

Analysis of the Contribution of the Southwestern Indian Ocean Tropical Cyclones (TCs) to December, January, February, March (DJFM) Rainfall Season over Tanzania

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ABSTRACT

The contribution of Southwestern Indian Ocean (SWIO) Tropical cyclones (TCs) to the December to March (DJFM) rainfall season over Tanzania was analyzed. Seasonal, monthly and daily rainfall data were obtained from Tanzania Meteorological Authority (TMA), while data for sea surface temperatures (SSTs), relative and specific humidity, zonal and meridional winds were acquired from NOAA (NCEP – NCAR). Tropical Rainfall Measuring Mission (TRMM) daily average

gridded rainfall estimates were used. The observed and gridded rainfall data for each TC day were extracted and computed to monthly and seasonal totals for all TCs and non TCs days. Correlation between DJFM TCs and DJF/DJFM rainfall were determined. Inter annual variability between TCs and DJF rainfall was analyzed. Wind patterns at 850 - 200 mb, relative humidity (850-700mb), vertically integrated horizontal wind and moisture divergence (1000-500 mb) for two TC events (Izilda and Fobane) were analyzed. The results revealed that, TCs contribution to the DJFM rainfall was very significant. The influence of TCs to monthly total rainfall showed a general increasing trend from north to south along the coast of Tanzania, with a southwest to northeast alignment. On the other hand correlation between DJFM TCs with DJF rainfall was relatively weak at some stations while few stations including Dodoma and Tabora were showing relatively higher correlations of about 0.39 ($p \leq 0.05$) suggesting that these stations are highly vulnerable to the TCs impacts. Moreover, results had shown that the distribution of TCs rainfall prone areas run from southern parts (Mtwara) through central parts (Dodoma) to northeastern highlands (Kilimanjaro). Analyses revealed that 700 mb wind vectors, integrated moisture fluxes and their convergence from Congo air mass, northwesterly and northeastern Indian Ocean air masses were the main contributors of rainfall over Tanzania during TCs events. Conclusively, the study showed that TCs has significant contribution to the DJF and DJFM rainfall in Tanzania, thus more studies for understanding the dynamic of TCs in relation to rainfall is required for improving the weather forecasts in Tanzania.

Key words: Tropical cyclone rainfall days, relative and specific humidity, vertically integrated moisture flux and divergence, December to March (DJFM) rainfall

INTRODUCTION

Seasonal rainfall in East Africa (EA) mostly occurs during March to May (MAM) and September to November (SON) and even up to December (SOND) in some areas, whereas in other areas including northern coastal Tanzania these rains occur during October to December (OND), and are normally known as short rains (Kabanda and Jury, 1999; Mpeta, 2002; Kai et al 2021(a and b)). In East African, Tanzania in particular seasonal rainfall is driven mainly by the migration of the Inter-Tropical Convergence Zone (ITCZ) in combination with the atmospheric circulation patterns that brings rainfall (Hastenrath 2001, Godwin, 2005, Anyah & Qiu 2012). The ITCZ migrates southwards through Tanzania in OND, reaching the southern of the country in January and February (JF) (Janowiak, 1988), and returning northwards in MAM. This migration causes northern parts of Tanzania (bimodal sectors) to experience two distinct wet periods (i.e. OND and MAM), whilst the southern, western and central parts of the country (unimodal sectors) experience one wet season that lasts from November, through April or May (McSweeney, et al. 2008; Mpeta, 2002, Mbululo, 2012).

The positional variations of the ITCZ are sensitive to inter-annual variations of the Indian and Atlantic Ocean SST (Ogallo et al. 1988; Ogallo, 1988; Goddard and Graham, 1999). Because the rainfall is positively correlated to SST (especially during DJFM and SON), the onset, duration and intensity of these rainfalls vary considerably inter-annually. The variability of the short rains has been related to large scale phenomena such as El Niño Southern Oscillation (ENSO), Farmer (1988); Ogallo (1988); Hutchinson 1992; Nicholson and Kim (1997, 1998) and the east-west circulation over the Indian Ocean (IO) Beltrando and Cadet 1990; Hastenrath et al. (1993); and Hastenrath, (2000). The Indian monsoon dynamics control the SSTs off the Somalia coast

and are known to play an important role in the variability of the short rains (Philippon et al., 2002). Over Tanzania, annual rainfall is greatest in lowland areas towards the coast and also around Lake Victoria, and lowest in central and northeastern regions Kabanda and Jury (1999).

On the other hand, over the SWIO region tropical cyclones season starts from November and ends in May, with its marked by peak cyclone activity in December to March (DJFM) (Mavume et al., 2009), and its highest frequency on East Africa (EA) is during January and February (Mavume *et al.*, 2009, Kai, 2018). These TCs, which are often associated with heavy rainfall, enhance the DJFM rainfall over the unimodal areas, and bring rains over some areas of bimodal regime which are characterized by either dryness or little rainfall during DJFM (Kai, 2018, Kai et al 2021b). These rains can even result into flooding in some areas (Jury et al., 1993; Virtat et al., 2003, Kai et al 2021a). Over the EA region more efforts have been made in understanding the influence of various oscillatory phenomenon ENSO, Southern Oscillation Index (SOI), Madden Julian Oscillations (MJO) and their contribution to the variability of the seasonal rainfall, as well as how this rainfall maps the region over different seasons (MAM, OND among others). Several studies including Ogallo (1983, 1988 and 1989); Barring (1988); Beltrando (1990); Nyenzi (1990); Nicholson (1996), Kabamda and Jury, (1996), and Indeje et al., (2000) have contributed to the understanding of rainfall mechanisms in the region, including temporal and spatial variability e.g., variability related to ENSO among others.

Though TCs do not commonly make landfall in Tanzania even if forecasted (Kai et al 2021c), but their associated rainfalls can be heavy and cause severe damage in most areas (Jury et al., 1993; Virtat et al., 2003, Kai, 2018; Kai et al., 2020). On the other hand, these rains can be of benefit to some socio-economic sectors, such as livestock keeping (over dry/arid areas like Dodoma in Tanzania), energy production (feeling the Dams and reservoirs), water resource management, and vegetable production. For strategic planning there is a need to have a clear understanding of the contribution of the seasonal TCs associated rainfalls to the DJFM seasonal rainfalls over Tanzania as well as understanding which areas are susceptible to these rainfalls, so that measures to reduce risks of damage can be undertaken, and positive effects taken advantage of. In line to this argument, and the fact that rainfall contribution due to TCs occurrence is not yet documented in EA and Tanzania in particular, thus, this study was aimed at quantifying the contribution of TCs associated rainfall and understanding the spatial distribution of the TCs associated rainfall during the DJFM period over Tanzanian coastal and interior areas.

DATA AND ANALYSIS METHODS

Data

Since TCs occurrence may affect the whole country with deferent degrees of strength (depending on its position and track), thus the study domain was decided to be the whole country without considering rainfall regime boundaries. The study used the daily and monthly rainfall records acquired from TMA for most station in Figure 1. These rainfall stations were categorized based on their locations and rainfall regime. For instance, stations over the coastal strip including Zanzibar, Dar - es - Salaam, Tanga, Pemba Mtwara and Lindi; northeastern highland stations of Arusha, Moshi and even Mwanza falls on the bimodal rainfall regime, whereas stations including Dodoma, Iringa, Mbeya, Bukoba, Kagera, Musoma and Songea fall under unimodal rainfall regime. As for data categories, stations of Arusha, Mwanza, Kigoma,

among others were having both the monthly and daily long term records whereas stations of Bukoba, Kagera, among others were having only monthly rainfall records (Figure 1).

TCs records along the SWIO region for the period of 34 TCs seasons (i.e. December, 1977 to March, 2011), were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS, Basin.SI.libtracs_all.v03r04, <http://www.ncdc.noaa.gov/oa/ibtracs/>, the data was described by Knapp *et al.* (2010; 2013). This data include the name, date, and position of minimum surface pressure, and maximum wind speed of TCs for every 6-hour interval. The data was sorted to obtain TSs and TCs that only fall over the domain of 39.5°E - 71°E and 2.5°S - 22.5°S. Data records which were missing both central wind and central pressure were omitted. Most of such gaps were found in 1978-1982. In this work we studied only the cases of TSs with wind speeds (W_s) of $17.5 \text{ ms}^{-1} \leq W_s \leq 32.4 \text{ ms}^{-1}$ and TCs with $W_s \geq 33 \text{ ms}^{-1}$.

