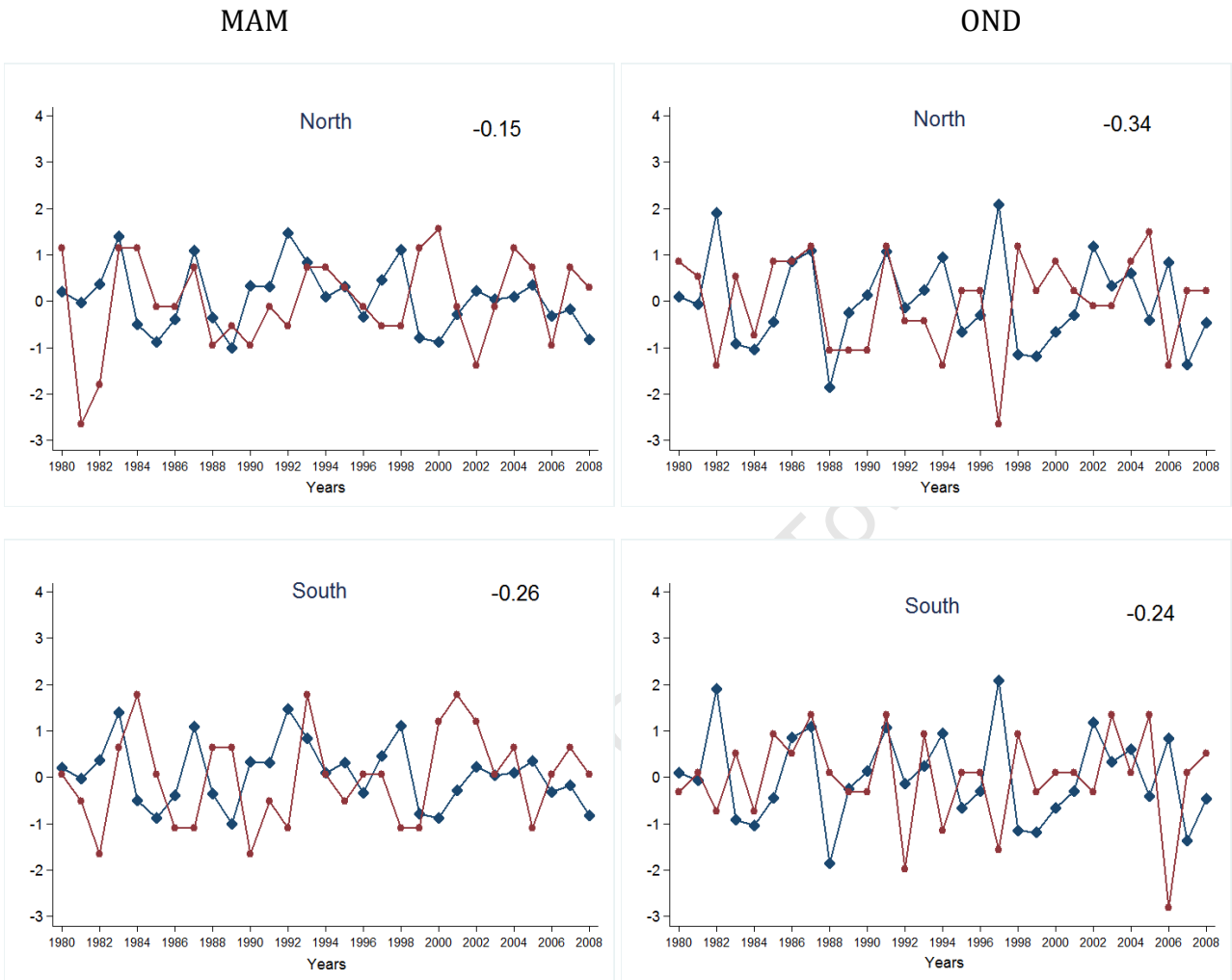


Figure 13: Niño 3.4 SST (blue) with standardized dry spell frequency anomalies (red) computed for Kenya region with their respective Pearson correlation values.

3.5.2.3 Wet spell frequency with IOD index

The IOD-wet spell frequency link is similar to the ENSO relationship in OND but now it is weakly positive in MAM (figure 14). For dry spell frequency, there is a relative robust negative link with IOD in OND (figure 15). For MAM, the correlation coefficients are almost zero.

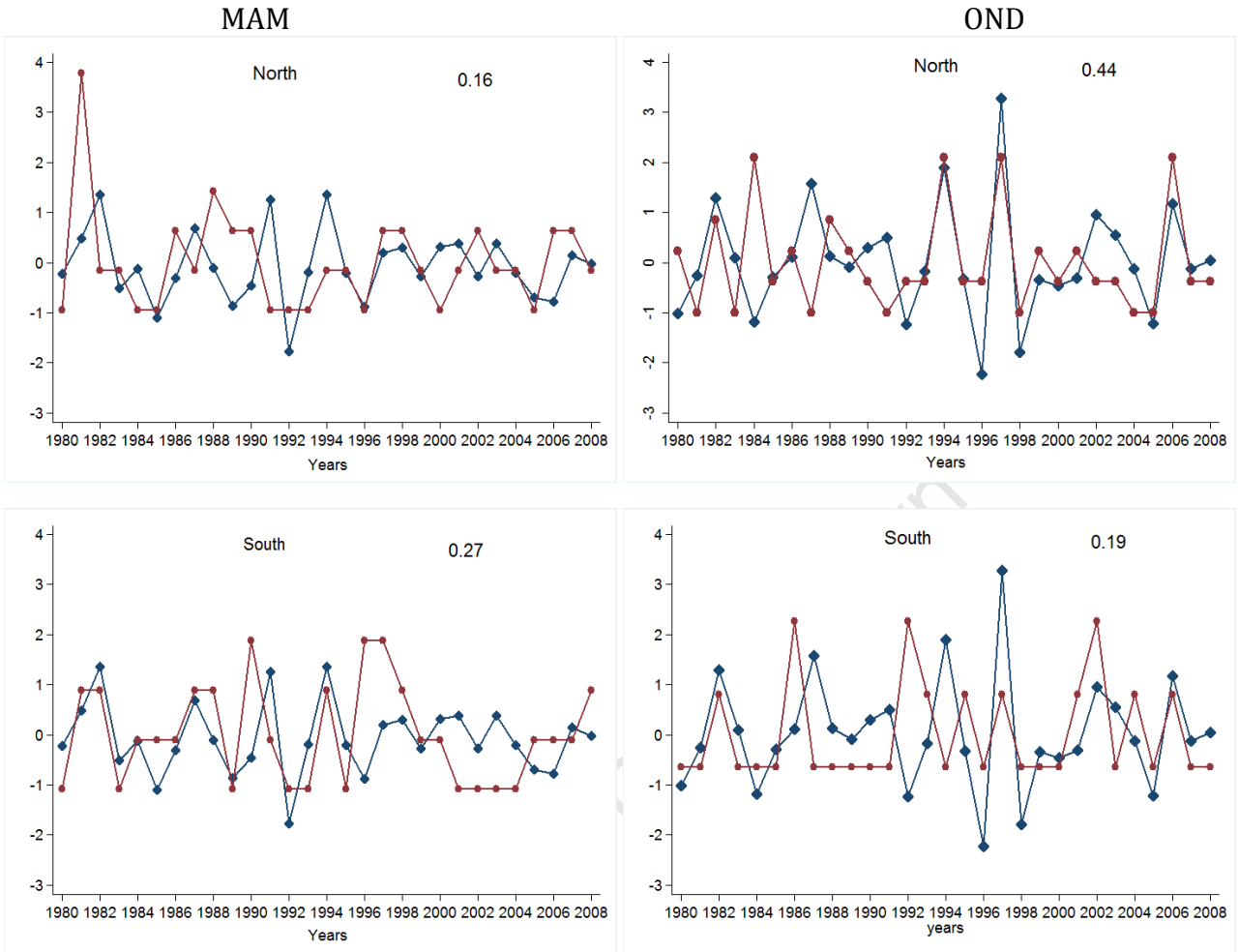
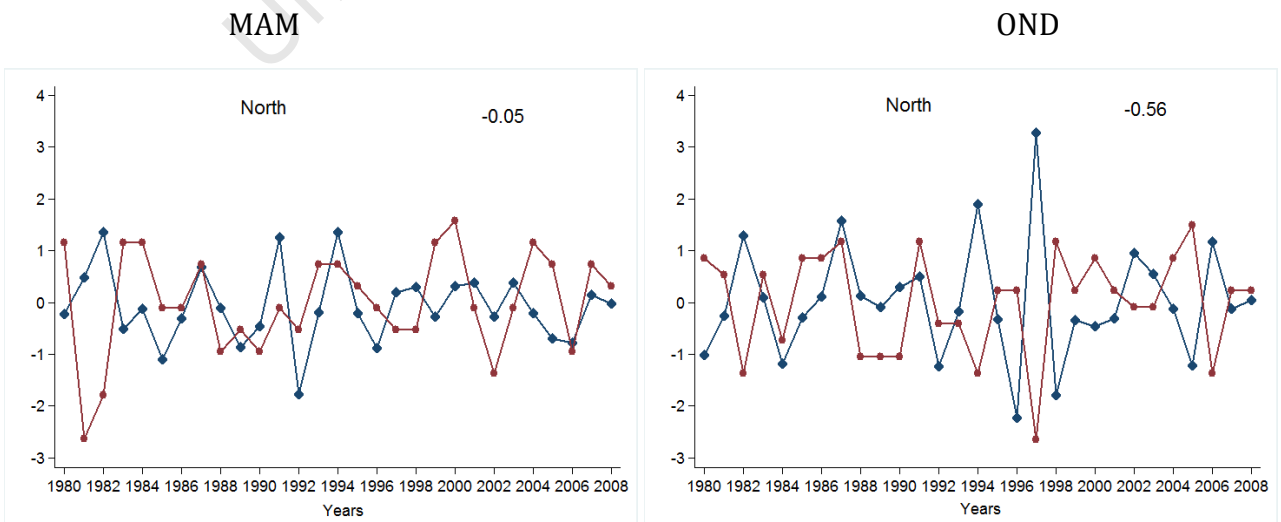


Figure 14: IOD index (blue) with standardized wet spell frequency anomalies (red) computed for Kenya region their respective Pearson correlation values.

3.5.2.4 Dry spell frequency with IOD index



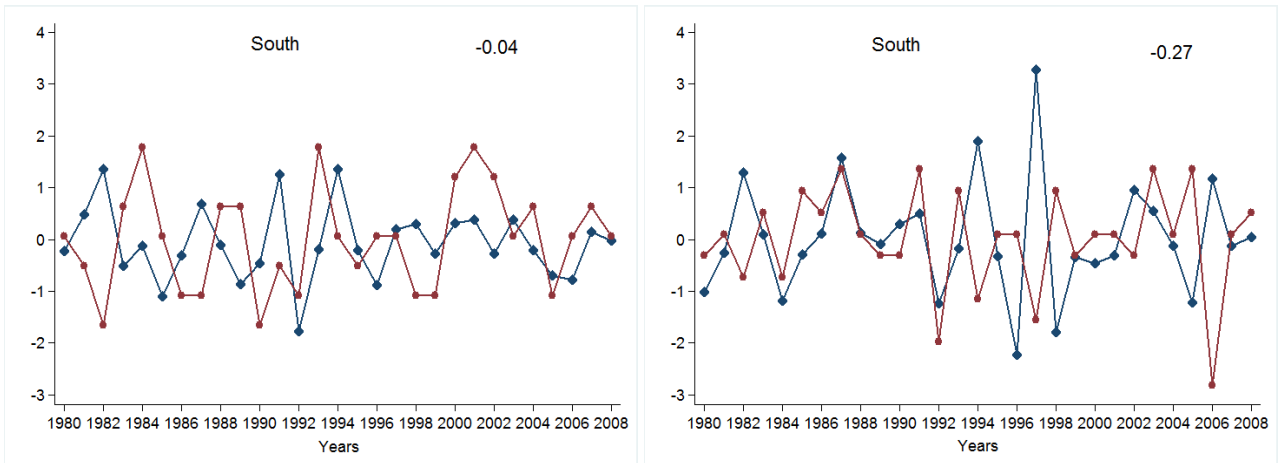


Figure 15: IOD index (blue) with standardized dry spell frequency anomalies (red) computed for Kenya region with their respective Pearson correlation values.

For dry spell frequency, a relatively strong (particularly the north) relationship exists in OND whereas in MAM, the correlations are close to zero. For Kenya, the IOD relationships in OND are similar to those for ENSO as expected since the IOD reaches its maximum strength around this time. However, in MAM, the magnitude of the relationships (although relatively weak in each case) is greater for the IOD than for ENSO.

3.6 Trend

The objective of this section is to determine whether there is a statistically significant trend in the number of wet and dry spells or not over the time period. To remove the effect of the sample data being biased by large absolute values, standardized anomalies are used to create the plots. To test our null hypothesis (H_0) that there is no trend against the alternative hypothesis (H_1) that there is a trend, parametric tests were used. The parametric test considers the linear regression of variable Y on time X that follows the Student's t distribution. In this research, the null hypothesis (H_0) is tested against the alternate hypothesis (H_1) at 5% significant level. Therefore the H_0 is rejected when the computed value is greater in absolute value than the critical value.

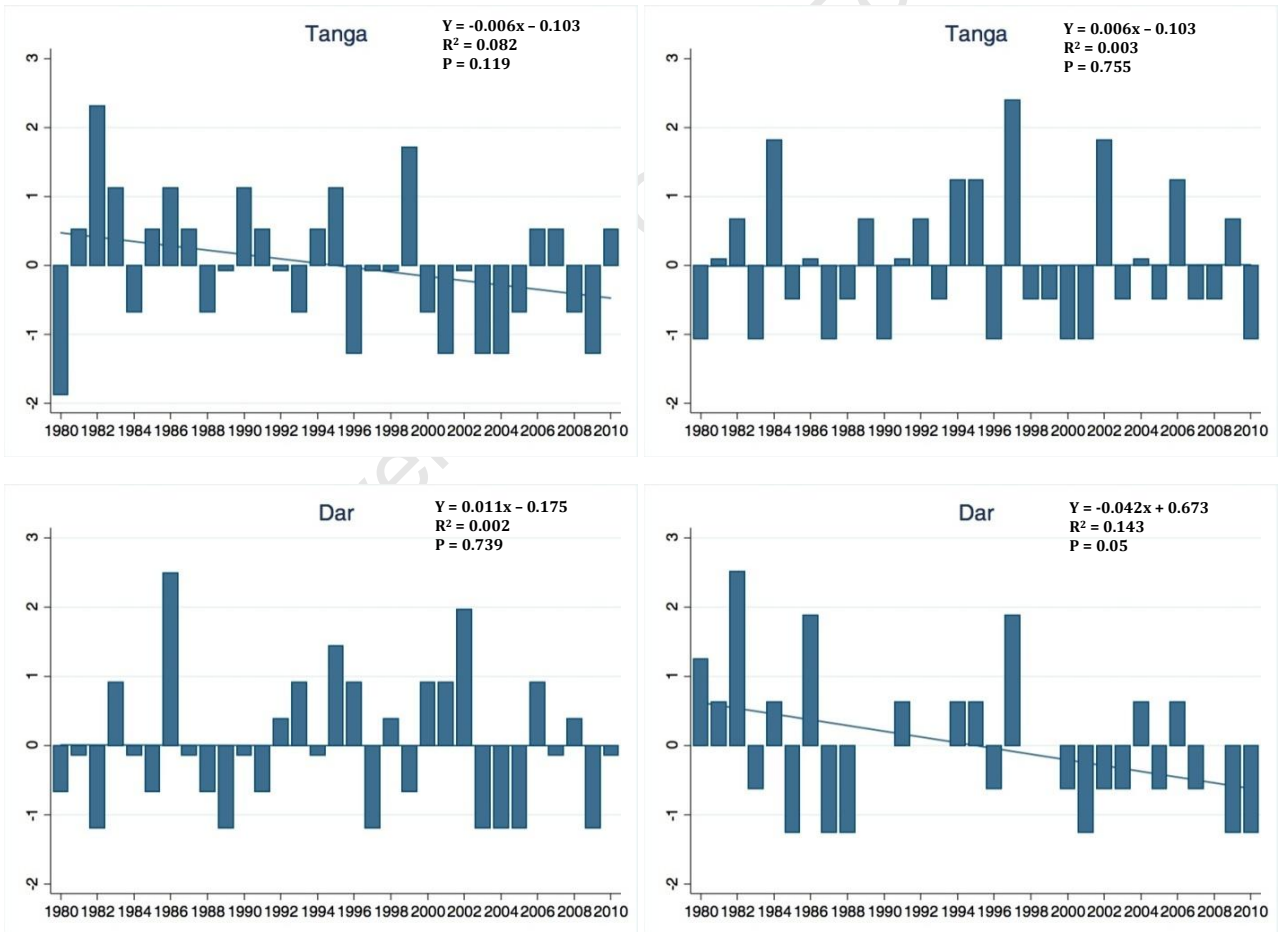
3.6.1 Tanzania

The analysis of trend focused on the individual stations in Tanzania and most of the stations show decreasing trend of the number of wet spells for both seasons except for Tanga during OND season and Dar during MAM season, which did not show any trend as the linear regression line is almost horizontal (Figure 16). Except for these two cases, the trend for the sites is not statistically significant using a 5% level student t test. In other words, a decrease in the number of wet spells is observed for most sites but this decrease is statistically significant only for the Dar site during the OND rainy season.

3.6.1.1 Wet spells trend

MAM

OND



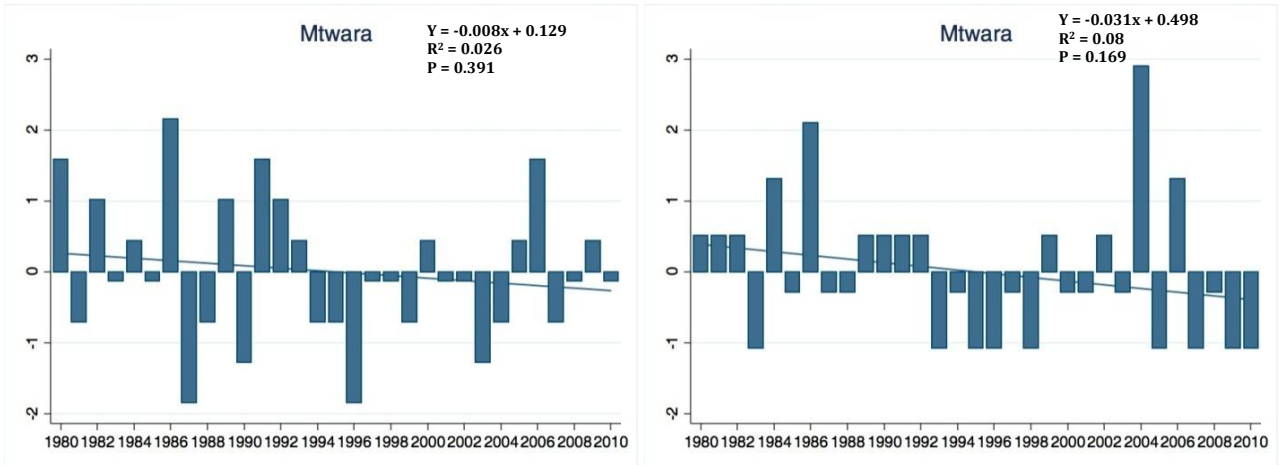


Figure 16: Trend in the number of wet spells for OND rainy season and MAM rainy season computed for Tanzania region showing calculated linear equation, R^2 value and the p value at 5% significance level.

3.6.1.2 Dry spells trend

For the dry spells, most of the sites in the Tanzania region show an increasing linear trend for both seasons but the trend for the sites is not significant at 5% level student t test except at Mtwara in OND. In other words, an increase in the number of dry spells is observed for most sites but this increase is statistically significant only for the Mtwara site during the OND rainy season.