Moreover, various re-analysis products covering the study period of 1978 -2011 were used. These datasets include monthly and daily mean gridded SSTs and their anomaly Smith *et al.* (2008); Xue *et al.* (2003) which were acquired from National Oceanic and Atmospheric Administration (NOAA) through International Research Institute (IRI) library (IRI/LDEO Climate Data Library) having a horizontal resolution of $2^\circ \times 2^\circ$. Other datasets include the monthly and daily mean gridded zonal (u) and meridional (v) winds, daily mean surface pressure, mean sea level pressure (slp), daily and monthly mean relative humidity (Rh) and specific humidity (q) of which all were acquired from National Center for Environmental Prediction (NCEP) in association with National Centre for Atmospheric Research (NCAR) i.e. NCEP/NCAR reanalysis 1 (Kalnay *et al.*, 1996) with horizontal resolution of $2.5^\circ \times 2.5^\circ$. Furthermore, TRMM daily average rainfall estimates version 3B42 V7 (Lonfat, *et al.*, 2004) with a spatial resolution of $0.25^\circ \times 0.25^\circ$ and temporal resolution running from December 1998 to March 2011 was used. To process the gridded data sets Climate Data Operators (CDO) <https://code.zmaw.de/projects/cdo/wiki> version (1.41) developed by Uwe and Luis, (2009) was used, in conjunction with open sourced software such as R, Grads and Suffer.

Methods

Simple correlations (at $p \leq 0.05$) between the DJFM TCs frequencies with the DJF/DJFM rainfall were calculated. Inter annual variability of DJFM TCs and DJFM rainfall standardized anomalies was analyzed. Rainfall records for each TC rainy day (which is technically defined in section 3.3) from each station were extracted and their monthly (i.e. December, January, February and March) and seasonal (DJFM) totals were calculated. Moreover, TCs day and non TCs day rainfall records from TRMM were extracted using the CDO commands. The files were merged to get the monthly and seasonal records, where the mean and percentage rainfall contribution for TCs days on each month and season was calculated. We have used TRMM estimates because it provides highlights of the most definitive climatology of rainfall in hurricanes Lonfat *et al.* (2004), as well as suggesting average rain rates based on the strength of the Hurricane (e.g. rain rates of 11 to 13 mm/h from the eye to 50 km radius for category 3-5 hurricanes, dropping to 7 and 3 mm/h at 100 and 180 km radii and 6 to 7 mm/h for hurricanes of category 1-2 Lonfat *et al.* (2004).

Moreover, Mestas-nuñez *et al.*, (2007); Peter and David, (2004) relation (i.e. equations 1 and 2) were used to calculate the vertically integrated horizontal wind vector and its divergence

(vihwd) and moisture flux and its divergence (vimfd) from surface to 500 mb. This was done only for the case study TCs of Izilda (2009) and Fobane (2014) used in this study. These storms either wetted (enhanced the rainfall) or dried (declined the rainfall) most areas of Tanzania. Furthermore, overlays of slp, wind vectors at 200 mb, 500 mb and 700 mb for each day of TCs (Izilda and Fobane) were developed. The overlays of slp and wind vectors were aimed at observing the developments and decays of the systems as compared to source and sinks of vimfd and vihwd. Indeed, the sources were defined as the evaporation from the ocean and other sources, whereas sinks were the tropical cyclones associated rainfall.

The vertically integrated water vapor flux vector is given by

$$q = \int_{top}^{surface} qVdp / g \dots\dots\dots (1)$$

Where q is the specific humidity, V is the velocity of the wind vectors and p is the surface pressure and g is the gravity.

Since storms can be vertically developed to out of troposphere we used surface to 500 mb moisture column to calculate of vertically integrated moisture divergence (equation 2)

$$vimfd = \frac{1}{g} \int_{500}^{1000} (\partial uq / \partial x + \partial vq / \partial y) dp \dots\dots\dots (2)$$

Where u , v , q , p and g takes the same meaning as in equation 1 above; i.e. vimfd is calculated by summation of the horizontal moisture flux convergence over the intervals 1000 – 925, 925 – 850 mb among others. We used the finite centered differences on a lat/lon grid to approximate the term between brackets in equation (2). In calculating vertically integrated moisture convergence negative sign was used in equation (2). In calculating the vimf, vimfd, vihwd and vihwd Grads functions vint and hdivg were used.

RESULTS

Tropical Cyclones Izilda and Fobane and their Rainfall Influence to Tanzania

Tropical cyclone Izilda was a short lived TC formed in Mozambican Channel (MC) from 24th - 28th November, 2009, with its highest strength centered at approximately 45°E, 25°S on 27th November, 2009. Based on its position, TMA reported that Izilda resulted into suppressed rainfall over the Northeastern highlands and northern parts of Tanzania coastal line and disrupted rainfall patterns over the country even on areas which fall under the influence of seasonal rainfalls of DJF (WMO, 2010). To investigate the issued TMA warning we used NCEP/NCAR reanalysis zonal (u) and meridional (v) winds at 850 and 200 mb, sea level pressure (slp) and relative humidity (Rh) at 850 and 700 mb to analyze the influence of Izilda to the weather of Tanzania. Results revealed that Izilda suppressed rainfall over Tanzania by inducing a continental ridge centered at southern Mozambique, where on 28th November 2009 the ridge system covers most parts of Tanzania resulting in subsiding air which induces the dry conditions (Figure 2b). The 850 mb wind vectors (Figure 2d) and streamlines (figures not shown) showed that the country was under influence of divergent flow except over the coastal strip i.e. the low level moist southeasterly flow from the ocean converged at the coastal areas, resulting in diffuent flow over the entire country. Along the northeastern low level trough converged over the coast resulting in rainfall aligned along the coastal stripe. The 200 mb

stream line (figure is not shown) level had low cyclonic flow over southwestern parts of the country with a cyclonic ridge over the coast. These conditions suppressed wet conditions. In general, 850 mb and 200 mb wind vectors and streamlines showed an evidence of increased low (upper) level divergence (convergence), and hence reduced moisture uplift, over most parts of Tanzania. Relative humidity at 850 mb and 700 mb Figure 3 (b & d) was very low, ranging from 10 - 60% over many inland areas and 40 - 50% in coastal areas (Figure 4b). The southwestern parts of the country (west of Lake Tanganyika) were having higher moisture content. At 700 mb the entire coast and most parts of the country were rather dry except over Lake Victoria. Figure 3 (b and d) show that the vertical moisture column from 850 - 700 mb was very weak. During 27th and 28th March, 2009 there was little change in the vertical wind profile, a phenomenon which results in moist air advection and convective cloud formation. Though the climatological and the daily (28th November, 2009) SST anomaly during Izilda was positive and high ranging from 0.4 - 2°C (Figure 6 a & c), but the position and the dynamics of the TCs resulted in declined rainfall over Tanzania. In summary, most parts of Tanzania except the coastal strip and some patches of the southern parts were experiencing little rainfall on 27th March, but on 28th March the condition became drier for the whole country (even over unimodal rainfall regime areas) except over the coastal strip (Figure 4 a and b). In line with this, Tanzania weather observation stations showed that with the exception of the coastal stations most stations reported dry weather conditions with either very little or no observed rainfall.

Climatologically most of the southern, southwestern and western parts of the country should be experiencing seasonal wet weather conditions during the Izilda event, because the ITCZ is on its way northwards through the country in January to February (Ogallo, (1983, 1988, 1989); Nyenzi, 1990; Mpeta, 2002; Kabanda & Jury, 2010 amongst others) but the occurrence of Izilda changed the weather patterns and imposed dry conditions in most parts of Tanzania including the unimodal regime areas.

Unlike TC Izilda, Forbane (9th -13th February 2014), was very far from the Tanzania coast, but resulted into heavy rainfall and strong impact to most coastal and interior parts of the country. These impacts include flooding, falling of the trees at Unguja, Pemba and Pwani (region in mainland), and torning off of the public house roofs in most areas of Tanzania. For example, at Kilombero district in Morogoro more than 180 houses were damaged and Magole Bridge was broken, in Arusha at Mikocheni area more than 100 houses and 50 trees were affected. In general the TC Forbane lead to wet conditions over the coastal strip and most parts of the country. During its lifetime, entire basin was having high SSTs anomaly, with strongest anomalies at Mozambican channel and east of Madagascar, ranging from 1°C to 2°C (Figure 6b). This high SST anomaly favored the development and intensification of TC Fobane as well as its associated rainfall, with anomalous low pressure over the warm ocean (Figure 2a). The wind circulations at 850 mb (Figure 2c) demonstrates low level unstable conditions with most coastal and interior parts of Tanzania covered by linear convergent winds from northeasterly, northwesterly, westerly and other directions whereas at 200 mb (figure not shown) Tanzania was under the influence of strong southerly winds at the coast and strong southwesterly in the interior. Most areas over ocean and land were having increased deep moisture columns (Figure 3 a and c). Moisture fluxes from ocean evaporation over the cyclone areas and from Congo basin was converging in most of northern coastal areas and some interior parts of the country resulting in reported heavy rainfall and thunder activities.