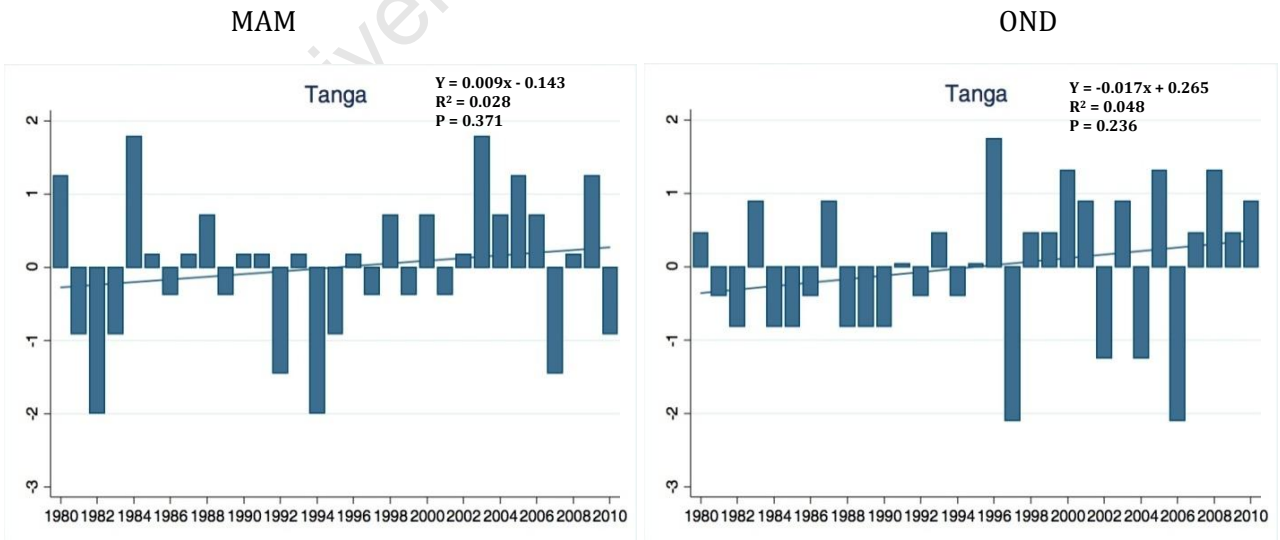




Figure 17: Trend in the number of dry spells for OND rainy season left and MAM rainy season right computed for Tanzania region showing calculated linear equation, R^2 value and the p value at 5% significance level.

3.6.2 Kenya

In Kenya the regions show increasing (decreasing) trend in the number of wet (dry) spells for both seasons (Figure 18 and 19). The trend for the sites is not statistically significant at 5% level student t test.

3.6.2.1 Wet spells trend

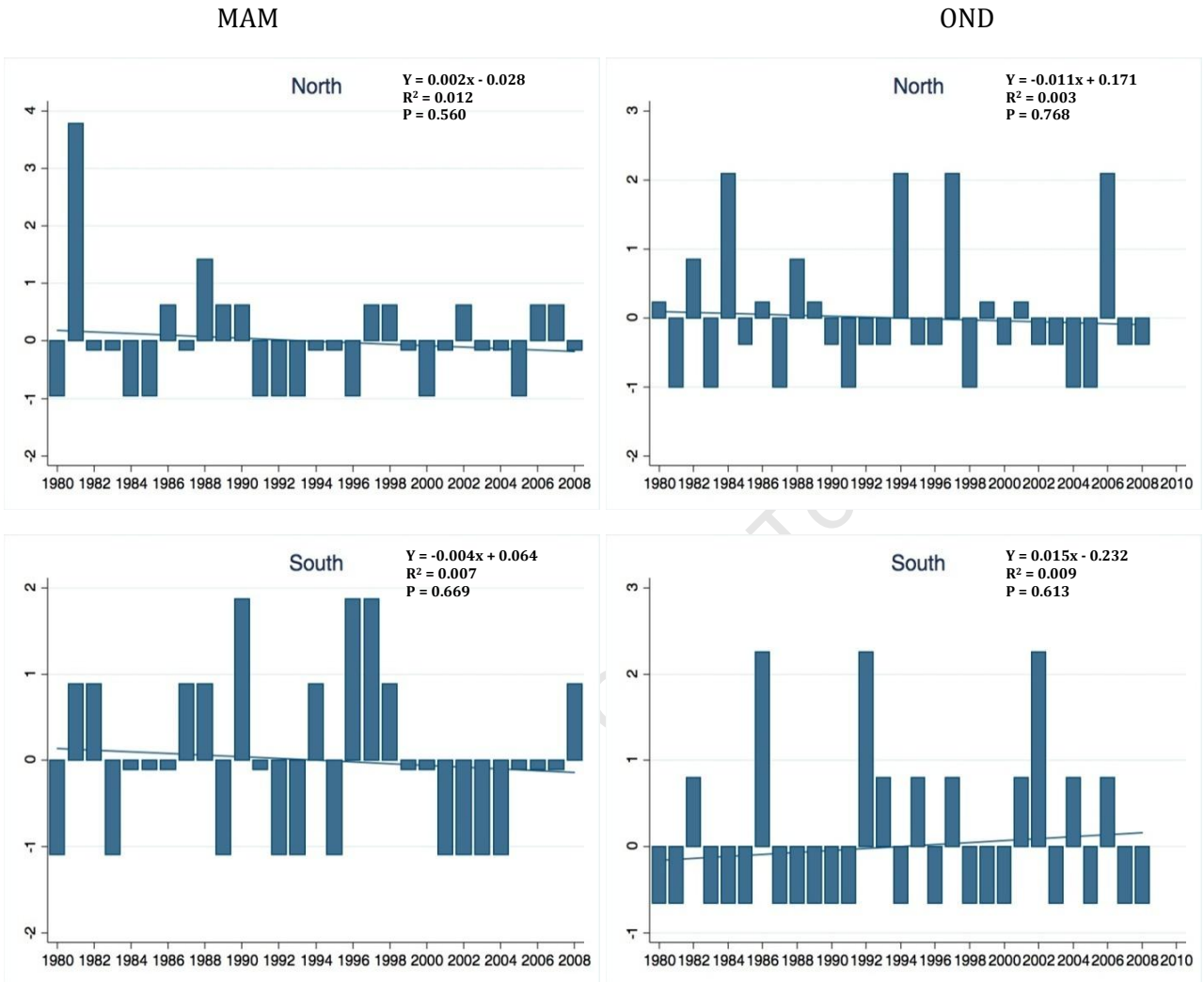


Figure 18: Trend in the number of wet spells for OND rainy season left and MAM rainy season right computed for Kenya region showing calculated linear equation, R² value and the *p* value at 5% significance level.

3.6.2.2 Dry spells trend

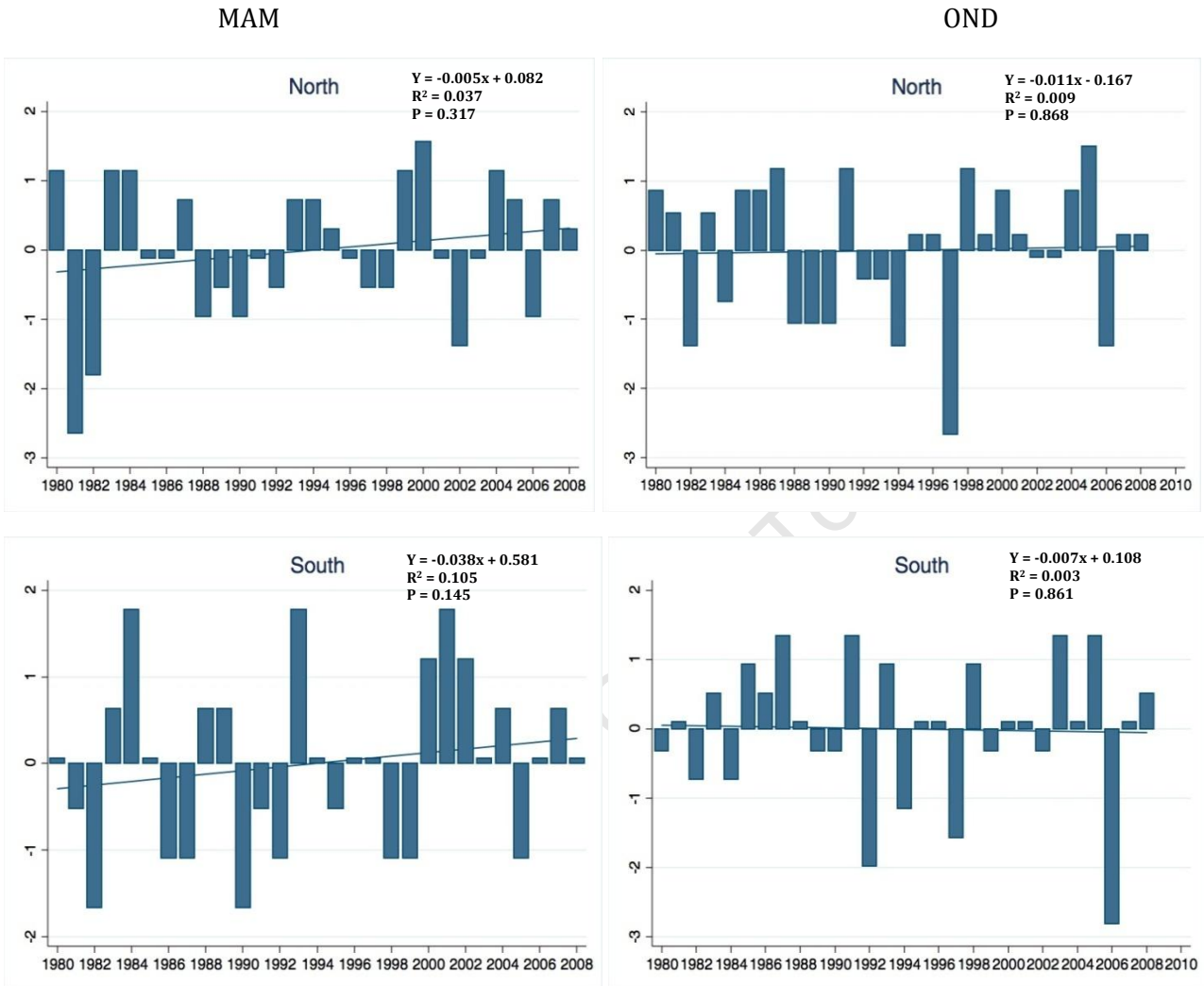


Figure 19: Trend in the number of dry spells for OND rainy season left and MAM rainy season right computed for Kenya region showing calculated linear equation, R^2 value and the p value at 5% significance level.

3.7 Spatial coherence of wet (dry) spell frequency

To demonstrate how the wet (dry) spells are linked to global SST patterns and more specifically the dominant tropical SST modes located in the Indo-Pacific Oceans, the rainfall characteristics (wet and dry spell frequency) are correlated with the global SST from HadISST dataset for the period 1980-2010 for Tanzania and 1980-2008 for Kenya. To investigate associated circulation patterns, NCEP-NCAR reanalysis zonal winds are correlated with wet and dry spell frequency. Figures 20-27 show the respective spatial correlation structures with SST anomalies in the Indo-Pacific basin and regional zonal wind anomalies for both regions.

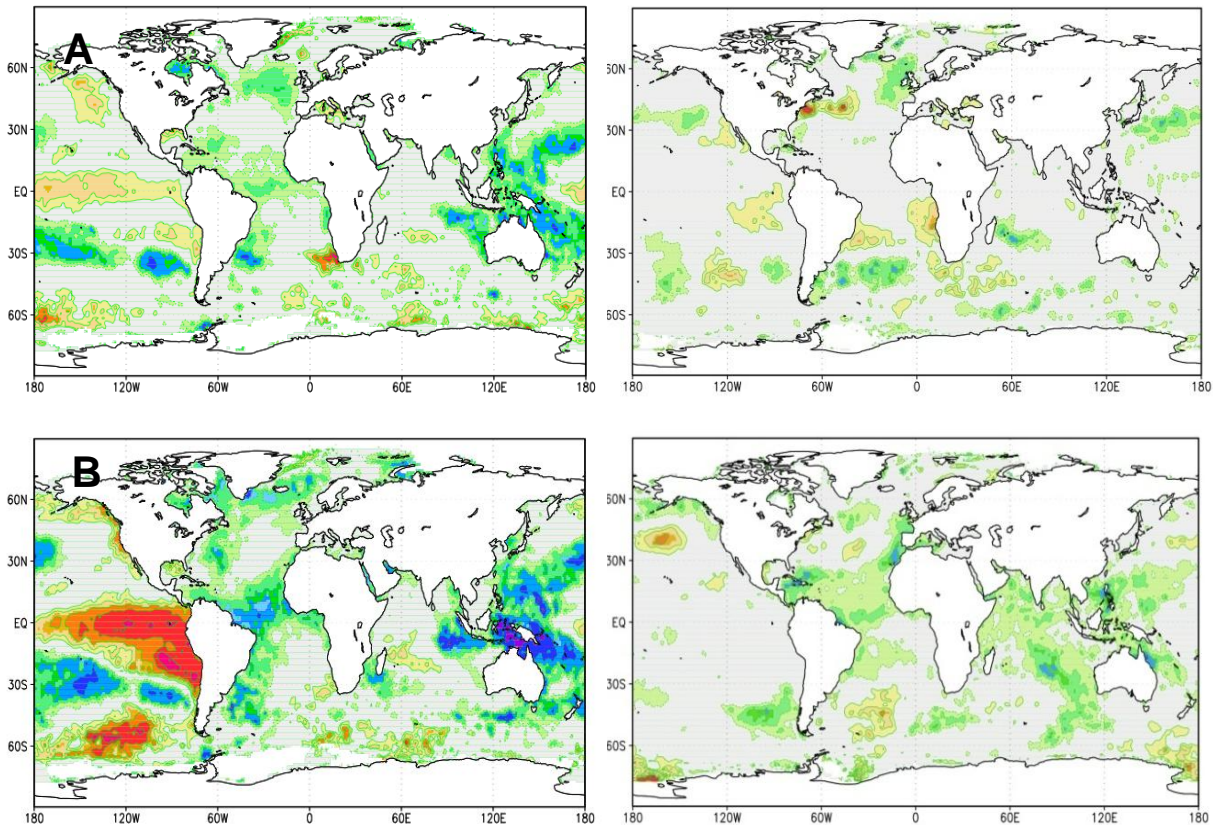
3.7.1 Tanzania

3.7.1.1 Wet spell frequency with Global SSTs

Figure 20 shows a strong ENSO SST signal for Dar and Mtwara during OND whereas that for Tanga is weak. Mtwara also shows an IOD signal during this season. For MAM, there are relatively weak negative correlations in the Indian Ocean for Dar and to a lesser extent Tanga with wet spell frequency

OND

MAM



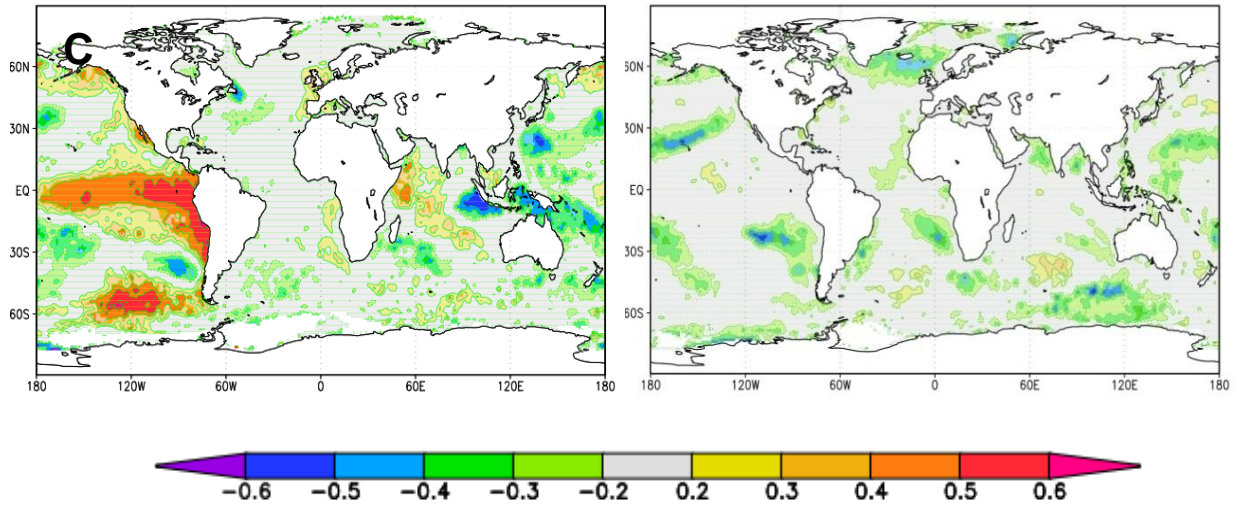


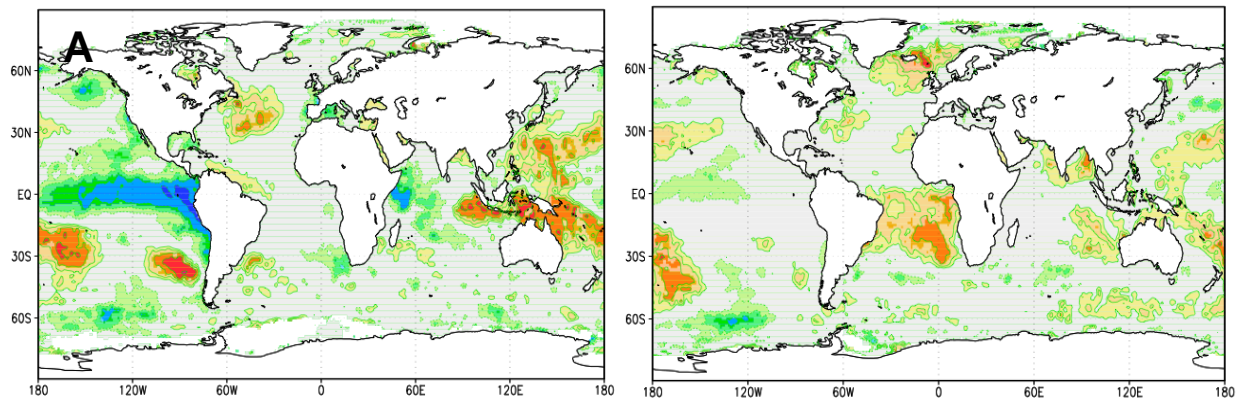
Figure 20: Plots of spatial correlations for OND and MAM 1980-2010 wet spell frequency with global sea surface temperature at 95% confidence level. Note: A (Tanga), B (Dar) and C (Mtwara)

3.7.1.2 Dry spell frequency with Global SSTs

The OND dry spell correlations (Figure 21) show a strong La-Niña pattern for all the three stations as well as a negative IOD in the case of Tanga. For MAM, there are positive SST correlations in the tropical South Atlantic (much of the Indian Ocean) for Tanga (Mtwara).