Fobane rainfall effect covered most of coastal stations where Mtwara and Kilwa (southern coast) were leading by having 200 mm and 130 mm as a six days total rainfall (Figure 4d). Moreover, the Global forecasting system (GFS) models results (Figure 4c) was consistent with observed rainfall at the coastal areas, and also indicated that most of the areas were forecasted to have moderate to heavy rainfall. Furthermore, strong land covers impacts of Fobane was experienced over Nungwi village in Unguja where local house, schools, churches and hospital lost their roofs.

Inter annul variability between DJFM TCs and DJFM Rainfall

The correlations between DJFM TCs and DJF rainfall anomalies at $p \leq 0.05$ revealed that, Dodoma and Mbeya were having higher correlations of 0.39, 0.39 and 0.35 indicating the rainfall in these areas to be more influenced by TCs. One to one correlations between DJFM TCs and DJFM rainfall reveals that only Mtwara was negatively correlated at $r = -0.43$ and -0.39 both TCs and TSs. The station to station correlation of DJFM rainfall was significantly high. This indicates that DJFM rainfall is mainly contributed by large synoptic scale systems (e.g. TCs, ENSO and SSTs among others) rather local factors; as supported or noted by Ogallo (1983); Beltrando (1990); Nyenzi (1990). Inter annual variability of DJFM rainfall and TCs shows a phase match of the two curves in most stations, where over the northern coast (Dar and Tanga), northeastern highlands (Arusha) and lake zone (Mwanza) most years with high/low DJFM rainfall are having higher/lower TCs frequency. El Niño years of 1994/95 etc were well captured by both TCs and rainfall in stations like Dar and Arusha. Same pattern holds for southern (Mtwara) to southwestern (Iringa and Mbeya) areas, but for capturing El Niño events of 1994/95 and 1997/98 the pattern was not well defined like in northern coast (Figure 5b). The El Nino event of 199/98 was not captured by TCs frequency at any station. In general most years with below normal/above normal TCs/TSs frequency were in line with below normal/above normal rainfall in most stations. This feature indicates that TCs are among the higher contributors of the DJFM seasonal rainfall in most stations over Tanzanian. Furthermore, four quadrants scatter plots between standardized TCs and DJFM/DJF rainfall (Figure 5c) showed that; the first quadrant indicated high TCs and high rainfall; 2nd indicated high rainfall low TCs; 3rd indicated low rainfall low TCs and last indicates low rainfall high TCs (quadrants counts are clockwise oriented). Since there are approximately 4080 days in DJFM of 34 years and only 6% are the TC days, thus the chance of having high/low rainfall out of the TCs days is high (Figure 5c); this could be the reason why the correlation between the TCs and the DJFM/DJF rainfall is low in most stations. But for those 6% DJFM day's their rainfall is highly controlled by the occurrence of the TCs.

When we set the standardized anomaly of DJFM TCs and rainfall at $\geq \pm 1\sigma$ (i.e. $+1\sigma$ indicates wet years and high TC and -1σ indicates dry years and few TCs). DJFMs of 1978, 1979, 1990 and 1998 were among well distributed wet seasons, followed by 1987, 1989, 1996, 1997, 2001, 2007 and 2010. Out of 11 stations at least six were wet and at least three were dry. These distributed wet conditions can be explained by either El Niño conditions of 1986-1987, 1997-1998 and 2006-2007 or the presence of high TCs frequency. The 1982-1985 seasons were among the longest dry DJFM seasons followed by 1991-1992 and 1999 - 2000 (strong La Niña year). Though 1982 - 1983 was marked to be strong El Niño year, and 1988 -1989 to be strong La Niña year but high TCs rates influenced rainfall deficit for the former and wet conditions for the later.

Besides, the analysis of wet/dry season which falls on high/low TCs frequency show that wet conditions of 1979, 1990, 1994 - 1997 and 2007 apart from being contributed by DJFM weather systems but the presence of more TCs was of significant contribution (Figure 5a), whereas dry conditions of 1982-85, 1991-1993, 1999-2000, a part of being influenced by strong La Niña event, but the small TCs frequency was another factor contributed to this dryness. Hence, through this analysis our study concludes that the presence of TCs either enhances or declines the DJFM rainfall, and this enhancement/declining may be increased or decreased with the increased of TCs frequency in the basin. Thus, based on (i) Izilda (ii) Fobane (iii) Bondo, Gafilo, Felleng and Bongani (figures are not given) (iv) DJF and DJFM inter annual variability of TCs and rainfall (v) brief description of the influence of 2008/09, 2009/10 TCs seasons to the rainfall over Tanzania (WMO, 2010) we conclude that depending on their positions, strengths and tracks, TCs can either influence/decline rainfall in our country. Since during their occurrence TCs controls the existing weather systems near it, we used this argument to make a strong assumption that **rainfall falling on a particular TC day to be known as TC day rainfall and that falls on non TC day to be known as non TC day rainfall**. Thus, using [IBTrACS](#) TCs/TSs archive all defined SWIO TSs/TCs days during DJFM were recorded, and DJFM daily rainfall data from all stations were sorted, and rainfall in each TC day (TC day rainfall), and non TC day (non TC day rainfall) were extracted and calculated into monthly and seasonal basis.

TCs and non TCs rainy days

The ratio between the total TC days rainfall (i.e. from 1st December to 31st March) to the total TCs rainy days revealed that most stations had standardized ratio of more than one standard deviation ($>+\sigma$), but few stations have ratio of ($>-\sigma$) indicating that, most stations receives high rainfall during the TCs occurrence. Additionally, the analysis showed that no TC was recorded on 1st December of any of the 34 TCs seasons, and most TCs (i.e. about 10-13 occurrences) were recorded on 25th to 31st January. Moreover, average rainfall per TC day show the highest TCs rainfall of 7.00 mm in Mbeya followed by 6.69 mm over Mtwara and the least was 2.26 mm over Tanga. As for the spatial mapping for daily average TCs rainfall (Figure 7a) showed the highest contribution mapped over southern to southwestern part of the country with an increasing alignment from southwest towards northeast. Over the coast, highest contribution was over Mtwara and decreases northward, towards northern coast. These results supports our hypothesis that TCs impacts increases southward, but also the results showed that the TCs rainfall impact increases southwestward and decreases northeastward of Tanzania. Generally, the bar charts for percentage contribution maps highest contribution over southwestern, central and lake regions and the lowest over the northern coast. Though Mtwara was expected to have the highest contribution because cyclone responses were expected more southward, but the highest % TCs rainfall contribution has been shown over central areas i.e. Dodoma and Tabora, where (Figure 7b) is an example of these bar charts.

The monthly totals are highly mapped on January and February (i.e. peak and frequent TCs period as noted by Mavume *et al.*, 2006), with lower values in December and March (Figure 7c). Across stations the results show that northeastern highlands (Arusha) and northern coast (Dar es Salaam and Tanga) and western (Kigoma) have the lowest values of TC based DJFM rainfall. This could be due to the fact that over northern coast and northeastern highlands only December is wet and the rest (i.e. January – February up to mid March) most areas are dry except during TC disturbance or any abnormal flow like El Nino. Over west (Kigoma) the TCs moist dragged westerly to northwesterly winds are dumped far from Kigoma, hence resulting

small contribution of TCs associated rains. An interesting case is that of Tabora and Dodoma (Figure 7c) which is known to be arid/dry areas, but their total DJFM TCs rainfall contribution of 3967 - 4285 mm is relatively higher compared to 1552 -2200 mm contributed by northern coast stations. The southwestern parts (Mbeya and Iringa) are having higher TCs based rainfall totals of 3576 - 4867 mm. This could be explained by the influence of TCs when they a tracking Mozambican channel and southeastern Madagascar. Furthermore, results mark the north south variation increasing from Tanga towards Mtwara, whereas over interior the strength is more on Mwanza, Mbeya, Dodoma and Tabora indicating the influence of TCs rainfall on uni - modal regime as compared to bimodal regime.