OND

MAM



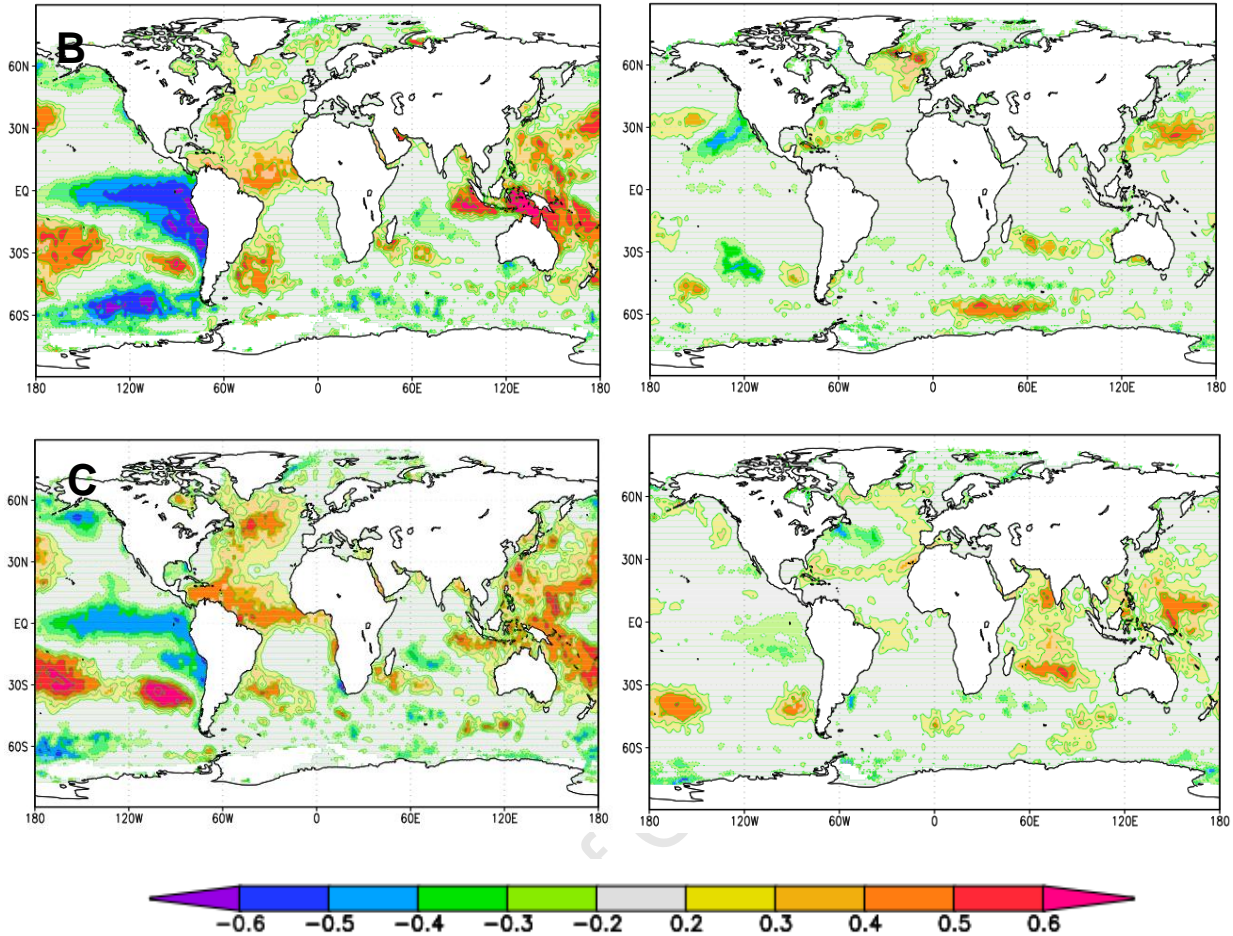


Figure 21: Plots of spatial correlations for OND and MAM 1980-2010 dry spell frequency with global sea surface temperature at 95% confidence level. Note: A (Tanga), B (Dar) and C (Mtwara)

3.7.1.3 Wet spell frequency with zonal winds

Increased wet spell frequency is correlated with strong zonal winds over the tropical Indian Ocean in all the three stations during OND (Figure 22). For MAM, there are much weaker positive correlations over the tropical Indian Ocean. It is noticeable that wet events are accompanied by large scale circulation anomalies across the whole Indian Ocean. A belt of anomalous easterlies covers the whole equatorial Indian Ocean and are associated with two broad high pressure centers on both sides of the equator.

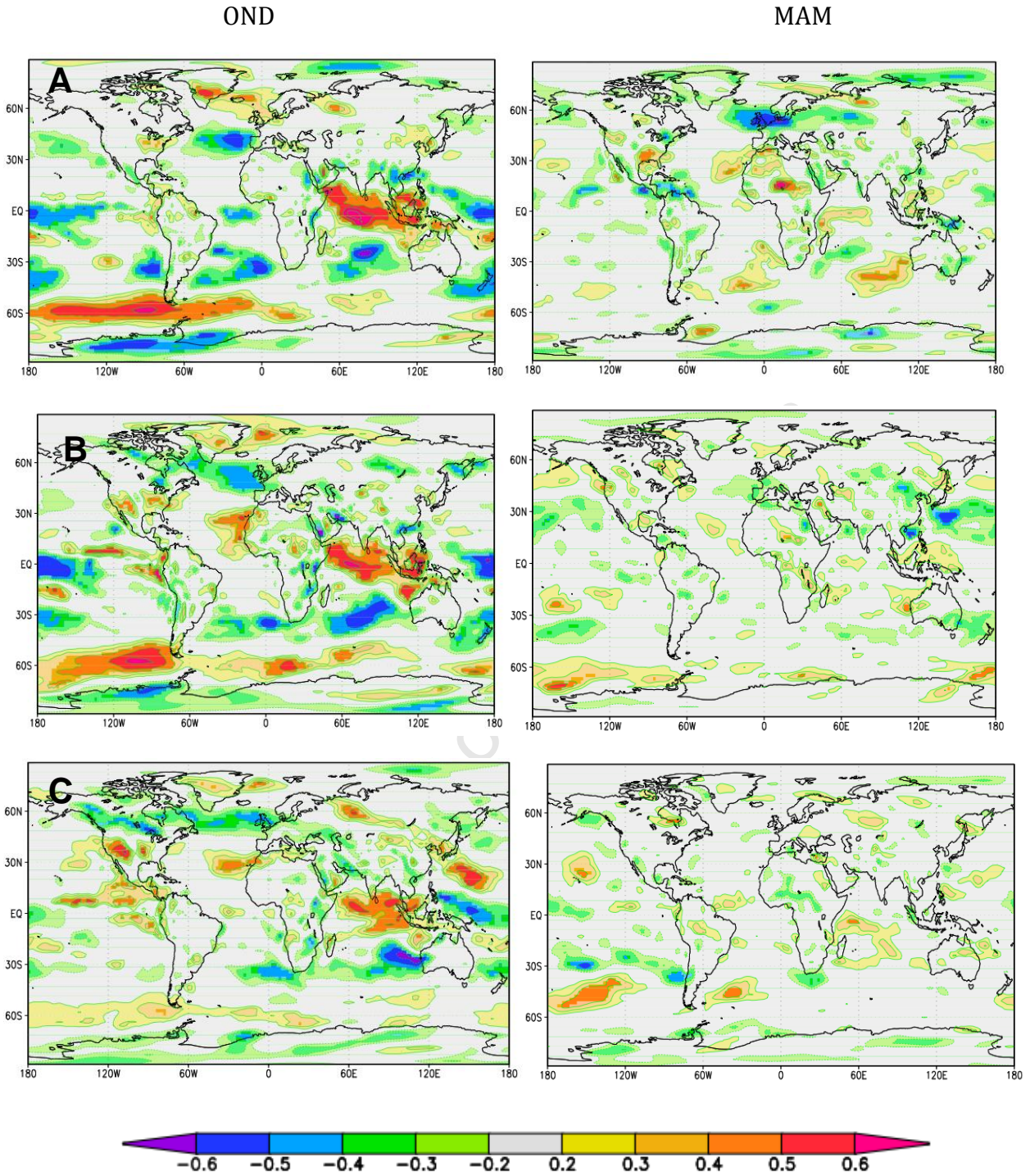


Figure 22: Plots of spatial correlations for OND and MAM 1980-2010 wet spell frequency with surface zonal winds at 95% confidence level. Note: A (Tanga), B (Dar) and C (Mtwara)

3.7.1.4 Dry spell frequency with zonal winds

Increased dry spell frequency is negatively correlated with zonal winds over the tropical Indian Ocean at all the three stations during OND (Figure 23). For MAM, there are much weaker correlations over the tropical Indian Ocean.