Spatial Distribution of the December to March TCs based rainfall

Spatial distribution of TCs % rainfall contribution for both observation (Figure 8 b) and gridded data (Figure 8e) revealed the higher percentage contribution ranging from 20-24% and 30 - 40% for observed and gridded data. This high % contribution was mapped over northeastern highland covering central towards southern parts, and is more eastward than westward with southwest to northeast alignment. This mapping of % contribution of TCs based rainfall could be explained by both north-south and east - west oscillation of the zonal arm of ITCZ and southwestward tracking of TCs. The % contribution for gridded data was mapped through the central corridor of highlands to the east of eastern branch of Great Rift Valley towards Kenya. This indicates that over these highlands DJFM rainfall are highly influenced by peak TCs season. Alternatively, based on position and strength of TCs, this contribution could be explained as the influence of northwesterly to westerly mid tropospheric moisture flow during the TCs events. The monthly spatial mapping of DJFM TCs rainfall reveals that, during December (Figure are not shown) northern coast was mapped with low rainfall as compared to southern coast, central towards southern and southwestern parts was mapped with higher rainfall of up to 1000 mm for observed and 1100 mm for gridded. This could be explained by the dominance of large-scales such as IOD (i.e. warmer SSTs anomaly at the western Equatorial Indian Ocean adjacent to the East African coastline) and the weather systems that are responsible for enhancing the TCs which in turn increase in the TC based rainfall. Figure (8 a & d) show that February TCs rainfall was more concentrated at the southern to southwestern highlands where both datasets have the same pattern for the JF TCs rainfall contribution. This could be dues to position of TCs to be more southward at Mozambican channel influencing the southwesterly flow towards the southern to southwestern. During March climatological studies have shown that, high rainfall was concentrated over, southern Tanzania and Mozambique Mpeta (2002). This rainfall was contributed by the seasonal dynamics of ITCZ as it moves northward, where the presence TCs has great contribution in rainfall mechanism for this season. Our results showed that, highest contour of ranging from 800- 1300 mb (Figures are not shown) was contoured from the south most part of the country towards southwestern to the central. Total contribution of DJFM TCs rainfall for both data sets (Figure 8 c & f) showed the same impact as that of monthly, where the highest contribution was over southern, southwestern and central areas, and declined DJFM TCs rainfall of less than 1500 mm was mapped over northern coast and northeastern sector.

DISCUSSION

Tropical cyclones are most natural devastating phenomenon which results in loss of human properties and even lives. SWIO basin is prone to these havoc events which brings a lot of impacts to the western coast of the Southern Indian Ocean (SIO), Tanzania being among the

impacted. Though TCs do not commonly make landfall over Tanzanian coast but it's influenced is experienced throughout the country with north-south and east-west varying magnitudes of impacts. The sucking effect of these cyclones induces the low to mid tropospheric (especially 700 mb) moist westerly, northwesterly to northeasterly from Congo basin and other areas to rush to the cyclonic deep pressure areas. This rushing dumps moist air over most areas of Tanzania and hence resulting into heavy rainfall and even flooding. The TCs and DJFM/DJF inter annual variability analysis revealed that most years with below normal TCs/TSs (few records) was consistent with below normal (with the exception of few years) in most stations while most years with high normal to above normal rainfall were in line with higher TCs frequency.

Through stations, the distributed wet conditions was associated with either El Niño conditions (e.g. 1986 - 1987, 1997 - 1998, 2006 - 2007) or the presence of high TCs frequency. The 1982 - 1985 seasons were amongst the longest dry DJFM seasons followed by 1991-1992 and 1999-2000 (strong La Niña year). Some exceptionality for ENSO conditions of 1982-83 (strong El Niño) and 1988 -1989 (strong La Niña) but the existence of high TCs rates has influenced rainfall deficit during 1982 - 1983 and wet conditions during 1988 -1989. The strong El Nino event of 1997 - 1998 was not captured by DJFM TCs but instead was captured by DJF rainfalls anomalies, this could be due to the reversal of SST gradients (i.e. SST was increasing from east to west) between November 1997 to June 1998, which was in contrast to climatology of SST gradients i.e. SST increases west to east (Webster *et al.*, 1999; Jury *et al.* 1993) this may results TCs to be formed far from defined SWIO region. Moreover, our result of the influence of warm and dry ENSO conditions to the DJFM rainfall and TCs are consistent with Janowiak, (1987) who indicated that the region between 0 -10°S and 20 -39.5°E, the warm ENSO condition accounts for 37% of the DJFM rainfall anomaly variability, while it accounts for 48% when restricted to cold ENSO conditions.

Moreover, results have shown that though TCs do not commonly make landfall over Tanzanian coast, but their rainfall influence was experienced throughout the country with north-south varying impacts. This could be due to northward movement of ITCZ (which is centered on 12°S Janowiak, (1987)) during DJFM, and which is responsible to the fluctuation of deep convection (OLR) which in turn results in (rising motion). The east – west varying magnitudes of TCs rainfall impacts could be due to east west oscillation of meridional arm of ITCZ, oscillation of IOD and reflection of Rossby waves which induces high SSTs which may increase the TCs counts. This increased TCs counts influences the high TCs rainfall. The TCs rainfall influence to Tanzania is due to introduced low level trough associated with upper level ridge or vice versa, the condition which results into rising/sinking air motion. This argument is well supported by (TMA, 2006) which explained the influenced of Bondo to the weather of Tanzania. The overall mean percentage station to station contribution of these rains was 19.2%, with a spatial maximum contribution running from 20 - 24% for observed data and 30 - 40% for gridded data, where both data mapped the highest contribution over central Tanzania. Tanga and Dar es Salaam have the least monthly total contribution while Mtwara, Mbeya, Tabora and Dodoma have high contributions.

Indeed, the analysis of integrated moist wind vectors and its divergence; and integrated moisture flux and its divergence (equations 1 and 2) of case study TCs (Figure 9 a-b) showed wind vectors which were easterly and parallel in most parts of the country (no linear convergence of winds) where the positive divergence values (i.e. negative convergence)

covered almost the entire country with the exception of small portion of the southern coast (Figure 9a). The integrated moisture fluxes (Figure 9b) revealed that small portion of southern coast, east of Lake Tanganyika and Victoria basin were experienced rainfall conditions due to elevated southwesterly fluxes which then turned to southerly and then easterly over the coast, with linear convergence over Lake Victoria and west of Lake Tanganyika. These areas were under the influence of negative vimfd values ranging from -0.1 to $-0.4 \times 10^{-5} \text{ (kgm}^{-2}\text{s}^{-1}\text{)}$. Other parts of Tanzania were facing dry conditions influenced by surface divergence and convergence aloft. The condition which was induced positive vimfd ranged from 0 to $0.1 \times 10^{-5} \text{ (kgm}^{-2}\text{s}^{-1}\text{)}$.

Unlike Izilda, TC Forborne showed the opposite condition to that of Izilda where moist wind vectors from north easterly and westerly linearly converged over most parts of Tanzania, with highest convergence level mapped over southwestern areas and northeastern highlands. Northeasterly wind vectors which move parallel to Somali and Kenya (coast) linearly converged over Tanzanian coast. For integrated divergence of wind vectors, high negative divergence (i.e. convergence) was mapped over areas of maximum wind vectors convergence indicating activeness of the areas. The same situation was shown vimfd that during this cyclone day the rainfall in most parts of the country was contributed by the moisture fluxes from northeastern sector of the IO and the westerly from the Congo basin. The elevated moisture from the cyclone due to Ocean evaporation and the sucked moist winds was the sources where rainfall from various areas of Tanzania was the sinks of this moisture.

The Overlays of the wind vectors (700,500 and 200 mb) for TC Gafilo (March 2004) and Fobane (Figure 9 c- d) showed the influence of 700 mb westerly to northwesterly and northeasterly wind vectors to the rainfall of Tanzania during the TCs events over the SWIO basin. All analyzed cases (i.e. Bondo, Fobane, Izilda, Gafilo, Helen and Felling) revealed that 700 mb wind vectors linearly converged to Tanzania. Fobane's integrated moist wind vectors and moisture fluxes flow were promising wet conditions while that of Izilda (Figure 9a-b) revealed drying conditions. Hence based on these examples of TCs of different seasons, we can conclude that based on its position and strength, the contributed rainfall due to TCs in Tanzania is highly influenced by 700 mb moisture fluxes from westerly, northwesterly and even northeasterly.