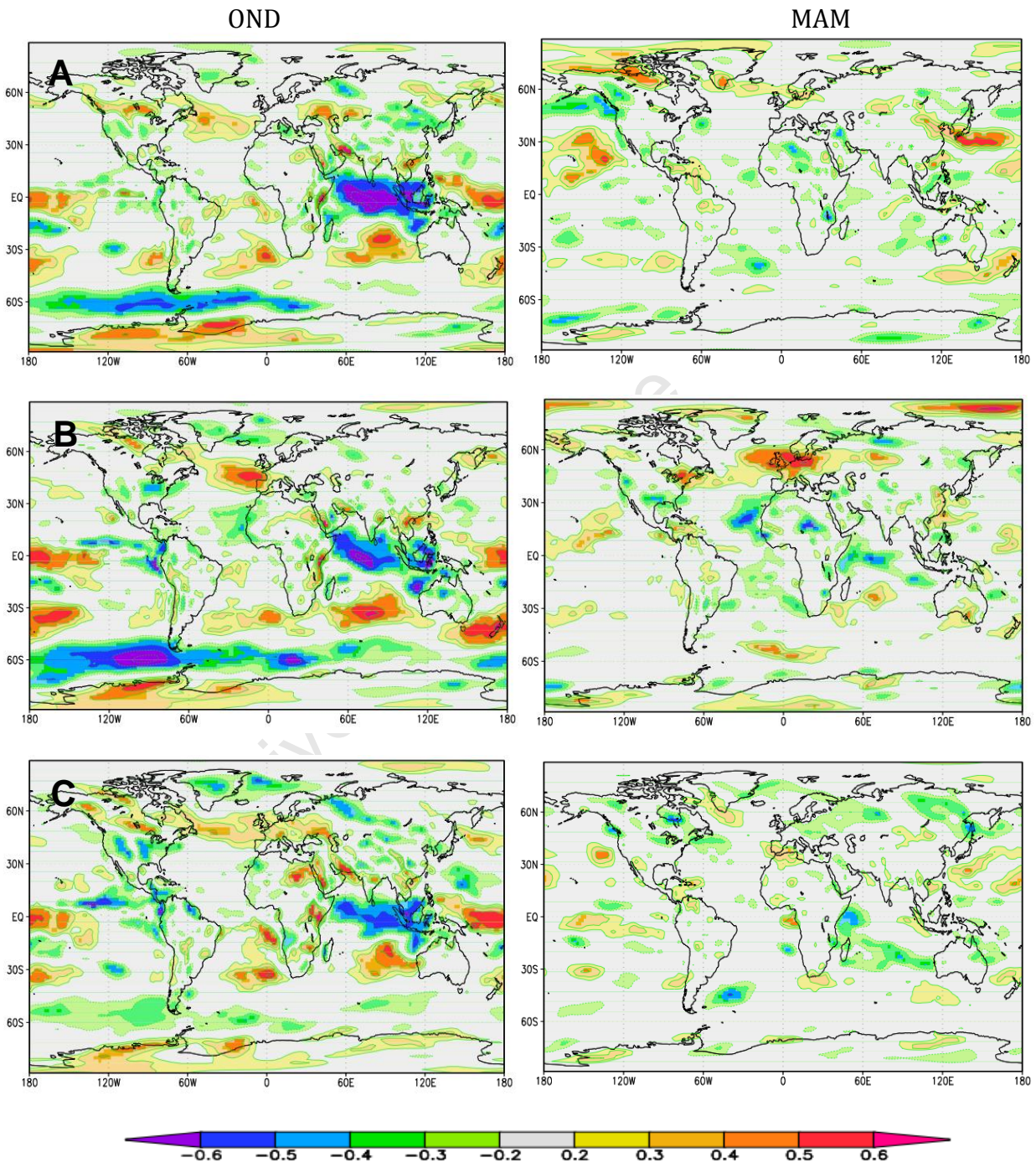


Figure 23: Plots of spatial correlations for OND and MAM 1980-2010 dry spell frequency with surface zonal winds at 95% confidence level. Note: A (Tanga), B (Dar) and C (Mtwara)

3.7.2 Kenya

3.7.2.1 Wet spell frequency with Global SSTs

Figure 24 shows an ENSO SST signal for both the north and south region during OND. Both areas also show an IOD signal during this season. For MAM, there are relatively weak correlations in the tropical South Atlantic Ocean and the mid-latitude South Pacific.

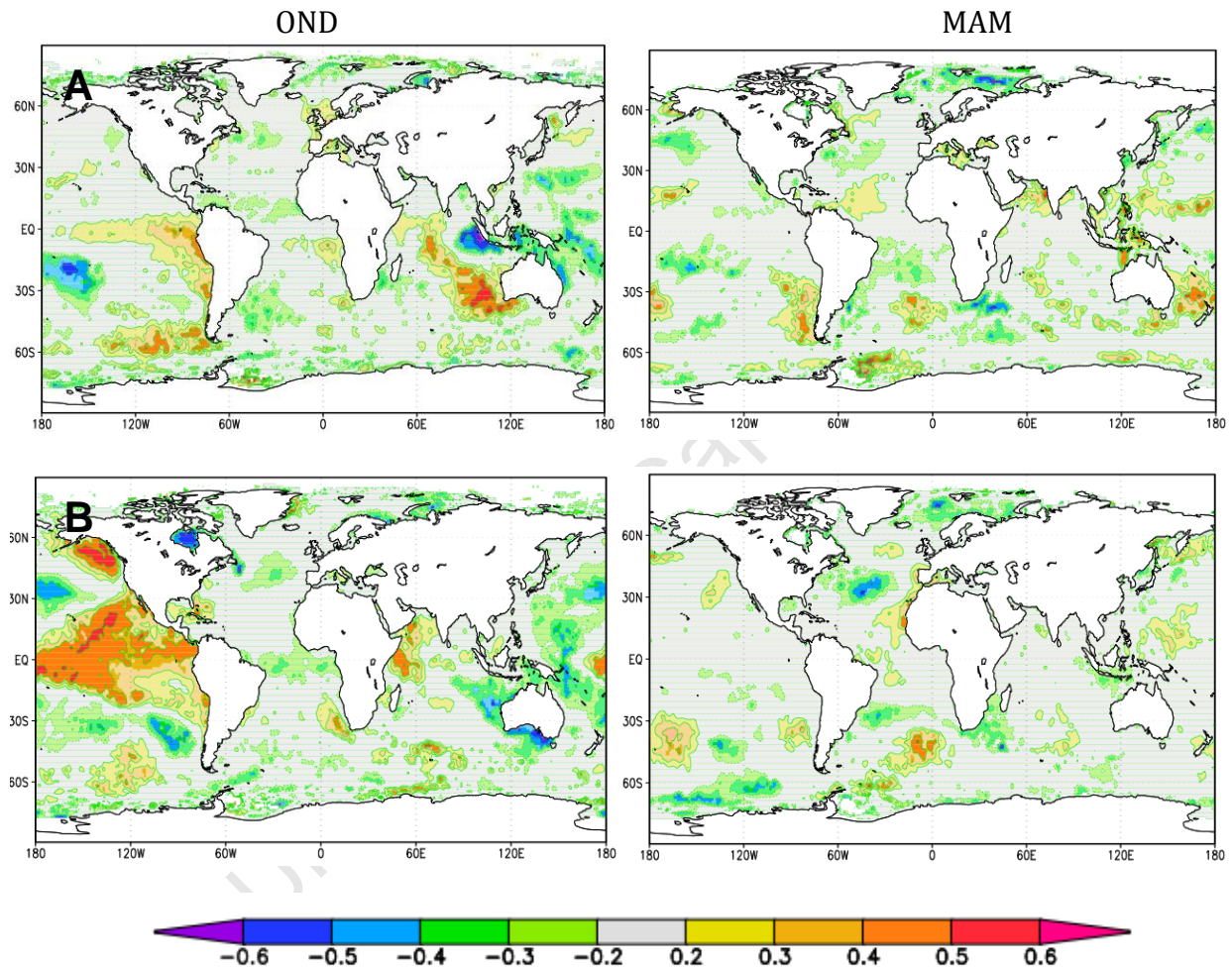


Figure 24: Plots of spatial correlations for OND and MAM 1980-2008 wet spell frequency with global sea surface temperature at 95% confidence level. Note: A (north) and B (south)

3.7.2.2 Dry spell frequency with Global SSTs

The OND (Fig. 25) show a relatively strong (weak) La-Niña pattern for the northern (southern) region as well as a negative IOD pattern. For MAM, there are weak positive SST correlations in the tropical South Atlantic in both areas as well as a weak negative correlation in the South Indian Ocean for the southern Kenyan area.

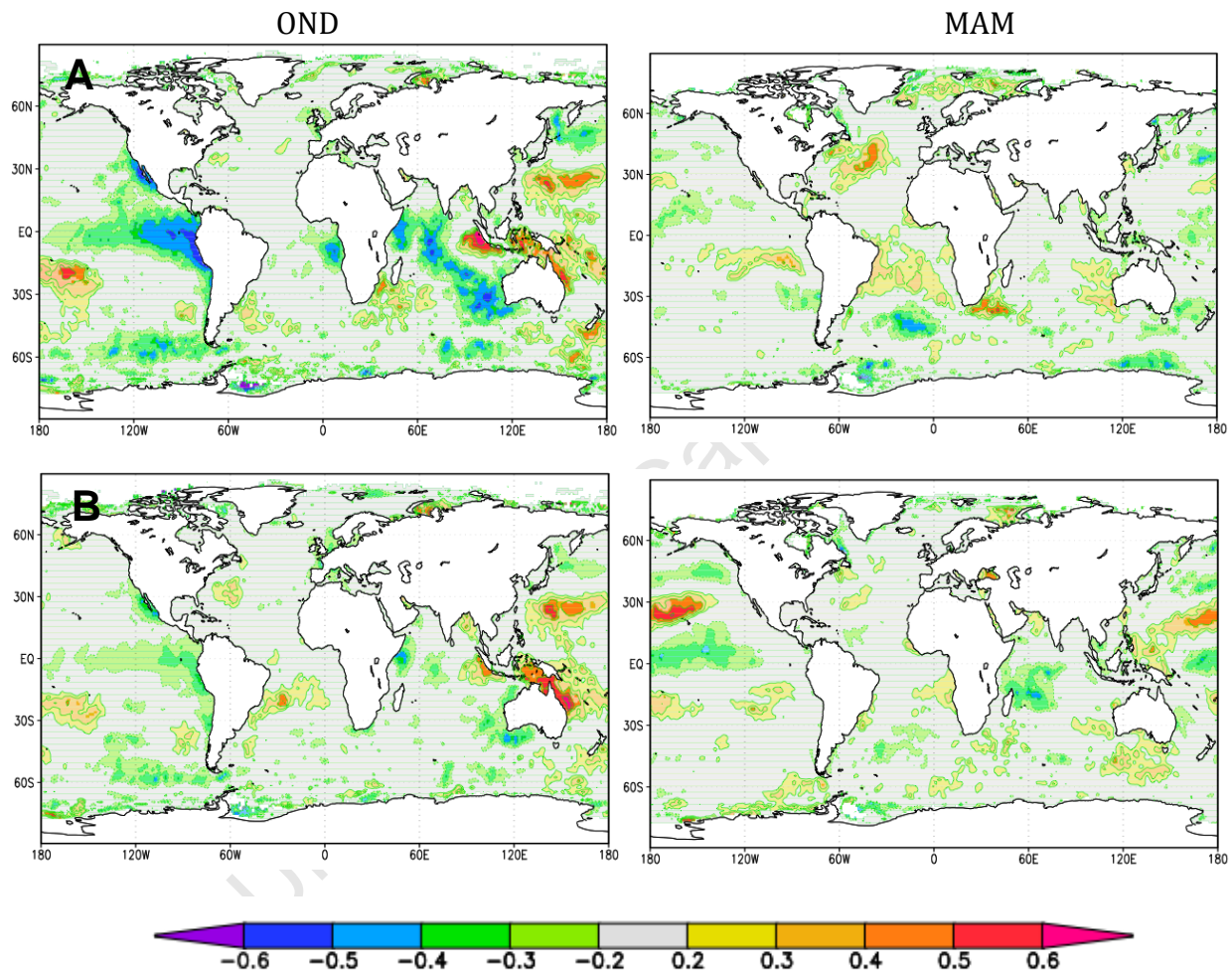


Figure 25: Plots of spatial correlations for OND and MAM 1980-2008 dry spell frequency with global sea surface temperature at 95% confidence level. Note: A (north) and B (south)

3.7.2.3 Wet spell frequency with zonal winds

Fig. 26 suggests that increased wet spells are linked to stronger equatorial westerlies over the Indian Ocean and stronger trade winds in the South Indian Ocean for both the northern and southern areas of Kenya. There are also weak negative correlations for both areas in the eastern equatorial Pacific implying an ENSO link. For MAM, the signals are less obvious; both the northern and the southern area have weak negative correlations near the East African coast, a larger area of such correlation in the subtropical South Indian Ocean, and positive correlation (westerly anomalies) over parts of the Congo Basin.