It is this wetting or drying behaviors of TCs which contributed to monthly TCs rainfall range from 440-1488 mm (for 34 seasons), with highest/lowest rainfall contributions occurred in JF/December. The spatial distribution of these rainfalls was highly mapped over southern coast as compared to northern coast, with high spatial variability alignment in northeast and southwest directions. Rainfalls associated to TCs though are havoc, but can be of advantageous to socio economic sectors including live stock, water harvesting and even energy sectors. Since Tanzanian climate is composed of wet and arid/dry zones (e.g. Dodoma and Tabora), there is a need to formulate policies concerning the harvesting, conservation and controlling the TC based rainfall. Moreover, since TCs rainfall impacts may results into significant land cover changes (e.g. TC Fobane) which may disrupt socio economic set up, there is a need to conduct the cost analysis studies to assess the approximate cost of losses incurred by TCs.

CONCLUSIONS

Based on the results and the presented discussion, the study concludes that

- (i) TCs have significant contribution to the DJFM rainfall in most parts of Tanzania.

- (ii) The level of TC based on rainfall contribution increases southward with central areas (arid areas) being susceptible to TCs rainfall.
- (iii) The east-west and north-south oscillation of the ITCZ causes more impacts to be registered southward than northward.
- (iv) The 700 mb moisture flux and its divergence/ convergence are the key instrument for TCs based rainfall over Tanzania.
- (v) More studies to be undertaken to critically understand the influence of TCs to the MAM and OND seasonal rainfall in Tanzania

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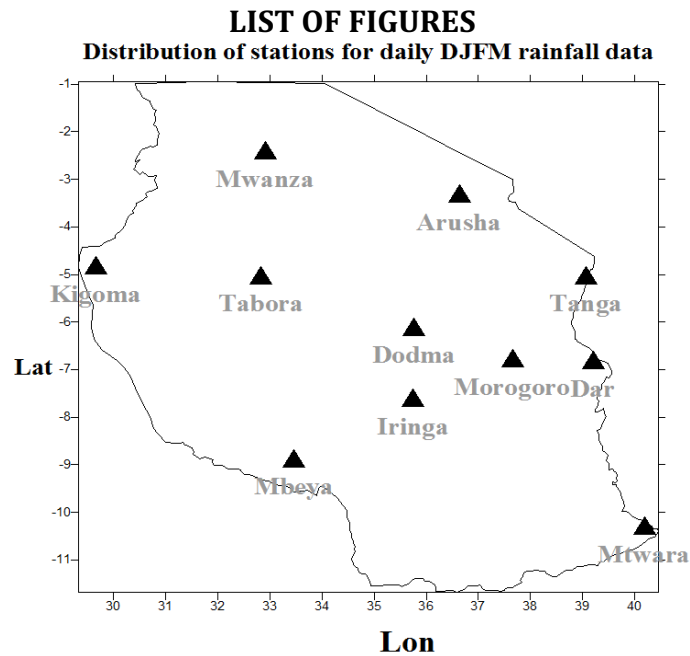
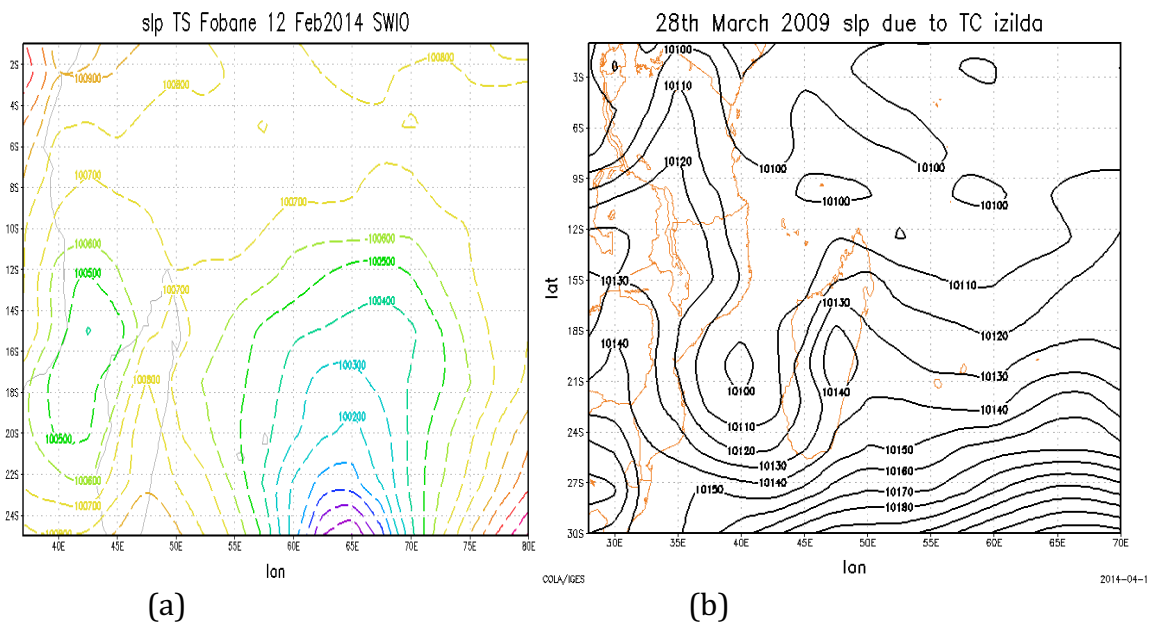


Figure 1: Daily rainfall stations used in this study (source TMA)



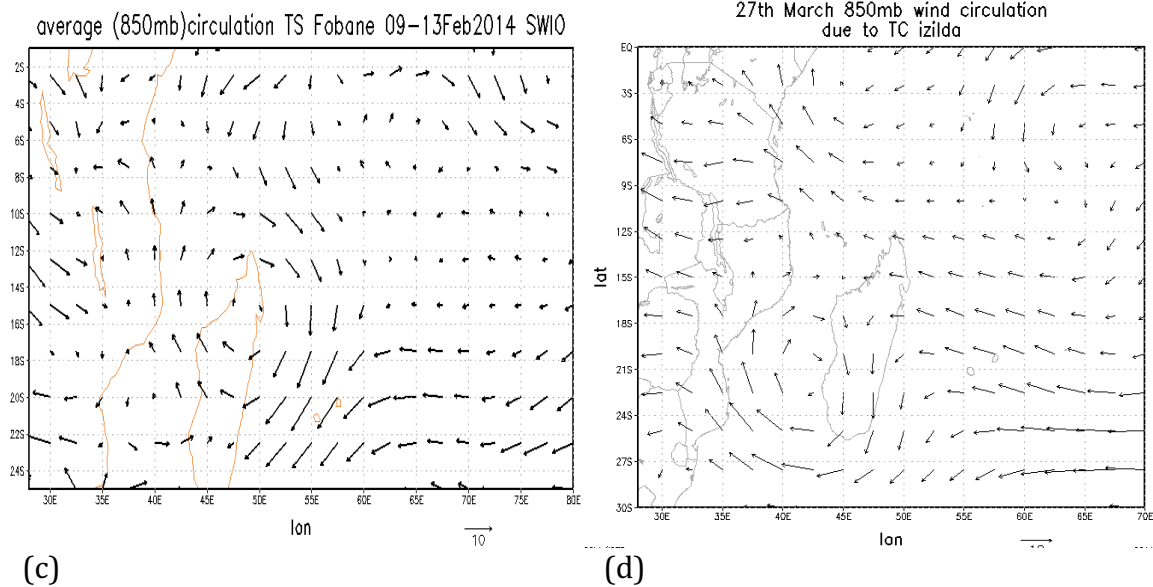
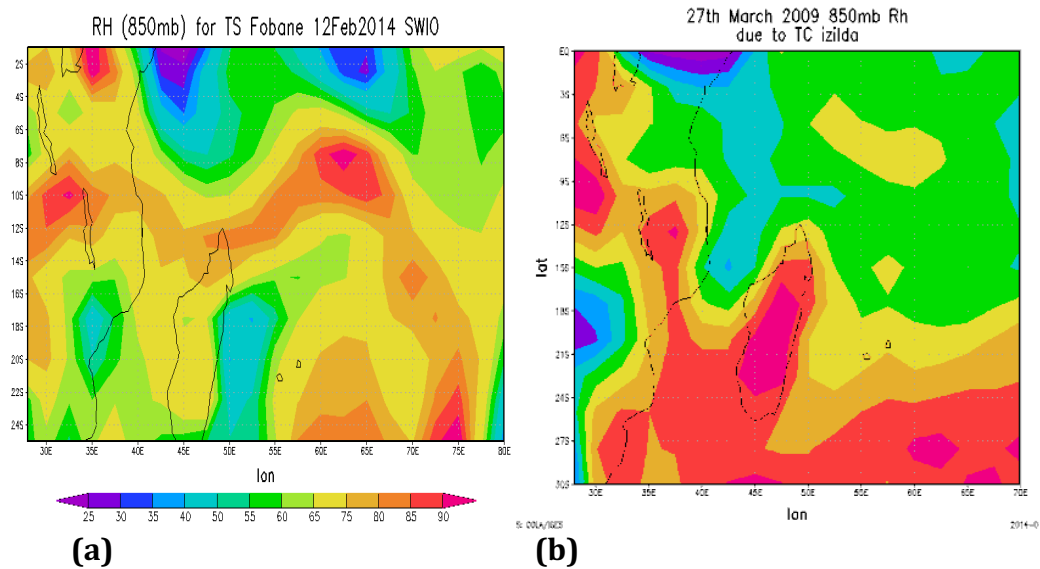