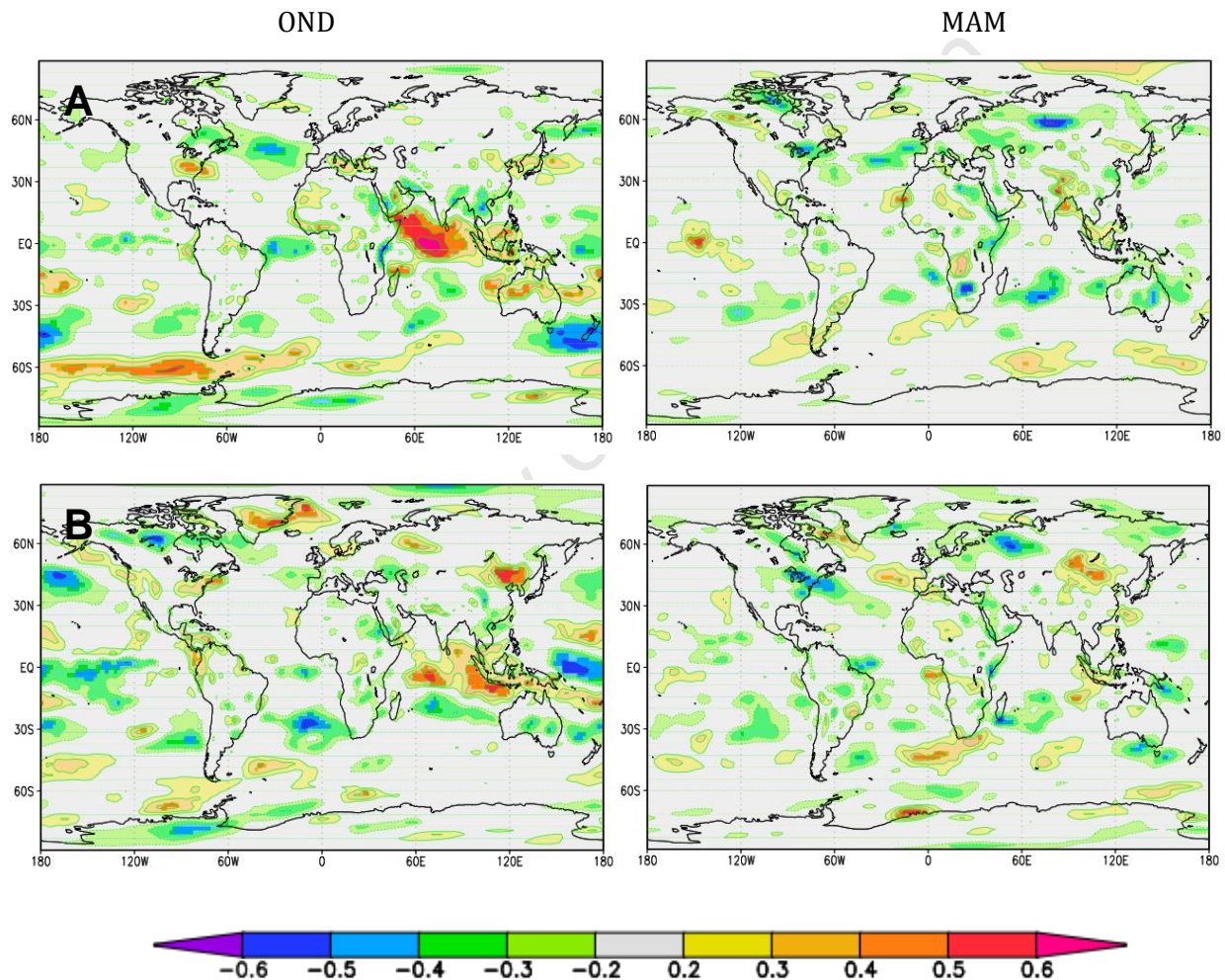


Figure 26: Plots of spatial correlations for OND and MAM 1980-2008 wet spell frequency with surface zonal winds at 95% confidence level. Note: A (north) and B (south)

3.7.2.4 Dry spell frequency with zonal winds

The correlations for dry spell frequency in Fig. 27 are roughly the reverse of those shown above in Fig. 26 for wet spell frequency. However, the magnitudes of the various correlation patterns are slightly stronger in the dry spell case.

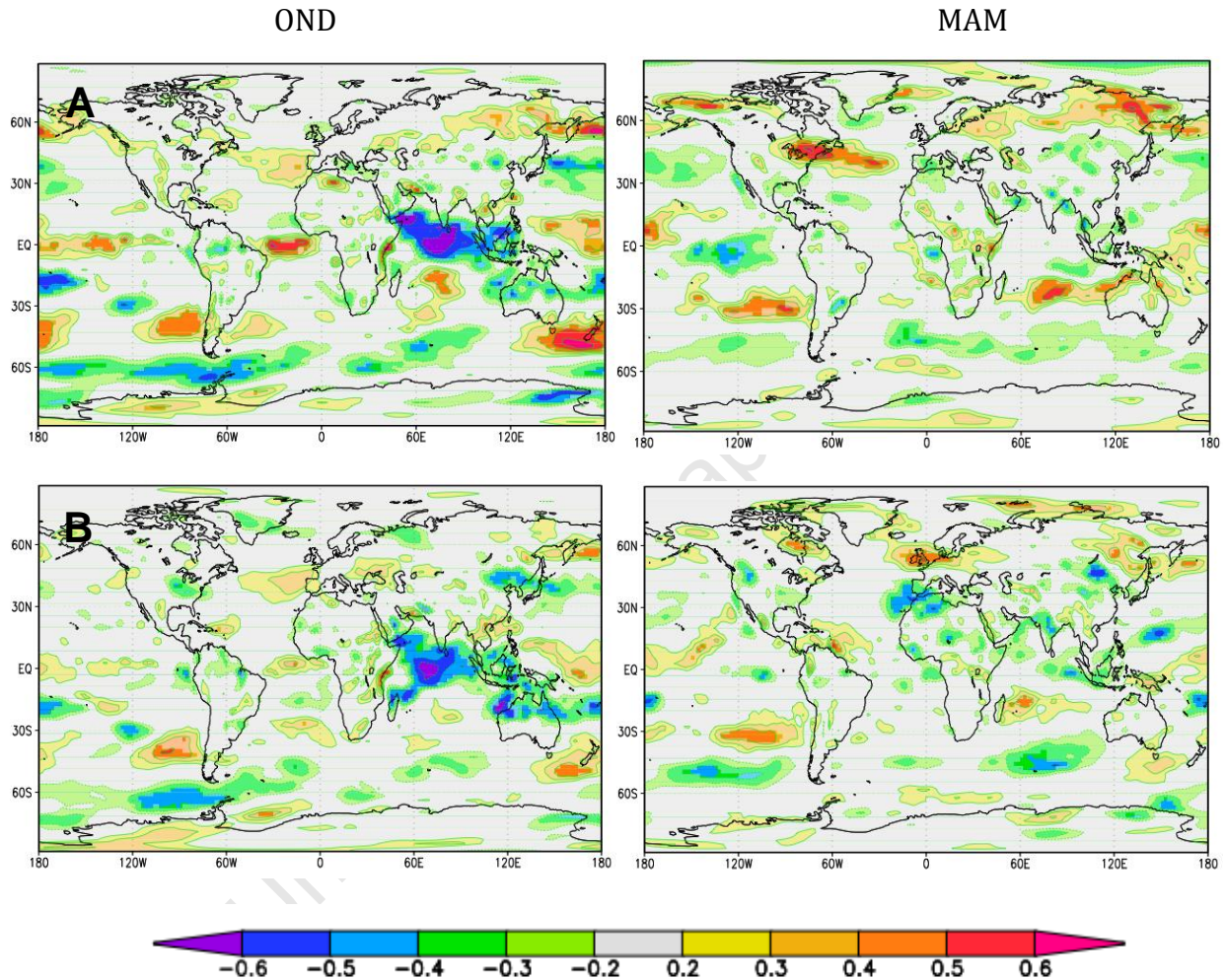


Figure 27: Plots of spatial correlations for OND and MAM 1980-2008 wet spell frequency with zonal winds at 95% confidence level. Note: A (north) and B (south)

Summary

In general, relatively high correlation values are found in the Pacific for the OND season and weak values for MAM season, reflecting the stronger ENSO signal in the former season. Over the Indian Ocean, larger correlations also occur in OND, reflecting the strong IOD signal in this season. Thus, Figures 20-27 give an impression that the wet and the dry spell frequency in both coastal Tanzania and Kenya are linked to both ENSO and IOD. Figures 22-23 (Tanzania) and 26-27 (Kenya) show an association of wet and dry spell frequency with surface zonal winds again showing stronger correlations in OND than in MAM. The largest values near Africa occur over the tropical Indian Ocean but there are also correlations in some cases over the tropical Atlantic Ocean and the Congo Basin. The latter results are consistent with those of Kijazi and Reason (2012) who linked increased rainfall in northern Tanzania to moisture advection from the Congo Basin.

University of Cape Town

CHAPTER FOUR: DISCUSSION

Much of the research in rainfall variability seems to use anomalies in seasonal totals as the base unit for studying and likewise seasonal forecasting efforts tend to revolve around trying to predict the probability that a particular season will experience above average, average, or below average rainfall totals. Although there is a great need to better understand anomalies in seasonal rainfall totals over the region and to improve skill in forecasting these, many user groups desire information in advance about specific parameters such as the number of wet and dry spells, onset and cessation, length of the dry and wet spell within the rainy season which have important application.