Figure 2: Sea Level Pressure (SLP) and 850mb wind vectors for TC Izilda and Fobane where (a) Fobane SLP (b) Izilda SLP (c) Fobane 850mb wind vectors (d) Izilda 850mb wind vectors over the DJFM (peak season)



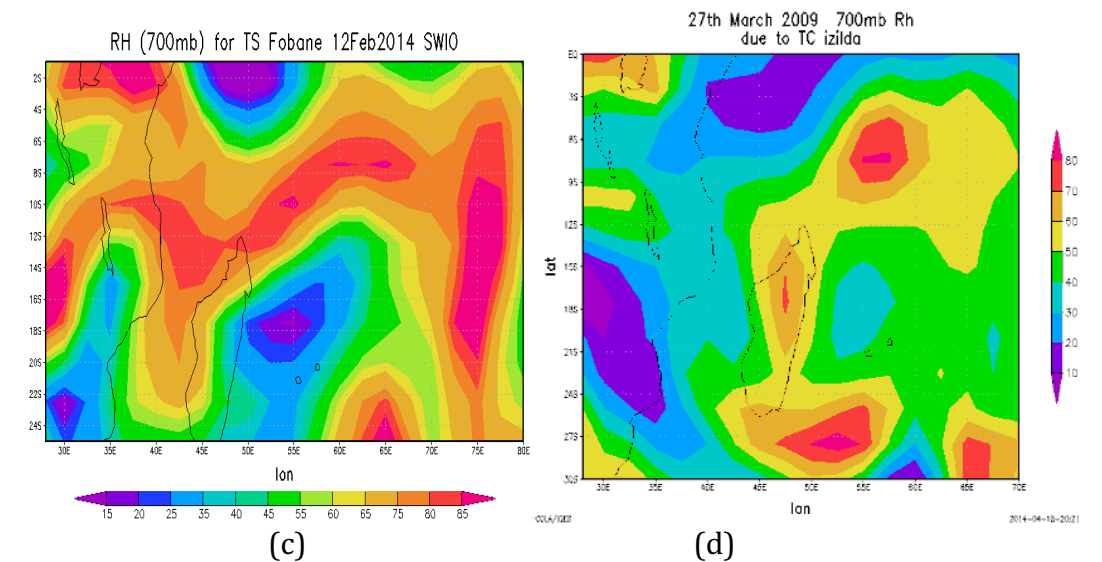


Figure 3: Relative humidity for Fobane and Izilda at 850mb (a & b) and 700 mb (c & d)

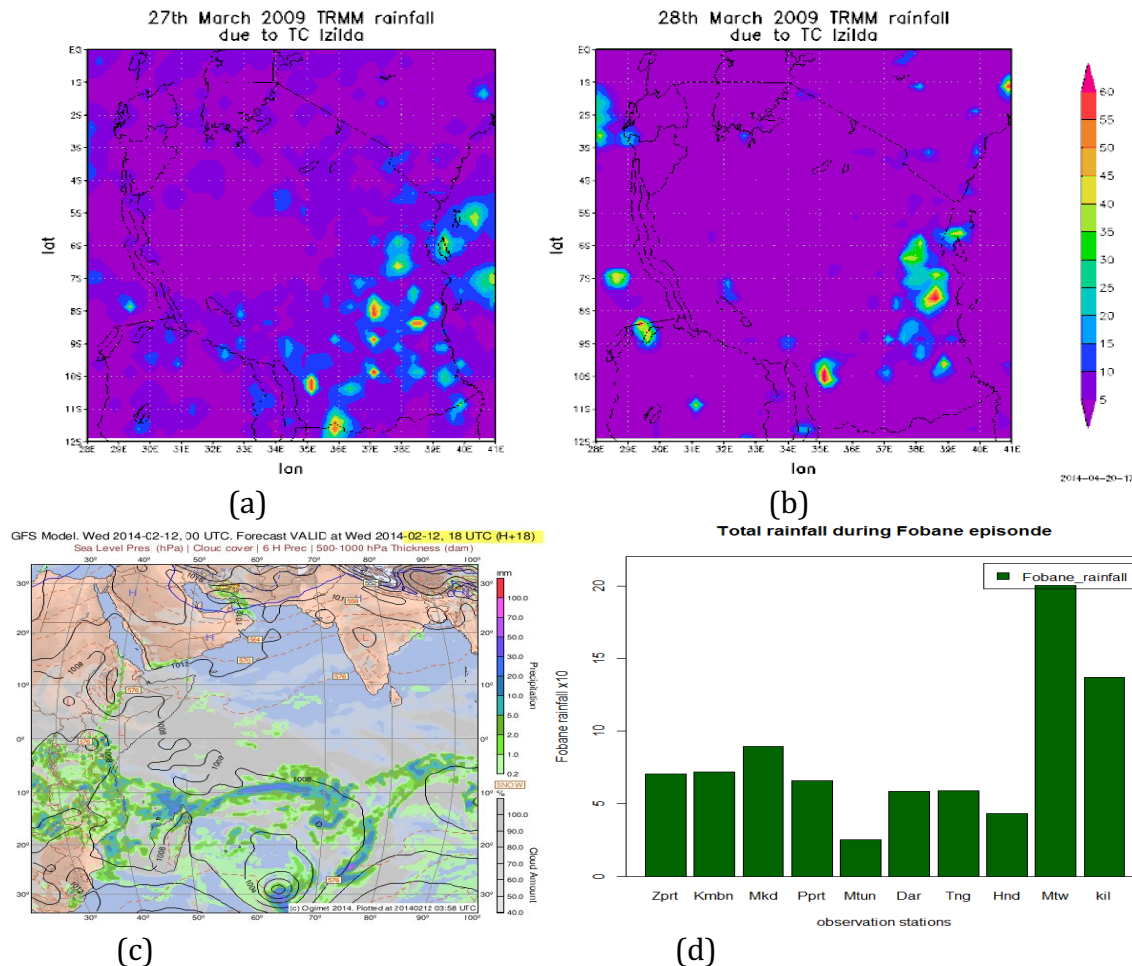


Figure 4: Rainfall conditions during the TC Izilda (a & b); Fobane (c & d). Note that (d) is the GFS model forecast for 12th Feb 2014 (source OGIMET; http://www.ogimet.com/tabla_predEQ.phtml);