It is therefore necessary to understand the general variability in rainfall for the East African coast region and assess whether there are any significant changes that have occurred. Figures 2 and 3 show that the seasonal rainfall amounts in coastal Tanzania and Kenya are characterized by pronounced interannual variations during both OND and MAM. It is best to note that the most important rainfall variability throughout the rainy season is related to global SST anomaly forcing; namely, that of the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Indeed, Indeje *et al.*, (2000) showed that ENSO was the dominant source of inter-annual rainfall variability across the East Africa region. Both ENSO and IOD patterns are evident in the spatial coherent plots (Figures 20, 21, 24 and 25).

Kijazi and Reason (2009) showed that the period from 1998-2005 stood out as featuring one of the worst droughts over Tanzania (despite 2002 being slightly wetter than average). They noted that almost the entire region experienced at-least 2 consecutive dry years during the period. The drought over the region was experienced in both seasons (OND and MAM) although for MAM the drought started around the year 2000 rather than in 1998. Figures 16-17 are generally consistent with their result since the anomalies in wet (dry) spell frequency tend to be negative (positive) during 1998-2005. According to FAO (2004), the number of African food crises per year has tripled from the 1980s to 2000s. Most of these crises are due to drought diminished water supplies which reduce crop productivity which then results in widespread famine in the region. It has been noted that when weighted by GDP impact, droughts pose a substantially higher risk than floods.

Most of the wettest seasons for both coastal Tanzania and Kenya tended to occur in the 1980's and 1990's with OND 1997 being by far the wettest season. This season coincided with one of the strongest El Niño events ever recorded as well as a strong positive IOD event. During OND 1997, the East African rains were in many areas 5–10 times the average, the highest in the century (World Meteorological Organization 1998), causing severe socioeconomic disruption. In general, the inter-annual variability of seasonal rainfall is remarkably coherent within the region particularly for the OND season which is characterized by greater spatial coherence and appears linked more closely with large-scale modes than with regional factors.

An examination of the circulation anomalies during ENSO and neutral events for the anomalous wet and dry seasons as discussed above indicate that the circulation patterns during the two events have some similarities. The anomalous wet (dry) conditions are associated with anti-cyclonic (cyclonic) anomalies over the western Indian Ocean. During wet seasons, there is an increased easterly flow of moist marine air from the Indian Ocean towards the coast of East Africa as observed in Figures 4 and 5, this reverses during dry seasons. There seem also to be low-level westerlies over the Congo Basin associated with increased rainfall over the region. The westerlies over the Congo basin lead to convergence of low-level moisture over the region with that originating from the western Indian Ocean. Mapande *et al.*, (2005) observed a similar pattern when they studied inter-annual rainfall variability over western Tanzania.

To shed more light on the conditions associated with increased rainfall over the region, plots of omega in the middle troposphere (Figure 7) show there is anomalous uplift (sinking) present during the wettest and driest ENSO seasons. During anomalous wet seasons, there is an ascending motion of the atmosphere that covers much of the western Indian Ocean closer to the East African coast which is consistent with the observed wet conditions. Together with the enhanced easterly flow of moist marine air over the region and relative moisture convergence, the plots show favorable conditions for enhanced rainfall during wet seasons. The circulation pattern changes during anomalous dry seasons where relative subsidence covers the region (Figure 5). The occurrence of subsidence over the region suggests unfavorable conditions for convection, consistent with the dry conditions. Consistent with

these results, Hastenrath *et al.*, (2007) found that the 2005 drought over Equatorial East Africa was associated with subsidence over the region.

Plots of lower level velocity potential anomaly (Figure 6) show occurrences of the ascending (descending) branch of the Walker circulation over the region reflecting eastward (westward) shift of the Walker circulation (Webster 1983) with increased (decreased) low level convergence (divergence) over the western Indian Ocean and East African region enhancing (reducing) convection consistent with increased (decreased) rainfall in the region during OND El Niño (La Niña) seasons.

From Tables 2 and 3, it is found that most of the stations from both countries have similar seasonal mean rainfall for the OND season. In MAM, there is a higher mean seasonal rainfall for Tanzania than for Kenya. The relationships between the various rainfall characteristics show that season with high rainfall generally have a higher number of heavy rain days (>10mm/pentad) and not necessary an increase in light rain days. This demonstrates that seasons with high rainfall may still contain prolonged dry periods.

Identifying any trends in wet and dry spell characteristics has important implications for agriculture, health, tourism, heavy industry and water resource management. Sequences of prolonged wet or dry periods are becoming an increasingly important component that needs to be taken in consideration for the management of water related resources but has received less attention in the region. However according to the IPCC (2007), it is likely that heavy precipitation events will become more frequent while it is similarly reported that the overall global land precipitation events have increased about 2% since the beginning of the 20th century. The East Africa region has suffered both excessive and deficient precipitation in recent years. The trend of individual stations in Figures 16-19 indicated that the number of wet (dry) spells showed a slightly decreasing (increasing) trend for most of the stations in both seasons. Most of these trends are not statistically significant. However, for Dar es Salaam during the OND season, there is a decreasing trend in wet spell frequency which is significant at the 95 % level as is the increasing trend in OND dry spell frequency for Mtwara.

The nature of ENSO and IOD and their relationships with rainfall characteristics was central to the current study and so it was important to consider their potential significance for the

wet and dry spell frequency. Evidence of a relationship between ENSO and dry spell frequency within the austral summer rainy season of western Tanzania has been presented (Mapande *et al.*, 2005). In this thesis, a fairly strong relationship was found to exist between wet and dry spell frequency and both the Niño 3.4 and IOD indices for both coastal Tanzania and coastal Kenya during OND (Figures 8-15) although the strength of the association varies from station to station and from season to season. Figures 2 and 3 suggest that OND seasons with simultaneous occurrences of El Niño and positive IOD event tend to be wettest in terms of rainfall amounts. The time series of anomalies in both wet and dry spell frequencies over the two regions during OND tends to track the Niño 3.4 and IOD indices reasonably well. Sliding correlations on a 10-year running window (results not shown), illustrated that there are some decadal variations in the strength of the relationships however.

Since ENSO and IOD are both related to the regional rainfall, it was interesting to see how wet and dry spell frequency varies with SSTs in the Indo-Pacific and with regional zonal wind circulation. The presence of ENSO and IOD-like SST spatial patterns in the correlations of either wet or dry spell frequency with Indo-Pacific SSTs (Figures 20, 21, 24 and 25) reinforces the linkage of these rainfall parameters with the large scale climate modes during the OND season. It also appears that the ENSO connection is stronger in Tanzania than it is for Kenya.

However, for the MAM season, there are less obvious linkages and no clear suggestion of either an ENSO or an IOD relationship although there are some areas of correlation in certain parts of the tropical Indian or Pacific Ocean. In some cases, there are relatively strong correlations with parts of the tropical Atlantic.

To shed further light on circulation patterns associated with anomalous wet and dry spell frequency, zonal surface wind correlations were plotted. The spatial correlations between the zonal winds and wet (dry) spell frequency is robust for the tropical Indian Ocean with a large area of positive (negative) correlation observed in OND, reflecting the ENSO/IOD signal in this basin. Some ENSO-like correlation patterns are also apparent in the tropical Pacific Ocean. As for SST, the correlation patterns in MAM show less obvious patterns in both the tropical Indian and Pacific Oceans, and there are also some signals in the Atlantic Ocean and over the Congo Basin.

The importance of these zonal wind correlation patterns is that they reflect changes in low level moisture convergence and moist static energy over the western tropical Indian Ocean and coastal East Africa, leading to changes in rainfall. As found in other studies, e.g. Black *et al.*, (2003), the east-west dipole in the SST anomalies coupled with an anomalous atmospheric zonal circulation cell provides the dynamically consistent mechanism for the rainfall variability in OND season. During El Niño (La Niña) and positive (negative) IOD, there is an eastward (westward) shift of the Walker circulation towards East Africa that tends to enhance (reduce) rainfall during the OND season. In addition, the reduced (increased) sea level pressure due to the presence of higher (lower) SST results in offshore (onshore) wind anomalies, thereby enhancing wet (dry) spells.

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CHAPETER FIVE: CONCLUSION

The rainfall characteristics studied here are important to end-users such as farmers and water resource managers, and the analysis undertaken here offers a valuable starting point in assessing the possible predictability of the rainy season. Weakly decreasing (increasing) trends in wet (dry) spell frequency during the 1980-2010 periods were noted but these are only statistically significant at two of the stations. This study outlines some of the important wind and SST patterns underlying the inter-annual variability in wet and dry spell frequency during the OND and MAM rainy seasons over the region. The region shows a coherent ENSO and IOD impact during OND but not in MAM.

The observed circulation features during wet seasons indicate warm SSTs in the Indo-Pacific, with enhanced low-level moisture convergence and uplift over the region. Consistent with this, the velocity potential plots during wet seasons indicated the position of the ascending limb of the Walker circulation over the region as expected for a season of well above average rainfall. The results also suggest that anomalous wet seasons may be associated with moisture flux from the Congo Basin and the tropical Atlantic Ocean. Broadly similar patterns can be identified in both seasons of heavy rainfall thus providing more confidence in the robustness of the results. A tendency for the frequency in wet and dry spells to track the Niño 3.4 or IOD index reasonably well was noted. Spatial correlation analyses of global SST anomalies with wet and dry spell frequency show that the dominant variability is related to the Indo-Pacific SSTs.

Wet and dry spell frequencies are not the only rainy season characteristics that end-users desire information about. The onset and cessation dates of each rainy season are also of great importance and there is a need for more research to be done on the relationships and predictability of these parameters. Given the relationships between the wet and dry spell frequency with Niño 3.4 and IOD indices, it may be possible to use the state of these climatic indices to predict the behavior of the wet and dry spell characteristics prior to the start of the rains. This possibility needs to be fully explored in future research, given the great importance of these fundamental aspects of the East African climate for core groups in agriculture, water resources, health, tourism and wildlife management.

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