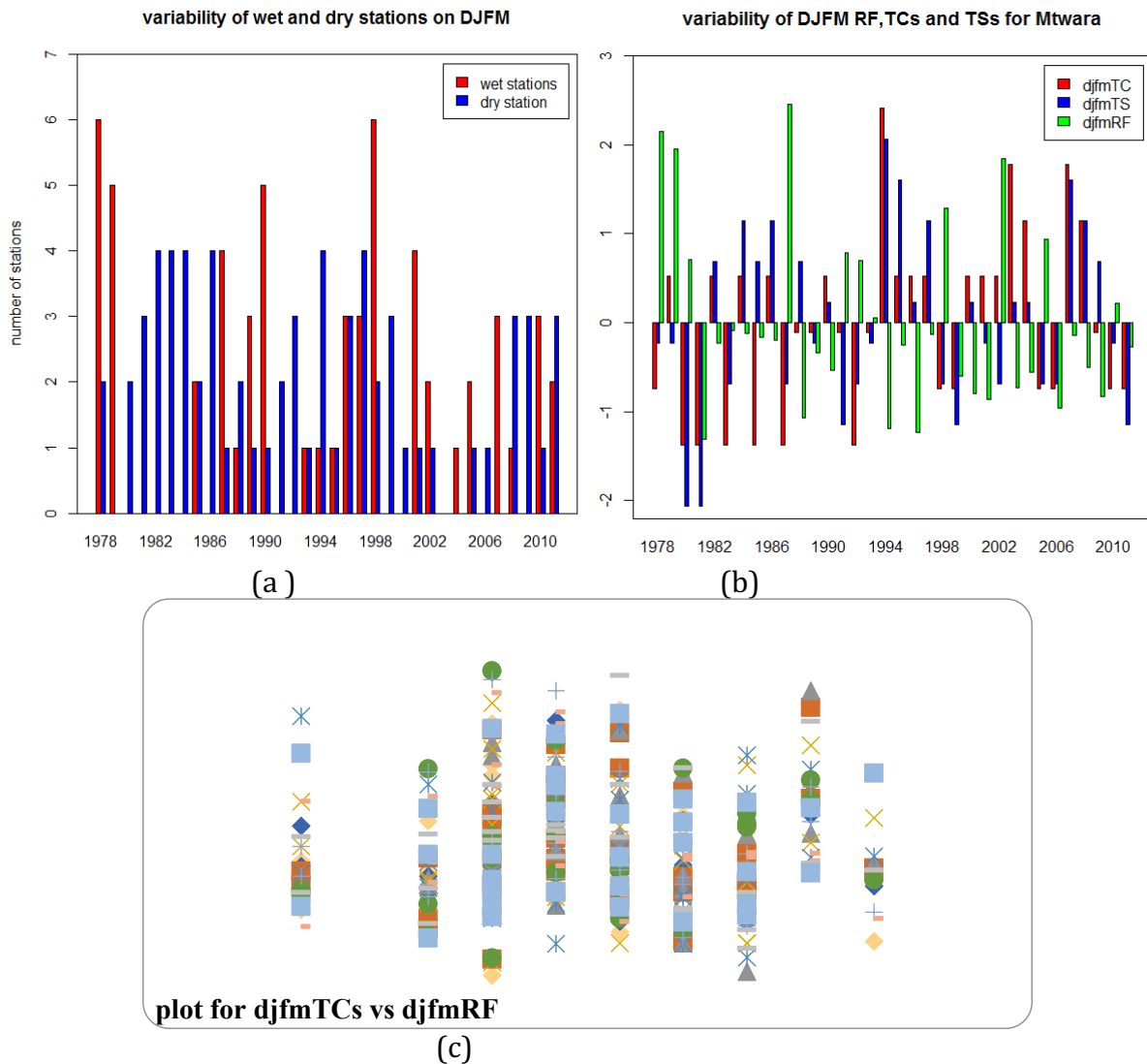


Figure 5: Inter annual variability of standardized anomalies for DJFM rainfalls, TSs and TCs, (a); wet and dry stations for DJFM seasons associated to low and high TCs conditions; (b) inter annual variability of TCs; TSs and NDJFM rainfall over Mtwara (c) scatter plot for standardized anomalies of DJFM rainfall and TCs, TSs for all 11 stations of (Figure 1)

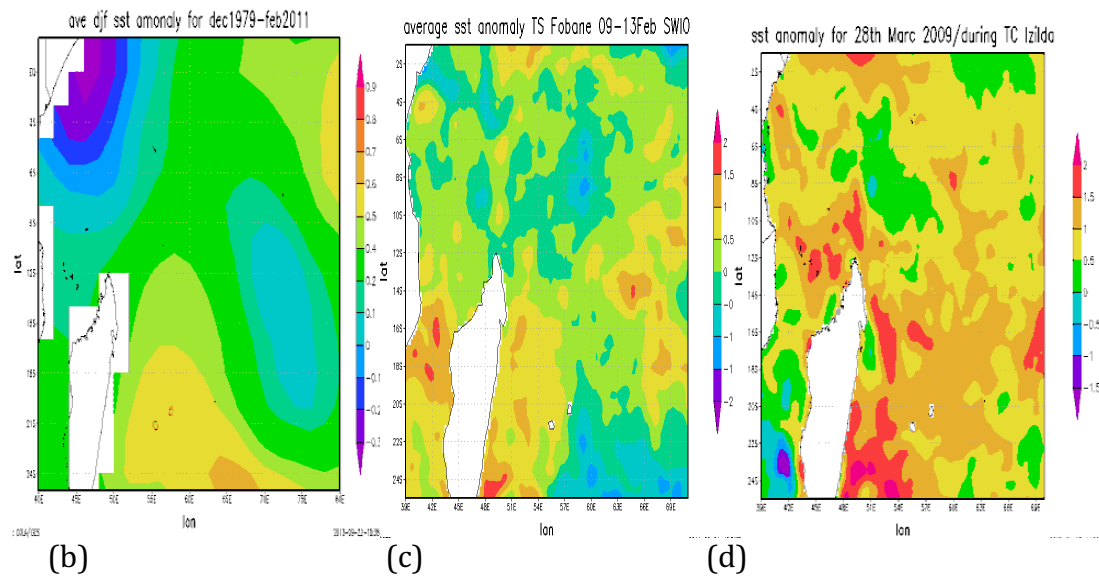


Figure 6: Climatology of SST anomalies for SON and DJF (a & b) as well as anomalies for specific events of Izilda (March 2009) and Fobane (Feb 2014) (c & d) over SWIO

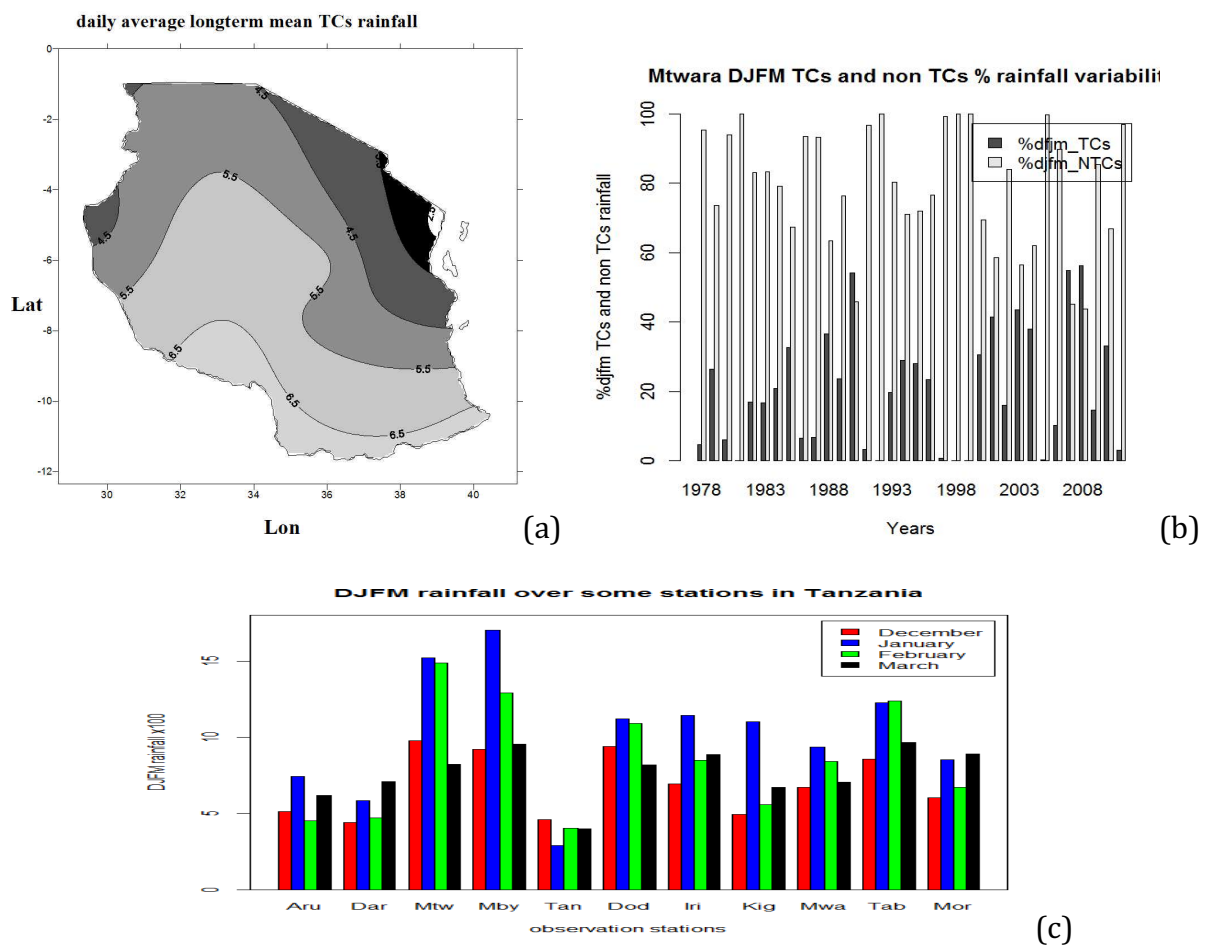


Figure 7: Spatial map for daily average TCs rainfall (a); % contribution of DJFM TCs rainfall over Mtwaru (b) and (c) total four months TCs rainfall over stations in (Figure 1)

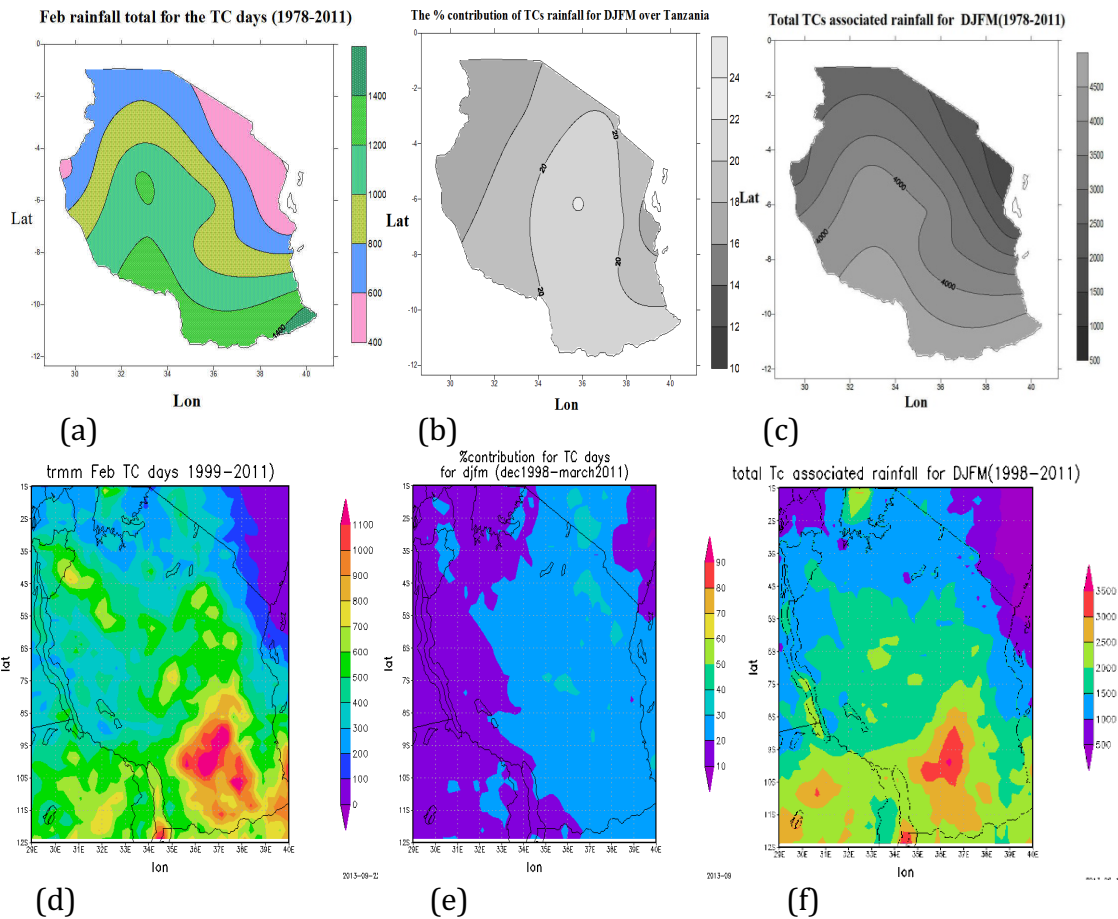
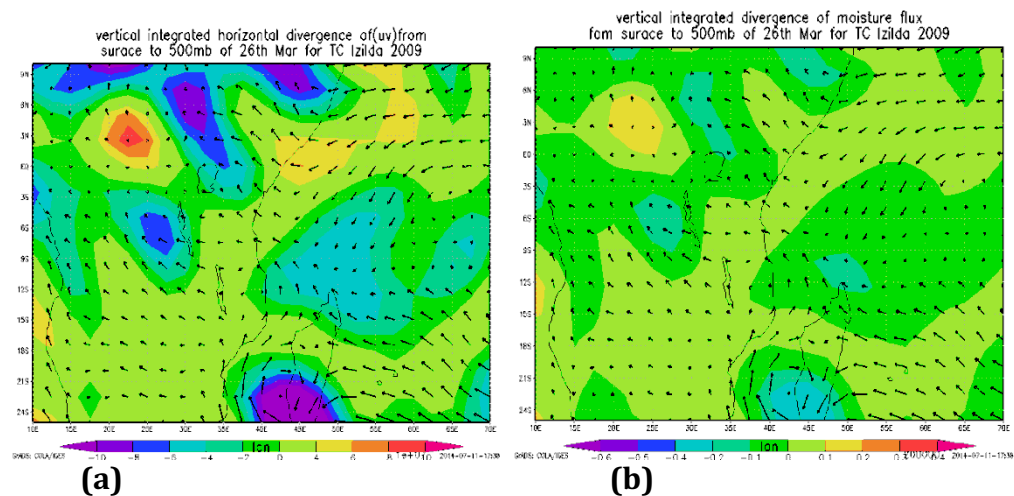


Figure 8: In situ and gridded TCs based rainfall contributions for DJFM; (a) In situ February contribution (a) In situ % contribution (d) In situ December –March TCs rainfall contribution; (d, e and f) same as (a, b and c) but for TRMM data



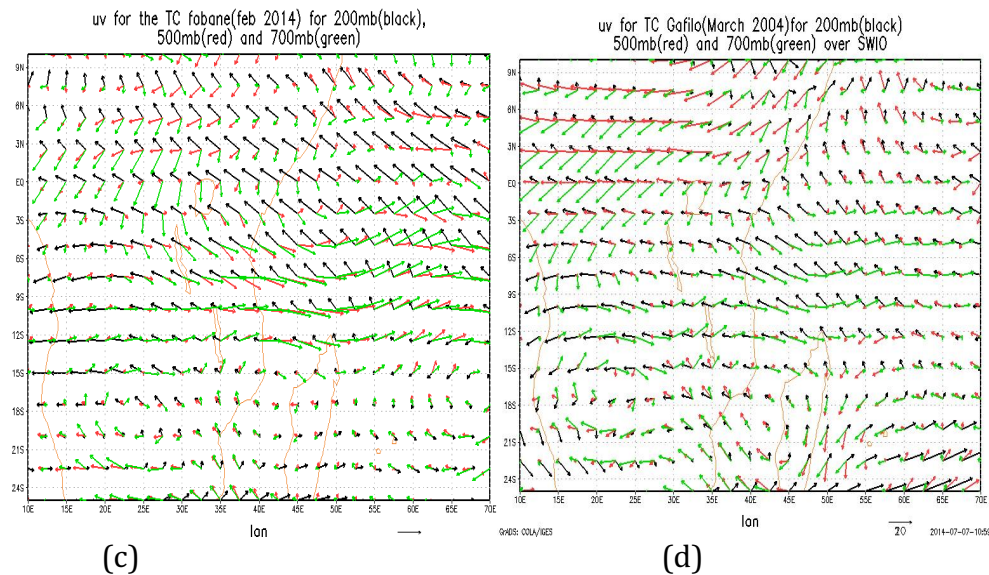


Figure 9: The derivatives of u , v and specific humidity during TCs season over SWIO; (a) overlay of the integrated wind vector and their horizontal divergence from surface to 500 mb for the TC Izilda (b) same as (a) but for moisture flux vectors (q_u , q_v) and its integrated divergence from surface to 500mb; (c & d) overlay of the wind vectors for 700 mb (green), 500 mb (red) and 200 mb (black) for TCs Fobane and Gafilo